The evolution of the East African margin offshore Mozambique: Geotectonic History and Petroleum System Analysis

Von der Naturwissenschaftlichen Fakultät
der Gottfried Wilhelm Leibniz Universität Hannover
zur Erlangung des Grades

DOKTOR DER NATURWISSENSCHAFTEN
Dr. rer. nat.

genehmigte Dissertation

von

Estevão Stefane Mahanjane BSc (Honours) in Geology, Lic.

geboren am 07. März 1974 in Alto-Changane, Mosambik

2014

Schlagworte: Mosambik, Beckenentwicklung, Erdöl-Systeme

Referentin: Prof. Dr. Jutta Winsemann

Korreferent: Prof. Dr. Bernhard Cramer

Korreferent: Prof. Dr. Stefan Weyer

Tag der Promotion: 16.06.2014

ABSTRACT

The East African margin offshore Mozambique is a frontier area that is underexplored and might contain considerable hydrocarbon reservoirs. This study provides new results regarding the overall geodynamic evolution of the region, especially the structural response to the initial rifting of Gondwana and the formation of new oceanic crust, the definition of the architecture of the Mozambique margin, and implications of the margin type for the stratigraphic, structural, and thermal history of the basin. This study also aimed at contributing to the understanding of the structural setting along the Davie Fracture Zone and the Rovuma Delta basin. The data sets include information from regional paleogeographic reconstructions, boreholes, and seismic reflection profiles used to depict events defining tectonic settings, and the lithostratigraphy of the possible source rocks for the petroleum system modelling. The structural evolution of the Mozambique margin is defined into a two rift stage break-up of Gondwana. The rifts are separated by a stretched continental zone, which forms a transitional zone along the Mozambique Coastal Plain. The break-up stage 1 encompasses the regional Karoo continental flood basalt formed by Karoo magmatism during the pre-rift and syn-rift stages of the continental separation around 182 ± 2 Ma. The presence of thick volcanic successions within the Zambezi depression associated to the activity of the Angoche coastal dykes at ~170 Ma explains the final stage of rifting phase and break-up stage, and the onset of oceanic sea-floor spreading. The transitional crust is overlain by widespread buried lava sheets (seaward-dipping reflectors) thickening up to ~ 13 km eastwards from the Lebombo-Limpopo Monoclines. The basin settings indicate significant episodes of rapid thermal subsidence accumulating more than 5 km of sediments in the Zambezi Delta depression and ~ 3 km in the Angoche basin shortly after the opening of the oceanic basin between Middle Jurassic and Aptian time. This occurred during the separation between the Mozambique basin and the conjugate Riiser Larsen Sea which is synchronous to the opening of the Somali and the Rovuma basins along the Davie Fracture Zone. A detailed seismic mapping of the offshore Rovuma deltaic system using data from 1990ies vintage identified two major arcuate complexes of a linked compressional and extensional system. While the Davie Fracture Zone discloses two settings: the detached compressional unit with prominent trailing thrust imbrications of massive growth wedge structures predominate in the south, and an extensional regime is abundant towards the north with symmetric grabens which are reactivated by the East Africa Rift System. The basement of the Zambezi depression and Angoche basins is made-up of thick volcanics associated with a significant increase of the basal heat-flow. The thermal and burial conditions were reconstructed by using 1-D and 2-D models (Petromod). The results indicate a premature primary cracking process of the Jurassic successions starting in Tithonian and migration in Aptian time. Except for the Zambezi depression where heat-flow continuously increased with the delta deposition, the distal Zambezi Delta and Angoche area experienced slow subsidence and a decreased sedimentation rate from Aptian onwards, keeping the source rocks active until the present time.

Key-words: Mozambique, basin evolution, petroleum systems

KURZFASSUNG

Die strukturelle und thermische Entwicklung des ostafrikanischen Kontinentalrandes vor Mosambik ist bisher nur wenig erforscht Diese Studie beantwortet wichtige Fragen der geodynamischen Entwicklung der Region, insbesondere die Entwicklung des initialen Riftings von Gondwana, die Bildung neuer ozeanischer Kruste, die Rekonstruktion der Architektur des mosambikanischen Kontinentalrandes sowie die nachfolgende stratigraphische, strukturelle und thermische Entwicklung der Sedimentbecken. Die Untersuchungen liefern auch einen Beitrag zum Verständnis der strukturellen Bedingungen entlang der Davie-Bruchzone und des Rovuma Delta-Beckens. Dazu wurde eine integrierte Studie durchgeführt, in die Informationen aus regionalen paläogeographischen Rekonstruktionen, Bohrungen und seismische Reflexionsdaten eingegangen sind. Mit Hilfe dieser Daten wurden strukturgeologische und lithostratigraphische Einheiten definiert. Nachfolgend wurden mögliche Muttergesteine für die Modellierung eines Kohlenwasserstoff-Systems identifiziert, um eine Höffigkeitsbewertung zu ermöglichen. Die strukturelle Entwicklung des mosambikanischen Kontinentalrandes lässt sich durch zwei unterschiedliche Riftstadien erklären. Diese Riftstrukturen werden durch eine Zone gedehnter kontinentaler Kruste getrennt, die eine Übergangszone entlang der Küstenebene von Mosambik bildet. Die Riftphase 1 umfasst die Bildung des regionalen kontinentalen Flutbasalts, der durch den Karoo Hotspot während der pre-rift- und syn-rift Phasen vor 182 ± 2 Ma gebildet worden ist. Mächtige magmatische Gesteine in der Sambesi-Senke verbunden mit der Dyke-Aktivität im Bereich der Angoche-Küsten mit einem Alter von ca. 170 Ma markieren die Rifting-Phase 2 und den Beginn der ozeanischen Meeresbodenspreizung. Die Kruste der Übergangszone wird durch weit verbreitete Lavadecken überlagert (gekennzeichnet durch seewärts einfallende seismische Reflektoren), deren Mächtigkeit östlich der Lebombo-Limpopo-Monoklinale auf bis zu ~13 km zunimmt. Die Beckenstrukturen zeigen markante Episoden schneller thermischer Absenkung, während derer kurz nach der Öffnung des ozeanischen Beckens zwischen dem mittleren Jura und dem Apt mehr als 5 km Sedimente in der Senke des Sambesi-Deltas und ~3 km Sedimente im Angoche-Becken abgelagert wurden. Dies geschah während der Trennung des Mosambik-Beckens von der konjugierten Riiser–Larsen-See, welche synchron mit der Öffnung des Somali-Beckens und des Rovuma-Beckens entlang der Davie-Bruchzone erfolgte. In einer detaillierten seismischen Kartierung des Rovuma-Deltasystems wurden zwei große bogenförmige Komplexe eines verbundenen Kompressions- und Extensionssystems definiert. Während die Davie-Bruchzone vornehmlich im Süden mit der abgelösten Kompressionszone mit den dahinter liegenden prominenten Überschiebungen von massiven Keil-Strukturen in Verbindung steht, herrscht in Richtung Norden ein Extensions-Regime mit symmetrischen Gräben vor, die durch das Ostafrikanische Rift-System reaktiviert wurden. Das Basement der Sambesi-Senke und des Angoche-Beckens besteht aus mächtigen Vulkaniten, die mit einer signifikanten Erhöhung des basalen Wärmeflusses einhergehen. Die thermischen Bedingungen und die Versenkungsgeschichte wurden unter Verwendung von 1-D und 2-D-Modellen bewertet. Die Ergebnisse weisen auf untermature primäre Cracking-Prozesse in den Jurassischen Folgen ab dem Tithonium und Migration im Apt hin. Mit Ausnahme der Sambesi-Senke, wo der Wärmestrom mit der Ablagerung des Deltas kontinuierlich anstieg, erfuhren das distale Sambesi-Delta und das Angoche-Becken eine langsame Absenkung und eine verminderte Sedimentationsrate vom Apt an. Daher sind die Muttergesteine bis in die Gegenwart vermutlich aktiv.

Table of Content

1. Introduction

1.1 Motivation and Goals

The East African margin offshore Mozambique (Figure 1.1) is a frontier area that is considerably underexplored. Despite the extraordinary exploration activities for the last seven years in the offshore Rovuma basin with massive gas discoveries (Law, 2011; Ladesma, 2013) adding to the onshore gas reserves, the long-standing academic interest in the volcanic passive margins, and the deep-water fold-and-thrust belt systems, little has been published about the petroleum systems, the Rovuma Delta, and the Davie Fracture Zone. The source rocks as one of the essential elements of the petroleum system (Magoon and Dow, 1994) remain unknown in Mozambique. The issue of the source rocks can be associated to some major open questions related to the evolution of this margin, which ascertain conditions of the early sedimentary deposition established in the basins immediately following their formation. Tentative investigations of source rocks (e.g. De Buyl and Flores, 1984; Nairn et al., 1991; Salman and Abdula, 1995) were performed focused on the Cretaceous and Tertiary litho-stratigraphies, and considered the basin to be gas-prone and immature. An alternative approach focusing on aspects linking the basin evolution and depositional environment to predict occurrence of the source rocks was based on the evidence from the conjugate margins and is presented in this study. It is anticipated that a syn-depositional euxinic environment is the most appropriate and unique environment for development of anoxia conditions essential for the source rock formation and preservation.

However, it is a fact that some issues related to processes of formation of the Mozambique continental margin still prevail, such as

(1) *the timing of the break-up, the character of the processes affecting the separation of the blocks, and the formation of new oceanic crust*;

(2) *the location of the boundaries between continental-transitional-oceanic crusts to define the type of the basement across the Zambezi depression and the un-discussed Beira High;*

(3) *the evolution of the Davie Transform and the development of the adjacent basins, and*

(4) *the tectonic setting of the Rovuma Delta basin is unknown*.

The first three concerns are related to the prediction of the early depositional sediments and the influence of the basement rocks on the basal heat-flow production.

At present, the discussion regarding the geotectonic history and evolution of the Mozambique margin is advocated by the Gondwana break-up concept. The origin of rifting and the break-up has been postulated by the theory of the Karoo hotspot generating mantle plumes that facilitated a spontaneous break-up of Gondwana at 182±2 Ma (Duncan et al., 1997; Riley and Knight, 2001; Svensen et al., 2012; Reeves and Mahanjane, 2013). In the south, the Mozambique margin is formed over a proto-oceanic rift accompanied by extensive volcanism associated to intrusive events (Klausen 2009), whilst the northern part of the margin where the Rovuma basin formed lies over transform margin settings. The rifting process has influence on the rate of the heat-flow, local rates of subsidence, and sediment accumulation, i.e., the stratigraphic, structural, and thermal history of the basin. Therefore, there is a direct implication for the geology and petroleum prospectivity due to the close relationship between the early heat-flow enhancement and the initial plume development, extensive volcanism and/or magmatic extrusions which normally continue into the post-break-up phase and contribute to the quality of source rock maturity.

The study was conducted in cooperation with the Federal Institute for Geosciences and Natural Resources (BGR) of Germany, which provided logistics, scientific advice and data collected over the Zambezi Delta area in 2007 with the purpose of investigation of the Mozambique basin in terms of its structure and formation history with special focus on the hydrocarbon potential. An additional dataset from the commercial industry was made available by the National Petroleum Institute of Mozambique (INP) as part of ongoing exploration projects. A full grant was provided by the INP for fulfilment of the studies.

This study aims at contributing to an innovative approach for the basin evolution and interactive processes by providing a link between the geodynamic history of the margin, the tecto-stratigraphy, and its implication for the petroleum system. This study also intends to contribute to a better understanding of the tectonic setting along the Rovuma Delta basin and the evolution of the Davie Transform and formation of the adjacent basins. New and published data are combined in various geophysical methods and modelling software to present evidence for the geodynamic evolution of the northern part of the margin. The results of the different analyses and models are interpreted and discussed.

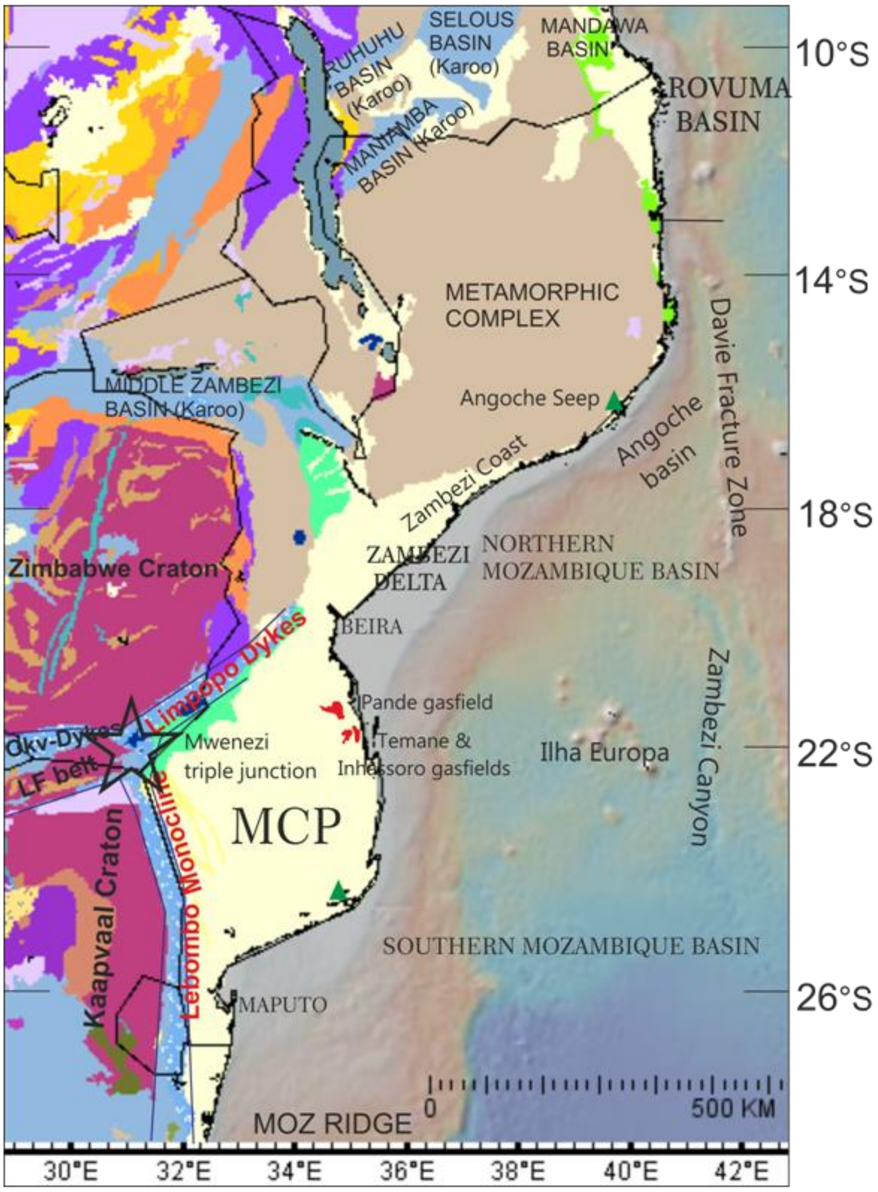


Figure 1.1 - Geological sketch map of SE Africa (after Ryan et al., 2009: the Lamont-Doherty Earth Observatory of Columbia University: http://www.geomapapp.org;) comprises important tectonic structures: the Mozambique sedimentary basins, the Archean cratons and the Karoo sedimentary and volcanics. The black star shows postulated Karoo-Mwenezi hotspot centre. Keys: MCP - Mozambique Coastal Plain, Okv-Okavango.

1.2 Petroleum Potential

Passive margins are important reservoirs of petroleum (oil and gas), which are important resources for many spheres of life. Large proportions of oil and gas are found at continental passive margins. For instance, these margins and continental rift basins account for 66% of the world's giant oil fields (Mann et al., 2003). Therefore, passive margins are petroleum storehouses because they are associated with favourable conditions for accumulation and maturation of organic matter. They develop anoxic basins in the early continental rifting; large sediment and organic flux, and the preservation of organic matter may contain oil and gas reserves.

The Mozambique continental margin can be regarded as an example of the East Africa margin proving the existence of an active petroleum system in both onshore and offshore sedimentary basins. The recently discovered massive gas fields (~ 2800 billion cubic meters) in the offshore Rovuma Delta basin (e.g. Ladesma, 2011) added to 130 billion cubic meters of the proven gas reserves in the onshore Mozambique basin (Instituto Nacional de Petróleo archives).

Besides the Mozambique margin, prospectivity of the remaining East African passive margin is indicated by the proven reserves reported in the MnaziBay, Songo-Songo, and Deep Sea gas fields in Tanzania (http://www.tpdc-tz.com/tpdc/). In addition, significant active oil and gas seeps preferably distributed along the Davie Fracture Zone from Tanzania to the Mozambique margin have been reported (ECL and ENH, 2000; Maenda and Mpanju, 2003).

In the Mozambique margin, the major question, however, concerns the source rocks. The result of drilling in the entire margin deeper than 4,500 m (e.g. Zambezi Delta) has not yet sampled a source rock of the reported oil shows and gas discoveries. Possible source rocks of Lower Cretaceous shale have been previously discussed (De Buyl & Flores 1986; Nairn et al., 1991; Salman and Abdula, 1995; ECL and ENH, 2000). The investigation of the petroleum systems in this work took into consideration the results of these authors. They are known only from the subsurface, and consisting of dark grey to black, thinly bedded, marly shale (Nairn et al., 1991). However, this study also focuses on potential Middle and/or Late Jurassic marine oil-prone source rocks which are restricted to syn-and post-rift basins along the Mozambique margin and deeply buried under thick young sediments. The maturity modelling of the source rocks in the Mozambique margin basins indicate a prolific thermal maturation and predicts timing and locations of hydrocarbon generation in the underexplored Zambezi Delta and Angoche basins in the northern Mozambique basin (Mahanjane et al. in review). The prospectivity indicated by this study calls for future exploration in the study area, including the Davie Fracture Zone. The results are supported by mapping both the variety of geometrically robust structural and stratigraphic play types, preserving similar configurations with those pooling hydrocarbons in the Rovuma basin.

1.3 Overview of the thesis and content of publications

The results of this scientific research are presented in four publications, covering the questions arose in section 1.1, and provides an insight into the evolution of the northern Mozambique margin.

Publication 1: A geotectonic history of the northern Mozambique basin including the Beira High - A contribution for the understanding of its development by Estevão Stefane Mahanjane, published in *Mar. Pet. Geol. 36 (2012) 1-12.doi:10.1016/j.marpetgeo.2012.05.007*

This study contributes to an innovative understanding of the geodynamics of the region, which play an important role for understanding the petroleum system. The tectonic and geological history of the northern Mozambique margin was investigated by interpretation of extensive two-dimensional seismic reflection data integrated with the analysis of paleogeographic models to depict the main structural elements, which are related to the process of Gondwana break-up and formation of the oceanic basins. Two rift phases are identified, leading to the establishment of the two break-up stages concept. The nature of the topographic high structure (Beira High) is studied by the rheology disclosing predominance of extensional deformation along the eastern edge, characterized by typical half-graben morphologies. In addition, the location of the oldest sea-floor magnetic anomaly (155 Ma) adjacent to the extensional domain suggests that at least part of it has a continental origin.

Publication 2: The Rovuma Delta deep-water fold-and-thrust belt, offshore Mozambique by Estevão Stefane Mahanjane and Dieter Franke, published in *Tectonophysics 614 (2014) 91–99, http://dx.doi.org/10.1016/j.tecto.2013.12.017*

This publication is a pioneer scientific work in the northern Mozambique margin. The paper provides a detailed description of the general appearance of deformational tectonic mechanisms along the deltaic system. The findings from this study depict two arcuate complexes within the Rovuma Delta formed by a gravity gliding system during the Miocene. The complexes are a classic linked system of a down-dip fold-and-thrust belt to an up-dip extension via shale-detachment. The shale-detachment shows a different rheology and thickness which define the style of the thrust system, varying between a single detachment surface and multiple detachments with thrust duplexes.

Publication 3: The Davie Fracture Zone and adjacent basins in the offshore Mozambique Margin – A new insight for the hydrocarbon potential by Estevão Stefane Mahanjane, submitted to *Marine and Petroleum Geology Ms. Ref. No. JMPG-D-12-00292R1*.

This publication gives an overview of the tectonic settings in this frontier area by focusing on the structural evolution along the Davie Fracture Zone during the active time. The main findings present two tectonic settings: The compressional tectonics is evident in the south and extensional tectonics in the north. The compressional tectonics form the Davie compressional zone, a prominent interior high running approximately north-south, is characterized by an event of transpression and contraction hosting several detached compressional structures with prominent trailing thrust imbrications of massive growth wedge morphology along the western edge of the Davie Fracture Zone. The compressional zone bounds two depressions; the Angoche basin is the southern depression which is formed by thermal subsidence during the opening of the Mozambique Channel. The Nacala basin is the northern depression which resulted from extensional tectonics subsequent to cessation of the transpressional phase, being later overprinted by the Late Cenozoic East African Rift System.

Publication 4: Maturity and petroleum systems modelling in the offshore Zambezi Delta depression and Angoche basin, northern Mozambique by Mahanjane, E.S.; Franke, D.; Lutz, R.; Winsemann, J., Ehrhardt, A.; Berglar, K. and Reichert, C., submitted to *Journal of Petroleum Geology*

This publication presents a reconstruction of the basin and an assessment of the hydrocarbon potential along the northern Mozambique basin. The study integrated reflection seismic data and modern basin modelling techniques to reconstruct the structural, burial and thermal histories of the basin. The structural and depositional history was determined by analogies of the paleogeographic reconstruction models to depict the appropriate timing for deposition of the possible source rocks. The assessment of the petroleum system used integrated information from the conjugate Dronning Maud Land Ocean Drilling Program (ODP) Leg 113 data, borehole data, and reflection seismic data. The 1-D and 2-D reconstruction models provide information of the thermal evolution, timing, and generation of hydrocarbons in the northern Mozambique basin. Except for the deeply subsided centre of the Zambezi Delta with early depletion and overmaturation, a prolific thermal maturation is found for the entire remaining northern Mozambique basin. All simulation models show secondary cracking of oil to gas which began in the Barremian.

2. Regional geological setting

2.1 Volcanic passive margins – some general aspects

The volcanic rifted margins described in the literature are established through continental break-up associated with the eruption of flood volcanism during pre-rift and/or syn-rift stages of continental separation (Courtillot et al., 1999, Menzies et al., 2002). In the active rift model the rupture is driven by hotspot or mantle plume activity. The basic principle shown in Figure 2.1 requires deeper melt generation and subsequent interaction with the continental lithosphere (Menzies et al., 2002). Plumes upwelling of hot mantle (mantle plumes) originate deep in the Earth and rise to heat and thin the lithosphere (Clive et al., 2008). According to Geoffroy (2005), when the lithosphere is heated, it gradually thins, weakens, and rises, until rifting and enhanced melting follows continental breakup, creating thicker than normal oceanic crust which sometimes reaches thickness between 10 and 40 km (Coffin and Eldholm, 1994; Eldholm and Coffin, 2000; Geoffroy, 2005; Coffin et al., 2006). Importantly, the early phase of volcanic activity produces extensive accumulations of basalts, rhyolite and other felsic rocks (Coffin and Eldholm, 1994, Menzies et al., 2002).

Commonly, the mantle upwelling is related solely to convection (Coffin et al., 2006) forming a pot of magma radiating to the surface as dyke swarms and sills. Repeated eruptions form a thick sequence of lava beds reaching a combined thickness of up to 20 km. These beds are identified on seismic reflection sections as seaward dipping reflectors of lava flows (Coffin and Eldholm, 1994, Menzies et al., 2002; Franke, 2013) and high-velocity ($V_p > 7.3$ km/s) lower crust seaward of the continental rifted margin (Franke, 2013). Hence, the geophysical evidence is an equivocal proof for the origin of plumes in the deep or shallow mantle, which characterize the transitional crust (Menzies et al., 2002). These zones are characterized by typical seismic velocities between 7.2-7.7 km/s and are usually interpreted as layers of mafic to ultramafic rocks that have underplated the transitional crust (Coffin and Eldholm, 1994, Menzies et al., 2002).

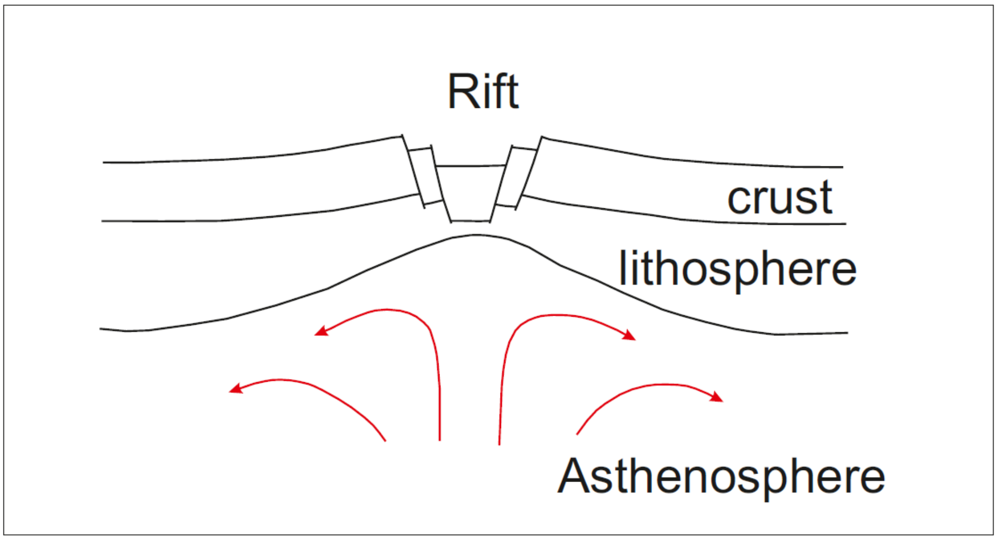


Figure 2.1 - Cartoon illustrating model of an active rifting mechanism (after Turcotte and Emerman, 1983). Arrows show processes which thin the lithosphere by ascending mantle convection, finally causing crustal doming and rifting

Volcanic eruptions are continuous processes spreading lava flows across transitional crust and onto oceanic crust. Due to the high rate of magmatic activity, the newly formed oceanic crust is much thicker than typical oceanic crust (Menzies et al., 2002).

The final post-rift phase is the basin-fill stage following the continued thermal subsidence of the transitional crust and the accumulation of sediments. Progressing sea-floor spreading leads to the formation of oceanic crust of normal thickness. Over time, this production of normal oceanic crust and sea-floor spreading leads to the formation of an oceanic basin (Menzies et al., 2002).

2.2 The structural evolution of the Mozambique volcanic passive margin

The evolution of the East African Mozambique margin is associated to the evolutionary scenario of the Karoo plume since 200 Ma, which caused the break-up between Africa and Antarctica (Segev, 2002). The plate reorganization of the Jurassic Gondwana large igneous province is more evident from the tectonic and geochemical relationships of the Ferrar and Karoo magmas suggesting a single important magma source juxtaposing the triple junction of the conjugate in the proto-Weddell Sea region (Elliot and Fleming, 2000) and the Mwenezi (or Karoo) proto-oceanic rift (Reeves, 2009; Reeves and Mahanjane, 2013). Both triple junctions are reconstructed into the Gondwana Supercontinent fit placed at Mwenezi at

~182Ma (http://www.reeves.nl/gondwana), to explain the Karoo/Bouvet hotspot (Reeves, 2009; Reeves and Mahanjane, 2013). In this model, rift-rift-rift triple junctions controlled by basement structure were generated by plume activity. The Zimbabwe and Kaapvaal cratons as well the Limpopo belt (Figure 1.1) influenced the structural development and configuration of the triple junction significantly by restricting magmatism and dyke injections. The triple arms, the northern Lebombo, Okavango, and Limpopo dyke swarms (Figure 2.2) were formed by a remarkably short-lived plume at 181-178.9 ± 1.4 Ma (Klausen, 2009; Elburg and Goldberg, 2000).

As the rift mechanisms is explained in the previous section, the Mwenezi triple rift formation is hypothetically driven by upwelling processes releasing large volumes of magmas and emplacement of dyke swarms radiating outwards in three directions from the hotspot. Theoretically, an active mechanism of rifting volcanism is triggered by the impingement of a mantle plume, causing regional updoming associated with uplift and the traction forces on the base of the lithosphere (Turcotte and Emerman, 1983).

The initiation time of the mantle plume has been reliably dated by ^{40}Ar/^{39}Ar and U-Pb Zircon methods from dykes in Gondwana (Svensen et al., 2012). The method records a short period of 3-4 Myr for the emplacement of the Lebombo Group (Karoo province) at approximately 183 ± 1 Ma (Svensen et al., 2012; Riley and Knight, 2001; Klausen, 2009; Duncan, et al., 1997) which preceded the successful initial break-up of Gondwana (Mahanjane, 2012). The impact of the very widespread Karoo plume activity resulted in significant uplift leading to the break-up between West and East Gondwana along the proto-oceanic rift between the Weddel Sea and the Somali basin (Segev, 2002). Drift of these blocks initiated as soon as the Proto-oceanic rift began opening associated to the eruption of very large volumes of dominantly basaltic magmas (Riley and Knight, 2001).

It turns out, however, that movement of East Gondwana was of dextral strike-slip along the Lebombo-Explora Fracture Zone to the west and the Davie Fracture Zone to the east (Figure 2.2), which define the limits of Africa-Antactica Corridor (Reeves, 2009). The evidence for spreading rifting is the age difference of the magma emplacement along the axis of the rift propagation from the Karoo hotspot. The evolution of the Lebombo-Explora Fracture Zone aided for magma emplacement along its axis, e.g. the short-lived ~ 1 Myr emplacement of the Ferrar tholeiites at ~ 180 Ma (Elliot and Fleming, 2000) and southern Lebombo MORB-like Rooi Rand dyke swarms at ~ 174 Ma (Riley and Knight, 2001). Hence, this provides a complete analogy on the African side by the Lebombo (Karoo) and on the Antarctic side by the west Explora Wedge, which gives insight into volcanism impingement accompanying Stage 1 of the break-up.

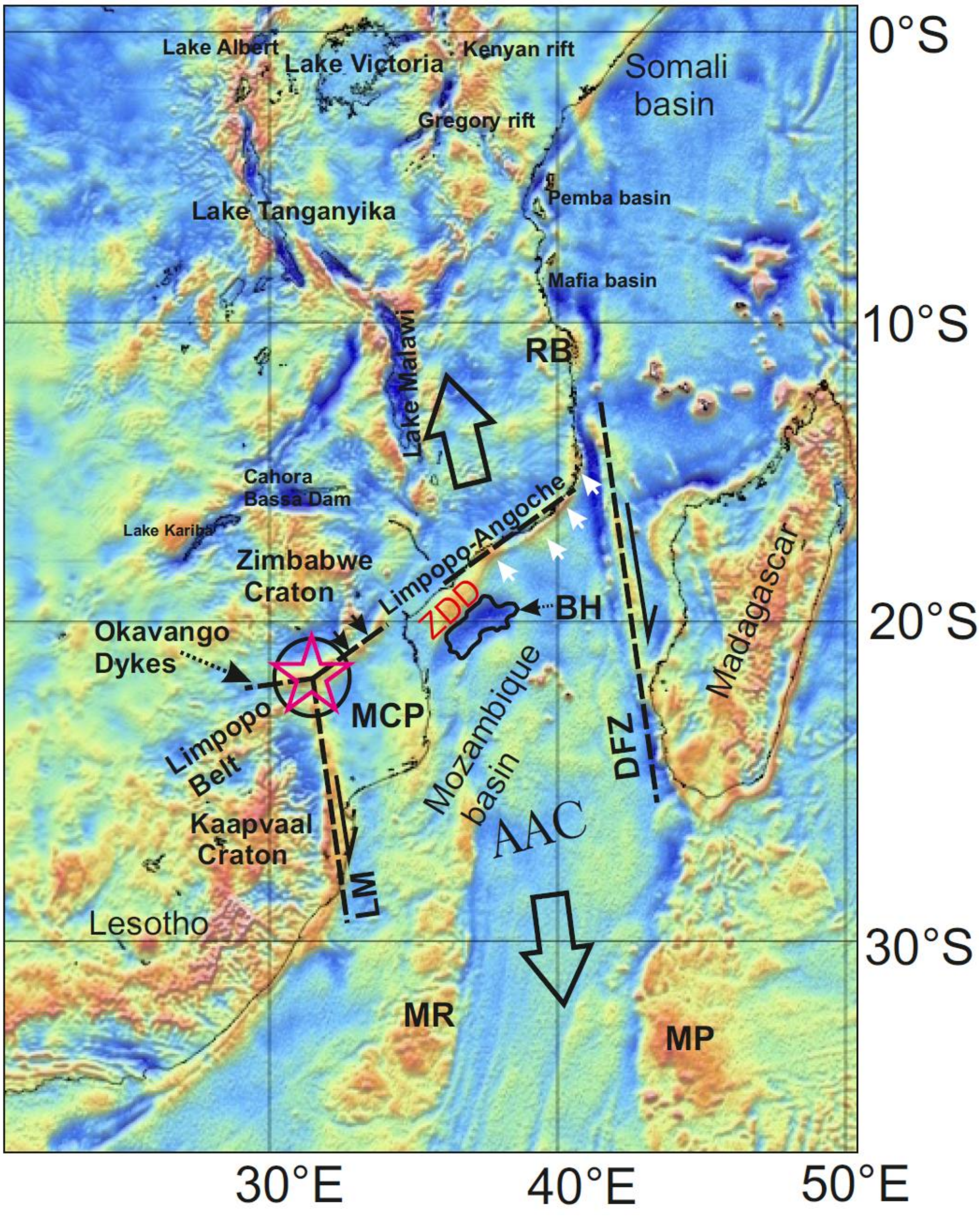


Figure 2.2 - Gravity anomaly map derived from satellite altimetry data (Sandwell and Smith, 2009) showing structural features of the Mozambique margin. The circle and red star show postulated Karoo hotspot centre which radiated in the three rift-rift-rift junctions composed of Lebombo monocline, Okavango dyke swarms and Limpopo-Angoche dyke swarms. The black arrows show initial rift volcanics, and white arrows are the youngest dykes along the Zambezi and angoche areas. Keys: AAC-Africa-Antarctica-Corridor, BH-Beira High, DFZ-Davie Fracture Zone, LM-Lebombo monocline, MCP-Mozambique Coastal Plain, MR-Mozambique Ridge; MP-Madagascar Plateau; RB-Rovuma basin; ZDD-Zambezi Delta depression.

According to Menzies et al. (2002), the inner seaward-dipping reflectors overlay transitional continental crust and postdate flood volcanism, synchronous with the syn-rift transition on the continental margin. They are composed of varying mixtures of subaerial volcanic flows, volcaniclastic and non-volcanic sediments which range in width from 50–150 km and are 5–10 km thick. In the Mozambique Coastal Plain, buried deposition of seaward-dipping reflectors has been described in the onshore seismic reflection data. They thicken eastwards up to 13 km (Anderson et al., 2013). They correlate pretty well with the conjugate western part of Explora Wedge (Hinz, 1981). In this view, the plains would resemble into a transitional crust (Leinweber and Jokat, 2011).

The gravity anomaly map of Figure 2.2 shows discontinuity of aerial magmatism along the Limpopo-Angoche rift-segment. This can be understood in the way that the "jump" indicates interruption of aerial plume magmatism as the continental stretching occurs. Likewise, it corroborates with seaward-dipping reflectors indicating a change in the magmatic source area from the Lebombo-Limpopo dykes to emplacement of the youngest Angoche coastal dykes at ~ 170 Ma (Reeves, 2000). This occurred when the north - south Lebombo Monocline came under compression because of plume activity. By then, capacity to extend further east (Cox, 1992) was limited due to anticlockwise rotation of Antarctica (with the Beira High) with respect to Africa (Leinweber and Jokat, 2012). The interpretation of rifting along the coastal Zambezi area is confirmed by a symmetrical graben setting along the Zambezi depression filled with thick volcanics (Mahanjane, 2012). Around 170-167 Ma during the Middle Jurassic (Bajocian-Bathonian) the spreading regime changed (Mahanjane, 2012; Anderson et al., 2013): Rift I is aborted in the offshore Zambezi depression area and Rift II started along the eastern edge of the Beira High, forcing East Gondwana to move southward. Deformational tectonic is dominated by extensive stretching and extensional tectonics forming tilted blocks within the central eastern part of the Beira High culminating in the break-up stage 2. Finally, the Beira High separates from Antarctica and remains part of the African plate (Mahanjane, 2012). This is also supported by interpretation of the onset of oceanic crust at the eastern Beira High where the break-up unconformity lies over the basement near the location of the sea-floor magnetic anomaly M26r (155.4 Ma) (Leinweber and Jokat, 2012). This anomaly gives the minimum time for the separation between the Mozambique basin and the conjugate Riiser Larsen Sea which is synchronous to the opening of the Somali basin and the Rovuma basin along the Davie Fracture Zone between mid-Jurassic and Aptian.

By interpretation of onshore dyke swarms, predominance of seaward dipping reflectors along the plains, existence of young post-magmatism dykes offshore the Zambezi depression, and prominent extensional tectonic with rift-grabens along the eastern edge of the Beira High, one may conclude that these events mark the boundaries between the crustal compositions.

2.3 Structural evolution of the Davie Transform Zone

The rotation of Antarctica during the final rifting stage caused a strike–slip movement between Madagascar and Somalia/Mozambique. The Davie Fracture Zone played an important role in moving Madagascar from the northern part of the East Africa margin before it demised at 120 Ma. Similar to the Lebombo-Explora Fracture Zone, the Davie Fracture evolved as a dextral strike-slip zone, opening simultaneously the Somali and Mozambique oceanic basins.

A transform margin style characterizes the structure of the Rovuma basin and western Madagascar during the rift-to-drift phases. The structural evolution of this basin has been described in the neighbouring Mandawa basin depicting a transitional setting from pull-apart basins formation in mid-Triassic time to rifting and break-up in the mid-Jurassic (Kreuser, 1995). Initiation of movement on the Davie Transform and spreading in the Somali basin around 165 Ma (Coffin and Rabinowitz, 1987) is coeval with the emplacement of the Angoche dyke swarms and the onset of sea-floor spreading between the Mozambique basins and the Riiser Larsen Sea.

The dextral strike-slip movement (Davie fracture) has obviously not affected the inner part of the fracture and still preserves its crystalline continental basement composed of granites, gneisses and meta-arkoses rocks, locally covered by deformed (flysch) sedimentary sequences (Bassias, 1992). However, a regional uplift was probably linked to extension of the East African Rifting System in the Miocene, this led to normal faulting and subsidence along the pre-existing crustal weaknesses, thus creating a series of grabens (depressions) along the axis of the Davie fracture (McCall, 1997). The Quirimbas and Nacala basins on the Mozambique margin and Pemba and Mafia basins along the Tanzania margin were formed likewise. The sedimentary basin-fill is completely dissected by numerous NNW and NNE oriented normal faults mostly reactivated by local extension associated to the East Africa Rift System (Mahanjane, in review).

2.4 Basin evolution history along the Mozambique continental margin

The evolution of sedimentary basins along the Mozambique continental margin fits within the overall development of the East Africa margin as a consequence of break-up of Gondwana in the Early to Middle Jurassic. The separation between West and East Gondwana formed several depressions along the Mozambique continental margin with two major basins: the Mozambique and Rovuma basins (Salman and Abdula, 1995), connected by the NNW-SSE oriented Davie Fracture Zone (Figure 2.2). Both depressions are modern passive margin basins containing a substantial sedimentary fill both onshore and offshore. The sedimentary successions of these basins developed in three stages: (i) Rifting and early drift phase from mid-Late Jurassic to Early Cretaceous, (ii) the late drift phase and evolution of the passive margin in the Late Cretaceous-Early Tertiary and (iii) the deposition of a deltaic complex from the Oligocene onwards.

Although these basins were formed contemporary, they exhibit different structural styles. The Mozambique basin has formed entirely over, and in association with, a volcanic margin. This is unlike the opening of the Rovuma basin, which was influenced by transform movement of Madagascar along the Davie Transform. Recalling the works of Emmel et al. (2011) and Roberts et al. (2012), in the Middle Jurassic a transtensional narrow rift characterized the early stage of the transform movement as a consequence of a rapid denudation phase associated onshore with an erosional response along the major dextral strike-slip fault. The subsidence of the Mozambique Channel region was driven by larger-scale crustal movements as uplift occurred, leading to normal faulting and subsidence that created a series of grabens (depressions) along the axis of the Davie Fracture Zone (McCall, 1997).

The rifting and separation between the two continental blocks along the Davie Fracture Zone (Africa and Madagascar) and opening of the Rovuma and Mozambique basin is minimum dated by the oldest sea-floor anomalies M25 for the Somali basin (Coffin and Rabinowitz 1992), and M33n for the Mozambique basin (Leinweber and Jokat, 2012). Since then, the main sedimentary successions of the basins accumulated and the modern continental margin was developed (Salman and Abdula, 1995).

The initial sedimentary fill was deposited during the earlier rifting stage in the mid-Jurassic time (Salman and Abdula, 1995) the sediment was derived from the fractured and eroded African basement (Bassias, 1992). At this stage, the first marine incursions extended into the Rovuma basin with deposition of the transgressive Mtumbei Limestone (Kreuser, 1995).

Although the existence of Late Jurassic marine sediments is speculative in the Mozambique basin, sedimentary successions are delineated by the seismic lines in the central part of the Zambezi Delta depression (Mahanjane et al., in review). Likewise, Early Cretaceous transgressive shallow marine successions are distributed in the southern and central areas overlying in parts eroded Karoo basalts and appear to be deeply buried in the Zambezi Delta depression (Salman and Abdula, 1995; Mahanjane et al., in review).

The last drift phase coincides with the separation of India and Madagascar at ~ 83 Ma (Segoufin and Patriat, 1981 in McCall, 1997), linked to volcanic eruptions along the crustal weakness of the Davie Fracture Zone (Bassias, 1992) and the beginning of the sea-floor spreading within the Mascarene basin (Salman and Abdula, 1995). The Mozambique passive margin developed and today forms part of the East Africa passive margin. Continuous tectonic subsidence in the Mozambique margin is consistent with the accumulation of uniform marine sequences and prograding onto the continental slope. In the northern part of the Mozambique basin, Paleocene-Eocene sediments occur both onshore and offshore and occupy the crustal depression as shallow-water shelf carbonate sediments in the Zambezi Delta (Mahanjane et al. in review). The sedimentation rate increased with development of the Zambezi and Rovuma deltaic complex during the Oligocene-Miocene in response to the early uplift and doming that preceded rifting of the Miocene East Africa Rift System (Droz and Mougenot, 1987).

The Zambezi Delta forms a classical passive margin deltaic system, producing a thick, eastward prograding wedge of clastic sediments. The Rovuma Delta is a classical passive margin deep-water thrust and fold belt system located at the northern part of the basin, displaying an eastward-thickening post-break-up sediment wedge with intensive listric slumpfaulting and associated down-dip delta-slope toe-thrusting to the east (Mahanjane and Franke, 2014).

2.5 Stratigraphy

The stratigraphic framework of the Mozambique margin has been described separately and in detail with regard to the Mozambique basin and Rovuma basin (Salman and Abdula, 1995). Previously, a great contribution to this description was presented by De Buyl and Flores (1986) and Nairn et al. (1991). Recently, Key at al. (2008) presented a revised litho-stratigraphy of the onshore Rovuma basin. For the purpose of developing some conceptual models, generalized stratigraphic charts were drawn to provide lithological information correlative with the main tectonic events for each publication. An innovative contribution to the uncovered areas, such as the Davie Fracture Zone and adjacent basins, and a detailed description of local stratigraphic evolution is presented in Section 4.3.

3. Data and Methods

The work presented here was conducted by using the drilling and seismic dataset from the Zambezi Delta and adjacent areas as well as geochemical information from wells in the Mozambique basin (Alconsultant, 1996), Tanazania (Maende and Mpanju 2003), Madagascar (Matchette-Downes, 2006), and an ODP well in Antarctica (Thompson and Dow, 1990). Reconstruction of the basin evolution was made using restoration techniques carried out with Petromod® software version 12.2.

3.1 2-D Seismic reflection profiles

The primary seismic dataset is rendered by the *Bundesanstalt für Geowissenschaften und Rohstoffe* (BGR) and was integrated to a considerably larger database composed of mixed old and nearly recent vintages, provided by the *Instituto Nacional de Petroleo* (INP) of Mozambique as part of ongoing exploration projects:

1. BGR 2007 - A total of 2650 m 2-D reflection seismic regional lines were acquired on-board of R/V MARION DUFRESNE Leg MD 163 using a 3,000 metres long streamer sourced by 5 G-Gun with a total volume of 2,600 in^3=42.6 Litres. The streamer consisted in total of 240 Channels, the shot distance was 50 metres and the sampling rate was 2 milliseconds. The total record length was 14 seconds. On-board processing using PROMAX 2D version 2003.12.1 followed the normal processing sequences and resulted in output data as post-stack Kirchhoff time migration;

2. MBWG 2000 speculative survey - A total of 1,300 km of 2-D reflection seismic filtered-migrated profiles consist of 8 dip zigzag lines covering the margin west of the Davie Fracture Zone. An array of Fibreoptic digital cable, 6,000m streamer carrying Tuned Sleeve airguns (Volume of 48.5 Litres), provided the source for the data collected in water depths between 100 and 3,000 metres;

3. MBWG 1998/99 speculative survey - covering the breadth of the Beira High, deep-water areas from the 1,000 metres isobath to beyond the 2,000 metres isobath in the Mozambique basin. A total of 3,000 km final migration 2-D reflection seismic were collected on-board of M/V EXPLORA using a 5,200 metres long streamer, energy source: 4 string airgun array (36.4 Litres), sample rate 2 milliseconds, processing record length 9,216 milliseconds, shot intervals 25 metres;

4. The old vintages include the British Petroleum (BP 1998) and Western Geco (GMC 1981/2) surveys covering the breadth of the Zambezi Delta depression, and Lonropet (LRP-98) filtered & scaled migration 2-D seismic lines transecting the offshore Rovuma Delta.

3.1.1 Depth Conversion

Depth conversion of the time-migrated data was carried out using the root-mean-square velocities derived from the last iteration of the stacking velocity analysis. Smoothing was applied to the root-mean-square velocities where strong lateral velocity gradients did not correlate with the stratigraphy. Tie points were used to check the root-mean-square velocities for consistency.

Depth conversion applied to time-migrated data is a reasonable method to transform seismic data with mild lateral velocity variations into the depth domain (Yilmaz, 1987). However, it should be noted that this method does not account for ray bending. This means that the exact positions and the slopes of lateral varying structures are not imaged correctly but the overall trend of the depth converted seismic section is acceptable.

Figure 3.1 shows a time-migrated seismic cross section before and after depth conversion was applied. The depth-converted section has a very smooth appearance without major kinks or gaps within the horizons pointing to a very good match of the root-mean-square velocities for the underlying geology. The close-up in Figure 3.1 shows how a reliable depth conversion changes the vertical proportions without disrupting the lateral coherency of the reflections.

3.2 Well data

The well data were compiled from the selected Sofala-1X, Nemo-1X, Divinhe-1, Mambone-1, Zambezi-3 and ZDE-1 wells (Table 3.1). They provide important stratigraphic information of the Zambezi Delta depression. With the exception of ZDE-1 well, drilled in 2007, all wells were perforated in the 1960ies. Among these wells, Sofala-1X, Nemo-1X, Divinhe-1 and Mambone-1 have intersected the Early Cretaceous stratigraphic units. Thus, they provide calibration data essential for maturity modelling.

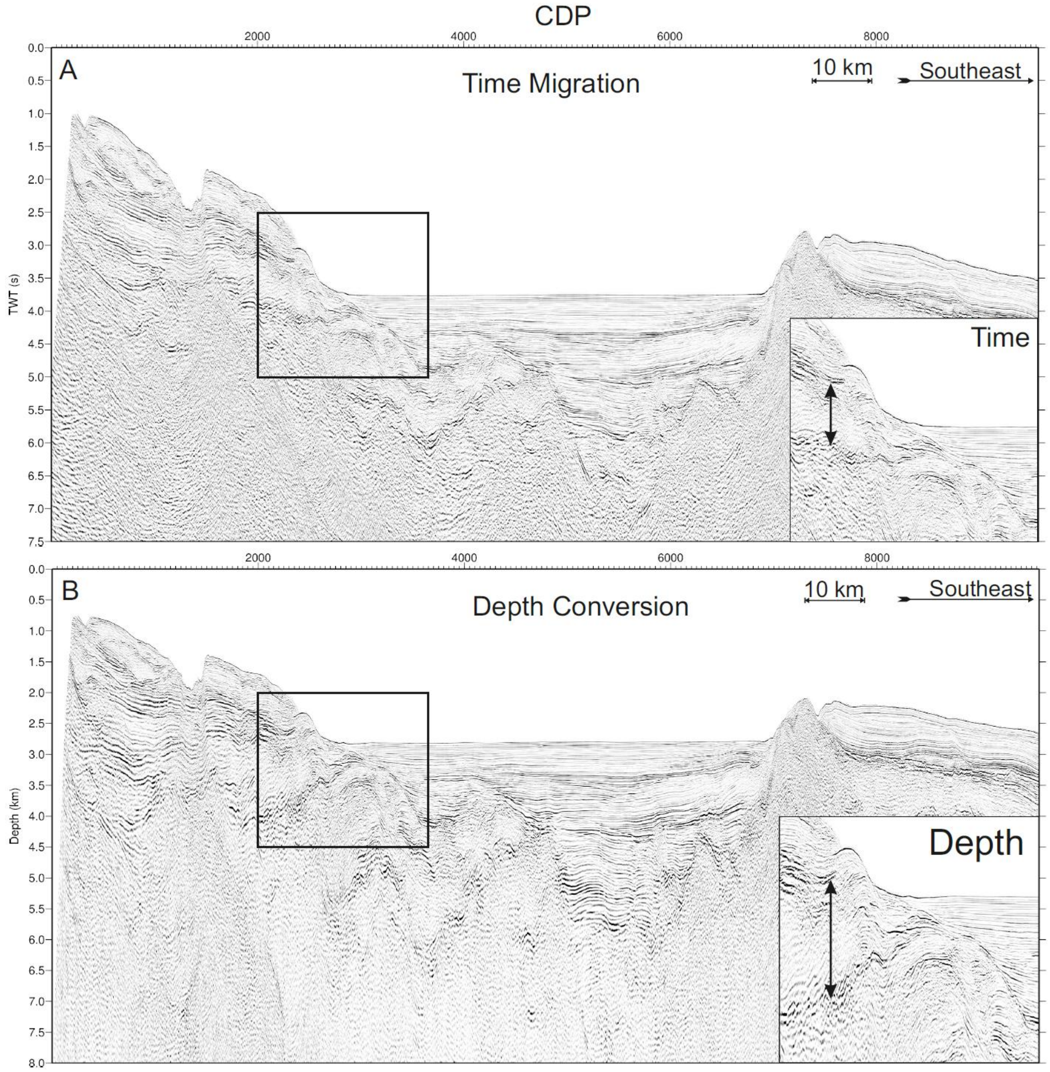


Figure 3.1 - Comparison of a time-migrated seismic section (frame A) to a depth converted seismic section (frame B). The black box marks the range of the close-up that is placed on the right hand side of the section. Please note the good lateral coherency of the horizons pointing to a clear match of the applied velocity function for the underlying geology.

3.3 Well-Seismic-Correlation

A well-to-seismic-correlation example is best demonstrated by Figure 3.2. The seismic line runs from the Nemo-1X (Shelfal area), on which the primary and other stratigraphic tops have been identified, out to beyond its intersection with Zambezi-3 (Delta depocentre). The seismic reflection data collected as a function of two-way travel-time below sea level is correlated to biostratigraphic data collected in function of depth in the well. The well data for correlation contain formation tops and checkshot data (depth-time relationship). The seismic profiles are visualized together with boreholes displaying the formation tops that correspond to prominent stratigraphic reflectors (boundaries) in time. The visual inspection in this cross-section shows reliable consistency on identification of the principal deposition sequences and important seismic stratigraphic markers intersected in both wells, base of which are identifiable.

Table 3.1 Mozambique basin – Selected Wells for the study

Well name	**Location**	**Total Depth (m)**	**Total Depth (Formation) Geological time**	**Drilling Results**
Divinhe-1	Onshore	3837.2	Sena Fm Middle Cretaceous	Gas shows in Domo Sands (Turonian) and Sena Fms and Lower Grudja (Maastrichtian)
Mambone-1	Onshore	3611.1	Basalts Lower Cretaceous	Gas shows in Lower Grudja (Maastrichtian)
Nemo-1X	Offshore	4122.8	Volcanic rocks Neocomian	Gas shows in Domo Sands (Turonian) and in Neocomian volcanic agglomerate
Sofala-1X	Offshore	3229.5	Lower Domo Shale Fm Lower Cretaceous	Gas shows in Domo Sands (Turonian)
Zambezi-3	Offshore	4506.2	Lower Grudja Fm Upper Cretaceous	Oil shows in Oligocene sandstones
ZDE-1	Offshore	3600	Oligocene	Gas shows in Miocene sandstones

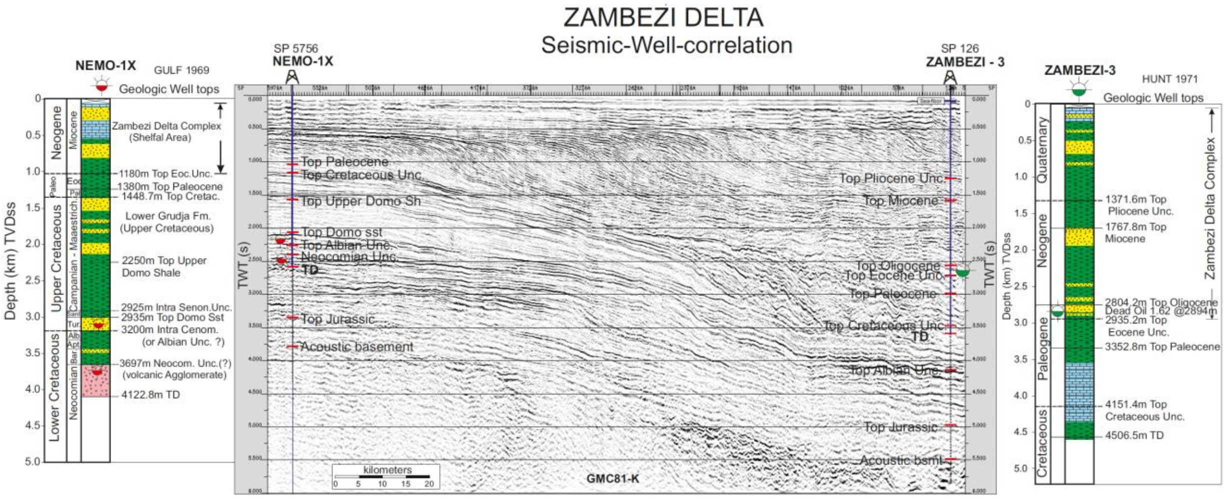


Figure 3.2 – Correlation between seismic and well data. The chronostratigraphy of the wells is obtained from the final well reports. Note Nemo-1X intersected the Lower Cretaceous successions and terminated in the Neocomian volcanics. The Jurassic and acoustic basement were correlated from the regional unconformities defined in the regional stratigraphy (Salman and Abdula, 1995).

3.4 Petroleum system modelling

A two-steps approach based on Mubarak and Miriam et al. (2009) and Peters et al. (2007) was taken to combine (1) model building using Geoquest seismic-interpretation software for building the basin with (2) PetroMod® petroleum system forward modelling software for simulating the extent and timing of hydrocarbons generation, migration and accumulation. Schlumberger's PetroMod® software employs “hybrid migration modelling”, which integrates full 2-D and 3-D Darcy flow with flow-path migration.

Input data include horizons of the buried rock units derived from the seismic interpretations, ages of the units, present and past rock-unit thickness, lithologies and physical properties of units, and various boundary conditions, such as present and past water depths, basal heat-flow, and surface or sediment-water interface temperatures. The geochemical data, such as the type and amount of organic matter in the source rocks and the kinetics for the conversion of kerogen to petroleum are also input parameters into the model.

In both models, the respective kinetic models by Pepper and Corvi (1995a) were assigned. In the northern Mozambique basin, the geologic input parameters include four Mesozoic- to Cenozoic-aged source-rock units, reservoir rocks, seal rocks, and overburden rocks. The critical moment is defined as a snapshot in time that best depicts the peak generation, migration, and accumulation of petroleum (Peters et al., 2007), which corresponds to 50% of the transformation ratio.

3.4.1 Model Calibration

1-D forward modelling is performed to examine the burial history at a point location, while two-dimensional modelling, along the cross-section, was intended to reconstruct the hydrocarbon generation, migration, and accumulation.

The thermal history was constrained by modelling four representative wells in the Zambezi Delta basin and five pseudo-wells: one in the deepest area along the Zambezi depression, two in the eastern edge of the Beira High, and the remaining two in the Angoche basin.

The basal heat-flow trend was computed from a crustal stretching model for the basin evolution based on McKenzie (1978). The calculation considered two rifting phases, one from 182 Ma to 166 Ma, and the post-rift phase between 166 Ma and present-day. The stretching factors Beta (β) of 1.5 for β-crust and 2.0 for β-mantle were used. The maximum basal heat-flow calculated values were 64 milliwatts per square meter (mW/m^2) within the Zambezi Delta and 40 mW/m^2 in the Angoche basin. Both calculated values are low compared to the global mean value of 65 mW/m^2 for this type of basin (Allen & Allen, 1990).

The thermal history model-predicted vitrinite reflectance (%R_0) values were calibrated against publicly available measured %R_0 data. The model calculates vitrinite reflectance values using the "Easy%R_0" method of Sweeney and Burnham (1990) in order to define the petroleum generation zones ("oil and gas window"). In general, intermediate burial/thermal modelled %R_0 values agree with measured %R_0 values (Figure 3.3). These procedural steps were conducted for all formations and locations, for which both type of %R_0 data were available, to calibrate the thermal input data. Where significant variation is noted, the calculated present-day heat-flow was calibrated to obtain a reliable fit between calculated and measured vitrinite reflectance from the well.

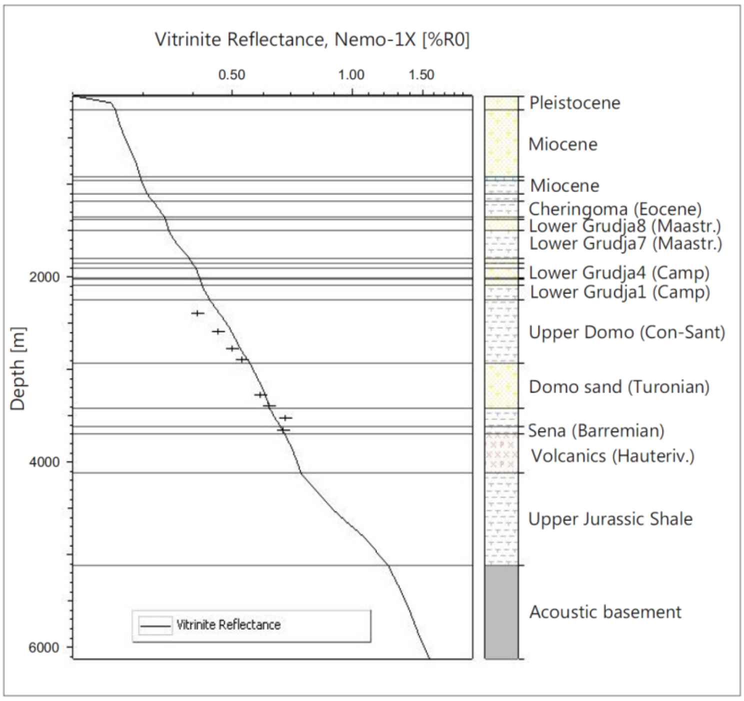


Figure 3.3 – Cross plot showing comparison of calculated and measured vitrinite reflectance. The heat-flow curves were calculated using a McKenzie crustal stretching model. A good fit between calculated and measured vitrinite reflectance is observed in the wells.

4. Scientific Manuscripts

This chapter presents the result of four publications submitted to international, peer-reviewed journals:

4.1. A Geotectonic History of the Northern Mozambique basin Including the Beira High – A Contribution for the Understanding of its Development

E. S. Mahanjane / Marine and Petroleum Geology 36 (2012) 1-12. doi:10.1016/j.marpetgeo.2012.05.007

Institute National Petroleum (INP), Av. Fernão Magalhaes N. 34, 2nd Floor, PO Box 4724, Maputo, Mozambique

Abstract

The interpretation of a comprehensive two dimensional (2D) seismic reflection data set discloses several rifting events for a typical passive rifted margin. Two major phases have been identified: Rift I phase is in agreement with the initial rifting of Gondwana postulated for the early Jurassic. This rift resulted in break-up stage 1 controlled by a north-eastern motion of Antarctica along the reactivated Pebane shear zone. Indications for lava flows were identified in the seismic profiles along the Offshore Zambezi depression. They form a link between early rifting, the initial break-up and early sea-floor spreading. The nature of these lava flows may be associated with the emplacement of thick volcanic dykes during post-rift magmatism that occurred when the Antarctica Plate (with the Beira High) drifted dextrally from the west to east until the Mid-Jurassic times. It is more likely that the break-up in stage 1 resulted from high tension due to strain relief of Rift I phase. Above all, the extensional deformation occurred in a narrow- rift mode. Therefore, the V-shape of the Offshore Zambezi depression suggests a possible rift-failure structure. This is best explained by the Reeves and de Wit model (2000). This model postulates that the motion of Antarctica changed to southward direction at around 170 Ma. Consequently a “rift jump” from the Offshore Zambezi depression in the northwest to the south-eastern edge of the Beira High occurred, and Rift II phase may have started leading to the break-up in stage 2. During this stage (Rift II phase) the extension migrated towards the east, thus thinning the crust, and exhuming the sub-continental mantle in the continental-ocean transition zone. The Rift II phase shows a sequence of half-graben morphologies confining the syn-rift infill that is subdivided in three units: syn-rift I, syn rift- II and rift sag. All three units appear to have developed under minor extensional regimes in the crust evidenced by gently dipping, low-angle detachment faults. With respect to the presence of the two rift phases, it is deduced that break-up and sea-floor spreading are diachronous within Rift I and Rift II segments.

Introduction

Major questions regarding the earliest phases of Gondwana break-up are related to episodes of Karoo (300-200 Ma) rifting in southern Africa that probably occurred along predominantly strike-slip faults with various trends but notably north-south and NE-SW (e.g. Cox,1992, Klausen, 2009). Major reactivation of the strike-slip faults occurred in the interval between 190 and 170 Ma, concurrently with the onshore emplacement of the Karoo and Ferrar volcanic provinces (Duncan et al., 1997; Courtillot et al., 1999; Reeves, 2000; Riley and Knight, 2001; Jokat et al., 2003; König and Jokat, 2006, Martin, 2007; Klausen, 2009). Subsequently, rifting has led to the break-up of the Super-Continent Gondwana. Cox (1992) proposed two break-up stages. The first is linked to the early Jurassic north-eastern motion of Antarctica along a reactivated shear zone. The second is a continental separation occurring in mid-Jurassic times when Antarctica and Madagascar moved southwards in relation to Africa as a single plate. The second stage is in agreement with the Reeves (2000) model, associating it with the emplacement of dykes parallel to the Zambezi coast at around 170 Ma (Reeves, 2000). The two stages model of Cox (1992) is based on the analysis of the Jurassic Karoo volcanism. In that regard, he found evidence of a gap of about 20 Ma between the onset of volcanism and the formation of the first oceanic crust. The earliest phase of Jurassic Karoo volcanism exhibits a major peak of activity at 200-190 Ma (Fitch and Miller,1984; Garner,1996), whereas sea-floor spreading is believed to have started around 170 Ma (Lawver et al., 1991b; Courtillot et al., 1999). The termination of rifting with the subsequent drift phase is constrained by magnetic spreading anomalies in the Mozambique basin. The oldest magnetic anomaly is tentatively dated as anomaly M24 (155 Ma) (Jokat et al., 2003) or M26 (155.3 Ma) (König and Jokat, 2010). The M26 anomaly is located 25 km off the south-eastern flank of the Beira High and within the area of this study. Considering these premises two major questions arise: *(i) identification of a more precise time frame and (ii) what was the structural response of the initial rifting between Africa and Antarctica?*

These questions are closely linked with the understanding of the nature and origin of the Beira High (BH). The BH structure is approximately 280 km long and 100 km wide, elongated in northeast-southwest direction, i.e. more or less parallel to the coastline (Zambezi Delta) (Figure 1). This structure is located in the deep water area (1000-2500 m) of the delta basin, buried by Mesozoic and Cenozoic sedimentary sequences. Its origin is still under debate with three conflicting opinions postulating that its character is either magmatic (oceanic), continental or sedimentary with an overprint by compressional forces.

Despite the size and the prominent position of the BH, there was only a small amount of data at hand that could be used for a detailed interpretation. Watts (2001) combined 2D flexural backstripping and gravity modelling to investigate the Mozambique rifted margin using a single northwest-southeast running profile. He suggests that the pronounced gravity anomaly between the BH and the coast is the result of the "edge effect". This effect is due to the juxtaposition of thick continental crust against the regularly thin oceanic crust. Hence, it was concluded that off the coast continental crust immediately adjoins to oceanic crust or thinned transitional crust, encompassing the BH. On the other hand, König and Jokat (2010) discussed the possibility of remnants of smaller continental blocks within the northern Mozambique basin that were displaced from the African continent during the phase of rifting between Africa and Antarctica.

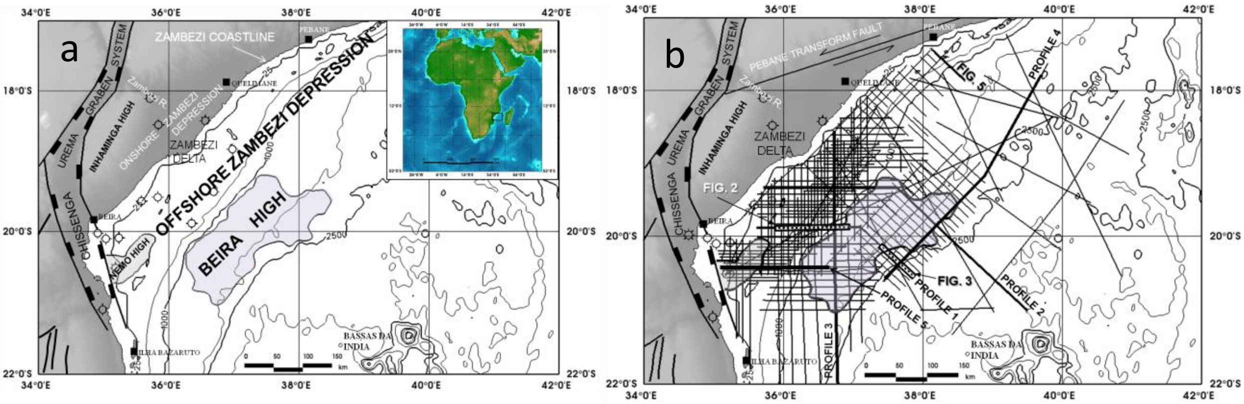


Figure 1 - General map of the northern Mozambique basin and the navigation map with the 2D seismic data track lines (a): The study area includes the Offshore Zambezi depression, which is delimited by the area between the Nemo High and the Beira High in the south. It branches off and dips to the north-northeast until the volcanic "high" referred to as coast-parallel volcanic dykes (Reeves, 2000) or near coast basalt (Raillard, 1990) situated near the Pebane area. (b) Illustration of the 2D seismic sip's tracks used for this study including the location of the Figures and profiles. Figures 2 and 3 depict two portions of Profile 1 flagged by white dashed lines. Tectonic features that predominate the onshore part of the study region: the Pebane transform fault (the Limpopo lineament in Cox, 1992) and the East Africa Rift System (EARS) consisting of the Chissenga and Urema Graben Systems.

In order to contribute to a better understanding of the BH, I make an approach on the basis of an extensive geophysical data set with integrated geophysical models. This is based on an interpretation of the 2-D reflection seismic with the contribution of gravity, and magnetic information acquired in the northern Mozambique basin. In summary, this paper gives a description of the BH. It also identifies the break-up stages and defines the Onset of Oceanic Crust.

The results presented here are based on the MOBAMASIS e LEG 163 (Reichert et al., 2008) cruise data acquired jointly by the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), the Alfred-Wegener-Institut (AWI), and the Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER) on board of RV Marion Dufresne in 2007, and on commercial geophysical data acquired both onshore and offshore the Zambezi Delta generously made available by the Instituto Nacional de Petróleo (INP) of Mozambique (Figure 1).

Gondwana break-up and the initiation of sea-floor spreading

Several questions concerning the initial Gondwana break-up are unanswered; mainly the timing of the break-up, the character of the processes effecting the separation of the blocks, and the formation of new oceanic crust in the Mozambique basin and the conjugate Riiser-Larsen Sea in Antarctica. The Gondwana break-up is proposed to have started between Pliensbachian and Toarcian [190e175 Ma: Duncan et al. (1997); Martin (2007)], or Bajocian (170 Ma: Reeves, 2000), Bathonian (167.2 Ma: König and Jokat, 2006) or later in the Oxfordian stage (157 Ma: Salman and Abdula, 1995).

The majority of the reconstruction models converge in terms of coincident ages (182 ± 2 Ma) between Ferrar and Karoo magmatism for the break-up commencement (Fitch and Miller, 1984; Duncan et al., 1997; Riley and Knight, 2001; Segev, 2002). This documents an early volcanic peak which resulted in the north- south oriented Lebombo around w190 Ma (Cox, 1992; Garner, 1996; Reeves, 2000; Watkeys, 2002; König and Jokat, 2006) or 182 Ma (Klausen, 2009) followed by remarkable formation of Okavango Dyke swam and associated rift, and emplacement of minor continental dyke swarms dated w181e178 Ma (Klausen, 2009).

Similarly, the age of the oldest oceanic crust is under discussion. Lawver et al. (1991b) and Courtillot et al. (1999) suggest 170 Ma as the age of the oldest sea-floor between Africa and Antarctica; this is in contrast to the age of 157.6 Ma constrained by magnetic anomaly M25 in the Somalia and Mozambique basins, initially proposed by Rabinowitz et al. (1983)

and Salman and Abdula (1995). Jokat et al. (2003) tentatively interpreted magnetic anomaly M24 (155 Ma) which is located north of magnetic anomaly M22 (152 Ma) previously identified by Segoufin (1978), Simpson et al. (1979), and Segoufin and Patriat (1980) as the oldest anomaly in the Mozambique basin. König and Jokat (2006) suggest that the rifting associated with the formation of the Mozambique/Riiser-Larsen Sea basins took place at the same time between 170 Ma and 160 Ma. This is in agreement with the age of the first oceanic crust proposed by Courtillot et al. (1999).

Modern palaeogeographic reconstructions e.g. Leinweber and Jokat (2012) show concisely that rifting between Africa and Antarctica began with anti-clockwise rotation of Antarctica with respect to Africa before the north-south rifting started.

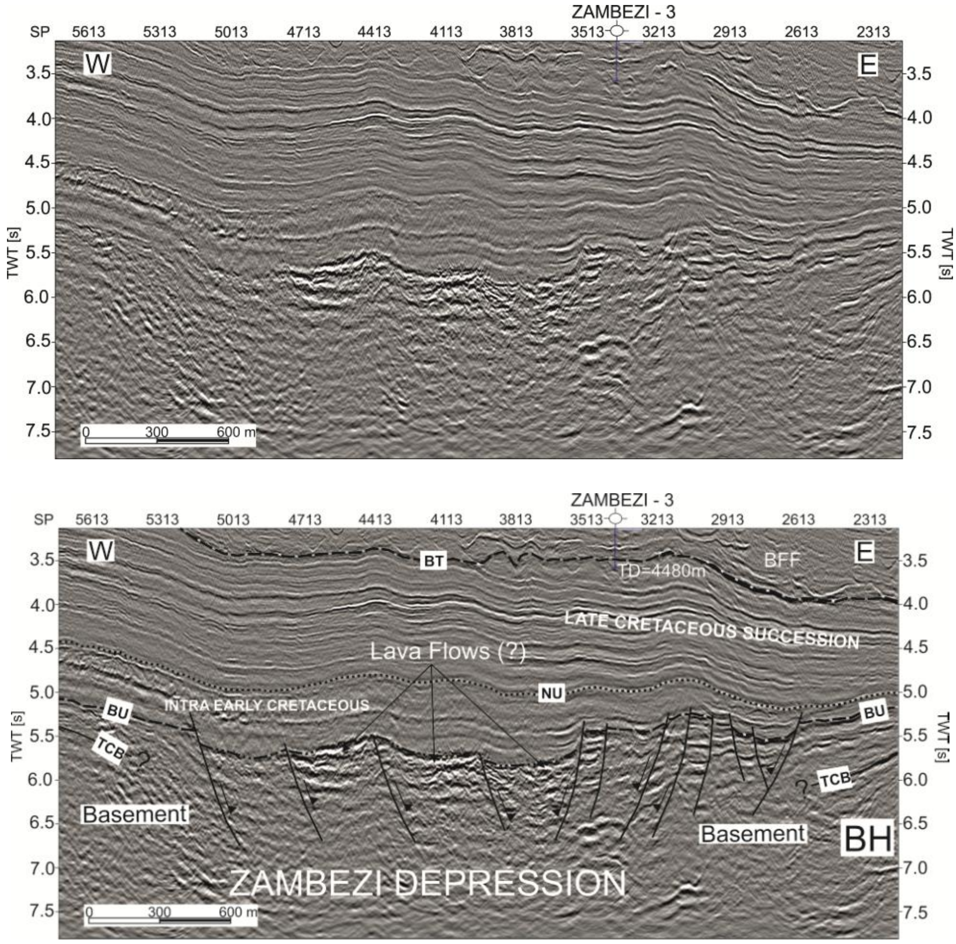
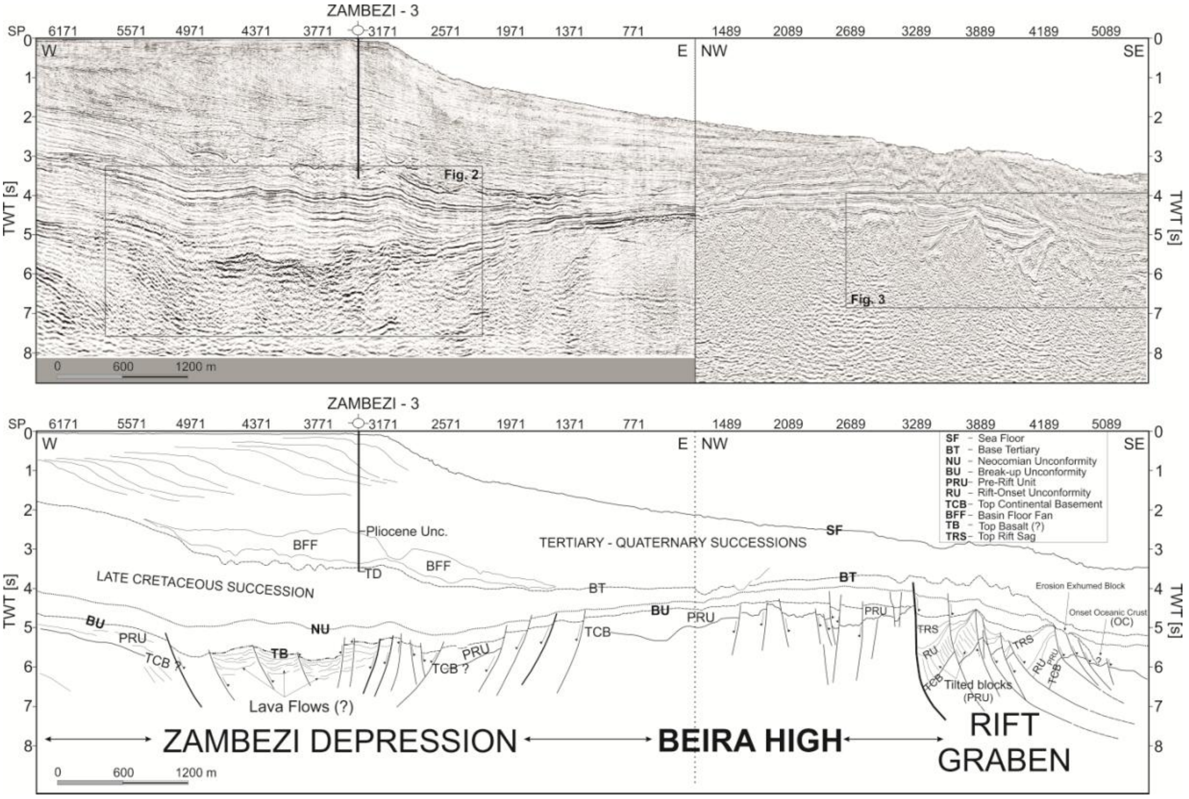


Figure 2 - Enlargement of the western portion of Profile 1. Upper panel: uninterpreted seismic section (migrated). Lower panel: appropriate interpretation as proposed in this study. Details of geotectonic structures and some sediment stratigraphy are shown. The rugged surfaces with high-amplitudes reflection may indicate the occurrence of lava flows. The morphology of the lava flows is at least partly controlled by faulting according to the respective seismic observation. One must take into account that the possible magma spread features (lava flows?) may have solidified and remained horizontal while the surrounding lava subsided during sediment compaction during some extensional deformation. See caption of Figures 1 and 4 for the abbreviations, and see text for discussion.

Subsequently the drift phase of the Riiser-Larsen Sea off Dronning Maud Land (Antarctica) started, as well as the formation of the Mozambique oceanic basin and the Somalia basin in the western Indian Ocean (Reeves and de Wit, 2000; Reeves et al., 2002; Jokat et al., 2003; König and Jokat, 2006). Hence, the reconstruction model that was based on a juxtaposition of Dronning Maud Land against Mozambique (e.g. Simpson et al., 1979) was modified to demonstrate the alignment between the Zambezi Coast (Africa) and Princess Ragnhild coast (Antarctica) (e.g. Cox (1992: fig. 4); Reeves (2000: figs. 3 and 4); Marks and Tikku (2001: fig. 7) and König and Jokat (2006: fig 11)). These models postulated an initial phase of east-west oriented rifting between Africa and Antarctica which is proposed to have occurred at around 165 Ma (Marks and Tikku, 2001); or 167.2 Ma (König and Jokat, 2006) and even earlier between 190 Ma and 182 Ma (Reeves, 2000; Martin, 2007). The final phase of north-south rifting and early drifting of East Antarctica from Mozambique (Africa) is deduced from magnetic anomalies M21 and M24 (Bergh, 1977; Segoufin, 1978; Simpson et al., 1979; Jokat et al., 2003), giving an age range between 147 Ma and 155 Ma.



Profile 1 - Regional cross-sections that were selected to exemplify the structures of the main geological setting and the seismic interpretation in the study area. In the upper panel 2D seismic (migrated) lines of a survey conducted between 1998 and 1999 are displayed. The record length was 9 s. The seismic acquisition has different parameters and consequently a different resolution. The profiles cross several features that give evidence for the two stages of the break-up process postulated in this paper. In the lower panel the appropriate seismo-stratigraphic interpretation is displayed as proposed in this study.

Data interpretation and results

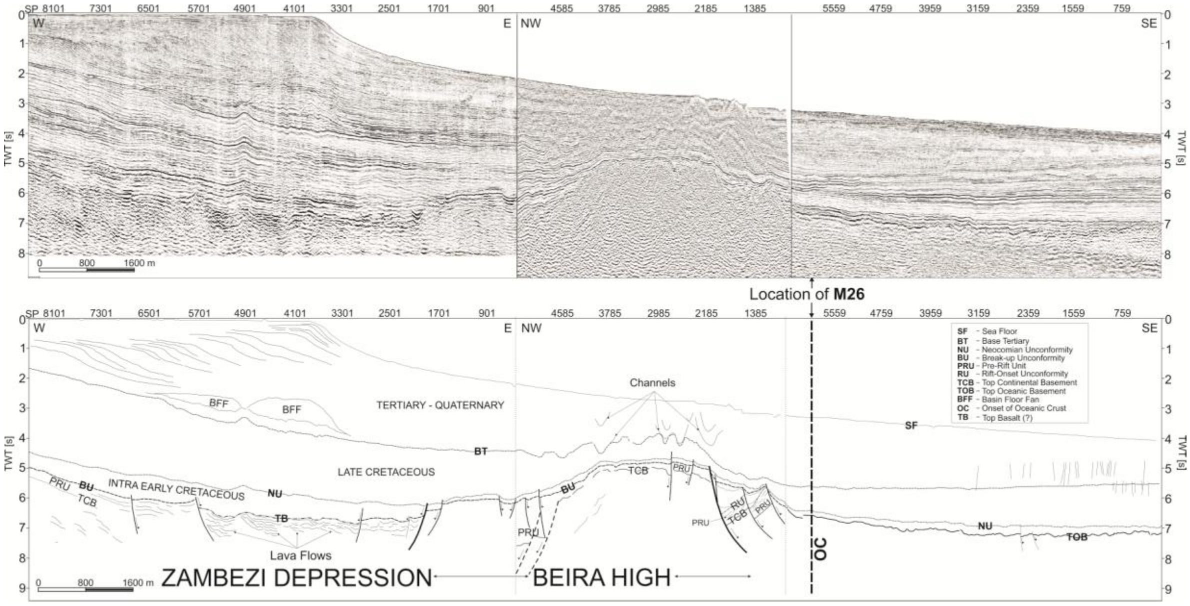
Multi-channel reflection seismics

The aim of the seismic interpretation is to provide insights into the geotectonic evolution of the southern margin of Mozambique, along the Zambezi coast, particularly the Beira High (BH). The BH structure reflects a complex geologic history; it is extensively faulted and preserves evidence of being affected by several tectonic events. The analysed seismic profiles (examples are presented as regional Profiles 1-5, see Figure 1b for location) are intersecting features that give evidence for the existence of two stages of break- up. Break-up stage 1 is manifested along the Offshore Zambezi depression, between the BH and the Zambezi Coast. In contrast, during break-up stage 2 most of the eastern edge of the BH was deformed. In the following, first the layered successions are described, then the rift-related structures and finally the continent-ocean transition to the east of BH.

Post-rift units

The post-rift units are not the focus of this paper. Hence, I provide a brief description of the general appearance: parts of the successions were penetrated by deep wells (De Buyl and Flores, 1986). This allows the identification of relevant geological events, particularly the Neocomian Unconformity (NU), Top Cretaceous/ Base Tertiary (BT), and Pliocene Unconformity (PU).

The post-rift successions are mainly Cretaceous and Cenozoic deposits. Below a thick sedimentary section [~ 4.0 s two-way travel time (TWT)] two important unconformities are identified (Profiles 1-5). At first, the top of the Intra Early Cretaceous (NU) defining the first marine sedimentary facies was deposited in shallow water on top of the eroded Karoo successions (Salman and Abdula, 1995) at around 130 Ma. The second is the Base Tertiary (BT), correlated from the information from the Zambezi-1 and Zambezi-3 wells (De Buyl and Flores, 1986, Salman and Abdula, 1995). Prominent high-amplitude reflectors dominate in the Early Tertiary. They are indicators for deposition of carbonate facies as well as for sequences of carbonate build-ups. They are topped by deltaic progradation facies (e.g. prominent basin floor-fans that stretch out over 2-3 km, e.g. on west of Profile 1 between Shot Points 5300-1400, and east of Profile 5 between Shot Points 2150-4150). There are also wide- spread buried submarine channels in the area over the BH (Profiles 2-5). Varying in size, these channels increase in quantity from the BH towards the southwest with heights that reach 2 s (TWT) and widths of up to 500 m. The northeast region of the BH typically consists of contourite deposits.



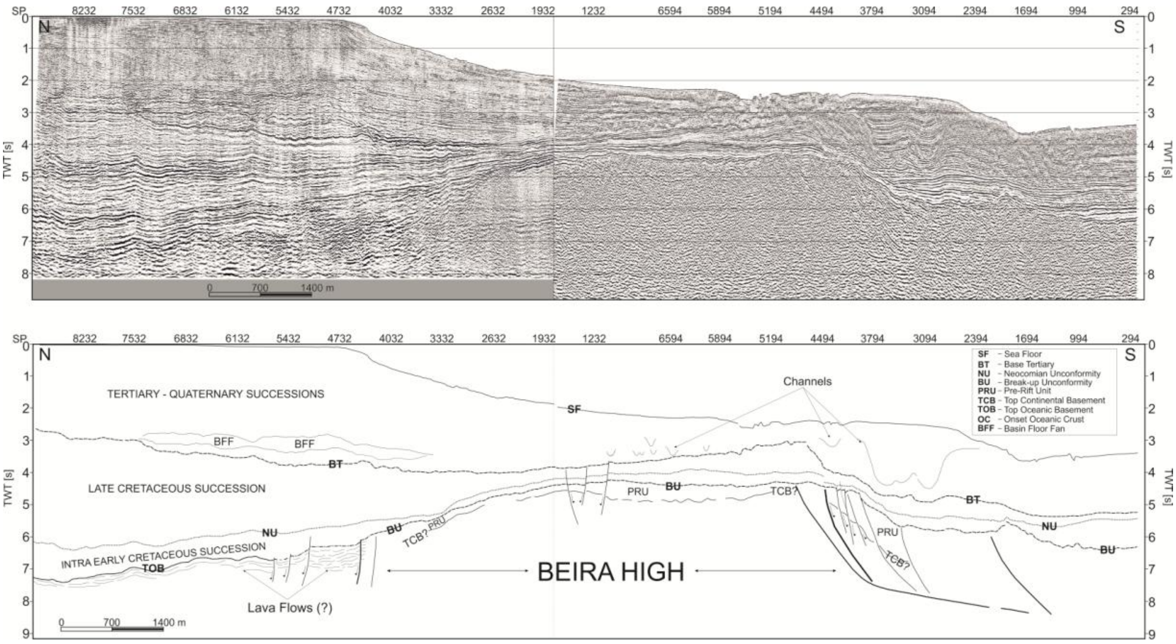
Profile 2 - In the upper panel 2D seismic (migrated) lines of a survey conducted between 1998 and 2000 are displayed. The record length was 9 s. The seismic acquisition has different parameters and consequently a different resolution. The profiles cross several features that give evidence for the two stages of the break-up process postulated in this paper. In the lower panel the appropriate seismo-stratigraphic interpretation is displayed as proposed in this study.

Break-Up Unconformity (BU)

The most prominent horizon is a distinct erosional unconformity that is interpreted as the Break-Up Unconformity (BU). This unconformity is likely to have been formed at the transition from Mid to Late Jurassic times. Further offshore, it merges with what is interpreted as the top of the oceanic basement (TOB) (Profiles 2-4). The BU represents an erosional surface with clear top-lap truncations of the pre-rift sediments, except in rift-grabens where it truncates the syn-rift sediments.

In the seismic reflection data the unconformity appears mostly as a continuous, prominent and high-amplitude reflector, particularly across the BH. One could suggest that the high was subjected to a major erosional event during break-up. The trace of this event however, shows consistency of the reflector which terminates downlap in the transition between continental and oceanic crusts in the east, north and southeast of the BH (Profiles 2, 3 and 4, respectively).

At the Nemo High (NH) and the BH (Figure 1) the BU is found at depths between 3.5-5.0 s and 4.0-6.0 s (TWT), respectively (e.g. Profile 5).



Profile 3 - In the upper panel 2D seismic (migrated) lines of a survey conducted between 1998 and 1999 are displayed. The record length was 9 s. The seismic acquisition has different parameters and consequently a different resolution. The profiles cross several features that give evidence for the two stages of the break-up process postulated in this paper. In the lower panel the appropriate seismo-stratigraphic interpretation is displayed as proposed in this study.

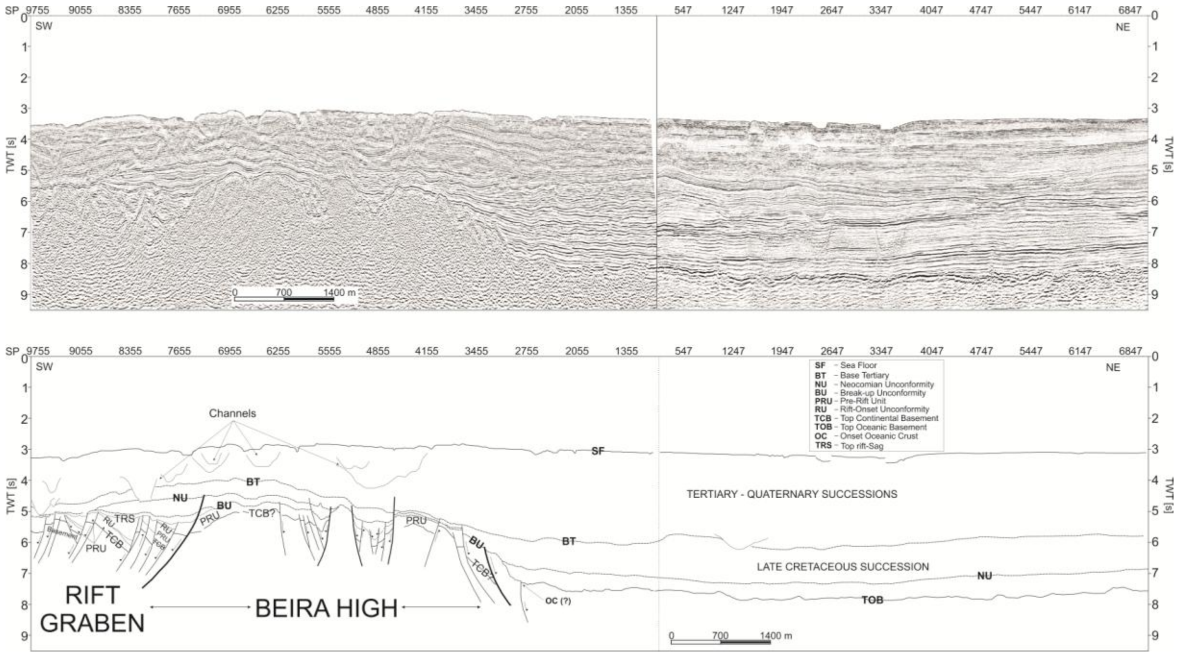
Pre-rift strata

Between the basement and the rift-related sedimentary successions layered successions (PRU) are occasionally identified, mostly stratified with moderate reflector amplitudes, losing their stratification towards the northeast within the Offshore Zambezi depression, where obviously chaotic filling occurs.

In the south-eastern part of the BH (within the rift-grabens) the top of the pre-rift succession is truncated by the Rift-onset Unconformity (RU). The pre-rift unit occurs between the interpreted Top Continental Basement (TCB) and the RU. It is manifested as a thick pile of tilted, moderate amplitude reflectors which are layered parallel to fault planes (about 850-

920 ms TWT thick), but change to a horizontal or sub-horizontal layering towards the southeast (see Profiles 1 and 4).

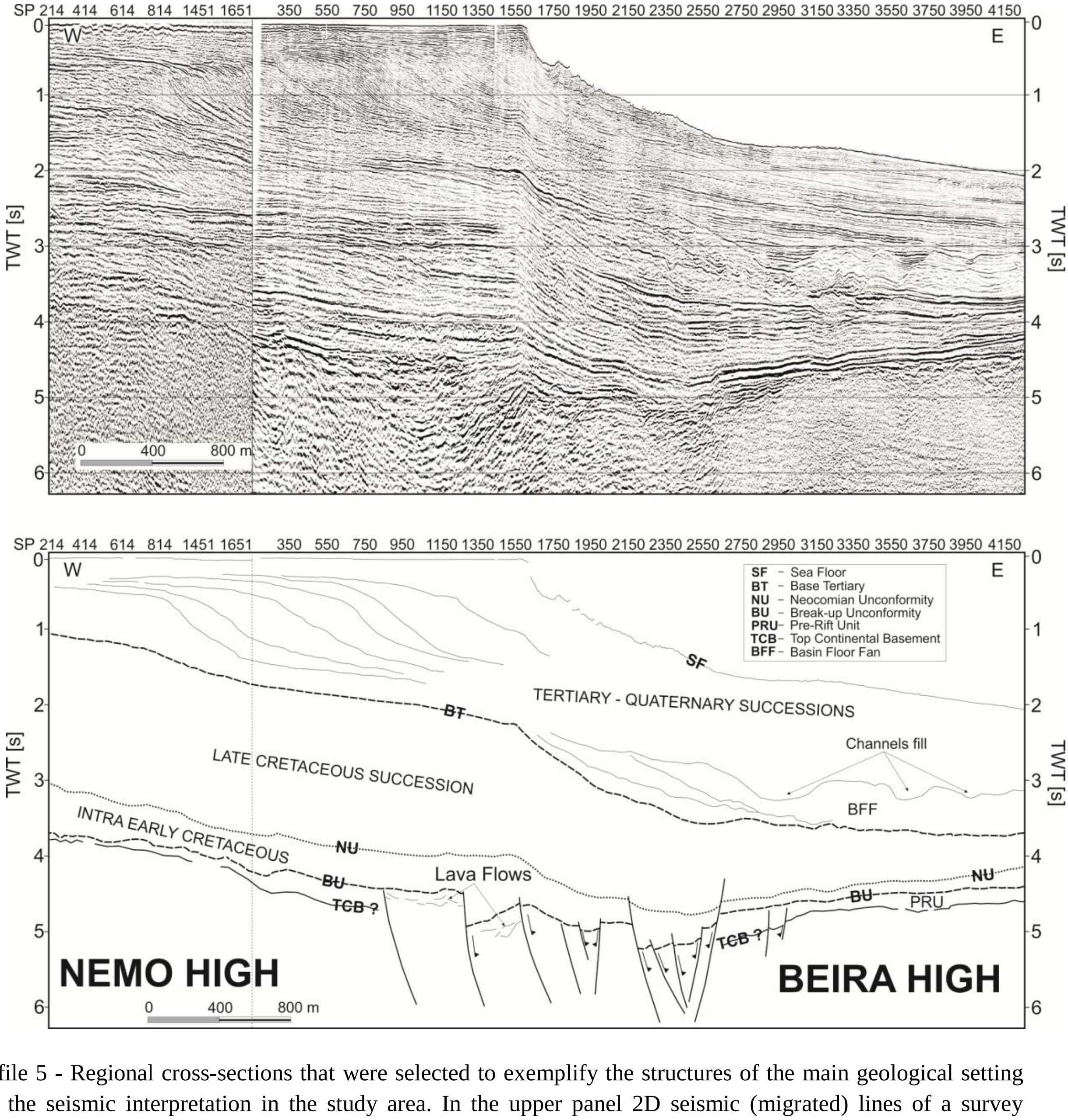
In the north-eastern BH (see Profile 4), the pre-rift succession is represented by a set of sub-horizontal reflectors that gradually change into horizontal reflectors seawards and that are truncated by the BU or RU. Therefore, the TCB and the BU delimit the unit that progressively pinches out towards the oceanic domain.



Profile 4 - Regional cross-sections that were selected to exemplify the structures of the main geological setting and the seismic interpretation in the study area. In the upper panel 2D seismic (migrated) lines of a survey conducted between 1998 and 2000 are displayed. The record length was 9 s. The seismic acquisition has different parameters and consequently a different resolution. The profiles cross several features that give evidence for the two stages of the break-up process postulated in this paper. In the lower panel the appropriate seismo-stratigraphic interpretation is displayed as proposed in this study.

Seismic expressions of volcanics

In the areas denoted as Offshore Zambezi depression, seismic reflectors characterized by high-amplitudes and low-frequencies are distinctly observed below the BU (e.g. on Profile 1 over a distance of about 2km between Shot Points 3200 and 4812).These reflectors occur in horizontal arrangement between 5.5s-6.0s TWT. Locally, they are bounded and fragmented by normal faults (Figure 2). The reflectors can easily be traced towards the north because they maintain their characteristic seismic image (e.g. on Profiles 2 and 3 located 60 km north of Profile 1). The sequence commonly exhibits a thick interval of strong reflections with moderate to good continuity, although small local disruptions occur (Figure 2). These reflectors occur only in the deepest part of the Offshore Zambezi depression basin. They are limited by normal faults on both sides (Profiles 1 and 2). Towards the east, these reflectors are bounded by an adjacent fault accurately at the BH slope. In the north of Profile 2 (e.g. north of Profile 3 within the depression), the reflectors gradually change to a hummocky morphology towards the northeast.



Profile 5 - Regional cross-sections that were selected to exemplify the structures of the main geological setting and the seismic interpretation in the study area. In the upper panel 2D seismic (migrated) lines of a survey conducted between 1982 and 1998 are displayed. The record length was 6 s. The seismic acquisition has different parameters and consequently a different resolution. The profile crosses features that give evidence for the stage 1 of the break-up process postulated in this paper. In the lower panel the appropriate seismo-stratigraphic interpretation is displayed as proposed in this study.

The top of the Continental Basement (TCB) is locally masked by this sequence (e.g. Profiles 1 and 2). This is especially evident in the south (e.g. Profile 5), where the poor imaging of the basement probably indicates reduced signal penetration. This is due to an increase in the frequency or thickness of the reflectors as compared to the northeast.

The geographical distribution of those reflectors stretches over an area that is approximately parallel to the Zambezi coast in the west and to the BH in the east, narrowing from latitude 20°30' S (~10 km south of Profile 5) and progressively widening north-eastward (e.g. it reaches a maximum width of 70 km on Profile 2). Concomitantly, the depth of the reflectors increases from 4.0 s to 7.5 s TWT in that direction.

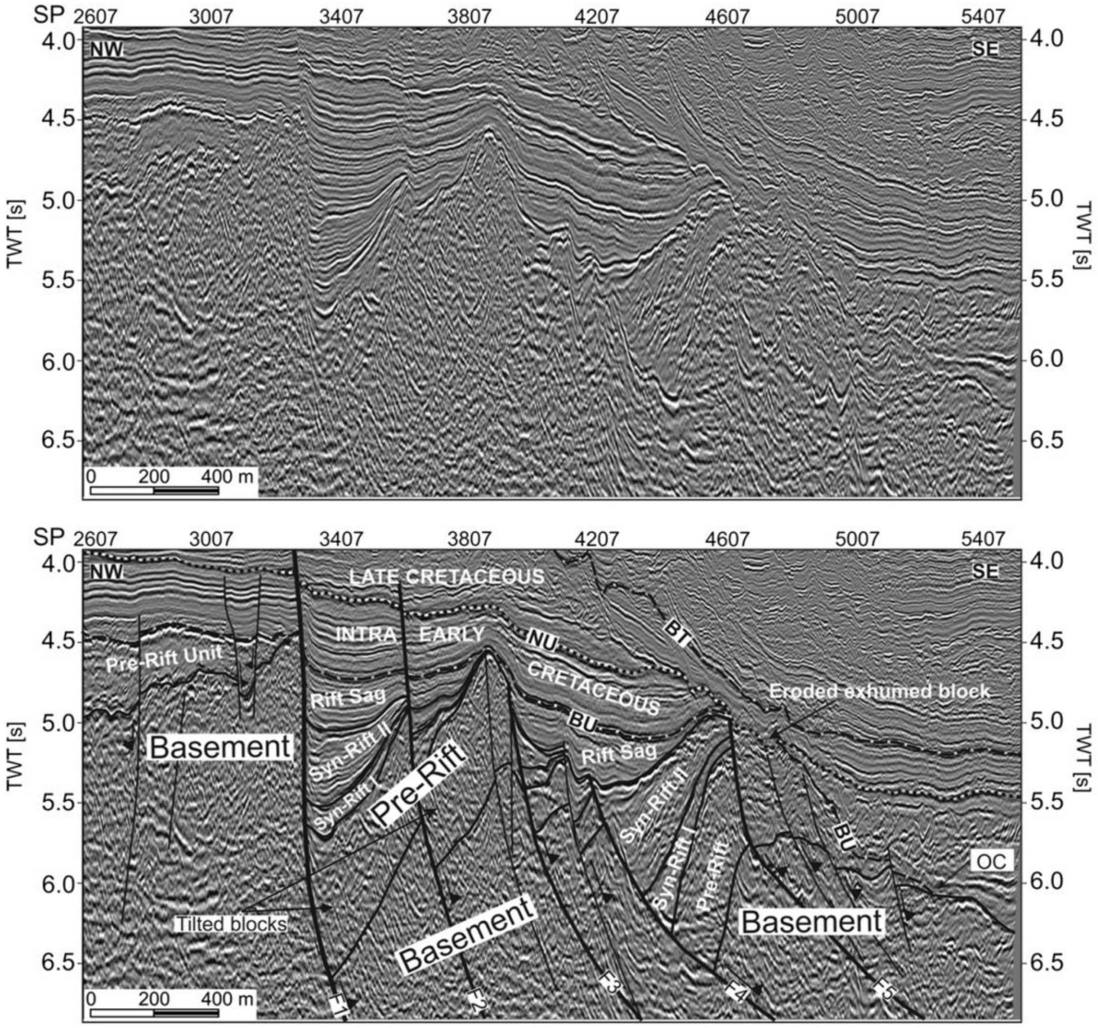


Figure 3 - Enlargement of the south-eastern portion of Profile 1. Upper panel: uninterpreted seismic section (migrated). Lower panel: appropriate interpretation as proposed in this study. Details of geotectonic structures and some sediment stratigraphy are shown. Prominent features are the rift-grabens with asymmetric half-graben morphology. Obvious are the continentward-dipping seismic reflectors (CDR) are indicated syn-rift, divergent sediment infill truncated by the footwall. In place of detachment faults tilted basement blocks were formed during the rifting phase. Along the pronounced anti-clockwise tilted blocks that underwent uplifting and erosion the Pre-Rift Unit is visible. See captions of Figures 1 and 4 for the abbreviations, and see text for discussion.

Two reasons support the favoured interpretation that lava flows are imaged by these particular seismic features. First of all, the rugged surface of this layer the strong reflectivity (high-amplitude), the wavelength and the geometries which suggest the presence of lava extrusions are strong indicators. Secondly, their occurrence is restricted to the area of the transitional domain (Profiles 1 and 2) and thus overlies the deepest basement in the rift-valley of the Offshore Zambezi depression (Figure 2). The reflection characteristics exhibit a strong similarity to the sill units described by Peron-Pinvidic et al. (2010) in the deep Newfoundland basin with its high-amplitude reflections. These are restricted to the area of the transitional basement, and thus only overlie the deepest basement parts. Peron-Pinvidic et al. (2010) consider the distribution of various sill-related features as indication for the existence of a centre of magmatic activity, which is characterized by strong, relatively continuous sill reflections. Moreover, local highs that are possible loci of magma injection and common fluid venting are features of the overlying sediments.

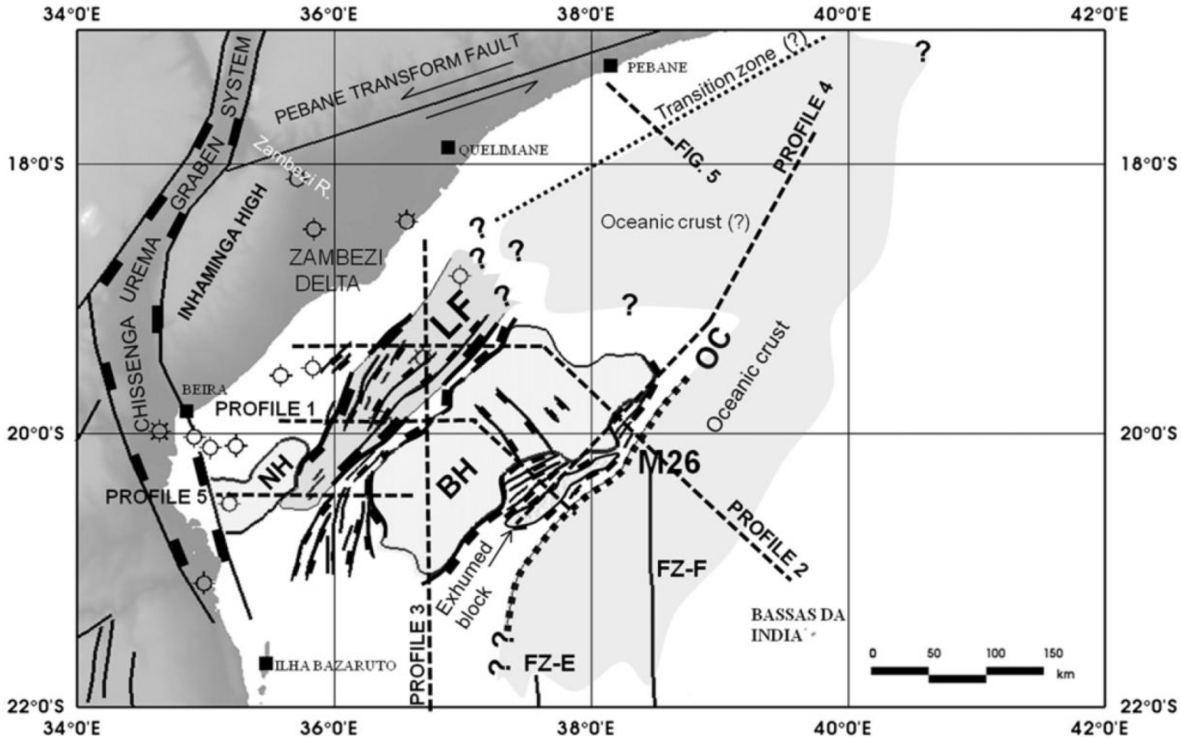


Figure 4 - The structural map that resulted from the seismic interpretation. The foremost geological features are the Beira High, the Nemo High and the lava flows. The Beira High is weakly deformed in the west by the Rift I event. On the other hand, the eastern edge displays evidence of several tectonic deformations during the Rift II phase. The majority of faults along the border of the lava flows indicate several rifting episodes during the Rift I stage. The NE-SW exhumed (uplifted) block (~100 km long) is the eastern border of the catchments for the syn-rift and rift-sag infills (see Fig. 3). OC is likely to coincide with the position of the sea-floor spreading magnetic anomaly M26 (König and Jokat, 2010). Key: BH - Beira High, NH - Nemo High, LF - Lava Flows, FZ - Fracture Zone, OC - Onset Oceanic Crust.

It is evident that almost all the potential lava flows occur in one stratigraphic level at the BU reflection (Profiles 1-3 and 5; Figure 2). The distribution of the potential lava flow indicates a relationship with the rifting event. It is likely that the extrusion of the sub-aerial lava flows was synchronous with the formation of a new ocean floor during the opening of the Offshore Zambezi depression. This interpretation (see Figure 2 and Profiles 1-3 and 5) is well supported by a pronounced positive gravity anomaly (Watts, 2001). This gravity signal indicates dense rocks such as e.g. volcanic extrusions and basalt successions, which provide significant density and magnetization (Hinze, 1985).

If this interpretation is correct, the distribution of the high-amplitude reflectors suggesting occurrence of lava flows increase their amplitude from northeast to southwest, thus leaving behind a new oceanic basin or highly thinned continental crust. Therefore, it can be concluded that also the size of area with lavas increases towards the north. Simultaneously, the thickness of the Jurassic sedimentary units progressively decreases until it completely disappears in that direction. Mapping the basement geometry reveals a clear dip from the Pebane volcanic outcrops (Raillard, 1990 and Cox, 1992) in the north towards south. This inclination can be traced until latitude S18°30'00" in the Zambezi River mouth, suggesting that this was the southern limit of the high magmatic influence.

Outside the Offshore Zambezi depression there are no comparable features that may be associated with the lava flows.

Beira High rifting

Widespread syn-rift deposits are restricted to the rift-grabens below a thick wedge of post-rift sediments (Figure 3). They show thickness of about 1.0 s (TWT). The deposits appear as both stratified and chaotic sequences with reflection amplitudes varying from moderate to high.

Generally, the rift-fill shows typical wedge-shape geometry and is between 860 ms to up to 1 s (TWT) thick. From a distinct unconformity separating two wedge-shaped syn-rift successions with different tilting, two rift phases are inferred. Age dating for the individual phases is difficult; however, the deepest part of the infill may represent sediments from the first rift-phase that was active in the Early Jurassic (Cox,1992). Conversely, the upper part of the rift-fill is likely to be related to the final rift phase preceding the break-up and sea-floor spreading in the Mozambique basin at ~155.3 Ma (König and Jokat, 2010)(Figures. 3 and 4) or 1.1 Ma later constrained by magnetic anomaly M25n (Leinweber and Jokat, 2012).

In contrast to the western and northern flanks, the eastern flank of the BH is strongly faulted (Figure 4). Here, the BH is juxtaposed to the oceanic crust by prominent normal faults showing asymmetric half-graben morphology. The normal faults are listric, cutting and strongly tilting the pre-rift succession (Figure 3). The base of the syn-rift unit is represented by the rift-onset unconformity (RU) with high-amplitude reflections. This interpretation consequently follows from the typical features of an angular erosional surface overlying unconformably the tilted pre-rift succession.

In general, listric normal faults are observed along the entire eastern flank of the BH. However, the area which is affected by faulting is wider in the central-east; between 37°10'E and 38°15'E. It reaches a length of about 120 km, and becomes narrower north-wards, only extending over 50 km (Figure 4). Five major listric faults (F1 to F5) could be traced all along the south-eastern BH (Figure 3). These faults define a 70km long and 30km wide half-graben system that runs more or less northeast-southwest. This graben system at the seaward slope of the BH (Figure 4) is bounded in the southeast by the exhumed block, which is strongly eroded at that position. Further north, where the BH gradually diminishes until its complete disappearance between 19°15'S and 19°28'S, the rift-grabens are situated directly adjacent to the oceanic basin (e.g. Profile 2).

The stratigraphy of the rift-graben infill suggests multiple rifting phases: syn-rift I, syn-rift II, and a rift-sag phase. Accordingly, these units have been interpreted as successions that are located between the packages of the pre-rift and post-rift successions, (Figure 3):

(1) Inside the rift-grabens, the complete syn-rift succession thickens progressively and continuously towards the north (from 600 ms TWT to 1.0 s TWT). This may be the expression of different stress angles during the rift evolution in different stages:

    a. **Syn-rift I phase** – the related sediments unconformably overlie the pre-rift unit separated by the erosional rift-onset surface (RU). The internal geometry varies from chaotic to divergent layered signatures towards the north. However, it is wedge-shaped everywhere. Its thickness increases eastwards to a maximum of 350 ms TWT.

b. **Syn-rift II phase** – the related sediment represents the thickest syn-rift unit with moderate to high-amplitude reflectors, diverging towards the hanging wall (i.e. wedge- shaped). Internally, the succession reveals bands of coherent divergent reflectors with high amplitudes. Few small-scale unconformities may be interpreted, but for simplicity I disregarded a further sub-division into sub-units. They reach a maximum thickness of about 650 ms TWT in the central rift-grabens.

(2) **Rift-sag phase** – Similar to the syn-rift infill, the expression of this phase occurs only inside the rift-valleys terminating with on-lap truncations against the pronounced anti-clockwise tilted block (uplifted block) (Figure 3 and 4). It is thicker in the central part of the rift-grabens reaching about 370 ms TWT, consisting of trough infill (channel infill) with moderate to high-amplitude reflectors. Overall, the seismic image reflects a pattern of sub-parallel to parallel reflections with high continuity.

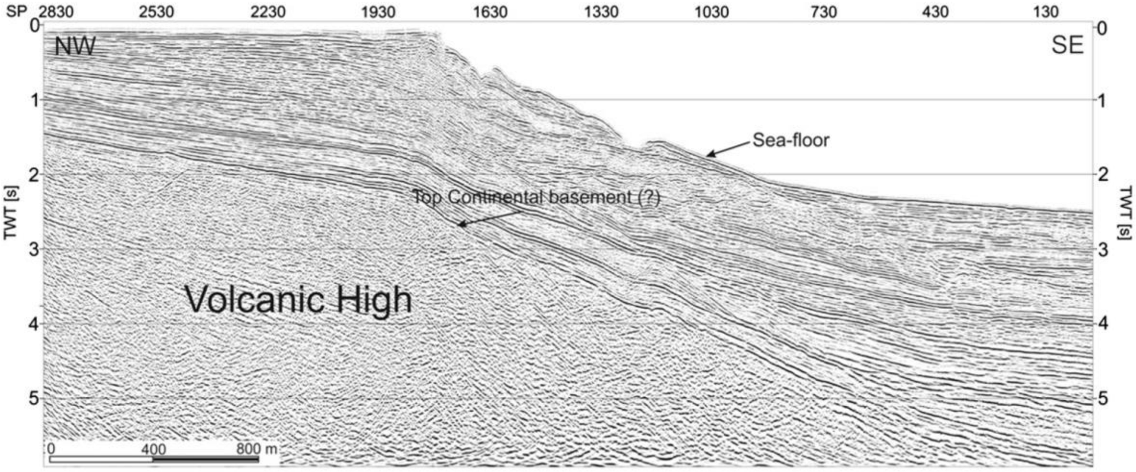


Figure 5 - Seismic section (migrated) in the area of the northern Offshore Zambezi depression. This is one of only few seismic reflection profiles that show a better data resolution in this region. The seismic image clearly depicts a high-amplitude reflector that is considered to represent the boundary between magmatic rocks (basement) and sedimentary successions (an arrow denotes its position). The basement is probably formed by the coast-parallel volcanic high (e.g. the coastal dykes mapped by Reeves, 2000) located onshore near the Zambezi coast. See Figure 1b for the profile location.

Onset of oceanic crust

The transition from continental to oceanic crust has been identified by the change of reflection patterns in that zone where the BU downlaps against the basement at about 6 s (TWT) in the southeast; and at about 7 s (TWT) in the northeast of the BH. The top of the inferred oceanic basement is characterized by high-amplitude reflectors and low frequency, which is typical for basaltic rocks. This reflection pattern can be continuously observed from the oceanic Mozambique basin to the proposed location of the oceanic crust, including the area where magnetic sea-floor spreading anomalies were identified (König and Jokat, 2010). The transition from continental to oceanic occurs within 5e10 km wide. It is yet unclear whether the Offshore Zambezi depression is underlain by an oceanic crust inferring a second oceanic crust. The 2D seismic lines at hand have short offset and/or short recording length, and the imaging of the basement is poor. However, few seismic sections show a better resolution (Figure 5) and the basement probably consists of the coastal-volcanic rocks (Reeves, 2000). A detailed delimitation of onset of oceanic crust beneath the Offshore Zambezi depression would require an investigation of the magnetic spreading anomalies. In any case, from the presence of the two rift phases it can be deduced that break-up and sea-floor spreading are diachronous within Rift I and Rift II segments.

Discussion

The results presented in Section 2 (Figure 4) indicate that the northern coast of the Mozambique margin is a passive rifted margin which developed in two different stages: The first stage is associated with post-rift magmatism extending from an area with coast-parallel volcanic outcrops (Pebane) to a narrow rift-failed zone with underlying lava flows between the Zambezi Coast and the BH; (2) the second stage is merely rifting one, mainly magma-poor, as described in Section 2.1.5 it is associated with highly deformed structures formed by extensional tectonics along the southeast of the BH (and Antarctica). This reveals different stages of rifting. Hence, the above arguments support a two stage model for Gondwana break-up.

Break-up stage 1

An important outcome of the 2D seismic mapping in this paper is the strong evidence for sub-aerial lava flows in the area of the Offshore Zambezi depression. The location of the sub-aerial lava flows, as well as the geometry, and lateral distribution suggests a close relationship between their origins, the initial break-up, and early sea-floor spreading as occurring in a well defined area within the deep part of that basin. The nature of the lava flows may be associated with the emplacement of the thick volcanic dykes (e.g. Figure 5) along the northern Zambezi Coast, possibly fed from Mid-Jurassic post-rift magmatism (Marsh, 1987 and Lawver et al., 1991a). Cox (1992) suggests that this magmatism was a result of the reactivation of the Pebane shear zone. Accordingly, the flows were probably restricted to a relatively narrow rift zone created during the rifting and the first sea-floor spreading between the Zambezi Coast and Antarctica (including the BH).

It may be speculated that further southwest of the Offshore Zambezi depression, a transition from continental-to-oceanic crust occurs (e.g. Profiles 1 and 2). The reflector characteristics show a gradual change from high-amplitude to hummocky patterns towards the northeast, therefore suggesting some sort of transition in that area. These indicators suggest a gradual formation of new oceanic crust from the northeast to the southwest, aligned with a zone of coast-parallel dykes.

I suggest here that Rift I had undergone a strain relief that resulted in high tension for break-up stage 1, that finally produced a narrow rift zone with a V-shape depression valley (Offshore Zambezi depression). The western flank of the Beira High had tried to open-up predominantly when the Antarctica Plate (with the Beira High) drifted dextrally more or less east-west until the Mid-Jurassic. A change in motion to the south (e.g. Reeves and de Wit, 2000 model) is the best explanation for a “rift jump” from the Offshore Zambezi depression in the northwest to the eastern edge of the BH in the southeast (break-up stage 2).

Break-up stage 2

The fault geometry of the major half-grabens (e.g. Figure 3; Profiles 1, 2 and 4) indicates extension in south-eastern direction. According to Kearey et al. (2009), the asymmetric morphology typifies a slow spreading system. This agrees with the initial spreading rate of about 15 km/myrs for the sea-floor in the opening of the Mozambique Channel (Simpson et al., 1979).

In the present paper at least two major rift phases can be clearly distinguished during which extensional deformation was accommodated along different parts of the BH, (1) The Rift-I phase predominantly affected the west-northwest BH by pronounced normal faults with small offsets. However, that phase only mildly affected the south-eastern BH; (2) The Rift-II phase can be associated with the period when Antarctica changed its drift direction towards south. The Rift-sag phase, is interpreted as post-rift phase developed with minor extensions of the crust evidenced by gently dipping low- angle detachment faults in the upper crust (Coward et al.,1987).

The top of the rift II phase discloses several erosional unconformities and rift infill episodes that suggest extensive stretching and extensional tectonics that resulted in tilted blocks in the central eastern part of the Beira High (Figure 3). Hence, it corresponds to the zone of a high tensional regime due to the resistance of the upper crust against deformation and rifting. The main tectonic feature is a low-angle detachment at the eastern flank. The seismic image suggests that it is compensated in the lower crust or possibly even in the upper mantle.

The termination of rifting, the following break-up and the formation of new oceanic crust are imaged by the change of the seismic properties to the east at the end of the adjacent faults and/or down-lapping of the BU against the basement (Profile 1, Figure 3). In this area, magnetic data are essential to identify the onset of oceanic crust. The magnetic anomalies M26 proposed by König and Jokat (2010) and M25n (Leinweber and Jokat, 2012) fit with the outcome of this study. In that context, the magnetic anomaly M26 constrains the onset of the break-up stage 2 and M25n indicate the transition zone between the Beira High continental crust and the oceanic basin. Both finally mark the onset of regular sea-floor spreading between 155.3 Ma and 154.2 Ma.

Conclusions

- A detailed interpretation of a 2D reflection seismic data set across the Offshore Zambezi depression reveals a pattern of low-frequency reflectors at the break-up stage. These may be interpreted as lava flows that previously were not observed in that region. The negative consequence of the lava flows is the attenuation of the seismic signal penetrating into deeper strata. Therefore, it is difficult to identify the basement type in that region. Considering the known facts it is suggested that these lava flows are probably associated with an early rift event between 182 and 170 Ma when Africa and Antarctica initially separated (Rift I), representing an episodic emplacement of magmatic material.

- The Beira High hosts several distinct sedimentary successions that can be attributed to different phases in the formation history of the continental margin; (1) pre-rift consisting of stratified and chaotic filling, in the south-eastern Beira High mostly predominate thick piles (~0.9 s TWT) of tilted blocks parallel to fault planes; (2) syn-rift is subdivided into two rift segments identified only within the rift-grabens in the south-eastern Beira High, the earlier rift infill is related to the Break- up 1 and rift II to the Break-up 2 phase; extensional tectonics terminated with a sag deposition; and (3) in the post-rift period marine, transition and deltaic sequences were deposited from Cretaceous to Recent.
- The Break-up Stage 2 is distinctly visible in the seismic data by vast rift-grabens at the eastern edge of BH. These developed in several stages, mostly with asymmetric geometry, a wider half-graben bounded by gentle normal listric faults, dipping to the southeast. The sediment infill is commonly defined by stratified divergent fill, wedge shaped, with a thickness up to 1 s TWT.
- The location of the onset of oceanic crust is inferred from the change of seismic characters seaward of the BH, where the BU intersects the oceanic basement in my interpretation.
- From the presence of: (1) a layered succession (pre-rift) below the BU and (2) rift-grabens at the eastern edge, it appears likely that the Beira High is of continental origin.

Acknowledgements

I would like to thank to: Eng. Arsénio Mabote and INP for funding this project and providing the data. I am also grateful to BGR for their assistance in writing this paper, organizing the logistics and the data. There are not enough words to thank Dr. Dieter Franke, Dr. Christian Reichert and Dr. Axel Ehrhardt for critically reviewing the manuscript. Your comments are highly appreciated. I would also like to thank Mr. Martin Block for technical discussions, support, and guidelines; Dr. Ingo Heyde and Dr. Berd Schreckenberger for the discussions about magnetic and gravity information; Prof. Dr. Jutta Winsemann (Leibniz University of Hannover) for the support and encouragement; the Alfred-Wegener-Institut (AWI) for the magnetic lineation data. Further, I would like to thank Laura Mahanjane for helping in the final edition of this paper. Finally, I thank the reviewers for their critical comments.

References

Bergh, H.W., 1977. Mesozoic sea-floor off Dronnig Maud Land, Antarctica, Nature, 269, 686–687.

Courtillot, V., Jaupart, C., Manighetti, I., Tapponnier, P., Besse, J., 1999. On causal links between flood basalts and continental breakup. Earth and Planetary Science Letters 166, pp. 177-195.

Cox, K. G., 1992. Karoo igneous activity and the early stages of the break-up of Gondwanaland, in Magmatism and the Causes of Continental Break-up, edited by B. C. Storey, T. Alabaster, and R. J. Pankhurst, Geol. Soc. Spec. Publ., 68, pp. 137–148.

Coward, M. P., Dewey, J. F., Hancock, P. L., 1987. Continental extensional tectonics. Geological Society Special Publication nº 28.

De Buyl, M., Flores, G., 1986. The Southern Mozambique Basin: the most promising hydrocarbon province offshore East Africa.- In: Halbouty, M.T. (ed.): Future Petroleum Provinces of the World, AAPG Memoir, 40, pp. 399-425, Tulsa, Oklahoma.

Duncan, R. A., Hooper, P. R., Rehacek J., Marsh J. S., Duncan, A. R., 1997. The timing and duration of the Karoo igneous event, Southern Gondwana. Journal of Geophysical Research, Vol. 102, No. B8, Pages 18,127-18,138.

Fitch, F. J., Miller, J. A., 1984. Dating Karoo igneous rocks by the conventional K-Ar and 40Ar/39Ar age spectrum methods. In: Erlank, A. J. (ed) Petrogenesis of the volcanic rocks of the Karoo Province. Geological Society of South Africa Special Publication, 13, 247-266.

Garner, P., 1996. Continental flood Basalts indicates a pre-Mesozoic flood/post-Flood boundary. CENTech. J., vol. 10, nº 1, 1996.

Hinze, W. J., 1985. The Utility of Regional Gravity and Magnetic Anomaly Maps. DOI: 10.1190/1.0931830346. Catalog No. 811E. Pages: 468.

Jokat, W., T. Boebel, M. König, U. Meyer, 2003. Timing and geometry of early Gondwana breakup, J. Geophys. Res., 108(B9), 2428, doi: 10.1029/2002JB001802.

Kearey, P., Klepeis, K. A., Vine, F. J., 2009. Global Tectonics. 3rd Edition, Wiley–Blackwell. 482 pages.

Klausen, M. B., 2009. The Lebombo monocline and associated feeder dyke swarm: Diagnostic of a successful and highly volcanic rifted margin? Tectonophysics 468, 42-62.

König, M., Jokat, W., 2006. The Mesozoic breakup of the Weddell Sea, J. geophys. Res., 111(B12), 102, doi:10.1029/2005JB004035.

König, M., Jokat, W., 2010. Advanced insights into magmatism and volcanism of the Mozambique Ridge and Mozambique Basin in the view of new potential field data. Geophysical Journal International, Volume 180, Issue 1, pages 158–180, January 2010.

Lawver, L., Gahagan, L. M., Dalziel, I. W. D., 1991a. Continental break-up and tectonic evolution. Nato Advanced Study Institute, 'Dynamic modelling and flow in the earth and planets', Alaska, June 1991, abstracts volume.

Lawver, L. Royer, J. Y., Sandwell, D. T., Scotese, C. R., 1991b. Evolution of the Antarctic continental margins, in Geological Evolution of Antarctica, edited by M. R. A. Thomson, J. A. Crame, and J. W. Thomson, pp. 533–540, Cambridge Univ. Press, New York.

Leinweber, V. and Jokat, W., 2012. The Jurassic history of the Africa-Antarctica Corridor - new constraints from magnetic data on the conjugate continental margins, Tectonophysics, Vol. 530-531, 87-101, doi:10.1016/j.tecto.2011.11.008

Marks, K. M., Tikku, A. A., 2001. Cretaceous reconstructions of East Antarctica, Africa and Madagascar. Earth and Planetary Science Letters 186 (2001) 479-495.

Marsh, J. S., 1987. Basalt geochemistry and tectonic discrimination within continental flood basalt provinces. Journal of Volcanology and Geothermal Research, 32, 35-49.

Martin, A. K., 2007. Gondwana Breakup via double-saloon-door rifting and sea-floor spreading in a backarc basin during subduction rollback. ScienceDirect. Tectonophysics 445 (2007) 245-272.

Peron-Pinvidic, G., Shillington, D. J., Tucholke, B. E., 2010. Characterization of sills associated with the U reflection on the Newfoundland margin: evidence for widespread early post-rift magmatism on a magma-poor rifted margin. Geophysical Journal International 182(1): 113-136.

Rabinowitz, P. D., Coffin, M. F., Falvey, D. A., 1983. The separation of Madagascar and Africa, Science, 220, 67–69.

Raillard, S., 1990. Les marges de l`Afrique de l`Est et les zones de fracture associees: Chaine Davie et Ridge du Mozambique-Champagne MD-60/MACA MO-11. PhD thesis, L'Universite Pierre et Marie Curie, Paris, pp. 1-272.

Reeves, C., 2000. The Geophysical mapping of Mesozoic dyke swarms in southern Africa and their origin in the disruption of Gondwana. J. Afr. Earth Sci., 30, 449-513.

Reeves, C., de Wit, M., 2000. Making ends meet in Gondwana: Retracing the transforms of the Indian Ocean and reconnecting continental shear zones, Terra Nova, 12, 272-280.

Reeves, C. V., Sahu, B. K., De Wit, M., 2002. A re-examination of the paleo-position of Africa's eastern neighbours in Gondwana. Journal of African Earth Sciences 34, 101-108.

Reichert, C., Neben, S., Adam, J., Aslanian, D., Roest, W., Mahanjane, E., James, E., Bargeloh, H., Behrens, T., Martin, B., Ehrhardt, A., Heyde, I., Jokat, W., Kallaus, G., Klingelhöfer, F., Moulin, M., Kewitsch, P., Schrader, U., Schreckenberger, B., and Sievers, J., 2008. Cruise Report, BGR07. R/V MARION DUFRESNE CRUISES MD 163 & MD 164. PROJECT MOBAMASIS. Tech. rep. Hannover, Bundesanstalt für Geowissenschaften und Rohstoffe (BGR).

Riley, T. R., Knight, K. B., 2001. Review Age of pre-break-up Gondwana magmatism. Antarctic Science 13 (2): 99-110 (2001) Antarctic Science Printed in the United Kingdom.

Salman, G., Abdula, I., 1995. Development of the Mozambique and Ruvuma sedimentary basins, offshore Mozambique. Sedimentary Geology 96 (1995) 7-41. Elsevier Science B.V. SSDI 0037-0738(94)00125-1.

Segev, A., 2002. Flood basalts, continental breakup and the dispersal of Gondwana: evidence for periodic migration of upwelling mantle flows (plumes). EGU Stephan Mueller Special Publication Series, 2, 171–191, 2002.

Segoufin J., 1978. Anomalies magnétiques mésozoïques dans le bassin de Mozambique, Comptes Rendus de l'Académie des Sciences, 287, 109–112.

Segoufin, J., Patriat, P., 1980. Existence d'anomalies mesozoiques dans le bassin de Somalie. Implications pour les relations Afrique-Antarctique-Madagascar, C.R. Acad. Sci. Paris 291 (1980) 85-88.

Simpson, E. S. W., Sclater, J.G., Parsons, B., Norton I., Meinke L., 1979. Mesozoic magnetic Lineations in the Mozambique Basin. Earth and Planetary Science Letters, 43 (1919) 260-264. Elsevier Scientific Publishing Company, Amsterdam.

Watkeys, M. K., 2002. Development of the Lebombo rifted volcanic margin of SE Africa. Special paper. In: Menzies, M. A., Baker, J., Ebinger, C. and Klemper, S. (eds) Magmatic Rifted Margins. Geological Society of America Special Paper, 362, p. 27-46.

Watts, A.B., 2001. Gravity anomalies, flexure and crustal structure at the Mozambique rifted margin. Marine and Petroleum Geology, 18, pp. 445-455.

4.2. The Rovuma Delta deep-water fold-and-thrust belt, offshore Mozambique

(1)E. S. Mahanjane and (2) D. Franke / Tectonophysics 614 (2014) 91–99. http://dx.doi.org/10.1016/j.tecto.2013.12.017

(1) Institute National Petroleum (INP), Av. Fernão Magalhaes N. 34, 2nd Floor, PO Box 4724, Maputo, Mozambique
(2) Bundesanstalt Für Geowissenschaften Und Rohstoffe (BGR), Stilleweg 2, 30655, Hannover, Germany

Abstract

We interpret two-dimensional seismic reflection data from the Rovuma Delta basin deep-water fold-and-thrust belts. Two major arcuate complexes with different architecture and extent are identified. While in the northern Palma arcuate complex a multitude of steep, east-dipping thrust-related fold anticlines formed above a single main detachment, in the southern Mocimboa arcuate complex multiple detachments resulted in the formation of thrust duplexes. In between the two arcuate domains, only few thrust-related fold anticlines developed.

Our interpretation of the Rovuma basin is a linked system of up-dip extension and down-dip compression that is mainly driven by gravity tectonics. Sediment loading and a hinterland uplift due to the development of the East African Rift System since the Oligocene is proposed as origin of the delta.

It is shown that the main, seaward-dipping detachment in Early Cenozoic strata is likely under-compacted and overpressured shale. Conversely, shale diapirism is questionable since the shape and location of such structures in the fold-and-thrust-belts appears simply indicating steeply dipping imbricated folds, rooted by a near vertical thrust.

We suggest that mainly a different rheology and thickness and thus efficiency of the shale detachment across the delta resulted in different morphologies and geometries of the deep-water fold-and-thrust-belts.

Introduction

Despite the long-standing academic interest in deep-water fold-and-thrust belts (DWFTBs), little has been published about the Rovuma Delta basin offshore NE Mozambique. The Rovuma Delta basin (Figure 1) has a proven prolific hydrocarbon fairway in NE Mozambique's offshore deep-water. Different sources report discovered in-place natural gas resources that may reach 100 Trillion Cubic Feet (e.g. Ledesma, 2013). The discoveries are trapped in complex tectonic structures in a system of extensional faults and compressional DWFTBs, and in deep-water submarine fans.

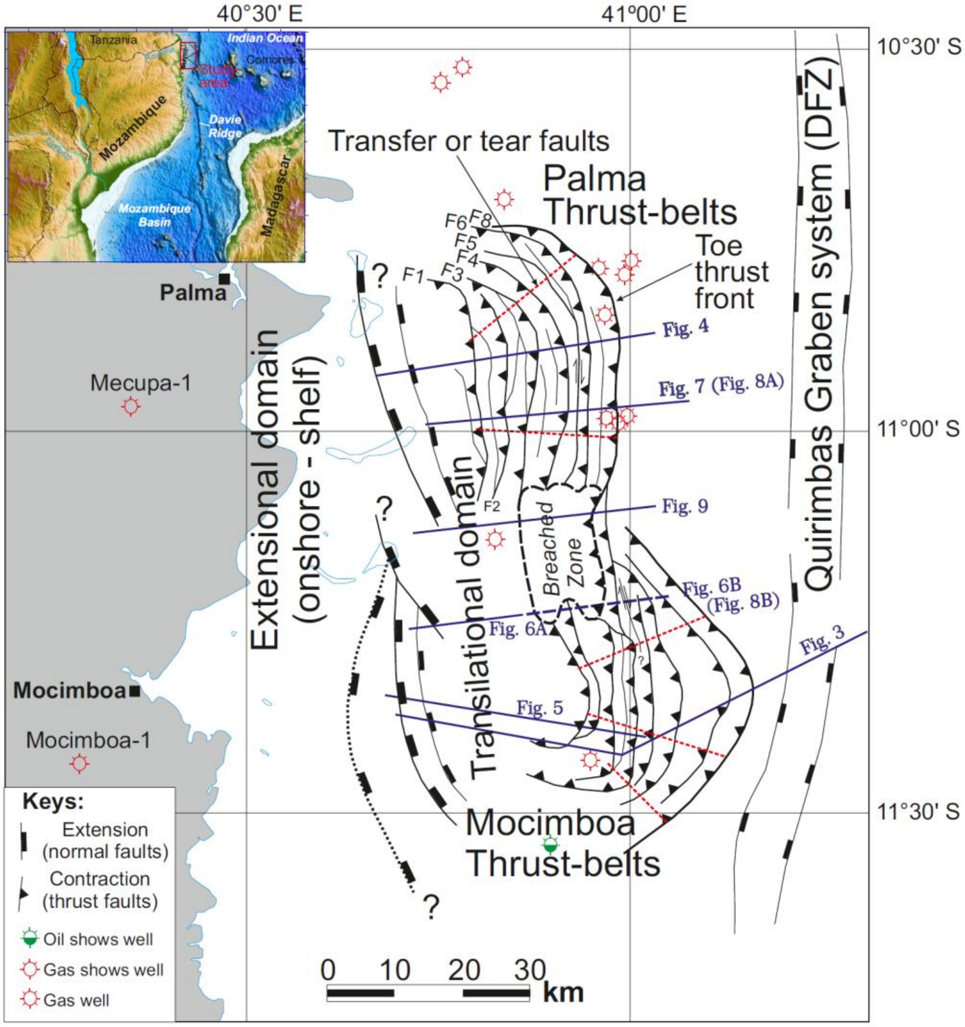


Figure 1 - Major structural elements of the offshore Rovuma Delta and the Quirimbas graben of the Davie Fracture Zone. The thrust-and-fold belts show a general E-W trend and are located in deep-water, between 1000-2000 m. Two major arcuate complexes developed to the south of the Rovuma River estuary: The northern Palma thrust belts and the southern Mocimboa thrust-belts. The location of the seismic example lines is indicated (dark blue).

Deep-water fold-and-thrust belts develop at both active and passive continental margins. At passive continental margins, gravity-driven systems prevail that are triggered by the rigid translation of a rock mass down the slope (Ramberg, 1981). Gravity gliding is usually associated with linkage of up-dip extension with a down-dip contractional toe region via a detachment zone (Morley et al., 2011). Thus, typically not the complete sedimentary section is affected but deformation is often limited to a mobile zone (usually either overpressured, undercompacted shale or salt) at the base of the gravity-driven system. The general principles of dominant controlling factor of gravity detachment systems are the (1) initial deposition of salt or massive shales to form an efficient regional detachment, and (2) progradation of a large delta or group of deltas which introduce massive volumes of clastic sediments into the basin (Morley et al., 2011). The mechanism of shale deformation differs from those for salt deformation due to their different rheologies (Morley and Guerin, 1996). Salt is a viscous material whose rheology is independent of temperature, burial or strain, resulting in continuous deformation until it becomes isolated into pods. In contrast, shale deforms primarily as the result of internal shear strength being reduced by overpressuring and dewatering of shales will stop their mobility (Weimer and Slatt, 2004). As a consequence of the detachment rheology, the structural styles between shale and salt gravity-driven systems differ (Sapin et al., 2012). Morley (2003a) showed the main difference is that, in the case of shales, the weak mechanic behaviour is not confined to a specific stratigraphic unit. Counter-regional normal faults, major listric faults that dip landward, have been described in both *shale-* and *salt-detachment*. However, according to Sapin et al. (2012), the counter-regional shale systems show an important amount of extension, in contrast to salt tectonics.

With this paper we aim at a better understanding of the tectonic setting along the Rovuma Delta basin. The main basis of the study was the structural mapping of approximately 1,500 line km of 2D multi-channel seismic data (filtered & scaled migration), transecting the Rovuma Delta DWFTB system (Figure 1). The dataset comprises two surveys: Lonropet (LRP-98) and Western Geophysical (MBRWG-00), collected in water depths between 500 and 2500 m (Figure 1). The seismic data were interpreted both in paper-record form and using workstation installed integrated Seismic Micro-Technology KINGDOM^{TM} software. We provide a detailed description of the general appearance of deformational tectonic mechanisms along the deltaic system. Our interpretation classifies the Rovuma Delta DWFTB as a gravity gliding system where the downdip fold-and-thrust belt is linked to updip extension via a detachment. The latter is suggested to be made up of overpressured shales.

Geological background

Tectonic evolution

Mozambique's passive continental margin originates from the breakup of Gondwana. According to Rabinowitz et al. (1983) the Africa–Madagascar breakup took place around 165 Ma, in the Middle Jurassic, followed by the southward motion of Madagascar and this is believed to have ended by the early Aptian (c. 121 Ma) (Rabinowitz et al., 1983) or middle Aptian (c. 118 Ma) (Bassias, 1992). Thermochronological and structural data from basement rocks proximal to the Rovuma basin margin indicate that only a narrow zone was affected by rifting (e.g. Daszinnies et al., 2009; Emmel et al., 2011), typical for a transtensional rift basin.

The NNW-SSE oriented Davie Fracture Zone controlled the southerly motion of Madagascar (Bird, 2001; Scrutton, 1978) along a dextral strike-slip system during Late Jurassic and Early Cretaceous times (Bassias, 1992). Several depressions formed along the Davie Fracture Zone, including the Rovuma basin during the time of the main movement (Mahanjane, submitted for publication). Northern Mozambique lies within a major N-S trending orogenic belt and the basement is made up of Late Proterozoic rocks of the Mozambique metamorphic belt (Salman and Abdula, 1995). In mid-Jurassic time a rapid denudation episode affected the Rovuma rifted margin, associated onshore with an erosional response along the major dextral strike-slip fault (Emmel et al., 2011; Roberts et al., 2012). From the Early Cretaceous on, the Davie Fracture Zone off Mozambique became inactive (Coffin and Rabinowitz, 1987; Coffin and Rabinowitz, 1992) and the western margin of the Rovuma basin then became part of the passive margin. The onshore sedimentary sequence in the Rovuma basin is bound to the west and south by gneisses, granulites and migmatites of the Mozambique Belt (Pinna, 1995), and to the east by the Indian Ocean (Hancox et al., 2002).

Stratigraphy

Sedimentary successions up to 10 km thick of the Rovuma basin widely resemble the tectonic evolution. The lithostratigraphy of the onshore Rovuma basin is described in detail by Key et al. (2008) and Smelror et al. (2008) while the offshore was addressed by Salman and Abdula (1995) and Emmel et al. (2011).

A summary of lithostratigraphy of the northern offshore Rovuma basin in Mozambique is presented in Figure 2. Sedimentary deposits comprise Middle Jurassic to Cenozoic strata (Salman and Abdula, 1995). It is an open question if there are Early Permian to Middle Jurassic Karoo age sediments below, as inferred by Salman and Abdula (1995) based on seismic correlations with the Tanzanian Selous basin. In fact, when reconstructing Madagascar back to its pre-breakup position the modern Rovuma basin is situated in between the Karoo basins Selous (Tanzania), Duruma (Kenya), and Morondava (Madagascar)

(Catuneanu et al., 2005) and the pre-drift sediments show general good correlation between these basins (Hankel, 1994). The main question is about extensive uplift and erosion resulting in a regional Early to Middle Triassic hiatus (Hankel, 1994) that may have caused the absence of Karoo sediments before sedimentation was resumed in the Ladinian in the Rovuma basin. However, the quality of the deep portions of the seismic reflection data at hand makes it impossible to definitely judge on the presence or absence of Karoo sediments in the Rovuma basin. If present in our interpretation such sediments would be found in what we indicate as basement.

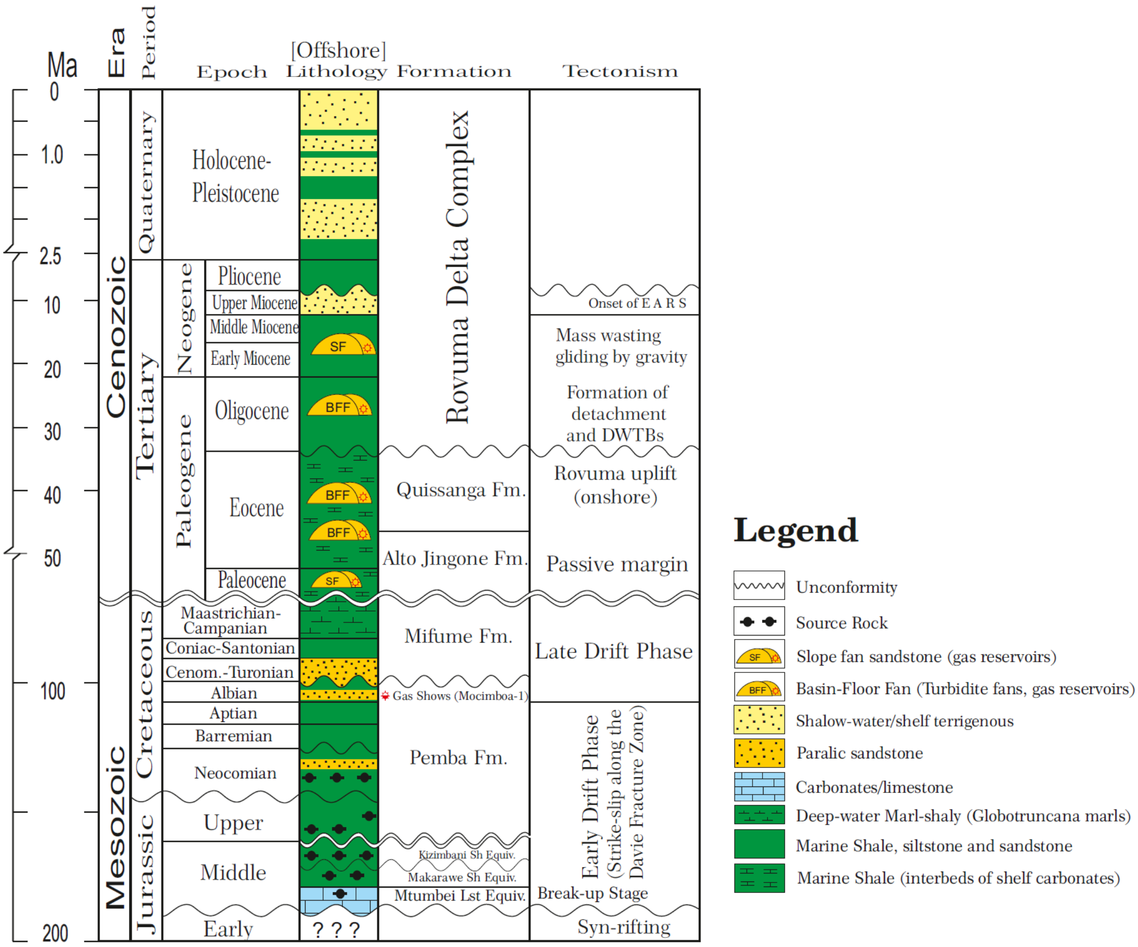


Figure 2 - Simplified stratigraphy of the northern offshore Rovuma basin based on ECL & ENH, 2000; Key et al., 2008; Salman and Abdula, 1995.

The Jurassic-Cretaceous successions of the Rovuma basin are related to the progressive break-up of south-eastern Gondwana. A Late Jurassic regional unconformity reflects a change to transform-controlled passive margin conditions as Madagascar moved southwards relative to mainland Africa (Raillard, 1990). Onshore the coarse basin margin sediments above the unconformity are referred to as the Macomia Formation and the marine sediments are referred to as the Pemba Formation (Key et al., 2008).

A Late Cretaceous marine transgression is proposed the origin of the Mifume Formation, which comprises several thousands of meters of predominantly grey marls or mudstones and calcareous sandstones (Key et al., 2008). Onshore it consists of thin layers (up to 70 cm) of interbedded sandstones which become coarser upwards (Key et al., 2008), where they grade into limestones.

During the Early Cenozoic the region still was affected by a transgression which reached a maximum in the Eocene, with regression setting in during the Late Eocene (Nairn et al., 1991). The Mocimboa-1 Borehole shows the rapid eastward increase in thickness of the post-Mifume Formation sediments from less than a few hundred metres to about 3000 m. The Paleocene-Eocene sediments encountered in the well are deep-water carbonate shales with a thickness of 130 m (Salman and Abdula, 1995). Paleocene-Eocene successions occur offshore as shelf carbonates with interbeds of calcareous sandstone and marls (Key et al., 2008; Smelror et al., 2008). In central to south Tanzania the accumulation of a thick, outer shelf, clay-dominated succession (the Kilwa Group) was deposited during Upper Cretaceous to Lower Miocene. Late Campanian to Middle Eocene aged clays are overlain with marked angular unconformity by Lower Miocene clays that are probably locally reworked and re-deposited earlier clays (Nicholas et al., 2006). Based on ECL and ENH (2000) and Salman and Abdula (1995) it is proposed here that such clay-dominated Paleocene-Eocene successions are widespread in the offshore Rovuma Delta.

The Rovuma deltaic complex consists of a thick, eastward prograding wedge of Cenozoic fluvial deltaic deposits (continental and paralic clasts) to shallow-water marine and deep-marine strata that overlie unconformably the interface of Palaeocene-Eocene successions (Key et al., 2008; Salman and Abdula, 1995). The offshore delta complex is characterized by sequences of marine shale, siltstone and sandstone which grade to paralic and continental clastics towards the onshore.

The origin of the delta formation is likely a regional uplift of eastern Africa, potentially linked to a doming in the Oligocene (Key et al., 2008) or at the earlier stage in the Lutetian (Roberts et al., 2012), prior to the formation of the East African Rift. Roberts et al. (2012) claim that this uplift modified continental drainage patterns and directions for major large river systems including the Nile, Congo, Zambezi and Rovuma (?) systems. A Miocene transgression led to shallow water marine sedimentation during progradation of the Rovuma delta contemporaneous with rift-related onshore sedimentation in the East African Rift System (Key et al., 2008).

Significant uplift and erosion occurred in southern Tanzania after the Late Miocene and likely also extended to the Rovuma basin. The coastal zone was effectively blanketed by fluvial and shallow marine sands and grits that are of Pliocene or younger age. This sequence suggests the denudation of a significant source region inland, possibly the basement of the Masasi spur to the west. If this were the case, then it would be contemporaneous with thermal doming and tilting which occurred across the Tanzanian craton(s) immediately prior to modern rift initiation in the north (Nicholas et al., 2007).

Interpretation of the 2D reflection seismic data

In the following the linked system of upslope extension, a transitional domain and the down-slope compressional domain (fold-and-thrust-belt) is described. The entire Rovuma Delta is located to the south of the present-day Rovuma River (Figure 1).

Extensional domain

The extensional domain comprises both an onshore and an offshore area. In the onshore area it extends about 50 km inland where elongated listric normal faults ramp down to a common detachment (Law, 2011). This domain continues for another 30 km in the offshore region, where again regional listric normal faults sole out at a major, seaward dipping detachment. The extensional deformation resulted in the formation of rollover structures, hanging-wall crest collapse grabens and counter-regional normal faults (Figure 3).

The structural style of the northern offshore extensional zone, which is linked to the Palma thrust-belt, is characterized by parallel to sub-parallel normal faults that strike NNW and dip to the ENE (~ 60°). The individual faults may align along the shelf for up to 45 km (Figure 1). Towards the east, the fault angle diminishes gradually from ~ 60° in planar rotational extensional faults to ~ 40° in listric normal faults. Consecutive pairs of listric normal faults deform most of the Cenozoic successions, resulting occasionally in sequences of half-graben structures (e.g. Figures 6A, 7).

The southern extensional zone (Mocimboa) is made up of a set of normal faults, striking more or less north-south, which are less steep (~ 45°) than in the northern domain. Here the normal faults extend for up to 50 km across the shelf.

At the seaward limit of the extensional domain, series of synthetic and antithetic faults and crest collapse structures are present (Figure 7).

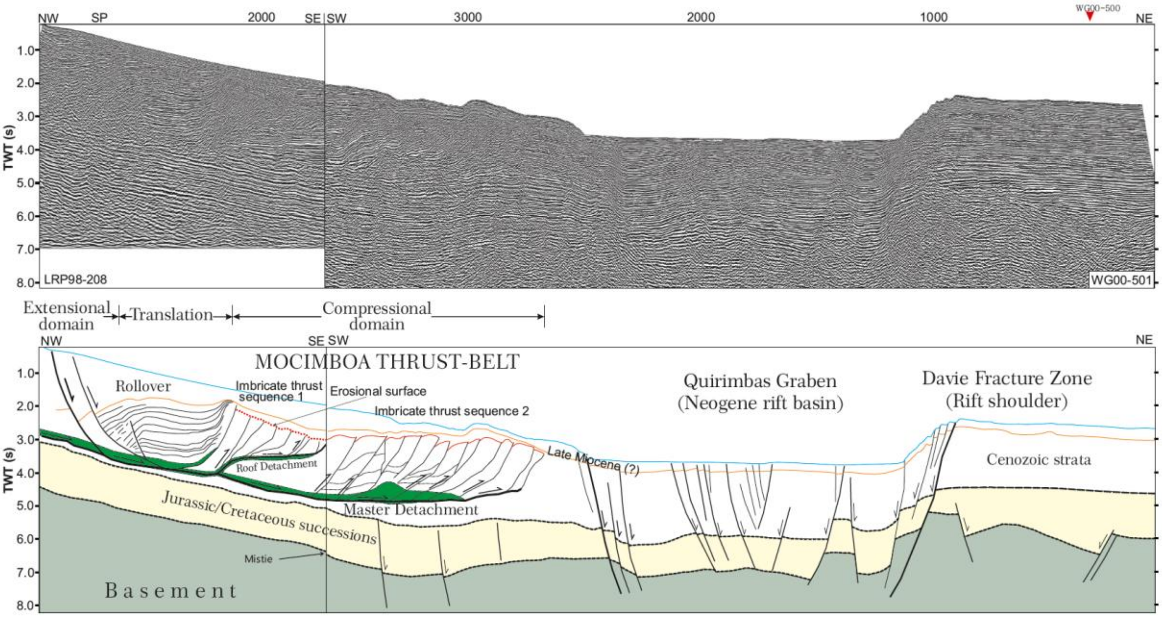


Figure 3 - Top: Composite reflection seismic lines showing the general architecture of the southern Rovuma deltaic system (Mocimboa). Bottom: Interpretation of extensional and compressional structures at the continental slope. The extensional zone is dominated by normal faulting resulting in rollover structures. Two prominent imbricate thrust sequences (toe thrusts) are extending towards the deep water area. Further seaward, rift-related extension is manifest in the Quirimbas Graben within the Davie Fracture zone. See Fig. 1 for location.

Translational domain

The translational domain is a relatively undeformed area between the extensional and the compressional domain. The length of the translational area in the *Mocimboa Complex* is relatively larger than that of the *Palma Complex*. This domain is typically less than 20 km wide (e.g. Figure 8) and occasionally the extensional domain is directly adjacent to the contractional domain.

Compressional domain

Mapping of thrust faults segments resulted in two morphologically prominent arcuate regions, the northern *Palma* and the southern *Mocimboa thrust-belts*. The width of the compressional area of the Rovuma DWFTB varies from ~ 18 km within the *Palma thrust-belts* to ~ 25 km at the SE portion of *Mocimboa thrust-belts* (Figure 1). The *Palma thrust-belts* cover an area of approximately 900 km^2 while the *Mocimboa thrust-belts* cover a smaller area, approximately 750 km^2.

Both arcuate regions show similar deformation styles with asymmetric imbricate fans and ramp-flat geometries. The DWFTBs are predominately offshore verging folds with some break-thrusts at their forelimbs. A series of splay faults branching off and ramping sequentially out of the main detachment results in imbricate fans separated with an average distance of 1.0 to 3.5 km between them (Figures 3, 4, 7).

The splay faults are convex upward with gentle dips at the surface. The most widespread geometry is that of blind thrusts terminating upward (ramp-up section) into markedly asymmetric fault-propagation folds. All thrust faults sole into a seaward dipping detachment that is imaged at between 3.2 s TWT to about 4.5 s [TWT] (Figure 6A, B). The about 2.0 km [1.8 s TWT] thick deformed sediments have been buried by the most recent sediment wedge of Pliocene-Pleistocene age levelling the continental slope at the seafloor. The detachment is buried between 4.0 km (3 s TWT) to 4.5 km (4 s TWT) (Figures 4, 7, 8A).

In both domains there are up to eight major successive thrust-related fold anticlines (F1 to F8; see Figures 1, 4, 7). We observe a general steepening of the forelimbs in landward direction from about 20° at the frontal anticline to a near vertical structure at the most landward anticline *F1* (~ 70°, e.g. Figure 4). The well-developed imbricate thrust faults and associated folds gradually die out to the east to form the forelimb imbrications in a narrow triangular sliver of rock which defines the front-toe thrust-belts before reaching the Neogene Davie rift grabens (Figures 1, 3).

A couple of thrust duplexes are distinct in our data in the southern *Mocimboa thrust-belts* (Figures 5, 6B). Here an upper imbricate-sequence is underlain by a second detachment. The top of the upper imbricate-sequence is strongly eroded, eliminating completely the shape of toe-thrusts (Figures 3, 5).

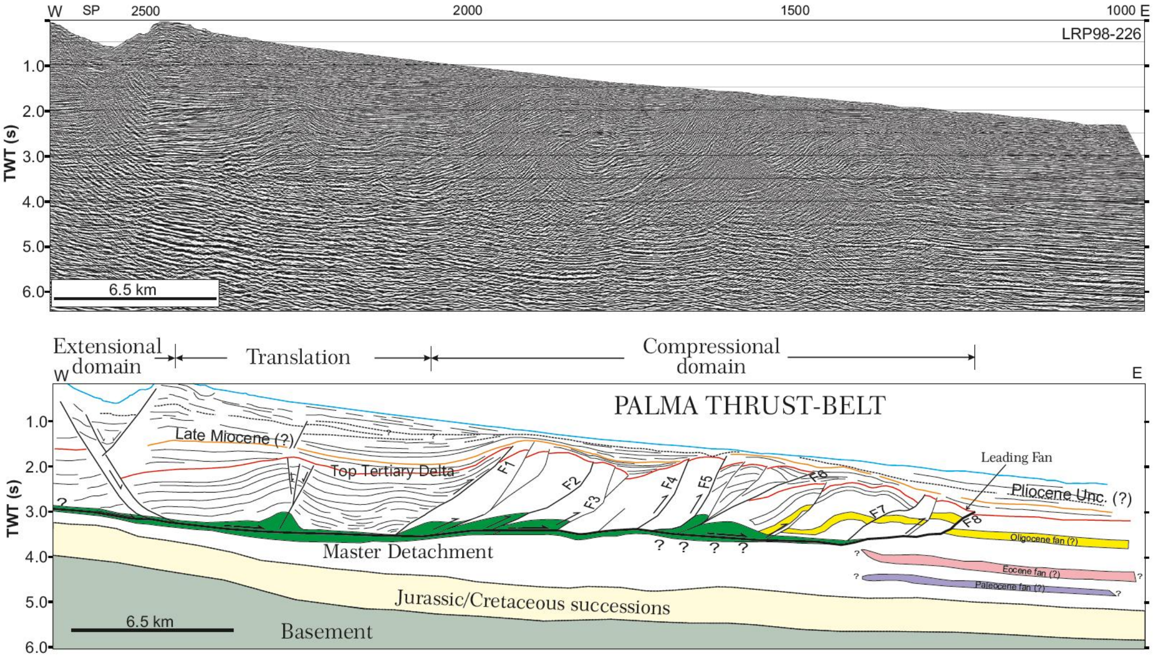


Figure 4 - Top: Reflection seismic lines showing the general architecture of the northern Rovuma deltaic system from the translation to the contractional domains of the the Palma Arcuate Complex. Bottom: Structural and stratigraphic interpretation showing basinward-dipping listric extensional faults in the west and an evolving counter-regional normal fault towards the contractional domain. Here a complex system of DWTFBs developed. See Figure 1 for location.

In general, the thrust-belts appear to be inactive since the Pliocene-Pleistocene except in the zone of steep breached imbricates located between the *Palma* and *Mocimboa thrust-belts*. In this area less thrust-related fold anticlines developed, the folds did reach the seafloor and subsequently were eroded (Figure 9). Forelimb imbrications resulted in a narrow triangular sliver which broadens upward and terminates at the synclinal axis, separating the branching imbricates.

Discussion

Formation of the Rovuma Delta deep-water-fold-belt

The architecture of the Rovuma Delta is basically that of an up-dip extensional region which is linked to a down-dip arcuate region with asymmetric imbricate fans and ramp-flat geometries. This fits quite well the model of gravity gliding down an inclined slope on a thin detachment sensu Morley et al. (2011). The Rovuma DWFTBs are dominated by imbricate thrusts underlain by a seaward-dipping detachment, whilst up-dip extensional province, strongly segmented by listric faults dominates the onshore and shelfal areas (Figures 1, 3).

The linked system stretches for about 130 km from the onshore coastal area over the offshore area as far east as the present location of the DFZ.

The fold belt probably developed at the toe of the slope mainly during the Oligocene and Miocene. Mass-transport occurs along a mobile layer of Paleocene/Eocene age, dipping seawards and serving as a basal detachment. On top of the fold belt an erosional unconformity of inferred Middle - Late Miocene age marks the termination of folding.

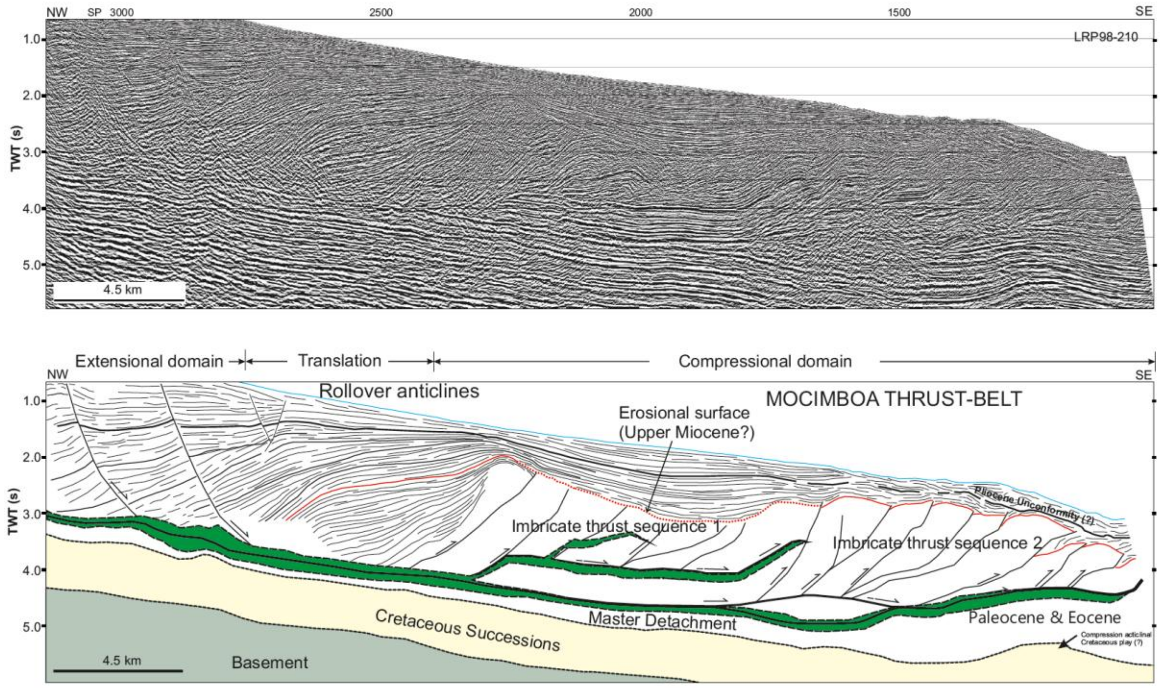


Figure 5 - Top: Reflection seismic lines showing the general architecture of the southern Rovuma deltaic system from the translation to the contractional domains of the the Mocimboa Arcuate Complex. Bottom: Structural and stratigraphic interpretation showing basinward-dipping listric extensional faults with rollover anticlines in the translational zone. The contractional region is dominated by DWTFBs with partly dual detachment surfaces resulting in thrust duplexes.

The regional Oligocene-Miocene deltaic system is underlain by a detachment which follows the general east-west trend of deformational settings (Figure 1). Modern rifting along the Rovuma basin is manifest by half-grabens that developed in the sedimentary strata with the controlling faults dipping and displacing eastwards (e.g. Figure 3).

There are in principal two scenarios that have caused the formation of the Rovuma deep-water fold-and thrust-belt: (i) Progradation of a large delta or group of deltas which introduced massive volumes of clastic sediments into the basin, (ii) uplift of the hinterland, or a combination of both.

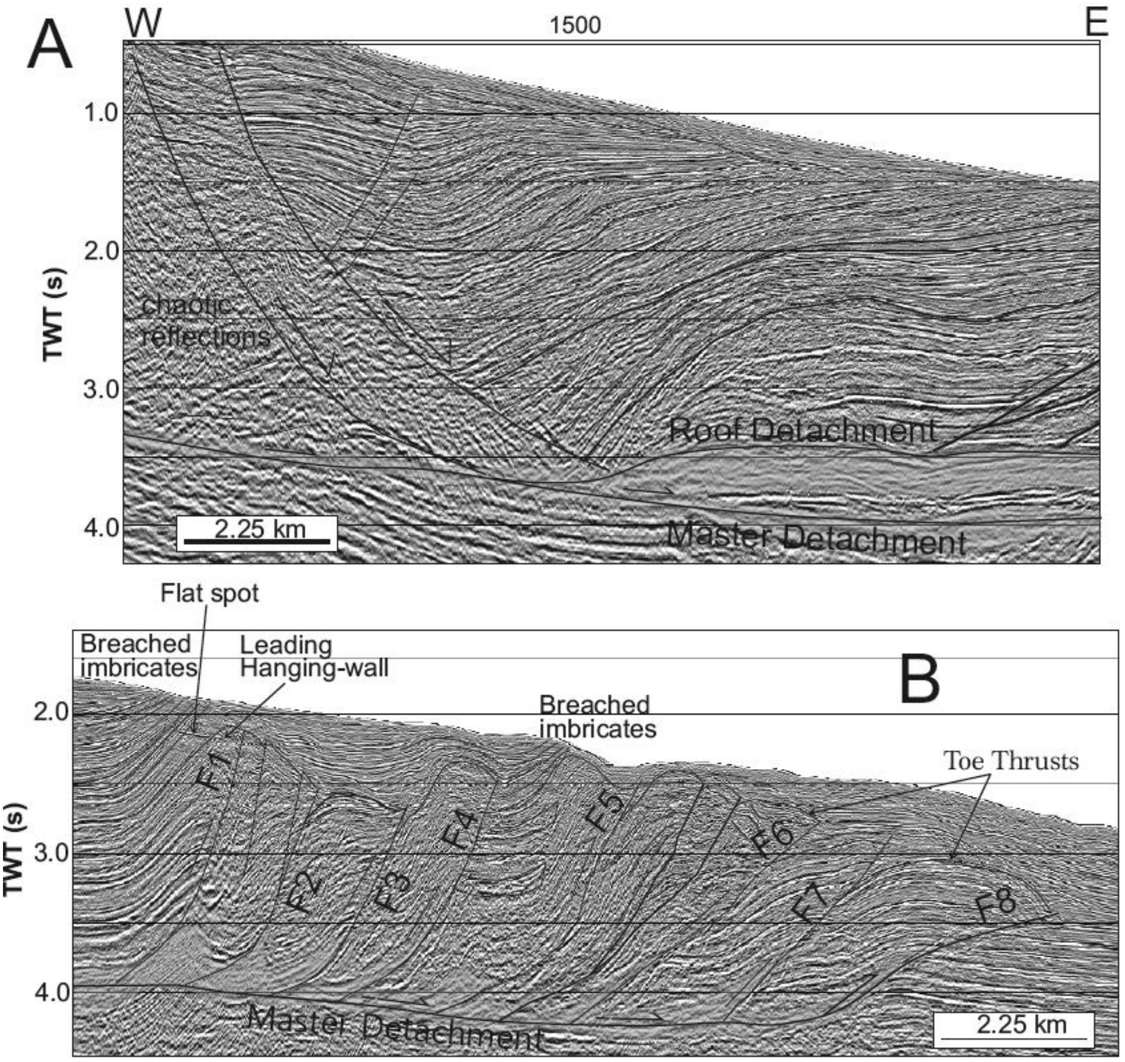


Figure 6 - Example seismic section (Profile LRP98-212) showing regional listric normal faults (A), that sole out at a major detachment fault in the southern (Mocimboa) extensional domain. The deformation resulted in the formation of rollover structures in the translational zone and two detachments in the east. (B) Shows the corresponding compressional structures that developed above a single master detachment. The grey area indicates mobile strata.

From the timing of formation of the deep-water fold and thrust belts there is a link to hinterland uplift in any case. Even if we assume that perturbation of forward propagation of the sedimentary wedge or presence of significant differential loading and gravity sliding did impose the offshore progradation and propagation of folds and thrusts (Hesse et al., 2009; Morley et al., 2011), the high deposition rate was controlled by river-transported sedimentation due to doming and erosion of eastern Africa associated with the development of the East African Rift System since the Oligocene (Chorowicz, 2005; Key et al., 2008).

Thus, the genesis of the Rovuma DWFTBs is likely linked to an uplift of the Rovuma hinterland, which triggering enhanced sedimentation and forced progradation of a delta lobe into the deep-water.

The Rovuma Delta shares many structural similarities with what is encountered in large deltas elsewhere, controlled by linked extensional and contractional gravity tectonic environments on passive-margins as the McKenzie, Gulf of Mexico, Amazon, Nile, Niger, NW Borneo, and Bight basin deltas (e.g. Morley et al., 2011).

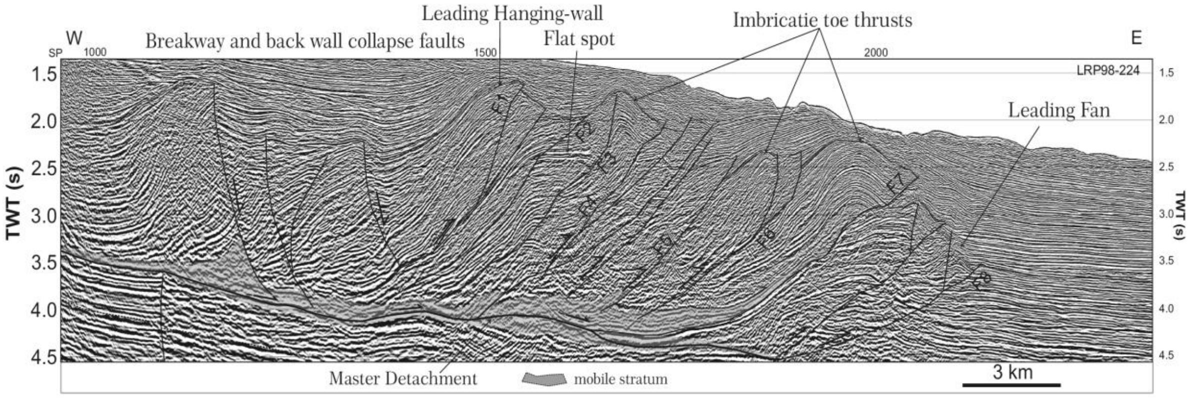


Figure 7 - Dip-line across the northern DWFTB complex of the Rovuma Delta. The eight major stacked imbricates are indicated as F1 to F8. See Fig. 1 for location. The extensional and contractional domains are located close together.

Evidence for a mobile shale-detachment

The similarities between structures resulting from shale and salt detachments are unquestionable. Diapiric-like structures are indeed widespread in the Rovuma basin and may point towards an interpretation of a thick salt detachment. Such “diapirs” or dome structures occur at a particular startigraphic level below the imbricate thrust-and-fold-belts (Figure 8A, B). Salman and Abdula (1995) suggested the presence of Middle and Lower Jurassic salt diapirs and salt ridges along the Rovuma basin coastline. Halogenetic deposits were suggested to extend from the Tanzania portion of the Rovuma basin into the northern Mozambique Rovuma basin.

However, the stratigraphic level of the detachment that is distinct in all seismic images is a major argument against a salt origin. Both extensional and compressional faults sole out above the Mesozoic successions and likely occur on a Late Eocene succession. This clearly postdates any potential salt layer which would be Jurassic in age. While salt typically leads to symmetric detachment folds, in the case of shale, contractional thrust and fold belts are dominated by asymmetric, basinward verging thrust imbricates and multiple detachment levels (Briggs et al., 2006). Moreover, variations in the efficiency of the detachment and major asymmetries are distinct throughout the Rovuma Delta. Development of thrust duplexes may have resulted from the efficiency of mobility along a *shale-detachment* in the basin, i.e., the southern part produced at least two prominent sequences of imbricate thrusts in the *Mocimboa thrust-belt* (Figures 3, 5, 6B, 8B). The stratigraphic sequence is duplicated here, which the older strata in the hanging-wall is thrust over the younger strata in the foot-wall. In contrast, in the *Palma thrust-belt* a single basal detachment with a single imbricate thrust sequence is dominant. The thickness of the mobile layer here is nearly uniform with a maximum of about 500 ms (TWT) (Figure 8A). The formation of counter-regional listric normal faults with large displacement is another argument for a shale detachment. Numerical modelling of *shale-detachment* structures like the Baram Deltaic Province and the Niger Delta indicates that a thick mobile shale section is required to generate the counter-regional fault province while a thin detachment does not produce counter-regional faults (Morley et al., 2011).

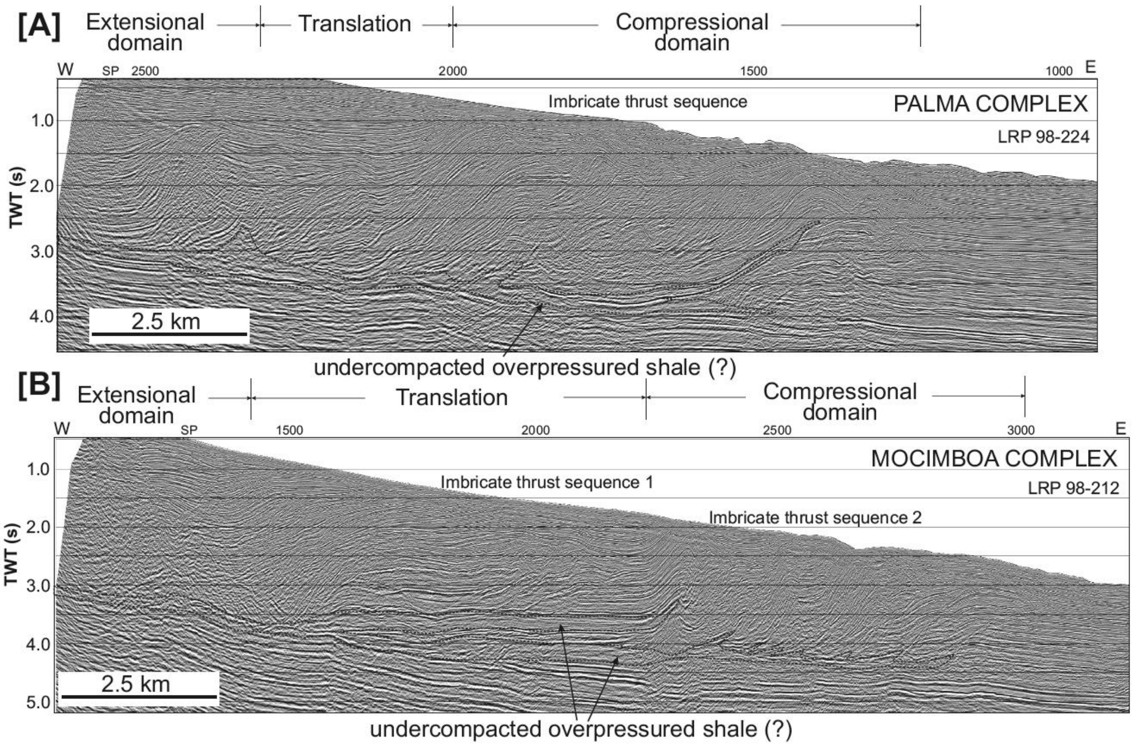


Figure 8 - Reflection seismic lines showing the structure and architecture of the mobile layers, forming the detachment in the northern Palma (A) and southern Mocimboa (B) complexes. Dome (or diapir geometries are often observed in the Palma Complex (A), while in the Mocimboa Complex duplicated detachments occur, with the formation of thrust-duplexes (B).

Analogous with the Niger Delta (Morley and Guerin, 1996) the under-compacted shale is assumed to contain overpressured fluids. A similar interpretation of thick mobile shales, forming a basal detachment, was presented earlier by Law (2011) for the Rovuma Delta. Such a layer was penetrated by the Mocimboa-1 and M'Nazi Bay-1 wells, close to the present day coastline of northern Mozambique and southern Tanzania (Salman and Abdula, 1995).

Shale diapirism?

Although the widespread dome structures in the Cenozoic sedimentary successions might be interpreted as shale diapirs (e.g. in the western portion of Figure 6B) the origin is difficult to deduce due to limited seismic resolution in imaging at the anticline cores and crests of shale structures. Such structures may be interpreted either as steeply dipping imbricated folds, rooted by a near vertical thrust or as diapiric bodies piercing the overburden. Sapin et al (2012) based on high-quality seismic data generally question the actual role of shale tectonics in shale-dominated deltas and so far only mud volcanoes (similar with description by Flowler et al., 2000) and small scale shale injections (Morley, 2003b) are known in the field. Morley et al. (2011), in contrast, argues for the presence of thick mobile shale sections underlying at least the extensional domain in the Niger Delta.

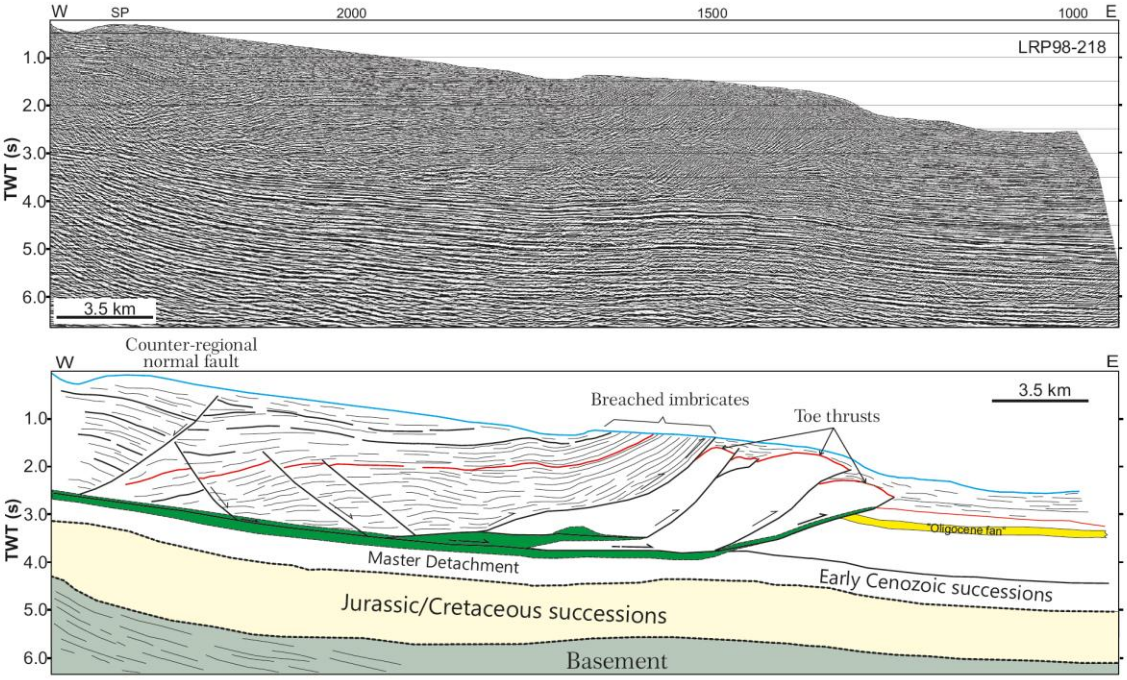


Figure 9 - Reflection seismic section transecting the breached area between the Palma and the Mocimboa thrust-belts. The breached imbricates reach the seafloor. In this region DWTFBs are less developed with few thrust sequences.

In case of the Rovuma Delta, the relative location of the "diapiric bodies" in the fold-and-thrust-belt may guide our interpretation. The well-developed imbricate thrust faults and associated folds gradually die out in the seaward direction and the frontal anticlines typically dip at moderate angles of about 20°. In the landward direction there is a general steepening of the forelimbs from moderate to near vertical structures at the most landward anticline F1 (~ 70°, e.g. Figure 4). At this position the "diapirs" are found. This implies in our view a thrust fault origin for these structures. We suggest that the dome structures initially developed as gently dipping anticlines that steepened during further deformation. At the moment, limited reflection-seismic imaging of steep structures hinders a definite interpretation.

Origin of the two arcuate DWFTBs

There are two distinct and separated *arcuate DWFTBs* in the Rovuma Delta. The question is what may have caused such differences. The general tectonic process resulting in the formation of the DWFTB is certainly the same in both regions.

Our preferred interpretation is that the nature of the detachment differs across the basin. The tectonic deformation may have occurred along a detachment with a different rheology and/or thickness in the two domains, resulting in difference of morphology and geometry of the structures. Variations in the efficiency of the detachment are distinct throughout the Rovuma Delta. For example the formation of thrust duplexes likely is related to the efficiency of the *shale-detachment* in the basin. The compressional faults in the northern domain are generally much steeper (~60° dips) than in the southern domain, where fault dips are about ~45°. This resembles the dip trends in the corresponding extensional domains. Another structural difference is the width of the translational zone. The southern domain has a wide translational zone, whilst in the north a narrow translational zone with well-developed rollover anticline structures predominates.

The thickness of the ductile layer, as interpreted in the reflection seismic data, varies considerably from thin detachment zones to massive chaotic zones, some 2500 ms TWT thick. These massive zones are characterized by elongate, narrow sub-vertical steep-sided zones with mainly chaotic reflections (Figure 8A). The impact of detachment layer thickness on thin-skinned fault geometry has been shown by Steward (1999). In the case of a *shale detachment* not only the thickness of the shales but also the internal shear strength must be considered. This means the important factor here is the thickness of the mobile portions of the ductile layer that depends on the magnitude of fluid overpressures.

At basin scale, the front of the overpressured domain migrated basinward as sediments prograded seaward. Only in the zone of steep breached imbricates located between the *Palma* and *Mocimboa thrust-belts* was the basinward limit of this deformation not only controlled by the sedimentary wedge but likely also by the nature of the detachment. The mobile layer forming the detachment is not completely absent in this region (Figure 9). It might be speculated that variations in Eocene deposition resulted in higher sand content in this region lowering the efficiency of the detachment.

Summary and conclusions

Two prominent arcuate deep-water fold-and-thrust belts (*Palma* and *Mocimboa arcuate*) formed in the Rovuma basin. The *Mocimboa arcuate complex* occupies a greater area than the *Palma complex*. Its compressional domain shows thrust duplexes with broad translation zone and well imaged rollover structures. In contrast in the *Palma arcuate complex* a single main detachment resulted in the formation of a multitude of steep, east-dipping thrust-related fold anticlines, of which the youngest, most eastward-located anticlines exhibits the shallowest dip. In between both arcuate domains only few thrust-related fold anticlines developed, the folds did reach the seafloor and subsequently were eroded.

The architecture of the Rovuma Delta is basically a classic up-dip extensional region, which is linked to a down-dip arcuate region with asymmetric imbricate fans and ramp-flat geometries.

The system is gravity-driven and formed in response to up-dip sediment loading and regional tilting above a main detachment which is located in Early Cenozoic strata. Probably an under-compacted and overpressured *shale detachment* surface served to ramp-up the gliding sediments by gravity-driven deformation to form deep-water fold-and-thrust-belts. Conversely, shale diapirism is questionable since their shape and location in the fold-and-thrust-belts appears simply to indicate steeply-dipping imbricated folds, rooted by a near vertical thrust.

We suggest that mainly a different rheology and thickness and thus efficiency of the *shale detachment* resulted in different morphologies and geometries of the Rovuma Delta deep-water fold-and-thrust-belts.

Acknowledgements

This paper has received support from the management of the *Instituto Nacional de Petróleo* (INP) including the data. Gratitude is also expressed to BGR and Dr. Christian Reichert for the logistical support they provided. This study contributes to a project funded by the German Ministry for Research and Education (BMBF; grant 03G0231A). Finally, appreciation is given to Laura da Prosperidade Mahanjane and anonymous reviewers for helping in the final edition of this paper.

References

Bassias, Y., 1992. Petrological and geochemical investigation of rocks from the Davie fracture zone (Mozambique Channel) and some tectonic implications. Journal of African Earth Sciences, 15(3-4): 321-339.

Bird, D., 2001. Shear margins: Continent-ocean transform and fracture zone boundaries. The Leading Edge: 150-159.

Briggs, S.E., Davies, R.J., Cartwright, J.A. and Morgan, R., 2006. Multiple detachment levels and their control on fold styles in the compressional domain of the deepwater west Niger Delta. Basin Research, 18(4): 435-450.

Catuneanu, O., H. Wopfner, P. G. Eriksson, B. Cairncross, B. S. Rubidge, R. M. H. Smith and P. J. Hancox (2005). "The Karoo basins of south-central Africa." Journal of African Earth Sciences 43(1–3): 211-253.

Chorowicz, J., 2005. The East African rift system. Journal of African Earth Sciences, 43(1-3): 379-410.

Coffin, M.F. and Rabinowitz, P.D., 1987. Reconstruction of Madagascar and Africa: Evidence from the Davie Fracture Zone and Western Somali Basin. Journal of Geophysical Research: Solid Earth, 92(B9): 9385-9406.

Coffin, M.F. and Rabinowitz, P.D., 1992. The Mesozoic East African and Madagascan Conjugate Continental Margins: Stratigraphy and Tectonics. In: J.S. Watkins, F. Zhiqiang and K.J. McMillen (Editors), Geology and Geophysics of Continental Margins, AAPG Memoir 53. The American Association of Petroleum Geologists, Tulsa, Oklahoma, U.S.A., pp. 207 - 240

Daszinnies, M.C., Jacobs, J., Wartho, J.-A. and Grantham, G.H., 2009. Post Pan-African thermo-tectonic evolution of the north Mozambican basement and its implication for the Gondwana rifting. Inferences from 40Ar/39Ar hornblende, biotite and titanite fission-track dating. Geological Society, London, Special Publications, 324(1): 261-286.

Emmel, B. et al., 2011. Thermochronological history of an orogen-passive margin system: An example from northern Mozambique. Tectonics, 30(2): TC2002.

Flowler, S.R., Mildenhall J., Zalova S., Riley G., Elsley G., Desplanques A., and Guliyev F., 2000. Mud volcanoes and structural development on Shah Deniz. Journal of Petroleum Science and Engineering 28 (2000) 189–206

Hancox, P.J., Brandt, D. and Edwards, H., 2002. Sequence stratigraphic analysis of the Early Cretaceous Maconde Formation (Rovuma basin), northern Mozambique. Journal of African Earth Sciences, 34(3–4): 291-297.

Hankel, O. (1994). "Early Permian to Middle Jurassic rifting and sedimentation in East Africa and Madagascar." Geologische Rundschau 83(4): 703-710.

Hesse, S., Back, S. and Franke, D., 2009. The deep-water fold-and-thrust belt offshore NW Borneo: Gravity-driven versus basement-driven shortening. Geological Society of America Bulletin, 121(5-6): 939-953.

Key, R.M. et al., 2008. Revised lithostratigraphy of the Mesozoic–Cenozoic succession of the onshore Rovuma Basin, northern coastal Mozambique. Journal African Earth Sciences, 111: 89-108.

Law, C., 2011. Northern Mozambique: True “Wildcat” Exploration in East Africa, AAPG Annual Convention and Exhibition. AAPG Search and Discovery Article # 110157 Houston, Texas, USA.

Ledesma, D., 2013. East Africa Gas – Potential for export, The Oxford Institute for Energy Studies, University of Oxford.

Mahanjane, E.S., (in review). The Davie Fracture Zone and adjacent basins in the offshore Mozambique Margin – A new insight for the hydrocarbon potential. Marine and Petroleum Geology.

Morley, C.K., 2003a. Mobile shale-related deformation in large deltas developed on passive and active margins. In: P.V. Rensbergen, R.R. Hillis, A.J. Maltman and C.K. Morley (Editors), Subsurface sediment mobilization, Geological Society London Special Publication. Geological Society London, London, pp. 335-357.

Morley, C.K. and Guerin, G., 1996. Comparison of gravity-driven deformation styles and behavior associated with mobile shales and salt. Tectonics, 15(6): 1154-1170.

Morley, C. K., 2003b, Outcrop examples of mudstone intrusions from the Jerudong anticline, Brunei Darussalam, and inferences for hydrocarbon reservoirs. In: Van Rensbergen, P. R., Hillis, R., Maltman, A. and Morley, C. K., Subsurface Sediment Mobilization, Special Publication of the Geological Society of London, 216.

Morley, C.K., King, R., Hillis, R., Tingay, M. and Backe, G., 2011. Deepwater fold and thrust belt classification, tectonics, structure and hydrocarbon prospectivity: A review. Earth-Science Reviews, 104(1-3): 41-91.

Nairn, A.E.M., Lerche, I. and Iliffe, J.E., 1991. Geology, basin analysis, and hydrocarbon potential of Mozambique and the Mozambique Channel. Earth-Science Reviews, 30(1-2): 81-123.

Nicholas, C.J. et al., 2006. Stratigraphy and sedimentology of the Upper Cretaceous to Paleogene Kilwa Group, southern coastal Tanzania. Journal of African Earth Sciences, 45(4–5): 431-466.

Nicholas, C.J., Pearson, P.N., McMillan, I.K., Ditchfield, P.W. and Singano, J.M., 2007. Structural evolution of southern coastal Tanzania since the Jurassic. Journal of African Earth Sciences, 48(4): 273-297.

Pinna, P., 1995. On the dual nature of the Mozambique Belt, Mozambique to Kenya. Journal of African Earth Sciences, 21(3): 477-480.

Rabinowitz, P.D., Coffin, M.F. and Falvey, D., 1983. The Separation of Madagascar and Africa. Science: 67-69.

Raillard, S., 1990. Les marges de L'Afrique de l'est et les zones de fracture associees: chaine Davie et ride du Mozambique,. Ph. D. Thesis, Univ. Pierre et Marie Curie, Paris, 270 pp.

Ramberg, H., 1981. Gravity, deformation and the Earth's crust in theory, experiments and geological application (2nd Edition). Academic Press, London, 452 pp.

Roberts, E.M. et al., 2012. Initiation of the western branch of the East African Rift coeval with the eastern branch. Nature Geosci, 5(4): 289-294.

Salman, G. and Abdula, I., 1995. Development of the Mozambique and Ruvuma sedimentary basins, offshore Mozambique. Sedimentary Geology, 96(1–2): 7-41.

Sapin, F., Ringenbach, J.-C., Rives, T. and Pubellier, M., 2012. Counter-regional normal faults in shale-dominated deltas: Origin, mechanism and evolution. Marine and Petroleum Geology, 37(1): 121-128.

Scrutton, R.A., 1978. Davie fracture zone and the movement of Madagascar. Earth and Planetary Science Letters, 39(1): 84-88.

Smelror, M., Key, R.M., Smith, R.A. and Njange, F., 2008. Late Jurassic and Cretaceous palynostratigraphy of the onshore Rovuma Basin, northern Mozambique. Palynology, 32(1): 63-76.

Stewart, S.A., 1999. Geometry of thin-skinned tectonic systems in relation to detachment layer thickness in sedimentary basins. Tectonics, 18(4): 719-732.

Weimer, P. and Slatt, R., 2004. Petroleum Systems of Deepwater Settings. Distinguished Instructor Series. Society of Exploration Geophysicists and European Association of Geoscientists and Engineers, 488 pp.

4.3. The Davie Fracture Zone and adjacent basins in the offshore Mozambique Margin – A new insight for the hydrocarbon potential

E. S. Mahanjane / Submitted to Marine and Petroleum Geology
Institute National Petroleum (INP), Av. Fernão Magalhaes N. 34, 2nd Floor, PO Box 4724, Maputo, Mozambique

Abstract

The interpretation of 2-D seismic reflection data provides a modern structural framework containing hydrocarbon potential in the present-day stratigraphic and structural traps of both the Davie Fracture Zone and the adjacent Nacala and Angoche basins. Possible stratigraphic traps were identified in submarine fan and channel depositional environments during Cretaceous to Tertiary times. Structural traps are mostly defined within compressional structures formed by a variety of fault-related folds and rift grabens within the Jurassic and Cretaceous successions.

The Nacala and Angoche basins form two depressions separated by the Davie compressional zone. This compressional structure is a prominent interior high running approximately north-south. An event of transpression and contraction characterizes the main tectonic setting commonly hosting several detached compressional structures along the western edge of the transform zone.

Both basins are associated with the Late Jurassic/Early Cretaceous rifting during the opening of the Mozambique Channel. The Angoche basin is proposed here to have formed by the earliest stage of break-up in mid-Jurassic time. The basin is landward bounded by Angoche volcanic zone, the NE-SW oriented dyke swarm branch of the Karoo magmatism at c.170 Ma.

Subsequent rifting and break-up led to the drift of East Gondwana fragment southwards along the dextral strike-slip faults. At ~ 150 Ma, this fragment separated clockwise about a pivot in the proximity of the Angoche basin leading to extension and rifting in the Rovuma basin and compression west of the DFZ seamounts further south. Consequently, the eastern boundary of the Angoche basin was compressed developing a typical growth wedge of massive thrusts imbrication structures while extensional tectonics created several depressions and rift-grabens forming Nacala and Quirimbas basins.

Basin stratigraphy is interpreted along seismic reflection lines and correlated to the regional stratigraphic information and wells from the Zambezi Delta and Rovuma basins.

Introduction

Recent gas discoveries in the Rovuma Delta basin in both stratigraphic and structural play-types (e.g. Law, 2011) call for further hydrocarbon exploration towards the south in similar structures within the Davie Fracture Zone (also called Davie Ridge or Davie Transform Zone). The offshore Angoche and Nacala basins are presently attractive for petroleum exploration.

The Davie Fracture Zone (DFZ) forms the continent-ocean transform boundary that crosses the Mozambique Channel between the Mozambique and Madagascar continental margins (Figure 1A). It is a prominent 2000 km long lineament bounding the Rovuma and Somali basins in the north-west and the Mozambique and Morondava basins in the south-east (Rabinowitz and Woods, 2006). The modern Davie Fracture Zone includes several seamounts, namely the St. Lazare, Paisley, Macua and Sakalaves seamounts (Figure 1A). Possibly, they are related to basaltic eruptions along the crustal weakness of the DFZ during the separation of India and Madagascar approximately 83 Ma (Bassias, 1992).

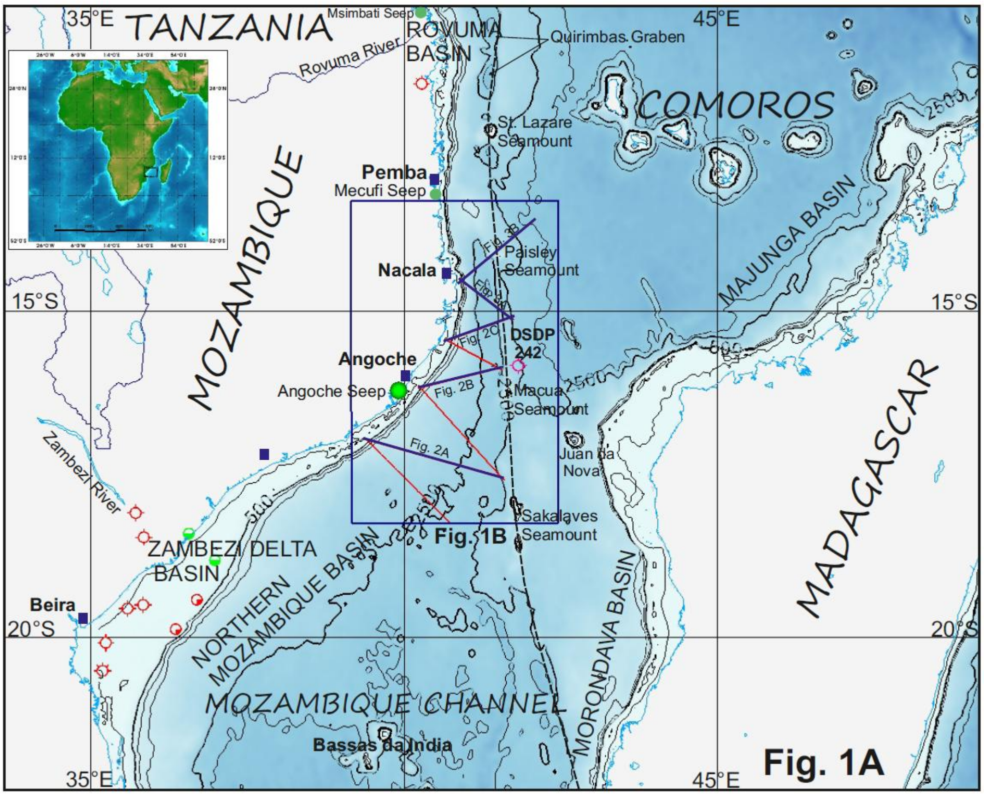


Figure 1A - General map of the northern Mozambique Channel and the navigation map with the 2-D seismic data ship's track zig-zag lines used for this study including the location of the Figures (dark blue). Tectonic features that predominate in the study region: the Central Davie Fracture Zone (dashed line), the chain of seamounts (Sakalaves, Macua, Paisley and St. Lazare), and the main sedimentary basins: Rovuma, Mozambique, Majunga, Morondava. Green full-circles: location of the oil seeps (ECL and ENH, 2000; Maenda and Mpanju, 2003)

Despite its prominent feature, the DFZ is relatively poorly studied as part of the frontier area. Structurally, DFZ developed as shear zone during the southerly movement of the East Gondwana fragment (with Madagascar as component), starting from initial break-up and lasting till the Early Cretaceous period (Coffin and Rabinowitz, 1987; Nairm et al., 1991; and Coffin and Rabinowitz, 1992). During the active phase, the fracture ridge was purely strike-slip movement (Reeves and Mahanjane, 2013), however, the present study indicates that DFZ had experienced other tectonic settings before Madagascar came to rest.

This paper contributes with an interpretation of the *Davie compression zone* and two rift basins, namely the Angoche and Nacala basins (Figure 1B). These basins are situated nearly in the south-western extremity of the fracture zone, bounded by the DFZ in the east and the Mozambique continental margin in the west. The interpretation is based on high-quality 2-D reflection seismic profiles transecting the basins and partially crossing the DFZ (Figure 1A). Horizon picking was done using the regional correlation of the seismic data with stratigraphic records from the Mozambique and Rovuma basins. The aim of this paper is to give an overview of the tectonic settings in this frontier area, to provide a description of local stratigraphy, correlating with the petroleum system known from neighbouring basins along the East African Margin.

Regional geology

The result presented by structural map of Figure 1B contributes to the tectonic framework of the region giving insight in the breakup of Gondwana and development of Davie Fracture Zone.

Paleogeographic reconstruction models from the recent studies using magnetic data in the Mozambique basin and the conjugate Riiser-Larsen Sea, e.g. König and Jokat (2010) and Leinweber and Jokat (2012), provide important new evidence of conjugate M-series magnetic anomalies between Africa and Antarctica that defines well their relative movements going backwards in time from the youngest M-series anomaly (about 125 Ma) until about 153 Ma.

Leinweber and Jokat (2012) depict the development of the Africa-Antarctica Corridor during the opening between Africa and Antarctica. They also tentatively date the onset of the sea-floor spreading in the Mozambique basin and conjugate Riiser-Larsen Sea using the oldest Magnetic anomaly M25n (154 Ma) in these basins. But the age of initial sea-floor spreading could be older than this period because, judging from the location of the anomaly, there is still left significant distance of oceanic and stretched continental crust, which is countable for timing of the onset stage. Extrapolating backwards in time before 154 Ma, Reeves and Mahanjane (2013) obtained a closure at the age of 167.2 Ma (König and Jokat, 2006) just before initial sea-floor spreading stated. This age is coherent with the last period of emplacement of the Angoche dyke swarm at c. 170 Ma (Reeves, 2000).

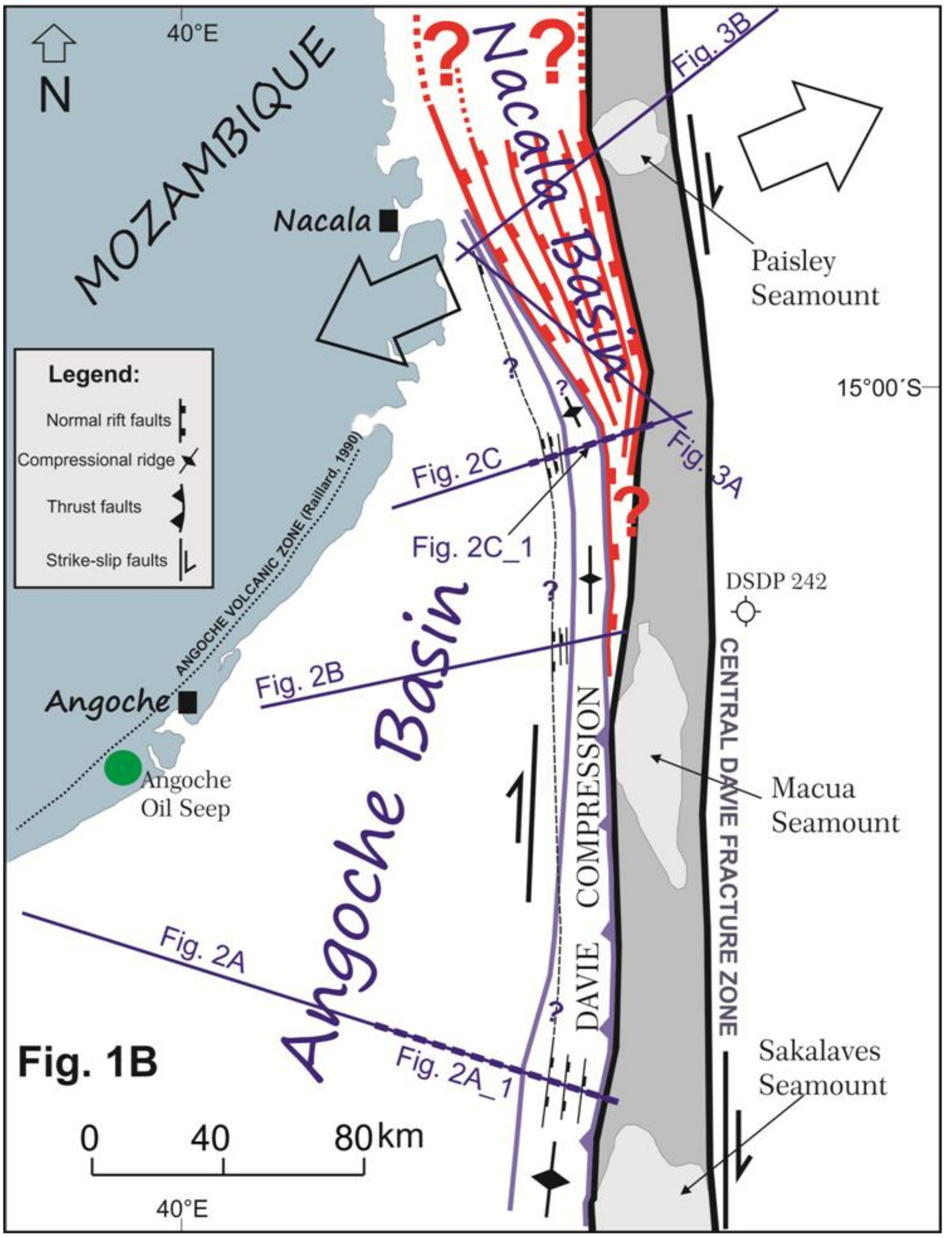


Figure 1B - The structural map that resulted from the seismic interpretation is displayed. The foremost geological features are the Davie compression, the Angoche and Nacala basins. Figures 2A_1 and 2C_1 flagged by blue dashed lines depict two portions of Figures 2A and 2C, respectively. The volcanic zone (dotted line) was mapped along the continental margin (Raillard, 1990). See text for discussion.

Besides, M25n is very close to the northernmost end of the N-S Fracture zone F (König and Jokat, 2010) created by southerly movement of Antarctica. Here, the anomaly defines the onset of the break-up stage 2 between Africa and Antarctica (Mahanjane, 2012). This break-up was the main stage between West and East Gondwana leading to initiation of the north-south oriented rifting-drifting phase creating a marginal fracture ridge (DFZ) in the east and the Lebombo Monocline in the west (Reeves and Mahanjane, 2013).

The early movement between East and West Gondwana was essentially dextral strike-slip on the proto-Davie Fracture Zone along a length, parallel to the present day coastline of North Mozambique and SE Tanzania (Reeves and Mahanjane, 2013). The onset of drift occurred probably in Middle Jurassic (Bajocian-Bathonian?) time (Kreuser, 1995). Subsequently, the East Gondwana block (consisting of Madagascar-India-Antarctica) separated from West Gondwana (i.e. Africa-South America), moving incrementally southward along the DFZ until Early Aptian (c. 121 Ma) (Rabinowitz et al., 1983) or middle Aptian (c. 118 Ma) (Bassias, 1992; Coffin and Rabinowitz, 1992). This occurred as soon as East Gondwana no longer had direct continent-continent contact with Africa (Reeves and Mahanjane, 2013). It is likely that a continental fragment that includes Madagascar has clearly separated clockwise about a pivot off the Mozambique coast (~ 15º South, Figure 1B), leading to extension and rifting in the Rovuma basin (offshore Mozambique-Tanzania) and compression west of the DFZ seamounts further south. In this regard, the SE corner of Madagascar (e.g. the model of König and Jokat, 2010) would lie off the coast between Nacala and Angoche at about 5 Ma before Jurassic-Cretaceous boundary time (i.e. ~ 150 Ma). Thus, the compression could already have started in the Jurassic, later reactivated by subsequent Cretaceous tectonism of northern Africa and current rifting of East Africa.

Moreover, the present position of Madagascar may not be identical to that at the end of the first period of activity of the DFZ. Likewise, a change of spreading direction along DFZ has occurred in Kimmeridgian (?). The DFZ before and after this change could be quite different, also regarding its location as indicated by the several transfer faults along its length.

From a sedimentary point of view, deposition started from Middle Jurassic (Bajocian) in the modern DFZ. An optimistic interpretation suggests dominantly lacustrine deposition along the DFZ, over a Proto-oceanic rift on both the northern and southern extremities of the fracture zone before the main strike-slip movement started. This is supported by facies of the

Makarawe Formation (typically shallow-water lagoonal and reefal sediments) correlated from the adjacent Tanzanian areas (Salman and Abdula, 1995).

The Oxfordian-Aptian successions overlay unconformably the mid-Jurassic deposits (Figure 1C). They are related to marine transgression of Paleo-Tethys between Africa and Madagascar in time span of 157-118 Ma (Salman and Abdula, 1995). Predominately, shelf carbonates and basinal sediments were deposited in restricted environment within local depressional basins in the East African margin.

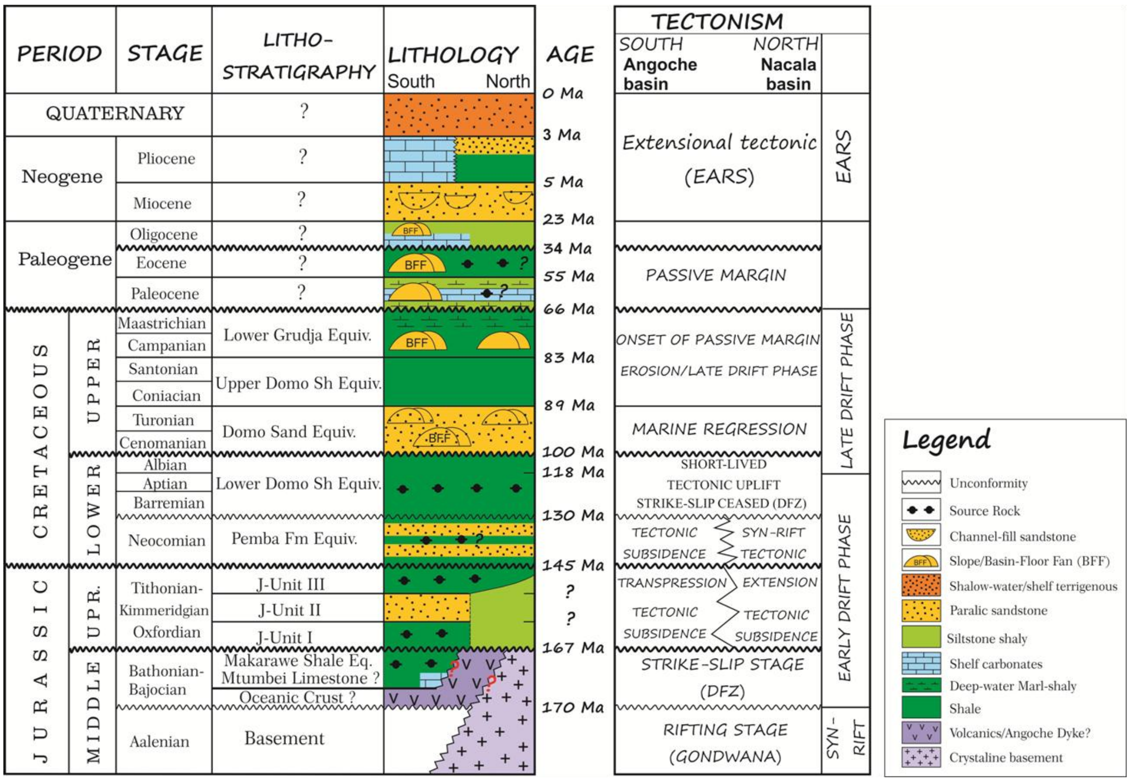


Figure - 1C – A simplified stratigraphy chart constructed based on the regional stratigraphic correlations and seismic interpretation

Database

The principal data for this study include 1,300 km of 2-D reflection seismic profiles consisting of 8 dip zigzag lines (Figure 1A) covering an area of approximately 73,000 km^2. This dataset is a subset of a considerably larger database provided by the National Petroleum Institute of Mozambique as part of ongoing exploration projects. Seismic data were collected by Western Geophysical in 2000 (speculative survey WG-00). An array of airguns provided the source for the data collected in water depth between 100 and 3000 m. All lines are filtered-migrated and the seismic data were interpreted both in paper-record form and by using Seismic Micro-Technology KINGDOM^{TM} software. The length of the seismic lines used in this paper only covers the western flank of the DFZ except navigation of Figure 3B (Figure 1A).

The principle of seismic sequence stratigraphy analysis described by Catuneanu et al. (2009, 2010, and 2011) was applied to integrate the approach for a detailed reconstruction of the basin-fill history, the prediction of rock types, and depositional environment, thereby indirectly delineating reflection packages in space and time.

Results and discussion

Regional Stratigraphic Correlation

A compilation of stratigraphic information from the Mozambique and Rovuma basins [Salman and Abdula (1995), ECL & ENH (2000)] was made and integrated with seismic ties for a better correlation of the regional stratigraphic records. The result is a simplified local stratigraphic chart shown by Figure 1C. The following unconformities/tops were selected to describe the main stratigraphic packages in the Angoche and Nacala basins:

i. *Top Cretaceous/Base Tertiary Unconformity* (66.0 Ma) corresponds to an erosional surface formed in association with the late highstand major regression during the late Drift phase in Late Cretaceous time.

ii. *Top Turonian* (89.8 Ma) is correlated from both Rovuma and Mozambique stratigraphies as the top of the first cycle of sedimentation associated with the development of the East Africa continental margin. A lowstand tract system dominated the sedimentation of clastics during the short-lived uplift linked to the cease of the strike-slip motion between Africa and Madagascar.

iii. *Top Albian Unconformity* (100.5 Ma) was formed by the main regression in the Neocomian/Aptian and resulted in non-deposition or erosion in the Mid-Cretaceous, associated with the end of Early Drift phase.

iv. *Upper Jurassic Unconformity* (145.5 Ma) is presented in the Rovuma basin stratigraphy (Salman and Abdula, 1995) as pronounced angular unconformity linked to the Late Jurassic marine section. The unconformity transgressed onto the African platform with the deposition of extensive platform carbonates, later replaced by prograding Upper Jurassic/Lower Cretaceous marine clastics.

v. *Drift onset Middle Jurassic Unconformity (Bajocian-Bathonian)* depict the initiation of movement on the Davie Ridge transform, which in marked by spreading in the Somali basin (ECL and ENH, 2000 report).

vi. *Top acoustic basement* depicts the top of basement underlying the sedimentary successions.

Seismic mapping and stratigraphy (Figures 2 and 3)

General appearances in the seismic profiles are described as follows:

(i) The acoustic basement is mapped on both sides of the DFZ (Figures 2C, 3A and 3B). On the western side (Angoche basin), the surface of the acoustic basement is a very steeply dipping reflector with no evidence of tectonism preserved (Figures 2A and 2B). In the eastern DFZ, mapping was done with help of the profiles crossing the fracture zone (Figures 2C, 3A, B). The top of the inferred acoustic basement is overall characterized by strong positive impedance contrast bounding well-stratified reflectors above and hummocky patterns below. The tracing of this reflector from western margin towards the east is difficult along the pre-kinematic margin due to the amalgamation with the Davie compressional structures (e.g. Figures 2B, C), while, in the Nacala basin, this reflector is identified below the Jurassic succession underneath the rift-grabens. Commonly, the basement is dissected by a series of NNW and NNE faults forming classical grabens (Figures 3A, B).

The composition of the material below the acoustic basement is hard to evaluate by using only the data at hand. However, the Angoche margin is a steeply dipping basement. The length of the steeping shape narrows down northwards until few tens kilometers in the area close to the Nacala basin. In map view, this interpretation ties pretty well with the Angoche volcanic zone (Raillard, 1990) more recently described as the Angoche dyke swarms (Reeves and Mahanjane, 2013). It is therefore correlated to the northern limit of the Karoo magmatism (basalt flows) supposed to have taken place during the final phase of Gondwana between 205-175 Ma (Salman and Abdula, 1995).

(ii) Jurassic successions are mapped in the basins. The presence or absence of Karoo sediments in the offshore DFZ cannot be ascertained from this seismic dataset. Besides, evaluating the extension of these sediments from the Karoo basins Selous (Tanzania), Duruma (Kenya), and Morondava (Salman and Abdula, 1995; Catuneanu et al., 2005) into the DFZ area leads to the conclusion that the DFZ is a later event after Karoo magmatism. Thus, Jurassic sediments are expected to be exclusively post-Gondwana deposits.

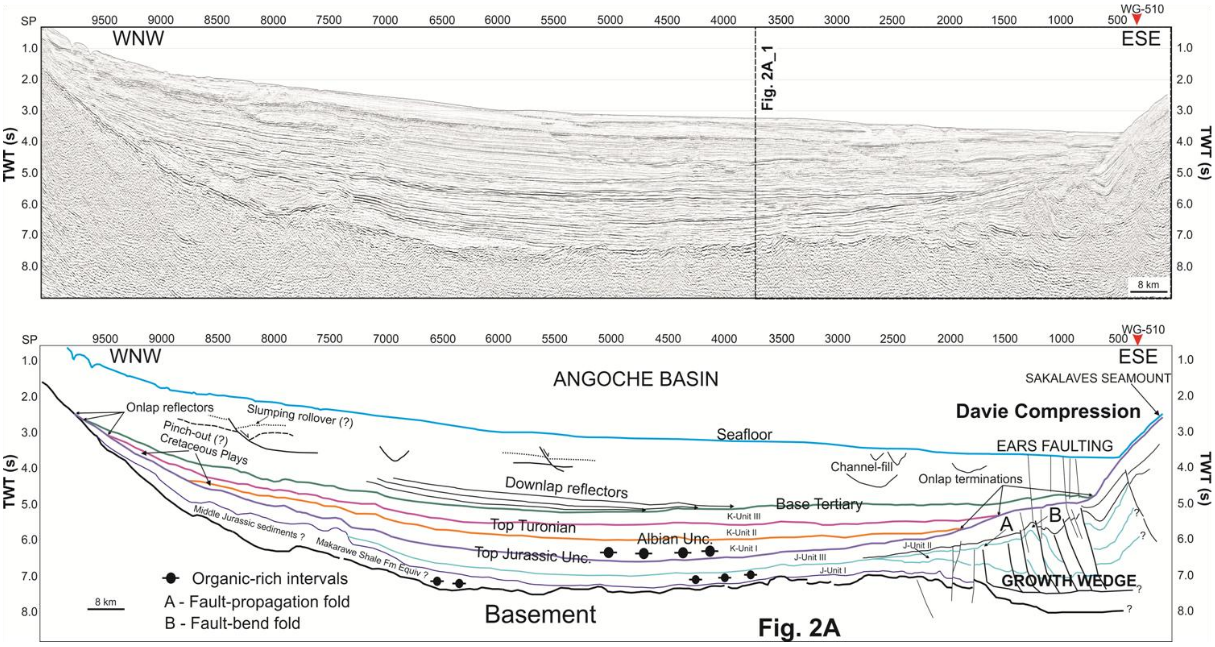


Figure 2A - In the upper panel is shown an uninterpreted 2D reflection seismic section (migrated). The profile crosses several features described in this paper: The Davie compressional zone and the Angoche basin. In the lower panel, the seismo-stratigraphic interpretation is displayed as proposed in this study. The stratigraphic evolution is described in the text. The Mid-Tertiary extensional tectonic (EARS) is shown by active young faults over the Davie compression. Jurassic and Aptian-Albian source rocks are expected from shallow-marine shale, see text for discussion.

Middle Jurassic successions

Salman and Abdula (1995) discussed the mid-Jurassic marine deposits in the Rovuma basin equivalent to marine sediments from Makarawe Formation, Mtumbei Limestone, and Kizimbani Shale known in Tanzania. The major question is how far these sediments could extend further south along the DFZ.

Notwithstanding, more than one kilometre of the Middle-Jurassic succession is mapped in this study as the post-break-up deposits, and correlated with the Makarawe shale (Bajocian-Bathonian) (Figure 1C). The top is marked by the 'drift onset unconformity' pronouncing the initiation of spreading in the Mozambique basin. It is distinctively traced in the south and central area of the Angoche basin topping reflection patterns of lower impedance contrast, gradually thinning seawards (e.g. Fig 2A, B). The ‘drift onset unconformity’ commonly parallels the steepness of the basement in the west, terminating onlap onto the acoustic basement in the slope area. Similar to the acoustic basement, tracing of this unit becomes difficult towards east underneath the *Davie compressional zone* (Figures 2A, B and C).

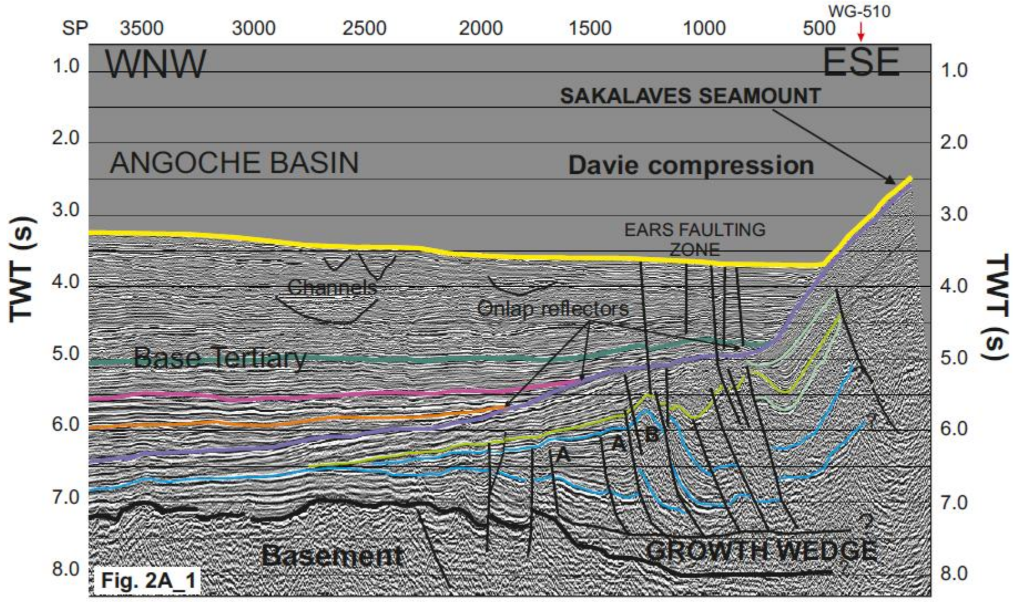


Figure 2A_1 - Enlargement of the south-eastern portion of Figure 2A presenting an interpretation as proposed in this study. The geotectonic structures and some sediment stratigraphy are shown in details. The prominent features are thrust imbrications of growth wedge structures underlying the Davie compression. Fault-related fold were identified within the thrust imbrications and form structural traps. Onlap terminations are the main characteristic of the sedimentary deposition in the Angoche basin over the Jurassic unconformity. See Figure 2A for the abbreviations, and text for discussion.

Late Jurassic successions

The entire Jurassic successions are faintly morphologically expressed and completely dissected by several imbricated thrust-and-fold-belts in the eastern edge of the Angoche basin (Figures 2A, B, C). Prominent internal reflectors delineate at least three distinctive post-rift units in the Angoche basin (*J-Unit I, II, III*). They are well-imaged within the *Davie compression zone*, characterizing a typical growth wedge from west (~1 km) to east (~3.5 km). *J-Unit II* pitches-out against *J-Unit I* in the west edge of the compressional zone (e.g. Figure 2A). Conversely, in the Nacala basin, Jurassic succession is syn-rift deposit with uniform internal configurations forming single unit (*J-Unit N*):

J-Unit I The maximum thickness of the Jurassic basal sequence is measured in the Angoche basin as ~1.3 km. The sequence is commonly thicker in the eastern direction and pinches out towards the west in the slope of the Angoche margin (Figures 2B, C). Although the seismic grid is sparse, this interpretation seems to be consistent within the Angoche basin (Figures 2A, B, C). Mahanjane et al. (submitted) are discussing the basin evolution of the northern Mozambique basin. The burial history shows a relatively rapid subsidence shortly after break-up started. A maximum of ~ 3 km of Bajocian-Valanginian sediments was already buried between Late Jurassic and Early Cretaceous contributing for thermal maturation at earliest stage of the basin evolution.

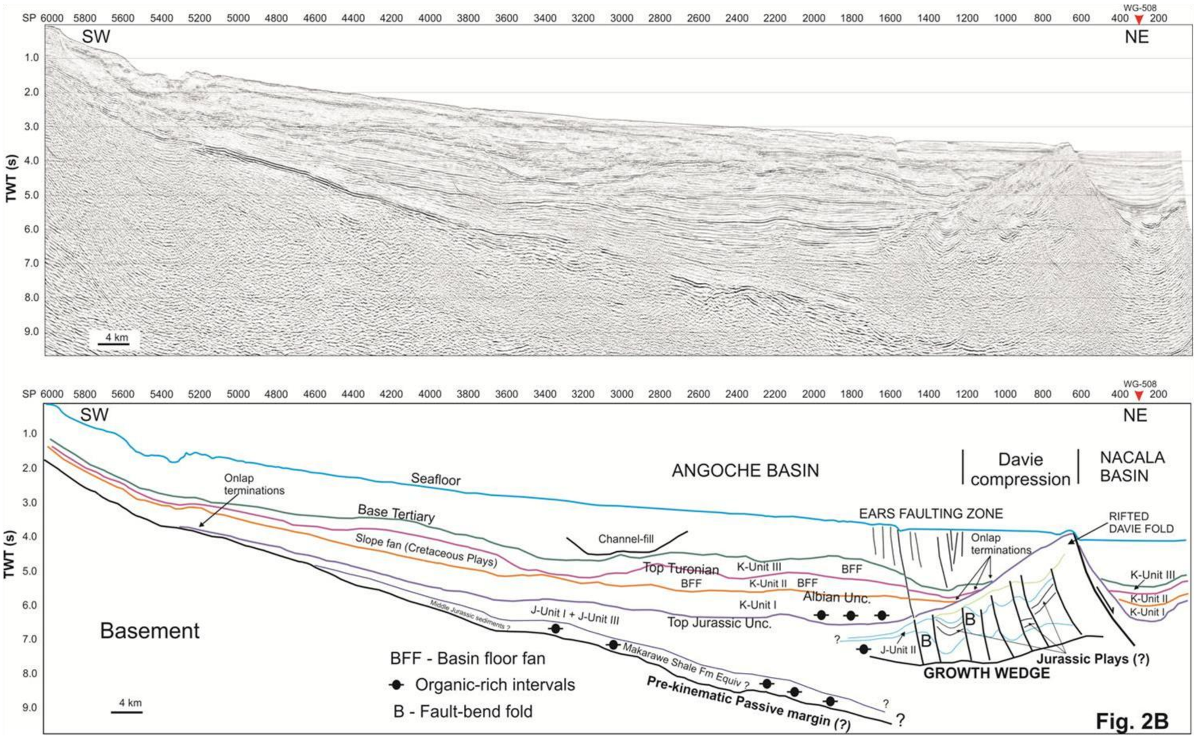


Figure 2B - In the upper panel is shown an uninterpreted migrated 2-D seismic section. The seismo-stratigraphic interpretation (the lower panel) display prominent thrust faults and fault-bend folds observed within the Davie compressional zone. The Continental basement is a very steeply dipping reflector that defines a pre-kinematic margin. The slope and basin floor fans are shaped by mounded configurations predominate in the K-Units. See text for discussion.

J-Unit II is only mapped within the *Davie compressional zone* dissected by imbricated thrust-and-fold-belts. This unit consists of a wedge growing towards the east, formed mainly by fault-propagation folds. In contrast, the basal detachment shallows to the west, where the fault-propagation folds turn into fault-bend fold (Figure 2A). The reflectors (wavelet frequency) are well-imaged layers expressing strong negative impedance contrasts, displaying an opposite polarity of the water bottom (see Figure 2C). However, additional data analysis is essential for accurate prediction of hydrocarbons.

J-Unit III The top is mapped as a regional unconformity topping the Jurassic successions from the compressional zone in the east until onlapping onto the acoustic basement in the Angoche margin (Figures 2A, B, C). The geometry of the seismic characters changes towards the north particularly on top of the *Davie compressional zone*, showing significant loss of the impedance contrast but maintaining the continuity of reflectors (Figure 2C). The sedimentary wedge is stratigraphically correlated to marine shale deposits from the adjacent Rovuma basin associated to transgression onto the African platform at the Late Jurassic (Salman and Abdula, 1995).

J-Unit N is the Late Jurassic succession mapped in the Nacala basin as single unit with approximately 1-2 km thick. The sedimentary wedge in this area shows seismic reflectors increasing impedance contrast from moderate to high amplitude within the rift-grabens. The geometry of these reflectors is commonly fragmented by synthetic and antithetic faults. Their shape suggests widespread syn-rift deposition of homoclinal wedge of drift deposits, which thickens drastically to the east towards the DFZ (e.g. Figure 3B).

(iii) Cretaceous sediments unconformably overlie the Jurassic successions in both basins with seismic reflectors of low amplitude on-lapping in both west and east directions. The seismic patterns in the basins suggest basin-fill predominated by a thick wedge sequence of layered sediments, sub-horizontal, overlying the Jurassic successions. Deposition style suggests facies with favourable juxtaposition of source and reservoir rocks. The Cretaceous successions are subdivided into three units (Lower, Middle and Upper Cretaceous, Figure 1C):

K-Unit I This is the basal sequence topped by a regional Albian unconformity associated with cessation of the strike-slip movement. Sediments of the *K-Unit I* reach maximum thickness in the Angoche basin depocentre. Approximately 1.5 km thick is recorded at the location of Figure 2A. This thickness decreases gradually in west and east directions, onlapping onto the slope of Angoche margin, and the *Davie compression zon*e. The seismic characteristics of the lowermost part consist of interplay of moderate to high amplitude reflections, expressing contrast between lithologies of different rock properties. The geometry of the reflection patterns changes gradually to the east, where low amplitude impedance contrasts predominate (uppermost part). Sediments of this unit show high correlation with stratigraphy of Rovuma (Pemba Formation Equiv.) and Mozambique basin (Domo Shale Equiv) (see Figure 1C). A description of the Pemba Formation and Domo Series equivalent facies has been provided by Key et al. (2008) and Nairn et al. (1991), respectively. The Domo Shale is regarded as potential source rocks known only in subsurface, consisting of dark grey to black, thinly bedded, marly shale (Nairn et al, 1991).

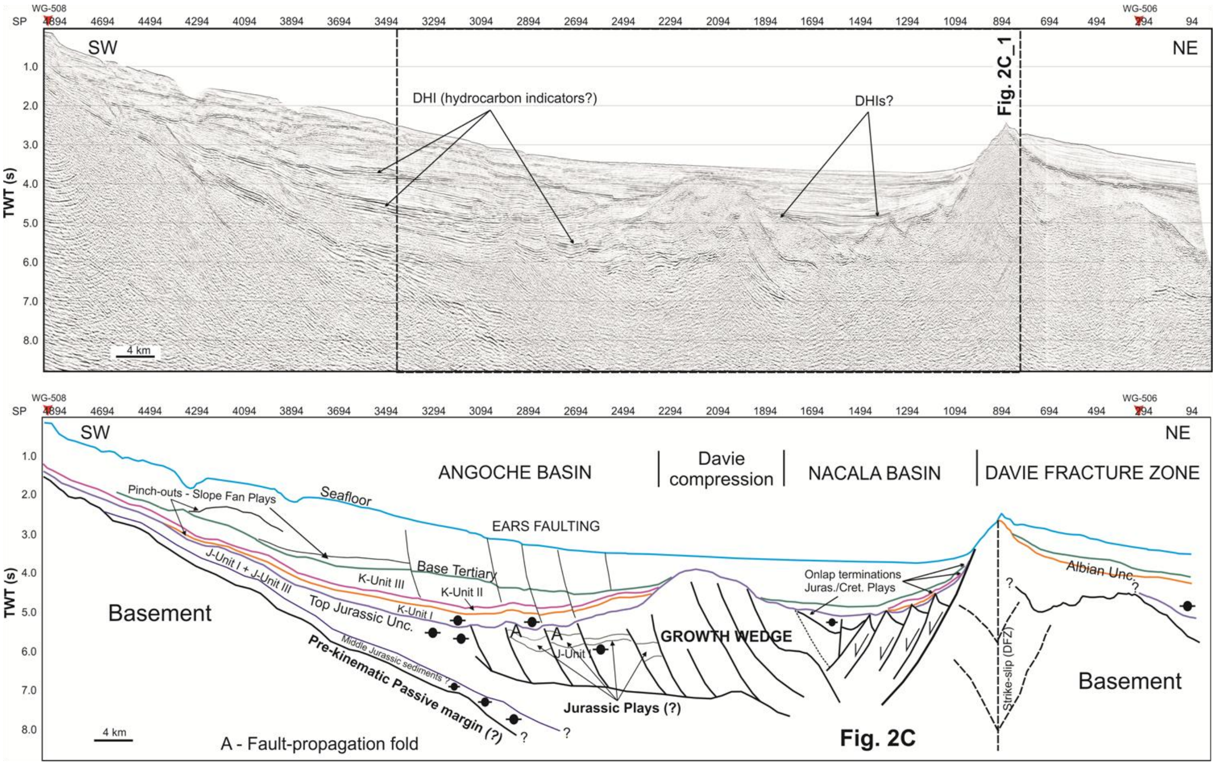


Figure 2C - An uninterpreted 2-D reflection seismic section is shown (upper panel). The profile transects the Davie compressional zone in a distance of ~ 35km long, the Angoche basin and partially the Nacala basin. The lower panel displays the seismo-stratigraphic interpretation including the proposed plays. Jurassic Plays are defined within the detached thrust fold-belts. Cretaceous and Tertiary plays are mainly stratigraphic traps defined by slope fan and onlap pinch-outs. See text for discussion.

Towards the Nacala basin, tracing of *K-unit I* indicates extensional tectonics dissected by several listric faults (Figure 3A, B). The maximum thickness in this basin is ~ 700 m. The *K-unit I* is also correlated on the eastern side of the DFZ described by seismic reflectors with more parallel configurations than the western side, suggesting gradual transition to open marine conditions;

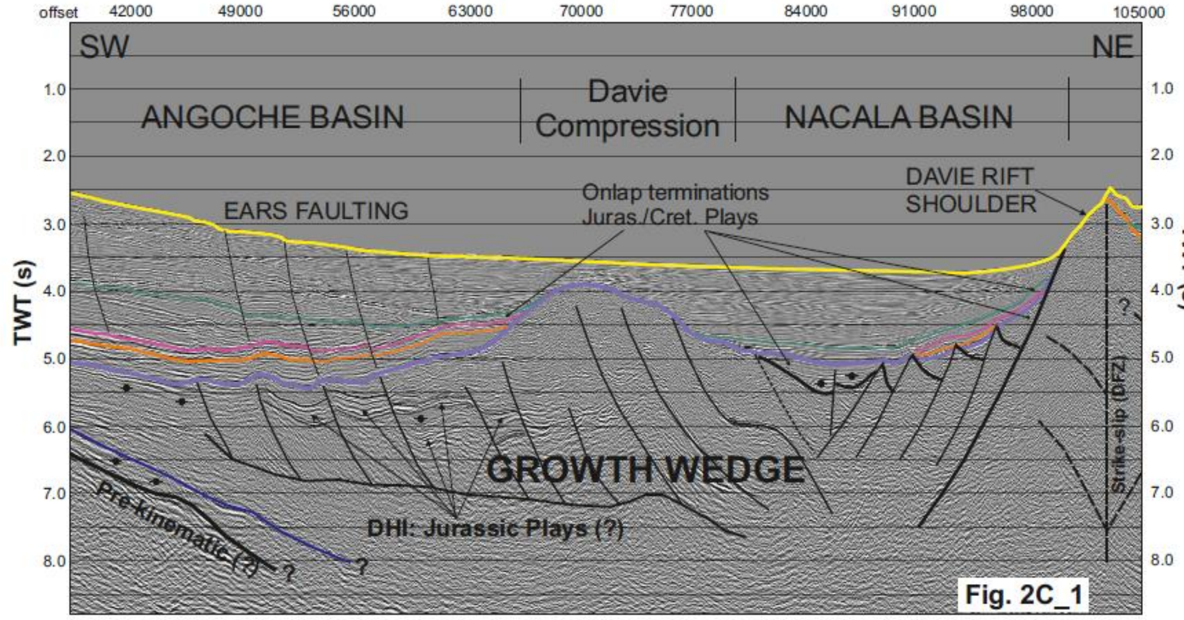


Fig. 2C_1 - Enlargement of the central portion of Figure 2C presenting an interpretation as proposed in this study. However, the illustration shows details of the morphology of the Davie compressional zone. Reflectors of moderate to high amplitude are imaged as potential Jurassic structural plays within the Davie compressional zone. Half-graben morphologies dissect basement along the DFZ during the rifting of Nacala basin. Active young faults rejuvenate the Mesozoic and Cenozoic successions as part of the Mid-Tertiary extensional tectonic (EARS). See text for discussion.

K-Unit II This is ~ 750 m thick of a stacked and more continuous section showing distinctive characteristic relief of the reflectors with moderate to high amplitude widespread in the central part of Angoche basin. These characteristics indicate a difference in seismic response comparatively with the lower and the upper units. A suitable correlation of the *K-Unit II* is made towards the north in the Nacala basin within the rift-grabens. However, in the Angoche basin, the principal morphologies show configuration of mounded patterns, suggesting slope fan or basin floor fan deposits (Figures 2A, B). The top reflector terminates onlapping onto the *Davie compressional zone* indicating possible stratigraphic trapping. Deposition during the Turonian time was influenced by marine regression caused by the short-lived uplift after cessation of the strike-slip motion along the DFZ. Hence, a typical lowstand clastic sediments are expected to be the litho-stratigraphic component of the Domo sandstone equivalent, enclosed between shales (Salman and Abdula (1995);

K-Unit III is topped by Cretaceous-Tertiary boundary pronounced by regional unconformity which was formed during the late Drift phase in Late Cretaceous time. At this period, the development of East Africa passive margin is proposed, typified by widespread marine transgression at the end of Cretaceous (Salman and Abdula, 1995). The impedance contrast along the reflection seismic is similar to that of *K-Unit I*. The seismic characters vary with depth and exhibit lateral change in the whole basin. Towards the central Angoche basin, reflection patterns with low to moderate amplitude are restricted to the lowermost part. In the uppermost part, typical mound-like reflectors predominate, suggesting slope and/or submarine floor fan deposits (Figure 2B). Similar facies have been described in the Mozambique basin with favourable interplay of sand and shale forming gas reservoirs and seal rocks of the Lower Grudja Formation.

(iv) The Tertiary to Recent successions are manifested by predominately south-to-north downlapping terminations onto the Base Tertiary unconformity. In Figure 2A, these terminations are barely visible on the seismic display, typifying a highstand system tract that develops lateral accretion of migrating point bars. They indicate ~ 800 m thick of prograding wedge from southwest to northeast, suggesting a predominance of sediment-feeding systems during the mid-Tertiary. Droz and Mougenot (1987) discussed the Serpa Pinto Valley and Zambezi Valley systems in the northern Mozambique basin linking them to the creation and erosion of the East African Rift System in Oligocene. Accordingly, the Serra Pinto Valley was the main path towards the north, filling the depression along the DFZ (Angoche basin) with massive depositional sequences. In the regional scale, reflector patterns indicate prograding wedge from NW of the Beira High, developing typical contourite deposits (Reichert et al., 2008).

On top of the prograding wedge, is ~ 1000 ms TWT of reflectors showing predominate mounds, slumping rollover and channel-fill deposits well-imaged in the south (Figure 2A). A prominent channel cut, with well-defined top and base, occurs at the shallow depths. These channels are well outlined by the seismic amplitude section (Figures 2A, B and 3B). In the Nacala basin, the reflection patterns have similar internal arrangement of the Angoche basin but are dissected by several listric faults (Figures 3A, B).

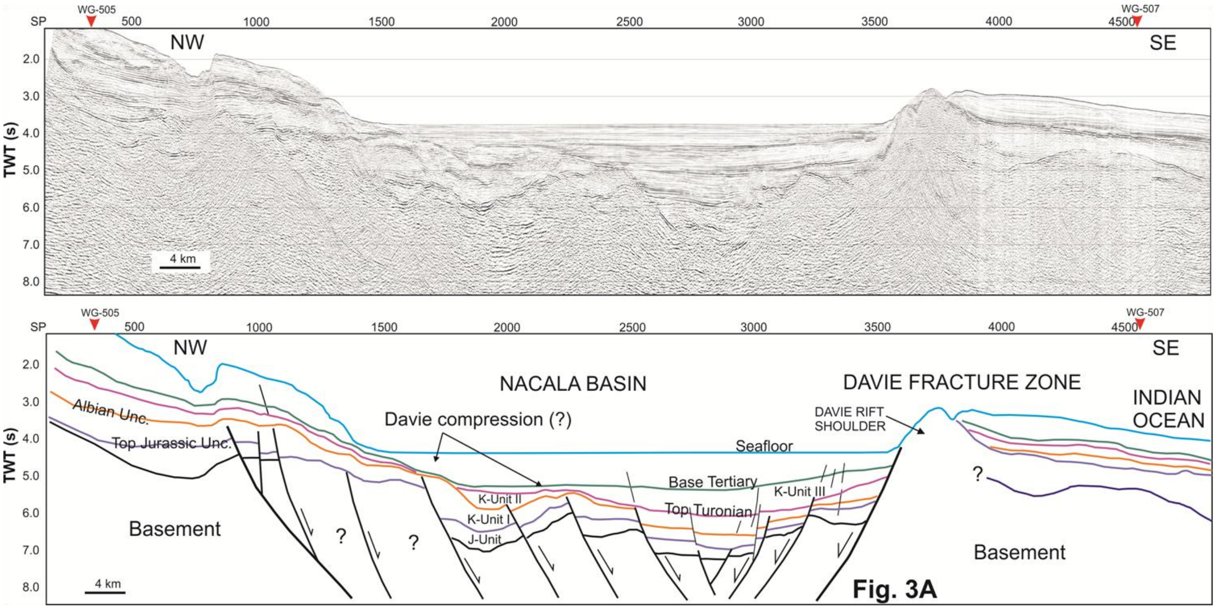


Figure 3A - The upper panel is uninterpreted migrated 2-D reflection seismic section selected to exemplify the main geological setting along the Nacala basin. In the lower panel is the interpretation of the extensional tectonics that led to the formation of the Nacala basin. Predominate, are synthetic and antithetic listric faults dissecting the entire stratigraphy including the basement along the western DFZ. See text for discussion.

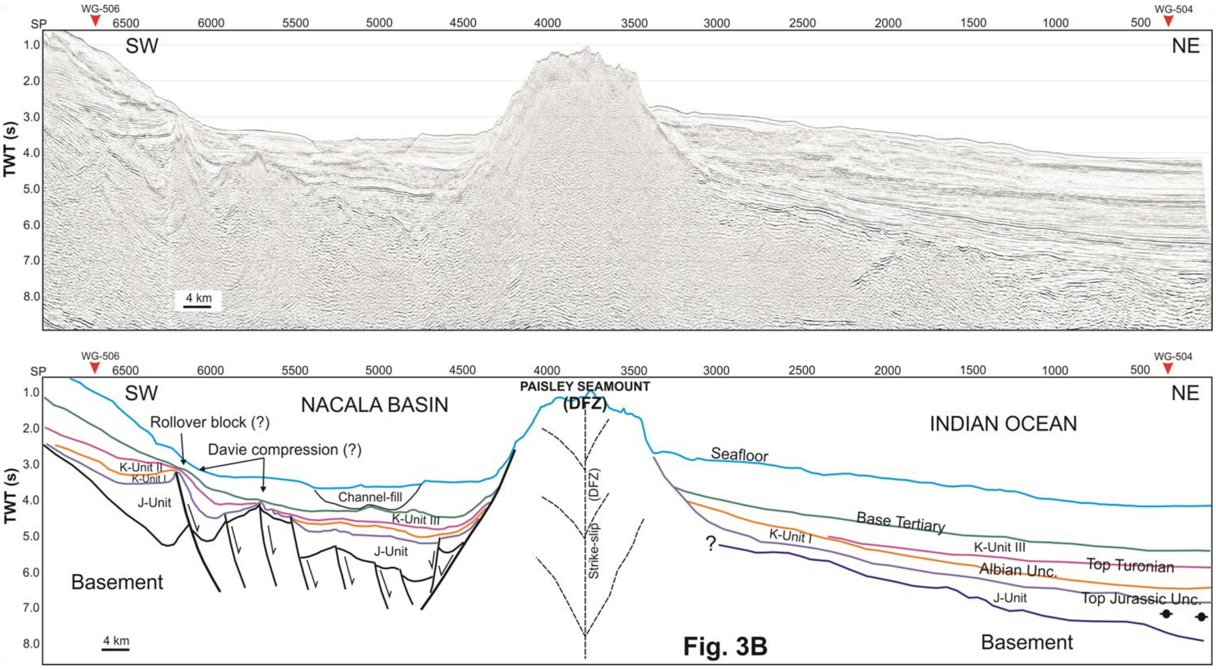


Figure 3B - The upper panel is uninterpreted migrated 2-D reflection seismic section transecting the DFZ at the location of the Paisley seamount. The seismo-stratigraphic interpretation (lower panel) displays the tectonic setting similar as described in Figure 3A. The extensional deformation (graben system) predominates in the west edge, while the Indian Ocean basin typifies a normal tectonic subsidence (east side) with no subsequent deformation. See, text for discussion.

Tectonic setting as seen from seismic

Figures 2A, B, C and Figures 3A, B show seismic sections crossing the DFZ and adjacent basins. The most prominent features in the western side of the DFZ are displayed here. The fault geometry gives the impression of a unique structural fracture; but two different tectonic regimes are identified, characterized by compressional and extensional tectonics, or a combination of both: (1) Compressional tectonics (that was previously not observed in that region) is presented by the most prominent feature, the *Davie compression* structure (Figures 2 A, B, C). It runs ± north-south bending to NW in the location of Figure 2C (see Figure 1B). The structure displays a ridge-like morphology migrating from the SE and progressively losing its character towards the northwest in the location of Figure 3A, B (see Figure 1B). The character of the *Davie compression* structure suggests a tectonic signature distinguished by transpression and contraction events. This setting is hosted by several detached compressional structures (like fold-belts) with prominent trailing thrust imbrications of massive growth wedge structures underlying the *Davie compression zone.* They are sub-parallel to the DFZ, which progressively dips seawards (Figures 2A, B, C). The compressional structures overlie a pre-kinematic (?) passive margin sequence developed during the earlier rifting and drifting stages in the mid-Upper Jurassic time. In the western side of the DFZ, tectonic subsidence occurred to form the Angoche basin. The shape of the basement in the west margin is interpreted as a typical volcanically active rift. It is controlled by limited brittle extension of the upper crust. If this interpretation is correct, the seaward dipping reflectors proposed by Reichert et al., (2008) in additional mapping of the volcanic zone by Raillard (1990) or Angoche dyke swarms by Reeves and Mahanjane (2013) along the Angoche continental margin support the interpretation of volcanic origin of this margin; (2) The extensional regime characterized by asymmetric half-grabens to symmetric grabens predominates from the central to the northern region. In general, listric normal faults bounding both sides are observed along the entire Nacala basin (Figures 3A, B). The area affected by the faulting widens to the northern basin forming a V shape, reaching a width of 50 km in the area close to the Nacala city (Figure 1B). The detachment faults commonly follow the continental margin. They propagate seawards to end in the DFZ (Figure 3A) and change the morphology gradually controlling faults dipping and displacing eastwards. They become a full-graben system towards the north where the Nacala basin becomes wider (Figure 1B). The graben system is expected to extend further north to correlate with similar tectonism overprints interpreted in the Rovuma basin (Mahanjane and Franke, 2014). Rifting along the western side of the DFZ formed a series of tilt-blocks in half-grabens in the transitional zone (at the location of Figures 2B, C); and (3) Both the imbricate wedge structures and extensional rift-grabens form a link between extensional tectonics in the north and deformation, with compressional tectonics, in the south. Extensional tectonics is manifested in the Nacala basin and compressional tectonics occurs along the *Davie compression zone*.

In general, the detachment surfaces of the growth wedges are located at depths between 7000 ms to 8000 ms (TWT) dipping towards the east. The lateral extension varies from 10 kilometres in the north to 20 kilometres in the south (Figure 1B at the location of Figures 2A, C). Towards the north, the compressional tectonics structure is gradually replaced by extensional half-graben to graben morphology. The lateral extension of the graben varies from 10 km in the south to 40 km in the north (Figure 1B). It is possible that extensional tectonics followed the cessation of transpression. The DFZ involved the Mesozoic compressional and extensional events that were rejuvenated by the Mid-Tertiary extensional tectonics (East African Rifting System).

Common normal faults stretching out and cutting the Cenozoic successions to the surface were consistently mapped in the seismic sections, favourably located on the top and western edge of the *Davie compression zone* (Figures 2A, B, and C). The interpretation based on their geometry indicates the onset of the reactivation of DFZ from the Oligocene onwards. It is considered to be a southerly extension associated with the modern East African Rifting System. In some places, the faulting appears to indicate an active tectonic regime, supported by the occurrence of seismicity along the DFZ in the present time (Coffin and Rabinowitz, 1987; Yang and Chen, 2008; U.S. Geological Survey).

Hydrocarbon potential

The critical aspects for hydrocarbon potential plays in the DFZ frontier area and adjacent basins are predictable from the structural mapping and stratigraphy of the DFZ, and fairways are identified for future exploration. A summary of the petroleum system (e.g. Magoon and Dow, 1994 and Peters et al., 2005) is presented by event chart of Figure 4. For the evaluation of the working petroleum system, it is taken into account that an effective organic-rich source rocks should be present and sufficiently buried as well as thermally mature (Peters et al., 2007).

Regrettably, the source rocks of the Mozambique continental margin basins are poorly understood, since no well drilled thus far has penetrated the possible Jurassic and/or Early Cretaceous shale and shelf carbonate deposits. Nonetheless, an effective source rock should be present within the DFZ and deep-water areas judged by the reported massive gas discovered in the Rovuma basin. In addition, there are active oil and gas seeps in the Rovuma basin and Angoche margin (Figure 1A). Additional information indicates Middle and Late Jurassic source rocks in the Mandawa and Ruvu basins, which are capable to generate oil and gas. For instance, Bajocian source rocks from Makarawe-1 well contain ~ 1.98-2.36% TOC, the Late Jurassic Nondwa shale in Mandawa basin exhibit 0.65-8.7% TOC (Maenda and Mpanju, 2003). Likewise, the Jurassic/Lower Cretaceous marine marls from Morondava basin contain up to ~ 5% TOC (Matchette-Downs, 2006).

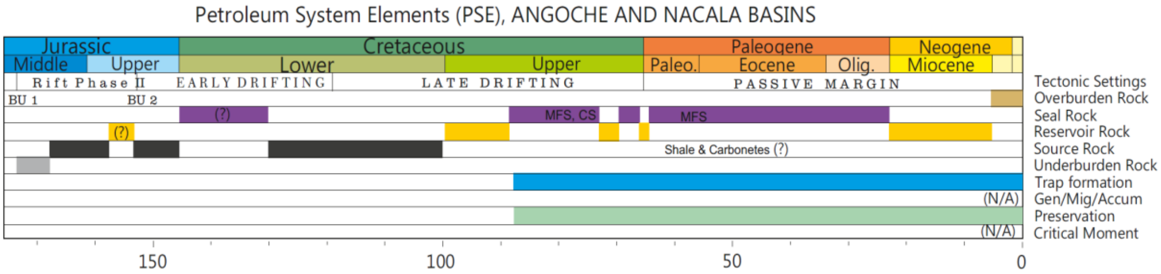


Figure 4 - Events charts for the potential petroleum system in the Davie Fracture Zone and adjacent basins. Please note, no maturity modelling was carried out in this study, the petroleum system chart is modified from Bird (1994), Peters et al. (2005), Mubarak and Mariam et al. (2009). The chart indicates the presence of elements of the Petroleum system depicted from the stratigraphy of Figure 1C. Age ranges of petroleum system are shown in coloured boxes. Generation and critical moment need to be estimated by maturity study. Keys: Gen/Mig/Accum-generation/migration/accumulation; BU–Breakup, CS–condensate sections, MFS–maximum flooding surface.

Geochemical data measured from the oil shows found in Mandawa basin indicate excellent hydrogen index up to 1000 mgHC/TOC, vitrinite reflectance (R0) between 0.5-0.9% (Maenda and Mpanju, 2003). The maturity window (R0) above “fits” well into the maturity model discussed by Mahanjane et al. (submitted). They suggest sufficient maturity of the possible Jurassic source rock to generate hydrocarbons at the present-day burial depth in the Angoche basin.

In general, both geometrically robust structural and stratigraphic play types occur along the DFZ and adjacent basins. Trapping developed from Late Jurassic to Cenozoic time preserving configurations similar to those pooling hydrocarbons in the Rovuma basin. The

Jurassic structural plays are predominately defined within the compressional structures and are formed by a variety of fault-related folds and fault-propagation folds geometries interpreted within the Davie compression zone (Figures 2A, B, C) whilst the stratigraphic trap plays are defined within Cretaceous and Tertiary successions by pinch-out geometries of submarine fans (Figures 2A, B, C).

Summary and Conclusions

The results of this study present structural elements of two basins separated by compressional zone, the Angoche basin in the south and Nacala basin in the north. The Angoche basin was formed by thermal subsidence during the earliest stage of the Gondwana break-up in mid-Jurassic time. The evidence of the timing is the regional scale Karoo-Explora Wedge magmatism widespread along the western flank of the Angoche basin. Typical steeply dipping basement bound the northern extent of the Angoche dyke swarms, dim-out in the Nacala basin overprinted by the Davie compressional zone. This compressional structure is well-imaged in the eastern flank of the Angoche basin, deforming completely the Jurassic succession along its extent. The compressional zone is more prominent in the south. It shows progressive loss of the character towards the northwest, being replaced by rifting of the Nacala basin. The depression is formed by series of NNW and NNE graben system developed further north in the Rovuma basin.

The petroleum systems identified on structural mapping include the following:

Effective structural and stratigraphic traps are present due to the good sealing structures, e.g. fault-related folds, and presence of numerous pinch-outs with anomalous amplitude reflectors. The stratigraphic play is identified from Jurassic to Tertiary time whereas the structural plays are defined in the Jurassic and Cretaceous intervals.

Geochemical data from neighbouring basins and the recent massive gas discoveries in the Rovuma basin confirm the existence of working source rocks along the DFZ. The possible source rocks are depicted within the stratigraphy of Jurassic, Cretaceous, and Palaeocene-Eocene (?) times.

Acknowledgements

This paper has received support from the management of the *Instituto Nacional de Petróleo* (INP) including the data. I would like to thank BGR and Dr. Christian Reichert for the logistical support they provided. The author also wishes to express his gratitude to Dr. Axel Ehrhardt, Dr. Norbert Ott, Martin Block, Dr. Walter Roest, the Associate Editor Dr. Allard W. Martinius as well as the reviewers Dr. Colin Reeves and Dr. Ian Kane whose helpful remarks and comments on the paper resulted in significant improvements of the final version. Finally, I would like to thank Laura da Prosperidade Mahanjane and Anna Hacker for helping in the final edition of this paper.

References

Bassias, Y., 1992. Petrological and geochemical investigation of rocks from the Davie Ridge Fracture Zone (Mozambique Channel) and some tectonic implications. Journal of African Earth Sciences, Vol. 15, No. 3/4, pp. 321-339.

Bird, K. J. 1994: Ellesmerian(!) petroleum system, North Slope, Alaska, U.S.A. In: Magoon, L. B. & Dow, W. G. eds.: The petroleum system – from source to trap, p. 339-358.

Catuneanu, O., H. Wopfner, P. G. Eriksson, B. Cairncross, B. S. Rubidge, R. M. H. Smith and P. J. Hancox (2005). "The Karoo basins of south-central Africa." Journal of African Earth Sciences 43(1–3): 211-253.

Catuneanu et al., 2009. Towards the standardization of sequence stratigraphy. Earth-Science Reviews 92 (2009) 1–33. doi:10.1016/j.earscirev.2008.10.003.

Catuneanu et al., 2010. Sequence stratigraphy: common ground after three decades of development. First break volume 28, January 2010. Stratigraphy. www.firstbreak.org © 2010 EAGE.

Catuneanu, O, Galloway, W. E., Kendall, C. G., Miall, A. D., Posamentier, H. W., Strasser, A.,Tucker, M. E., 2011. Sequence Stratigraphy: Methodology and Nomenclature. Newsletters on Stratigraphy, Vol.44/3, 173–245.

Coffin, M.F., and Rabinowitz, P.D., 1987. Reconstruction of Madagascar and Africa: Evidence from the Davie Fracture Zone and Western Somali Basin. Journal of Geophysical Research, Vol. 92, NO. B9, 9385-9406.

Coffin, M.F., and Rabinowitz, P.D., 1992. The Mesozoic East African and Madagascan conjugate continental margins: Stratigraphy and Tectonics. In: Geology and Geophysics of Continental Margins, AAPG Memoir, 53, edited by Watkins, J.S., Zhiqiang, F., and McMillen, K.J., pp. 207-246.

de Wit, M. J., 2003 Madagascar, Heads it's a Continent, Tails it's an Island. Annu. Rev. Earth Planet. Sci. 2003. 31. 231-48. doi 10. 1146/ annurev. Earth. 31. 100901. 141337.

Droz, L. and Mougent, D., 1987. Mozambique Upper Fan: Origin of Depositional Units. The AAPG Bulletin V.71, No.11 (November 1987), P. 1355-1365, 13 Figs.

Exploration Consultant Limited (ECL) & Empresa Nacional Hidrocarbonetos (ENH), 2000. The Petroleum Geology and hydrocarbon Prospectivity of Mozambique. Volume 1. Instituto Nacioal de Petróleo, *Archives*.

Key, R.M. et al., 2008. Revised lithostratigraphy of the Mesozoic–Cenozoic succession of the onshore Rovuma Basin, northern coastal Mozambique. Journal African Earth Sciences, 111: 89-108.

König, M., Jokat, W., 2006. The Mesozoic breakup of the Weddell Sea, J. geophys. Res., 111(B12), 102, doi:10.1029/2005JB004035.

König, M., Jokat, W., 2010. Advanced insights into magmatism and volcanism of the Mozambique Ridge and Mozambique Basin in the view of new potential field data. Geophysical Journal International 180 (Issue 1), 158-180. January 2010.

Kreuser, T. 1995. Rift to drift evolution in Permian-Jurassic basins of East Africa. In: Hydrocarbon Habitat in Rift Basins'. Ed. Lambiase, J. J. Geol. Soc. Spec. Publ. No. 80 pp 297-315.

Law, C., 2011. Northern Mozambique: True "Wildcat" Exploration in East Africa. Adapted from oral presentation at Forum: Discovery Thinking, at AAPG Annual Convention and Exhibition, Houston, Texas, USA, April 10-13, 2011. Search and Discovery Article # 110157 (2011). Posted June 20, 2011.

Leinweber, V., Jokat,W., 2012. The Jurassic history of the Africa – Antarctica Corridor e new constraints from magnetic data on the conjugate continental margins. Tectonophysics 530-531,87—101.doi:10.1016/ j.tecto.2011.11.008.

Maende, A. and Mpanju, F., 2003. Geochemistry and source rock potential of East African Passive Margin. EAPC 2003, Nairobi, Kenya.

Magoon L. B. & Dow, W. G. 1994: The petroleum system. In: Magoon, L. B. & Dow, W. G. eds.: The petroleum system − from source to trap. AAPG Memoir 60, 3-24.

Mahanjane, E.S., 2012. A geotectonic history of the northern Mozambique Basin including the Beira High – A contribution for the understanding of its development. Marine and Petroleum Geology 36 (2012) 1-12.doi:10.1016/j.marpetgeo.2012.05.007.

Mahanjane, E.S and Franke, D. 2014. The Rovuma Delta deep-water fold-and-thrust belt, offshore Mozambique, Tectonophysics 614 (2014) 91–99. doi:10.1016/j.tecto.2013.12.017.

Mahanjane, E.S.; Franke, D.; Lutz, R.; Winsemann, J., Ehrhardt, A.; Berglar, K.; and Reichert, C. (submitted) Maturity modelling and petroleum system of the northern Mozambique basins, off Zambezi Delta and Angoche basins.

Matchette-Downes, C., 2006. Petroleum potential of the Morondava Basin. Madagascar Promotional Meeting. Houston May 25th 2006.

Mubarak and Miriam et al., 2009. Basin and Petroleum Modelling. Oilfield Review Summer 2009: 21, no.2.

Nairn, A.E.M., Lerche, I. and Iliffe, J.E., 1991. Geology, basin analysis and hydrocarbon potential of Mozambique and the Mozambique Channel. *Earth-Sci. Rev.*, 30: 81-124.

Patriat, P. and Segoufin, J., 1988. Reconstruction of the Central Indian Ocean. Tectonophysics, 155, 211-234.

Peters, K. E., Lampe, C., Bird, K. J. & Magoon, L. B. 2005. 4-D modeling of the Shublik-Ivishak(!) petroleum system, North Slope, Alaska. Joint Meeting Pacific Section, AAPG & Cordilleran Section, Geological Society of America, April 29 - May 1, 2005, San Jose, California, Paper 40-4, Geological Society of America, Abstracts with Programs 37, p. 93

Kenneth E. Peters, Leslie B. Magoon, Carolyn Lampe, Allegra Hosford Scheirer, Paul G. Lillis, and Donald L. Gautier. 2007. A Four Dimensional Petroleum Systems Model for the San Joaquin Basin Province, California by (pp1713_ch12.pdf; 10.1 MB and appendix file; 10.2 MB compressed and 70.1 MB when expanded) doi:10.3133/pp1713.ch12.

Peters, K., Schenk, O., and Wygrala, B., 2009. Exploration Paradigm Shift: The Dynamic Petroleum System Concept. Swiss Bull. angew. Geol. Vol. 14/1+2, 2009.

Rabinowitz, P.D., Coffin, M.F., Falvey, D.A., 1983. The separation of Madagascar and Africa. Science 220, 67-69.

Rabinowitz, P.D., and Woods, S., 2006. The Africa – Madagascar connection and mammalian migrations. Journal of African Earth Sciences 44 (2006) 270-276.

Raillard, S., 1990. Les marges de l`Afrique de l`Est et les zones de fracture associees: Chaine Davie et Ridge du Mozambique-Champagne MD-60/MACA MO-11. PhD thesis, L'Universite Pierre et Marie Curie, Paris, pp. 1-272.

Reeves, C., 2000. The Geophysical mapping of Mesozoic dyke swarms in southern Africa and their origin in the disruption of Gondwana. Journal of African Earth Sciences 30, 449-513.

Reeves, C. and Mahanjane, E.S., 2013. Mozambique and its role in the downfall of Gondwana. Geological Society of Houston/Petroleum Exploration Society of Great Britain, London, 2013 September 11-12. http://pesgb.org.uk/events/event-165/.

Reichert, C., Neben, S., Adam, J., Aslanian, D., Roest, W., Mahanjane, E., James, E., Bargeloh, H., Behrens, T., Martin, B., Ehrhardt, A., Heyde, I., Jokat, W., Kallaus, G., Klingelhöfer, F., Moulin, M., Kewitsch, P., Schrader, U., Schreckenberger, B., and Sievers, J., 2008. Cruise Report, BGR07. R/V MARION DUFRESNE CRUISES MD 163 & MD 164. PROJECT MOBAMASIS. Tech. rep. Hannover, Bundesanstalt für Geowissenschaften und Rohstoffe (BGR).

Salman, G., Abdula, I., 1995. Development of the Mozambique and Ruvuma sedimentary basins, offshore Mozambique. Sedimentary Geology 96 (1995), 7-41. Elsevier Science B.V. SSDI 0037-0738(94)00125-1.

Scrutton, R. A., Heptonstall, W. B., and Peacock, J. H., 1981. Constraints on the motion of Madagascar with respect to Africa: Marine Geology, V. 43, P1-20.

Yang, Z., and Chen, W.-P., 2008. Mozambique earthquake sequence of 2006: High-angle normal faulting in southern Africa. J. Geophys. Res., 113, B12303, doi: 10.1029/2007JB005419.

4.4. Maturity and petroleum systems modelling in the offshore Zambezi Delta depression and Angoche basin, northern Mozambique

(1, 2, 3) Mahanjane, E.S.; (2) Franke, D.; (2) Lutz, R.; (3) Winsemann, J., (2) Ehrhardt, A.; (2) Berglar, K. and (2) Reichert, C. /

[Submitted to Journal of Petroleum Geology]

(1) Instituto Nacional de Petróleo (INP) – Av. Fernão Magalhaes N. 34 - 2° Andar, PO. Box 4724 Maputo, Moçambique.
(2) Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Stillweg 2, 30655 Hannover, Germany
(3) Institut für Geologie, Leibniz Universität Hannover, Callinstraße 30, 30167 Hannover, Germany

Abstract

We investigate petroleum systems and perform maturity modelling to predict the timing and locations of hydrocarbon generation in the underexplored Zambezi Delta and Angoche basins in the northern Mozambique basin. Prior to and during modelling, an effort was made to integrate all available geological, geochemical, and geophysical concepts and data.

Based on recent plate-tectonic reconstructions and regional correlation the presence of an Aptian-Albian and a Middle and/or Late Jurassic marine source rock is proposed.

Basin stratigraphy is interpreted along reflection seismic lines and calibrated against four critical wells in the Zambezi Delta. Thermal maturity was calibrated against measured vitrinite reflectance values from these four wells. Four 1-D models with calibration data and another five without calibration data indicate the maturity of possible source rocks at different locations in the Zambezi Delta and Angoche basins. Two 2-D petroleum system models, constrained by seismic reflection data, depict the burial history and maturity evolution of the Zambezi Delta basin.

Except for the deeply subsided centre of the Zambezi Delta with early depletion and overmaturation, we found a prolific thermal maturation for the entire remaining northern Mozambique basin.

We conclude that in both, the Zambezi Delta and Angoche basins, indications for natural gas can be explained by early maturation of oil-prone source rocks and secondary oil cracking which likely began in the Early Cretaceous. An exception is the distal part of the Angoche basin, where the majority of the proposed source rocks are all in the oil window.

Introduction

Mozambique shows among the East African countries the most notable hydrocarbon discoveries in the past years. In addition to the four proved onshore gas fields major new gas discoveries were made in the recent past years in the offshore Rovuma Delta basin, at the border to Tanzania (Figure 1A). Total proved natural gas reserves in the onshore Mozambique are about 4.5 trillion cubic feet, according to the Instituto Nacional de Petróleo archives. However, a source rock has not been sampled and today it is unclear if those gas accumulations were sourced by Middle-Late Jurassic marine shales that may have been buried under thick sediments and are now in the gas window, or if the gas was generated from a terrigenous and thus gas-prone source rock. The implication from the first possibility is that there may be some oil discoveries made offshore Mozambique in the future. Exploration activity at present concentrates on the north-eastern offshore edge of the country leaving the vast margins to the south underexplored and the type of petroleum systems here are highly speculative.

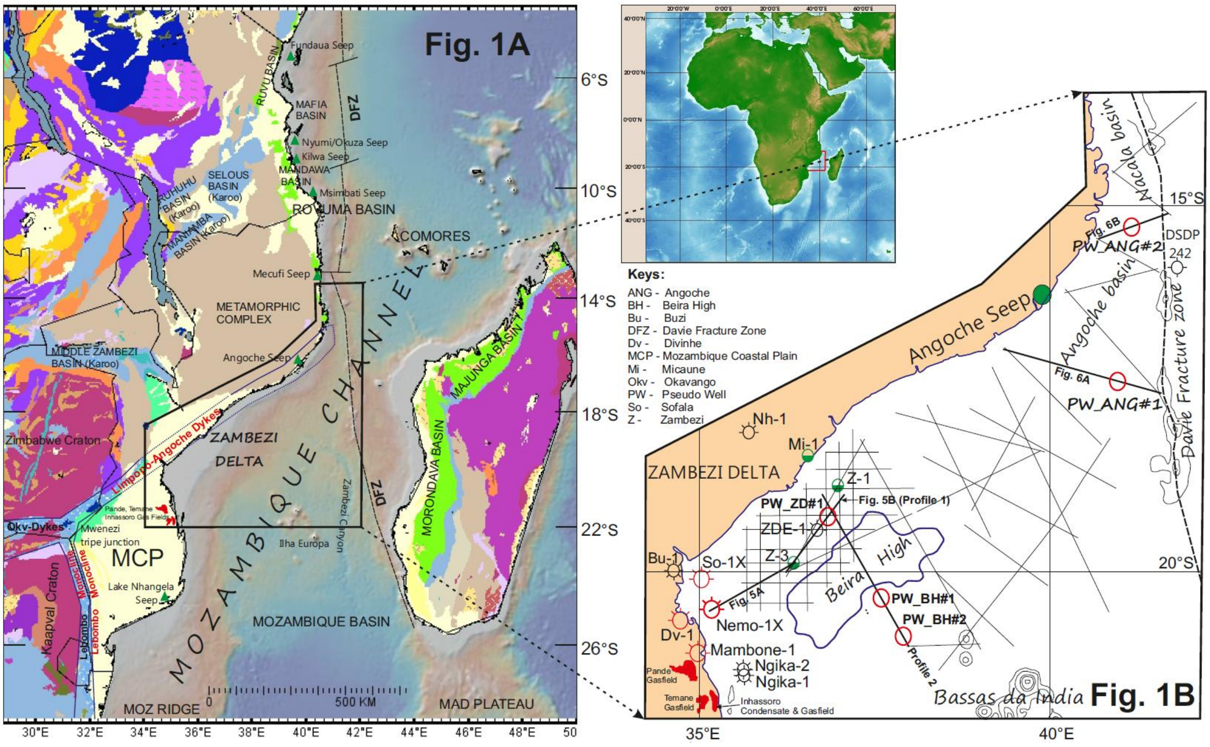


Figure 1 – (A) Geological map of SE Africa (after Ryan et al., 2009; source: the Lamont-Doherty Earth Observatory of Columbia University: http://www.geomapapp.org;) comprise important tectonic structures the Mozambique Channel and the main sedimentary basins of Mozambique, Madagascar and Tanzania. (B) Location Map of the 2-D reflection seismic lines and well sites. Outline of the Beira High, Zambezi Delta, and the Angoche and Nacala sedimentary basins.

In this contribution, we integrate information from regional paleogeographic reconstructions, boreholes and seismic reflection data to depict the litho-stratigraphy of the possible source rocks for petroleum system modelling. We test the maturity and timing of hydrocarbon generation from assumed source rocks by performing 1-D and 2-D petroleum system modelling along the underexplored southern continental margins of Mozambique.

Geological background and deposition of potential source rocks

The study area comprises the offshore region between the Lebombo Monocline and the Davie Fracture Zone of the Northern Mozambique basin (Figure 1).

The present-day setting has been derived from episodic rifting of Gondwana. Crustal extension between Madagascar, India, Antarctica and Australia on the one hand and Africa, Arabia and South America on the other hand commenced at the end of the Carboniferous, with a zone of weakness developing along the former Pan-African mobile belt. A series of intracontinental rifts and pull-apart basins were formed along East Africa and Madagascar from the Early Permian to the Triassic (e.g. de Wit, 2003).

The northern Mozambique basin can be divided into two tectonic settings: a passive margin and a failed rift. The passive margin is well pronounced along the Zambezi coast from Angoche basin down to the Zambezi estuary bounded by the modern coastline, while the failed rift passes down the Zambezi Delta depression between the passive margin (Zambezi coast) and the Beira High (Mahanjane, 2012).

The Mozambique basin is the result of a Permo-Triassic rifting episode. During this time span deposition of the predominantly terrestrial Karoo sequences occurred. There are frequently thick coal layers and sandstones interbedded in the volcanic-sedimentary successions of the Karoo sequences, which may be considered as gas-prone source rocks (ECL and ENH, 2000). There are also marine sediments reported within the early Karoo sequences. In Madagascar, thin and discontinuous Lower Permian stromatolite- and brachiopod-bearing limestone indicates marine conditions (de Wit, 2003). In the Zambezi valley the amount of shale present is higher and the faunal and floral content seems to be higher than in Zimbabwe and South Africa, indicating a basinal environment during the deposition of these Ecca shales more to the east (Nairn et al., 1991).

Nairn et al. (1991) suggested that if the Karoo exists in the lower Zambezi Graben it may possess enhanced source rock potential.

A marine ingression in the Middle Jurassic by the paleo-Tethys Sea (Figure 2) from the north is accepted for the Rovuma basin area in northern Mozambique (Salman and Abdula, 1995). A gradual facies shift from dominantly continental to mixed continental-marine during the Toarcian to early Bajocian is a widespread phenomenon in marginal basins of Kenya, Tanzania, and Madagascar, indicating the establishment of marine conditions, caused by a major transgression from the north Hankel (1994) during the Bajocian. Slightly older marine sediments of Toarcian and Aalenian age have also been encountered in boreholes in the southern Morondava basin, Madagascar (Geiger et al., 2004), which likely we believe that was close to the Rovuma basin in the Jurassic.

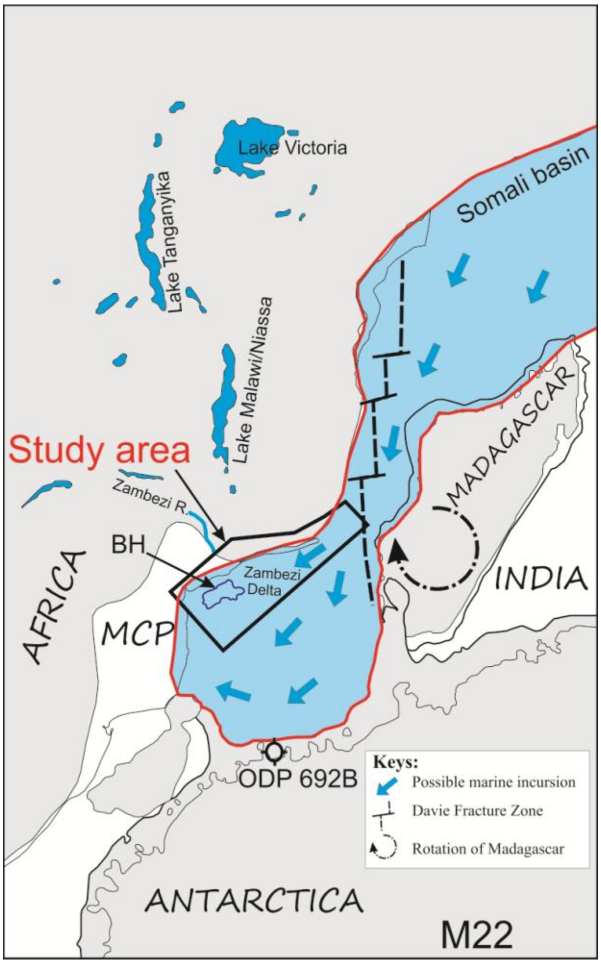


Figure 2 - A reconstruction model of breakup stage between the West and East Gondwana at 152 Ma (M22), modified from Eagles and König (2008). A marine ingression is indicated by blue arrows, reaching the northern Mozambique basin and conjugate Riiser-Larsen Sea (outlined by red line). The newly formed oceanic basin is still under restricted conditions, favourable for deposition of oil-prone source rocks.

The onset of the marine incursion in the early Mozambique basin is speculative. The movement of Madagascar along the Davie Fracture Zone probably started in the Middle Jurassic (early Bajocian; Geiger et al. (2004) and Madagascar attained its present position relative to Africa in the Early Cretaceous (at c. 120–130 Ma) (Rabinowitz and Woods, 2006). When exactly in this period from c. 160 Ma to 130 Ma the Mozambique Channel was opened to marine incursions is unclear. According to Salman and Abdula (1995) the paleo-Tethyan transgression extended widely in the Late Jurassic during Kimmeridgian and Tithonian times, resulting in disconformity deposition of Upper Jurassic marine shale and limestone in the North-Eastern African basins, including the Rovuma basin. According to these authors the sea likely also has penetrated into the northern part of the Mozambique basin (Figure 2). The now established formation of oceanic crust in the Mozambique basin in late Middle Jurassic times (Leinweber et al., 2013) supports this idea of a Late Jurassic extended transgression. Given this timing, post-rift subsidence did initiate already in the Middle Jurassic and by the Late Jurassic (magnetic anomaly M22r; c. 150 Ma) an up to 500 km wide oceanic basin did exist. This is about two times broader than the up to 2.6 km deep present day Red Sea.

From the earliest Cretaceous onward marine conditions was established in the Mozambique basin. According to Salman and Abdula (1995) by the beginning of the Cretaceous the marine transgression had reached the southern end of Africa. In southernmost Mozambique, Early Jurassic lavas, which overly the Karoo sequence are in places overlain by continental sandstones of the Red Beds. In other places the volcanics are directly overlain by the marine Cretaceous (Aptian-Albian) Domo shales (Nairn et al., 1991), regarded by Kamen-Kaye (1983) as potential source rocks, which pass eastward into open marine deposits. A 45 m succession of Valanginian calcareous claystones was penetrated at Site 692B of ODP Leg 113 on the conjugate continental margin, Dronning Maud Land in the Weddell Sea, Antarctica (Thompson and Dow in Barker, Kennett et al., 1990). The carbonate contents of the claystones range from 0.8% to 42%, averaging 17.17% ± 12.97%. Geochemical analyses indicate petroleum source rock of excellent quality, which contains only Type II kerogen with hydrogen Index values between 300 and 600 mg HC/gTOC (Figure 3) and bears no oxidized laminae. The occurrence of continuous anoxia, i.e. the absence of macroscopic cyclicity, has been explained by Thompson and Dow (in Barker, Kennett et al., 1990) by the existence of a series of restricted basins in progressively deeper waters, the proximal basins acting as sediment traps for the distal ones. One of the latter, with its sill located permanently within the oxygen minimum zone during Valanginian time, could have provided an appropriate depositional setting.

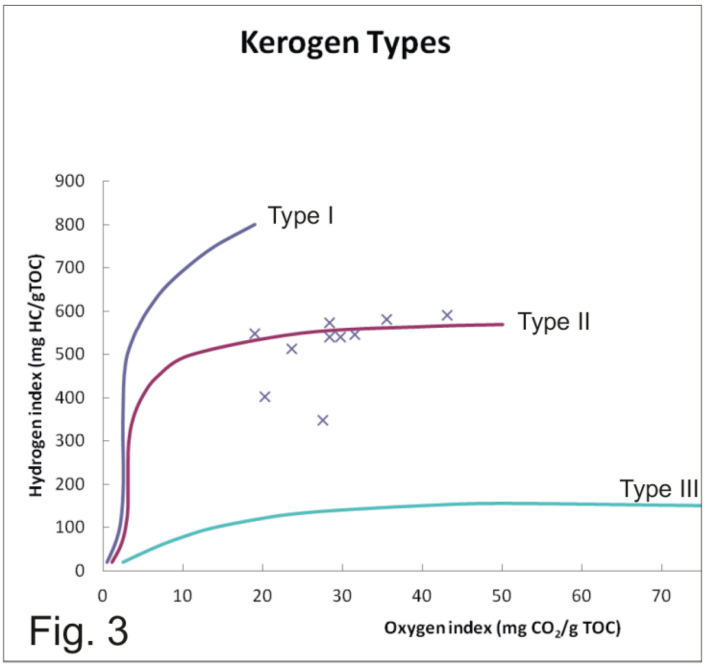


Figure 3 - Geochemical analyses (shipboard) data (Rock-Eval) of Valanginian-Aptian sequences from ODP Site 692B (Thompson and Dow in Barker, Kennett et al., 1990) plotted into a pseudo Van Krevelen-type diagram, shows predominant Type II kerogen.

Indications for the presence of an oil-prone source rock are found onshore Mozambique, to the east of the Lebombo monocline. There is oil seeping at Lake Nhangela and there were oil shows in Cretaceous sections in several wells, close to the shore (ECL and ENH, 2000).

Possible Cenozoic source rocks of the Zambezi River basin (Nairn et al., 1991) are not excluded but will not be considered in this study. Karoo-age sediments are unlikely present in the offshore region under study. Sediments of this age are widespread within the intracratonic basins in Tanzania, Mozambique and South Africa and the equivalent Sakoa Group of the northern Morondava basin in Madagascar (Figure 1A). The Permian Ecca Group contains coals and carbonaceous mudstone and is dominantly gas prone. Onshore Mozambique, sediments of the Ecca Group are widely developed, commercially feasible seams of hard coal. Whilst Early Triassic lacustrine shales are believed to have sourced heavy oil reserves in the Tsimiro field, and the bitumen in the Belomanga Tar deposits in the Morondava basin. Significant exploration wells have been drilled in the Mozambique Plain down to ~5 km, and did not encounter Karoo series, confirming that deposition of these sediments is confined within the Middle- and west Lower Zambezi Graben.

In the following we consider two possible oil-prone source rocks: An Aptian-Albian oil-prone, Type II kerogen-dominated marine source rock, which is inferred from the conjugate margin of Dronning Maud Land, Antarctica (ODP Site 692B) and a speculative Late Jurassic Type I or II kerogen source rock that may have been deposited during the earlier sea-floor spreading phase, particularly in the north-eastern part of the study area. The oldest possible source rocks (Syn-rift I Jurassic?) would be restricted to syn-rift deposits at the south-eastern flank of the Beira High and the Middle Jurassic post-rift sediments identified in the southernmost Angoche basin (Figure 4).

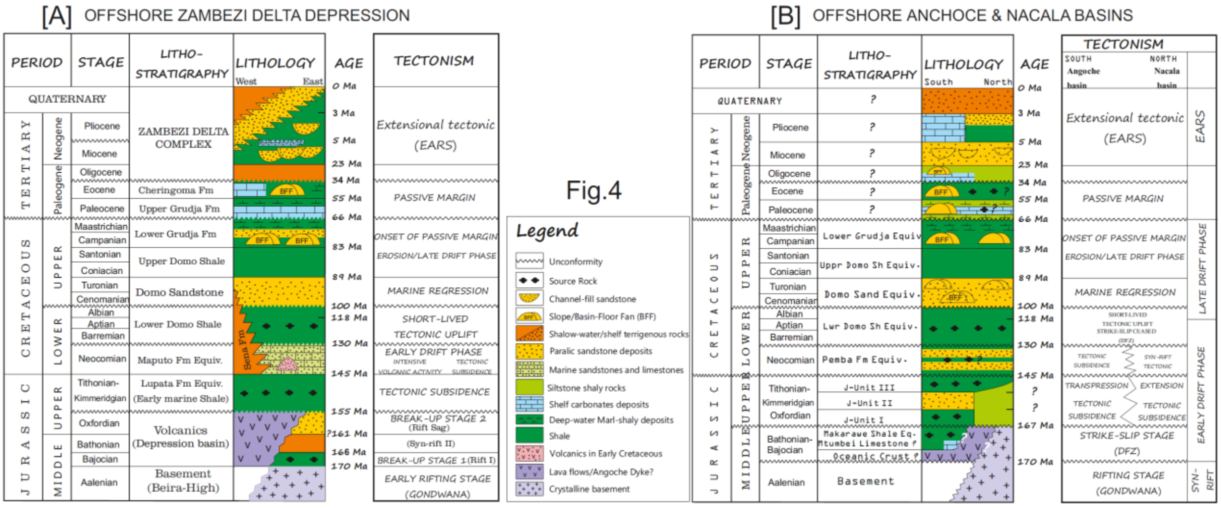


Figure 4 - Simplified stratigraphic charts from (A) the offshore Zambezi Delta basin [After ECL & ENH (2000); Salman and Abdula (1995), Mahanjane (2012)], and (B) the offshore Angoche and Nacala basins, along the Davie Fracture Zone (after Mahanjane, in review).

Data and Methods

Data

The data base includes a total of 3,000 km lines of 2-D seismic reflection data, covering the area from the shelf to distal part of the Zambezi Delta: The data set is provided by (1) the Instituto Nacional de Petróleo (INP) of Mozambique, namely, the surveys by Western Geco (GMC 1981/2); British Petroleum (BP 1998); Western Geophysical (WG 2000); (2) the joint scientific expedition (BGR 2007 survey) by the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Alfred Wegener Institut (AWI) and the Institut Français de Recherche pour l’Exploitation de la Mer (IFREMER).

The well data was compiled from four Key wells: Sofala-1X, Nemo-1X, Divinhe-1, Mambone-1 (Figure 1B). Two wells are located onshore near the shoreline and the other two in the modern-day shelf. A well-seismic-tie profile correlating stratigraphies between Nemo-1X and Zambezi-3 wells is presented in Figure 5A.

Depth Conversion

Depth conversion of the time migrated seismic data was carried out using the root-mean-square (RMS) velocities derived from the last iteration of the stacking velocity analysis. Smoothing was applied to the RMS velocities where strong lateral velocity gradients did not correlate with the stratigraphy. Tie points were used to check the RMS velocities for consistency.

Fig.5

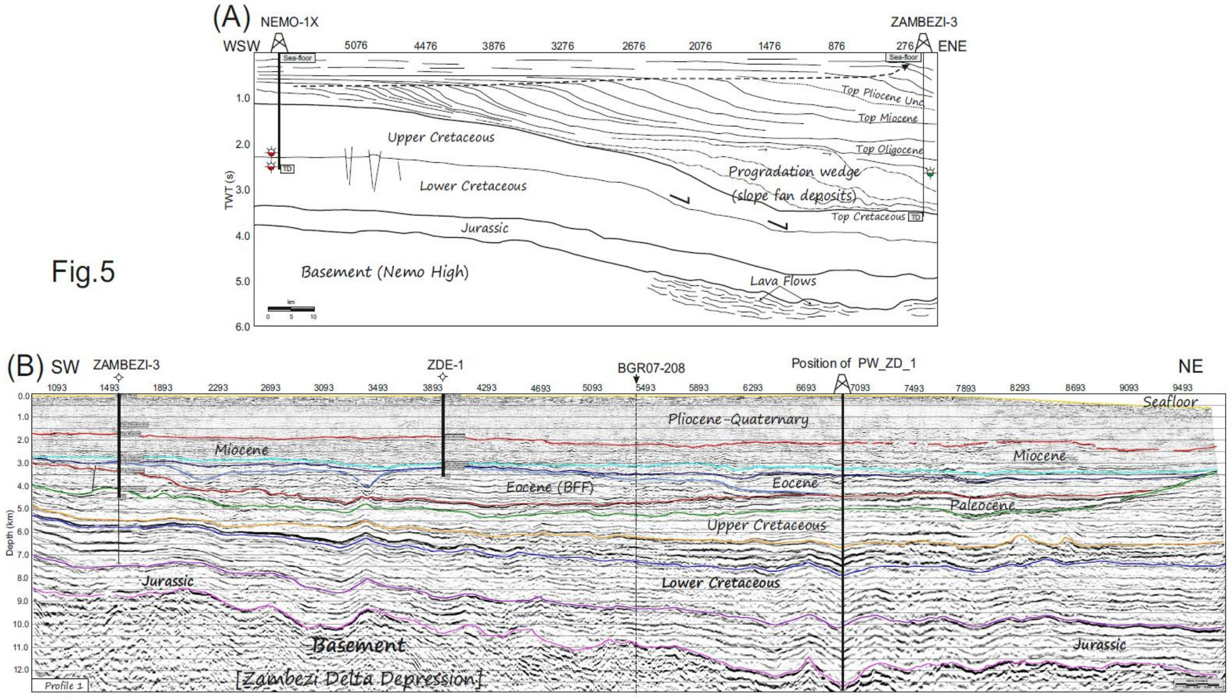


Figure 5 - (A) Line drawing interpretation showing the correlation of the stratigraphy between the Nemo-1X and Zambezi-3 wells. Note: position of shelf edges during Oligocene–Miocene; widespread slumping at shelf edge during Eocene lowstand; and Lava flows; (B) Typical seismic reflection profile from the Zambezi Delta depression with interpreted horizons and position of wells and the PW_ZD#1 (see Figure 1B for location).

Correlation and calibration

1-D modelling:

1-D basin and petroleum system modelling of the Zambezi Delta depression was performed using borehole and calibration data compiled from four key wells with reported gas and oil shows in Cretaceous sandstone reservoirs.

The 1-D forward models were used to calibrate the heat-flow model, which was then used in the 2-D modelling. The key wells provide a good age control down to the Early Cretaceous stratigraphic units, leaving up to 5000 m sedimentary strata down to the basement open for interpretation. Available Rock-Eval pyrolysis data (in the INP archive) indicate organic-lean sediments with TOC values generally less than 1% and Hydrogen Index (HI) values between 20-55 mgHC/gTOC for the drilled Lower Cretaceous shales (Lower Domo Shale/Sena Formation). The geochemistry data indicate T_{max} values ~ 440ºC within the shelfal ZDD and organic petrography determined vitrinite reflectance values of maximum 0.76% R_0 (Table 1).

Geochemical data of the Aptian-Albian source rocks were correlated from conjugate Dronning Maud Land ODP Site 692B. Rock-Eval analyses of this site indicate HI values between 300 and 600 mg HC/gTOC and low OI values (≤20 mgCO_2/gTOC) (Thompson and Dow in Barker, Kennett et al., 1990). Plotting this data into a pseudo Van Krevelen diagram indicates predominance of Type II kerogen (Figure 3). The drilled 45 m thick succession of claystones in this subset averages 7.5% TOC and 375 mgHC/gTOC of HI, hence, presenting petroleum source rocks of excellent quality (Thompson and Dow in Barker, Kennett et al., 1990). Slightly higher initial TOC and initial HI values of 8% and 500 mgHC/gTOC, respectively were used for our models.

For the simulation we classified all possible source rocks as organofacies B and assigned the respective kinetic models from Pepper and Corvi (1995a). Kinetics from Sweeney and Burnham (1990) were applied for vitrinite reflectance calculation, and petroleum generation zones ("oil and gas window") were defined based on vitrinite reflectance.

Five pseudo wells were generated to estimate source rock maturity and timing of hydrocarbon generation in the unexplored areas of the northern Mozambique basin. (Pseudo-well) PW_ZD#1, PW_BH#1, and PW_BH#2 were extracted from the 2-D models along Profiles 1 and 2 (Figure 1B). PW_Ang#1 and PW_Ang#2 are located along the seismic profiles WG00-511 and WG00-507, respectively (Figures 1B, 6A-B) in the Angoche basin.

Modelling in this untested basin is based on geochemical data from the Ruvu and Mandawa basins (Tanzania); Morondava basin (Madagascar) and DSDP Site 242 borehole. Upper Jurassic/Lower Cretaceous marine marls represent good Type II/III source rocks in the Morondava basin with ~ 5% TOC and HI 300 mgHC/gTOC (Matchette-Downs, 2006). While the Middle Jurassic (Bathonian) source rocks in PW_Ang#1 are correlated with Type II/III source rocks reported in Makarawe-1 well (Ruvu basin) with about 1.98-2.36% TOC (Maende and Mpanju, 2003). The geochemistry data from Mandawa basin (Tanzania) shows similar parameters as Site 692B indicating up to 8% TOC and 1000 mgHC/gTOC (Maende and Mpanju, 2003). For the location of well PW_Ang#1 we assume an oceanic crust (basalt) and well PW_Ang#2 is intended to evaluate the source rock maturity along the Davie compression. Here there is considerable uncertainty about the basement type due to compressional structures (Figure 6B), however for modelling we assigned a continental basement (granite) based on our data interpretation precluding the possibility of the oceanic crust along the Davie Fracture Zone (e.g. Figure 6).

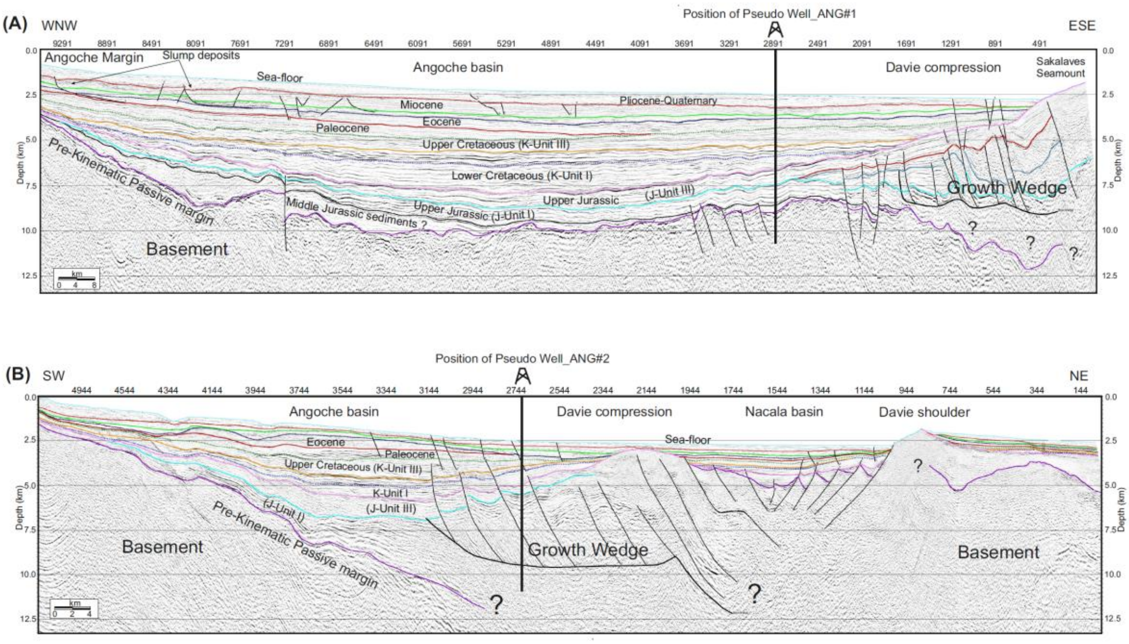


Figure 6 – The 2-D reflection seismic interpretation and pseudo-wells. (A) A WNW-ESE running line, transecting Angoche basin depocentre, Davie compression zone and partially the central Davie Fracture Zone. (B) A SW-NE running line across the northern Angoche basin. A well-imaged steeply dipping basement, the Davie Compression and the Nacala basin are distinct (see Figure 1B for location).

Table 1 – Geochemical data (INP archive)

Well ID		Depth	Geological	Age	TOC	HI	% R_o	T_{max}
ID	Location	(m-bss)	Formation	(Ma)	(%)	(mgHC/gTOC)		(°C)
Divinhe-1	Onshore	3137-3350	Lower Domo Sh	112-100	0.52	30	0.76	-
Mambone-1	Onshore	3039-3258	Sena	145-93.6	0.90	20	0.67	403
Nemo-1X	Offshore	3419-3512	Lower Domo Sh	125-100	0.80	55	0.63	447
Sofala-1X	Offshore	2950-3300	Lower Domo Sh	99.6-94	0.66	52	0.70	430

2-D modelling:

Two representative seismic profiles are oriented NE-SW (PROFILE 1) and NW-SE (PROFILE 2) (Figure 1B). PROFILE 1 runs along the Zambezi Delta depocentre, and intersects Zambezi-3 and ZDE-1 wells, which are essential for stratigraphic control. PROFILE 2 intersects PROFILE 1 and runs across the Beira High structure and its rift-grabens towards the south-east. The subsurface geology can be analysed down to ~ 13 km on these seismic lines. Stratigraphic correlation was made first between Nemo-1X and Zambezi-3 (Figure 5A), and later we tied Profile 1 to the Zambezi-3 well. Forward petroleum system modelling was then performed using calibration data from 1-D models of the offshore Nemo-1X and Sofala-1X wells. Kinetic parameters were assigned based on gross depositional environments and stratigraphic ages. For assessment of maturity levels, we have chosen the beginning, peak oil, and end of oil expulsion to correspond to transformation ratios of 10 percent, 50 percent, and 95 percent, respectively (Table 2). They were selected to better depict the generation, migration, and accumulation of petroleum (Peters et al., 2007). Magoon and Dow (1994) define the critical moment as the time between the peak expulsion and depletion of the generative potential of the source rock, which correspond 50% of the transformation ratio.

Boundary conditions (Paleo-water depth, Sediment-water-interface-temperature, and Heat-flow)

The Paleo-water depth is estimated from the age of the first phase *Rift I* (182 Ma), which was controlled by tectonic subsidence and eustatic change of sea-level through time (Walford et al., 2005).

Sediment-water-interface-temperatures are based on paleo-surface temperatures for latitude of each well location. The calculated values in the northern Mozambique basin using an option in PetroMod® that relates geologic age and mean surface paleo-temperature based on plate tectonic reconstructions to present-day latitude (Wygrala, 1989). For instance, at 165 Ma we obtain temperature of 23°C, and 145 Ma is 18°C (145 Ma). The calculated present-day Sediment-water-interface-temperature is 22 °C.

The basal heat-flow trend was computed from a crustal stretching model for the basin evolution based on the McKenzie (1978) simple shear model. The rifting phases started at 182 Ma (Duncan et al., 1997; Klausen, 2009; Reeves and Mahanjane, 2013) and lasted to 166 Ma (Leinweber et al., 2013), with the post-rift phase between 166 Ma and present-day. The stretching factors Beta (β) of 1.5 for β-crust (corresponding to the formation of oceanic crust) and 2.0 for β-mantle were used. The hinge of calculated heat-flow using the McKenzie (1978) model is at 166 Ma (maximum of 64 mW/m^2), which corresponds to the emplacement of lava basalts and early formation of oceanic crust in Mid-Jurassic times. However, the thermal cooling phase was affected by occasional magmatism during the Neocomian, adding locally additional heat to the basin. Likely these rocks are limited in aerial extent as indicated by their location on seismic data and some wells (Nemo-1X and Mambone-1). The thermal gradient along the DFZ is obtained from DSDP Site 242 (~ 27°C/km) compared with gradient from Morondawa basin (Madagascar) ~ 36°C/km. A comparatively low gradient is explained by slow subsidence rates associated to periods of relative starved sedimentation during the basin-fill.

Two major unconformities in the Late Cretaceous and Early Oligocene were included in the 1-D models and were associated with the erosion of about 10 m and 100 m of sediments, respectively. The Sofala-1X well showed a good match between the measured vitrinite reflectance values and calculated vitrinite reflectance using the heat-flow from the McKenzie model (Figure7A). At the Nemo-1X well the calculated vitrinite reflectance resulted in too high values. Therefore, we slightly lowered the present-day heat-flow to 30 mW/m^2 in order to get a good fit between measured and calculated vitrinite reflectance (Figure 7B).

Constant heat-flow values of 60 mW/m^2 and 70 mW/m^2 were used for the onshore Divinhe-1 and Mambone-1 wells, respectively. These values were obtained from geochemical reports (Alconsult International, 1996) and resulted in a good match between measured and calculated vitrinite reflectance values (Figure 7C-D). The values from the Sofala-1X well, which showed a good match between the measured and calculated values were used for the 2-D modelling.

Results and Discussion

Seismic interpretation and basin evolution

The stratigraphic framework (Figure 4) provides lithological information correlative with the main tectonic events of our conceptual model. The seismic interpretation consists of ten stratigraphic horizons (Figure 5B), which were described earlier by Mahanjane (2012) and Mahanjane (in review) for the Zambezi Delta depression and Angoche and Nacala basins, respectively. A generic events petroleum system chart (Magoon and Dow, 1994; Peters et al., 2005) depicting timing of individual petroleum elements for the study area is presented in Figure 8. Briefly, we summarize the basin evolution (Figure 9):

The burial history started with the deposition of Late Jurassic (marine) and Early Cretaceous sediments that are unconformably overlain by ~ 2 km of mid- to Late Cretaceous deposits. The thickness of the Jurassic sedimentary wedge varies from few tens of meters over the Beira High to ~ 2.8 kilometres in the Zambezi Delta depression trough (Figure 9A). Towards the south-eastern Beira High, this succession overlays the syn-rift sediments in the rift-grabens (Mahanjane, 2012) (Figure 9B).

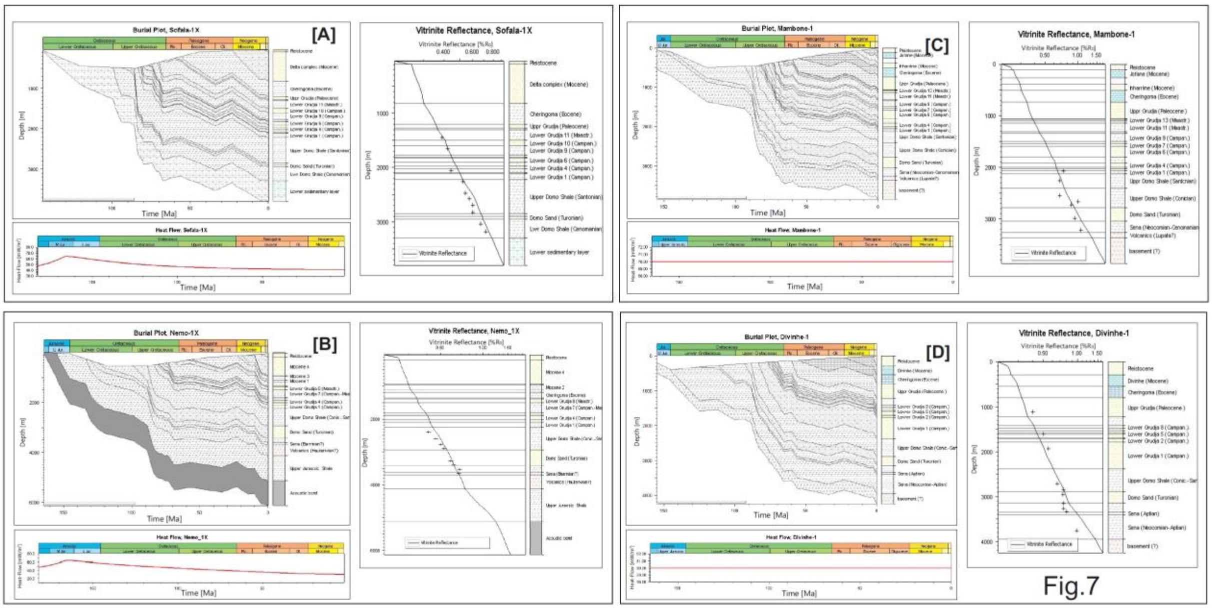


Figure 7 - 1-D models showing burial history and vitrinite reflectance of the critical wells. The heat flow curves were calculated using a McKenzie crustal stretching model. A good fit between calculated and measured vitrinite reflectance is observed in the wells. Divinhe-1 and Mambone-1 wells used constant heat-flows (see Figure 1B for the well locations).

At 120 Ma, basin subsidence and deposition had resulted in the accumulation of ~ 4 km of sediments in the main depocentre. This was increased 20 Ma later to ~ 6 km at about 100 Ma (Figure 9A). Towards the Davie Fracture Zone, basin subsidence and depositional processes were relatively slower. Regional ties make it likely that up to one km of Middle Jurassic sediments accumulated between the Bajocian and Bathonian on the acoustic basement in the Angoche basin (Figure 6A). The Late Jurassic sedimentary succession is characterized by reworked and deformed strata within the Davie compressional Zone (Mahanjane, in review). Sedimentation reached a maximum of ~ 3 km in the Angoche basin between Late Jurassic and Early Cretaceous times (Figure 6A). The internal geometry exhibit patterns of post-rift onlap terminations on both, east and west directions against the Angoche continental margin and the Davie Fracture Zone, respectively (Figure 6).

Turonian to Maastrichtian deposits apparently were deposited on the regional eroded surface of the underlying Aptian-Albian marine deposits. In the Zambezi Delta depression, the Late Cretaceous is typified by the development of widespread transgressions accompanied by accumulation of interbedded marine marls and non-marine siltstones (Lower Grudja Fm), prograding onto the continental slope (Salman and Abdula, 1995). A relatively rapid deposition of shallow-water carbonates, which are thinning towards the slope and deep-water basin, dominated the sedimentation on the outer edge of the shelf during the Paleocene (Figure 9A, 99.6 Ma).

Along the entire northern margin, rather uniform Cretaceous and Early Tertiary sedimentary sequences accumulated and prograded onto the continental slope. A regional erosional event separates the Upper Cretaceous marine sequence from dominantly marine Tertiary sediments. Deposition was accompanied by an uplift event and erosion in the Late Oligocene, resulting in the absence of this succession from the onshore to the shelfal area (e.g. critical wells). The last episode of high sedimentation rates is connected to the onset of Zambezi Delta progradation in the Late Oligocene/Early Miocene.

At 33.9 Ma, ~ 10 km of sediments had accumulated in the Zambezi trough (Figure 9). In contrast, in the subsiding Angoche basin only ~ 500 m of shallow-water marine clastics were deposited during the Miocene, indicating slow rate of sedimentation which characterize a period of sediment starvation in the area. Which, fairly increased (~750 m) during deposition of non-marine siltstones/sandstones in the Pliocene (Figure 6A) associated to development of the sediment-feeding systems from onshore Zambezi Delta to area of Davie Ridge (Droz and

Mougenot, 1987). During the Miocene to Quaternary the formation of extensive submarine canyons dissecting the older strata took place in the Zambezi Delta depression and extensional deformation affected the Quirimbas and Nacala submarine grabens along the Davie Fracture Zone.

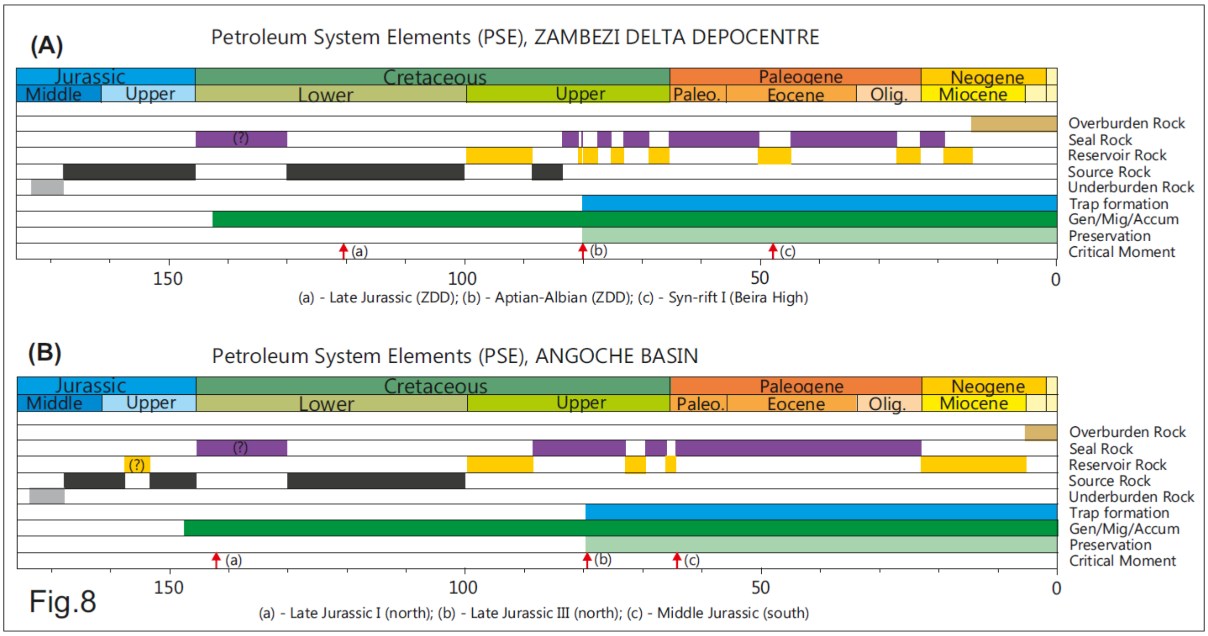


Figure 8 – Event charts depicting timing of the petroleum system along the Zambezi Delta and Angoche basins. The time span is represented by coloured horizontal bars. (A) Three critical moments were depicted for (a), (b) and (c). The event chronology for the Zambezi Delta indicates unfavourable timing (a) for accumulation of hydrocarbons generated from Late Jurassic source rock; (b) and (c) is favourable timing for the Aptian-Albian and syn-rift I source rocks. (B) More favourable timing for the critical moments (b) and (c) for accumulation of hydrocarbons in the Angoche basin. Although traps may have formed too late (Campanian) to contain oil and gas generated in Middle-Late Jurassic, they might have formed in time to hold remaining fluids. The critical moment (red arrow) was chosen to be the approximately half-way through the period of hydrocarbon generation (50% transformation ratio)

Maturity Study and Petroleum System Modelling

1-D MODELLING

The burial history plots and the calculated vitrinite reflectance overlays (Figure 10A(1)-F(1)) show the maturity evolution for the different well locations from immature, through the oil window, to overmature in the deeper part of the sites in the Zambezi Delta depression and Angoche basin.

The shelfal area

At the location of Nemo-1X well (Figure 10A(1)) the Late Jurassic to Valanginian succession entered the main oil window (0.70 % R_0) at ~ 98 Ma. The Late Jurassic source rocks entered the late oil window (1.0 % R_0) at ~ 75 Ma and have remained there until the present-day (1.25 % R_0), except for the 100 m of the basal strata, which is in the wet gas window. The Barremian (Sena) to Aptian-Albian (Domo) source rocks are in the early oil window since the Late Cretaceous (~ 70 Ma) until present-day (0.67 % R_0).

As shown by the maturity models, vitrinite reflectance values generally are below 1.25 % R_0, keeping both possible source rocks in the oil-generative stage (Figure 10A). There appears to be considerable scope for Late Jurassic and Early Cretaceous successions sourced oil to migrate up into Middle and Late Cretaceous reservoirs depending upon seal integrity of the intervening units. The 1-D model of the Nemo-1X well explains the oil shows and thus confirms reasonable input data used for the modelling.

The central area (Zambezi trough)

The well PW_ZD#1 (Figure 10B) is at the location of the thickest buried sediments (~ 13 km) in the Zambezi trough. The burial and thermal geohistory indicate the Late Jurassic source rocks entered the oil window close to the Late Jurassic–Early Cretaceous boundary (~148 Ma). The base of the Late Jurassic sediments entered the gas window during the Barriasian and is overmature since the Late Cretaceous (~ 85 Ma). The Early Cretaceous succession entered the dry gas window in the Late Campanian.

The thermal maturity model along the central axis of the Zambezi Delta depression indicates that at the base of the basin depocentre sediments passed through the oil and gas maturity windows already in the Early Cretaceous. This early maturation primarily results from rapid deep burial of Late Jurassic sediments and from enhanced heat-flow during the opening of the oceanic basin.

Both potential source rocks have lost their hydrocarbon generation potential: (1) the Late Jurassic source rocks between 85 Ma (oil) and 65 Ma (gas); (2) the Early Cretaceous source rocks between 32 Ma (oil) and 5 Ma (gas) (Figure 10B (2)). This high maturation level indicates that the natural gas shown by some wells may have resulted from secondary cracking of oil to gas (Pepper and Dodd, 1995), instead of originating from a typical terrigenous Type III source rock. Simulation results show that hydrocarbon charging occurred mainly before the deposition of the Middle and Late Cretaceous reservoir rocks (see Figure 8A).

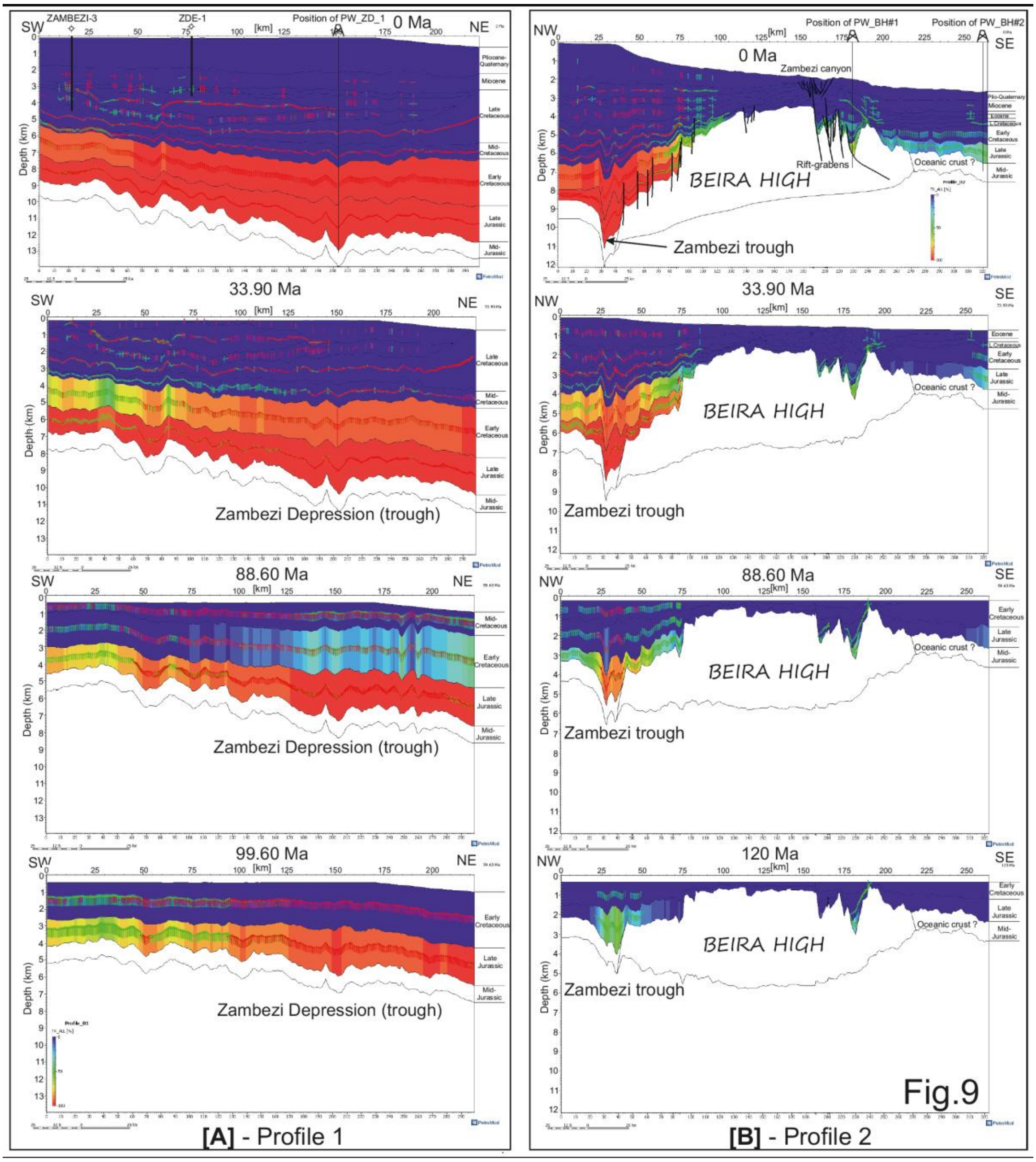


Figure 9 - 2-D models of 5 stages basin evolution overlay the source rock transformation ratio. Kerogen in the Late Jurassic and Early Cretaceous sediments undergoes increasing transformation to petroleum as the layers are buried. The transformation ratio is color-coded from blue (0%) to red (100%). In central axis of the basin, by 120 Ma, the mapped Late Jurassic source rock had started hydrocarbon generation and expulsion, reaching 100% transformation at 88 Ma. The present-day plot shows that the source rocks are currently undergoing transformation as it is buried in the slope and south-eastern Beira High. The regional migration paths are shown in the models (see Figure 1B for location).

The eastern Beira High and rift-grabens

Burial and thermal histories along and adjacent to the eastern flank of the Beira High and rift-grabens are shown in Figure 10C-D. The plot of well PW_BH#1 (Fig 10C(1)) indicates that the *Syn-rift I* Jurassic source rocks entered the oil window at ~ 145 Ma and stayed there until present day, except for the 190 m of lowermost portion, which entered the wet gas window at ~ 28 Ma (Figure 10C(2)). The Late Jurassic succession is currently within the early oil window (<1.0 % R_0), which it entered in the early Maastrichtian (~ 70 Ma). The basal Early Cretaceous rocks started to generate oil at ~ 25 Ma, the remainder of the upper part is immature (Figure 10C(1)). The plot of well PW_BH#2 (Figure 10D) indicates that the Late Jurassic succession entered the oil window at ~ 115 Ma and has remained there until the present-day (Figure 10D(1)). The majority of the Early Cretaceous sediments are mostly immature except the basal section which entered the oil window in the Middle Eocene (~ 42 Ma).

The significantly low maturity level in this area is explained by the present-day burial depth of the source rocks. The syn- and post-rift tectonic subsidence results from the direct impact of the geodynamic processes associated with rifting and break-up. The *Syn-rift I* Jurassic source rocks were already buried at depth of 2700m at 145 Ma, forced by rapid subsidence during the crustal stretching prior the main break-up stage (Mahanjane, 2012). A significant enhancement of basal heat-flow anticipated maturity of the mid-Jurassic buried sediments in the Tithonian time. Subsequent basin evolution represent a period of slow subsidence rate (~ 2.5km/145 Ma) in the distal delta area (e.g. eastern Beira High) resulting ~ 5-6 km of total present-day buried sediments in the eastern and over the Beira High. This is two times less than the central axis of the Zambezi Delta depression. Consequently, significantly delay maturity of the Late Jurassic and Early Cretaceous sediments (Figure 10C-D).

The Angoche basin

Pseudo-Wells PW_Ang #1 and PW_Ang #2 are located in the Angoche basin (Figures 1B and 6A-B). When considering the geohistory plot of pseudo wells it is important to note that they have no calibration data. The heat-flow model of PW_Ang #2 (Figure 10-F(2) is computed using default data from Sofala-1X well, while PW_Ang #1 was calculated by a McKenzie model assuming oceanic crust and hence a lower heat flow of 20 mW/m^2 is calculated (Figure 10E(2)). Sediments from the Cretaceous onwards in the well PW_Ang #1 are immature whilst the Middle and Late Jurassic *Unit I* (Figure 4B) have entered the oil window since the Mid-Cretaceous. The Jurassic *Unit III* entered the early oil window in the Late Campanian. PW_Ang #2 shows that the lower unit of the Late Jurassic succession entered the wet gas window in the Albian (~110 Ma) and has remained there until the present-day. The upper unit of the Jurassic remains in the oil window since 105 Ma. The late-Early Cretaceous to Quaternary successions are immature (Figure 10F(1)).

A change from rapid tectonic subsidence to slow rates of sedimentation and subsidence in Aptian-Albian times influenced the maturity evolution. At the location of well PW_Ang #1, maturation history is influenced by lower radiogenic heat generation in the oceanic crust compared with well PW_Ang #2. However, the earliest sediments in the Angoche margin were already buried at 4.5 km depth in the Late Jurassic sufficient for hydrocarbons generation from the deeply buried Jurassic sediments since the Tithonian (~ 147 Ma) in the compressional zone and Valanginian (~ 136 Ma) in the main basin. In other hand, a subsequent very low sedimentation rate (1.7 km/100 Ma) contributed to the low transformation ratio of the uppermost Jurassic and Early Cretaceous sediments.

The presence of a working petroleum system is indicated by oil seeping in the Angoche area (ECL & ENH report, 2000). PW_Ang #1 indicates that Middle Jurassic and early Late Jurassic successions have reached their peak hydrocarbon generation (50% TR) at ~ 65 Ma and ~ 46 Ma, respectively. Presently, both successions remain the hydrocarbon generative window (Figure 10E (2), Table 2).

In the compressional zone, a slightly higher maturation trends is observed in well PW_Ang#2 compared to the southern area of the basin. The present day burial depth of the Late Jurassic sediments is approximately 5 km. Modelled %R0 indicates that the Late Jurassic (Unit I) source rocks generate oil prior to and during the Early Cretaceous over most of the Davie compression and in the Angoche basin region (Figure 10F (1). A major question is, whether Jurassic reservoir rocks were already deposited before peak oil expulsion (50% TR) during the Barriasian (Figure 8B). Furthermore, uncertainties remain for the seal rock deposition (Pemba Formation) in the Early Cretaceous (Figure 4B). Encouraging is the presence of inversion structures (e.g. fault-propagation folds) for trapping hydrocarbons (Figure 6B). At ~ 110 Ma, in the basal Late Jurassic succession secondary cracking of oil to gas commenced at a burial depth of ~ 4.8 km.

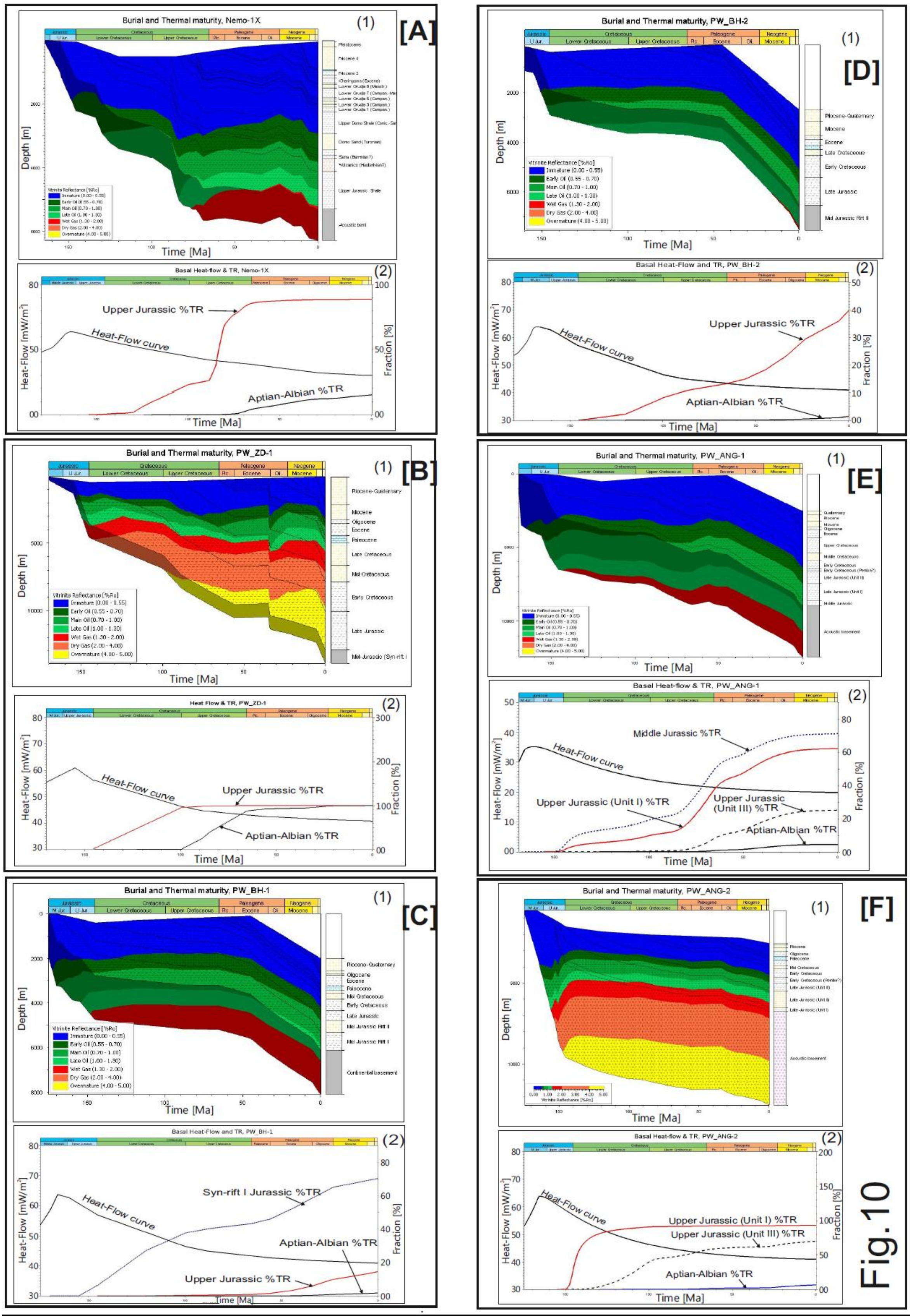


Fig.10

Figure 10 - 1-D models showing burial and thermal maturity, and transformation ratio curves. They were selected to show present-day maturation stage from the shelf, depocentre, Beira High until Angoche basin.

Table 2 – Comparison of thickness, original total carbon (*TOC), and original hydrogen index (*HI) with timing of initial, peak, and the end of oil expulsion for the Middle, Late Jurassic and Aptian-Albian source rocks in depocentre or generative areas in the northern Mozambique basin.

Source rock	Depocentre or Area	Thickness (m)	*TOC (%)	*HI (mgHC/gTOC)	Initial Expulsion (10% TR) Ma	Peak Expulsion (50% TR) Ma	End Expulsion (95% TR) Ma
Aptian-Albian	Shelf	192	8	300-600[500]	42	(15%)	(15%)
	ZDD Depocentre	2210	8	300-600[500]	95	80	32
	Beira High (graben)	~ 510	8	300-600[500]	(1.5%)	(1.5%)	(1.5%)
	Beira High (eastern)	~ 910	8	300-600[500]	(1.5%)	(1.5%)	(1.5%)
	Angoche	515-590	4-5	89-[300]	(<5%)	(<5%)	(<5%)
Late Jurassic III	Angoche	505-824	4-5	64-1000[400]	120$^{(N)}$-60$^{(S)}$	79$^{(N)}$-(25%)	(70%)-(25%)
Late Jurassic I	Angoche	240-1100	4-5	64-1000[400]	147$^{(N)}$-98$^{(S)}$	143$^{(N)}$-46$^{(S)}$	(93%)-(62%)
Late Jurassic	Shelf	~ 500-900	8	300-600[500]	118	83	(88%)
	ZDD Depocentre	2820	8	300-600[500]	142	123	98
	Beira High (graben)	450	8	300-600[500]	22	(15%)	(15%)
	Beira High (eastern)	~ 1100	8	300-600[500]	90	(40%)	(40%)
Middle Jurassic	Beira High (graben)	100-796	8	300-600[500]	140	48	(70%)
	South Angoche	357	1.98-2.36	35-[200]	136	65	(71%t)

* Correlative information from ODP 692, Madawa and Morondawa basins. Values in parenthesis are present-day transformation ratios. [ ] – used in the modelling. (N) – North, (S) – South, TR- transformation ratio.

2-D MODELLING

The 2-D models are based on interpreted and depth converted 2-D seismic profiles (see Figure 5B, 9A-B). The thermal maturity history shows that outside of the basin depocentre rocks from the Late Cretaceous to Recent remain immature. As shown in Figure 9, sediments of the Late Jurassic and Early Cretaceous in the basin depocentre (Zambezi trough) have presently reached 100% of transformation ratio (TR). The hydrocarbon generation (10% TR) had started at 142 Ma at the base of the Late Jurassic rocks (Figure 9B). At ~ 120 Ma, during the Aptian, the Late Jurassic source rocks reached transformation ratios of 50% at the north-western side of the Beira High, concomitantly with the onset of hydrocarbon expulsion (e.g.

Figure 9B). Modelling shows that possible source rocks in the rift-grabens and at the outer edge of the Beira High generated hydrocarbons continuously until present time. The deeply buried Syn-rift I Jurassic rocks experienced the peak of oil expulsion (50%TR) in the Mid-Eocene (see Figure 10C(2)), and reached its maximum transformation ratio of 70% at the present time (Figure 9B at 0Ma). The onset of cracking of oil and dry gas generation is depicted in mid-Oligocene by TR of 55%. Similar to the Late Jurassic rocks, for the Early Cretaceous source rocks in the depocentre hydrocarbon generation and expulsion had started shortly after deposition. The basin evolution shows a progressively increase of sediment-fill starting in the Late Jurassic and lasting until the late Albian, and totaling in 5.5 km thick sedimentary strata by this time (Figure 9A, 99.6 Ma stage). Onset (10% TR) and peak expulsion (50% TR) occurred between Cenomanian and Campanian times, having reached transformation rations of 95% in the Early Oligocene (Figure 9A at 33.9Ma; Table 2).

Basinward, along the NW slope of the Beira High, both Late Jurassic and Early Cretaceous sediments are presently in the main oil window in depth range between 4,200 and 6,000 m (e.g. Figure 9B at 0Ma). The peak generation (50% TR) occurs within a ~ 70-100 m thick interval of the Late Jurassic source rocks at depth varying between 4,900 and 5,500 m. Further SE, only 40% of the kerogen in the Late Jurassic source rocks was converted to hydrocarbons up to date, keeping these sediments in the early to main oil window (see PW_BH#2 and Figure 9B). The Early Cretaceous sediments remain immature (< 2% TR).

Conclusions

This study integrates reflection seismic data, well data and petroleum systems modelling to predict the timing and locations of hydrocarbon generation in the underexplored portion of Mozambique's margin. The maturity of possible source rocks as well as the critical moment for HC generation is determined for the Zambezi Delta and Angoche basins.

Based on recent plate-tectonic reconstructions and regional correlation the presence of possible source rocks is investigated. An Aptian-Albian source rock is assumed by analogy from the conjugate margin in Antarctica, where an ODP well penetrated a prolific Type II source rock. Furthermore, we assume a possible source rock from the Middle and/or Late Jurassic based on recent plate-tectonic reconstructions and geochemical data from the adjacent Morondava and Mandawa basins with proven source rocks of high quality properties.

Thermal maturity was calibrated against measured vitrinite reflectance values from four wells in the Zambezi Delta depression. For the offshore wells heat-flow was found to fit the data when using a simple-shear rifting model. Four 1-D models with calibration data and another five without calibration data (pseudo-wells) indicate the maturity of possible source rocks at different locations in the Zambezi Delta and Angoche basins. Two 2-D maturation models, constrained by seismic reflection data, show the burial history and maturity evolution of the Zambezi Delta basin.

The models show that in the Zambezi depocentre and Angoche basin, syn-rift and post-rift sediments reached the main phase of hydrocarbon generation and expulsion in Late Tithonian and Early Barriasian times as a consequence of rapid subsidence and high heat-flow. The difference in subsidence between the two basins resulted in different degree of maturation with time. A considerable package of sediments was deposited between the Late Jurassic and Early Cretaceous resulting in rapid thermal maturation but unlikely in the deposition of suitable reservoir and seal rocks in this part of the basins. In the deeply subsided centre of the Zambezi Delta depression early depletion (100% TR) of the Jurassic source rocks occurred at 85 Ma. In consequence this part of the margin is overmature at present and it appears questionable if this area is prolific.

The burial history underpinned by modelled vitrinite reflectance (1-D models) and 2-D models of the basin evolution underlain by transformation ratio indicate a prolific thermal maturation. With exception of the Zambezi Delta basin depocentre, the entire remaining northern basin is prolific area.

Towards the Angoche region, rapid tectonic subsidence and sediment deposition in the Late Jurassic/Early Cretaceous resulted in early maturation of the Late Jurassic source rocks, which are presently in the gas window. Comparatively low depositional rates from Aptian onwards delayed the process of hydrocarbon generation, keeping the Late Jurassic rocks within the oil window.

A typical Type III terrigenous source rock is not necessary to explain the traces of dry gas measured in wells in the onshore and shelfal area. In both, the Zambezi Delta and Angoche basin, secondary cracking of oil to gas began in the Barremian. Hence, the gas reported in the Mozambique basin may have been generated by a generally oil-prone source rock.

Acknowledgements

This paper has received support from the management of the *Instituto Nacional de Petróleo* (INP) including the data. Gratitude is also expressed to BGR for the logistical support they provided.

References

Alconsult International 1996. The Hydrocarbon Potential of Mozambique. Part of 'East Africa Regional Hydrocarbon Study' for ENH on behalf of C.I.D.A.

Coffin, M.F., and Rabinowitz, P.D., 1987. Reconstruction of Madagascar and Africa: Evidence from the Davie Fracture Zone and Western Somali Basin. Journal of Geophysical Research, Vol. 92, NO. B9, 9385-9406.

de Wit, M. J., 2003 Madagascar, Heads it's a Continent, Tails it's an Island. Annu. Rev. Earth Planet. Sci. 2003. 31. 231-48. doi 10. 1146/ annurev. Earth. 31. 100901. 141337.

Droz, L. and Mougent, D., 1987. Mozambique Upper Fan: Origin of Depositional Units. The AAPG Bulletin V.71, No.11 (November 1987), P. 1355-1365, 13 Figs.

Eagles, G., and M. König, 2008. A model of plate kinematics in Gondwana breakup, Geophys. J. Int. , 173 , 703–717, doi:10.1111/j.1365-246X. 2008.03753.x.

Exploration Consultant Limited (ECL) & Empresa Nacional Hidrocarbonetos (ENH), 2000. The Petroleum Geology and hydrocarbon Prospectivity of Mozambique. Volume 1. Instituto Nacioal de Petróleo, Archives.

Hankel, O. (1994). "Early Permian to Middle Jurassic rifting and sedimentation in East Africa and Madagascar." Geologische Rundschau 83(4): 703-710.

Klausen, M.B., 2009. The Lebombo monocline and associated feeder dyke swarm:diagnostic of a successful and highly volcanic rifted margin? Tectonophysics 468, 42-62.

König, M., Jokat, W., 2010. Advanced insights into magmatism and volcanism of the Mozambique Ridge and Mozambique Basin in the view of new potential field data. Geophysical Journal International 180 (Issue 1), 158-180. January 2010.

Leinweber, V.T., et al., The crustal structure of the Central Mozambique continental margin - Wide-angle seismic, gravity and magnetic study in the Mozambique Channel, Eastern Africa, Tectonophysics (2013), http://dx.doi.org/10.1016/j.tecto.2013.04.015

Maende, A. and Mpanju, F., 2003. Geochemistry and source rock potential of East African Passive Margin. EAPC 2003, Nairobi, Kenya.

Magoon L. B. & Dow, W. G. 1994: The petroleum system. In: Magoon, L. B. & Dow, W. G. eds.: The petroleum system − from source to trap. AAPG Memoir 60, 3-24.

Mahanjane, E.S., 2012. A geotectonic history of the northern Mozambique Basin including the Beira High – A contribution for the understanding of its development. Marine and Petroleum Geology 36 (2012) 1-12.doi:10.1016/j.marpetgeo.2012.05.007.

Mahanjane, E.S., (in review). The Davie Fracture Zone and adjacent basins in the offshore Mozambique Margin – a new insight for the hydrocarbon potential. Ms. Ref. No. JMPG-D-12-00292R2.

Matchette-Downes, C., 2006. Petroleum potential of the Morondava Basin. Madagascar Promotional Meeting. Houston May 25th 2006.

McKenzie, D. 1978. Some remarks on the development of sedimentary basins. Earth and Planetary Science Letters, 40 (1978) 25-32

Mubarak and Miriam et al., 2009. Basin and Petroleum Modelling. Oilfield Review Summer 2009: 21, no.2.

Nairn, A.E.M., Lerche, I. and Iliffe, J.E., 1991. Geology, basin analysis and hydrocarbon potential of Mozambique and the Mozambique Channel. Earth-Sci. Rev., 30: 81-124.

Pepper, A.S. and Corvi, P.J., 1995a. Simple kinetic models of petroleum formation. Part I: oil and gas generation from kerogen. Marine and Petroleum Geology, Vol. 12, No. 3, pp. 291-319, 1995.

Pepper, A.S and Dodd, T.A., 1995. Simple kinetic models of petroleum formation. Part II: oil-gas cracking Marine and Petroleum Geology, Vol. 12, No. 3, pp. 321-340, 1995.

Peters, K. E., Lampe, C., Bird, K. J. & Magoon, L. B. 2005. 4-D modeling of the Shublik-Ivishak(!) petroleum system, North Slope, Alaska. Joint Meeting Pacific Section, AAPG & Cordilleran Section, Geological Society of America, April 29 - May 1, 2005, San Jose, California, Paper 40-4, Geological Society of America, Abstracts with Programs 37, p. 93

Peters, Kenneth E., Leslie B. Magoon, Carolyn Lampe1, Allegra Hosford Scheirer, Paul G. Lillis, and Donald L. Gautier, 2007. Petroleum Systems and Geologic Assessment of Oil and Gas in the San Joaquin Basin Province, California. *Edited by* Allegra Hosford Scheirer. U.S. Geological Survey Professional Paper 1713. Chapter 12.

Rabinowitz, P.D., and Woods, S., 2006. The Africa – Madagascar connection and mammalian migrations. Journal of African Earth Sciences 44 (2006) 270-276.

Reeves, C., 2000. The Geophysical mapping of Mesozoic dyke swarms in southern Africa and their origin in the disruption of Gondwana. Journal of African Earth Sciences 30, 449-513.

Reeves, C., de Wit, M., 2000. Making ends meet in Gondwana: retracing the transforms of the Indian Ocean and reconnecting continental shear zones. Terra Nova 12, 272-280.

Reeves, C. and Mahanjane, E.S., 2013. Mozambique and its role in the downfall of Gondwana. Geological Society of Houston/Petroleum Exploration Society of Great Britain, London, 2013 September 11-12. http://pesgb.org.uk/events/event-165/.

Ryan, W.B.F., S.M. Carbotte, J.O. Coplan, S. O'Hara, A. Melkonian, R. Arko, R.A. Weissel, V. Ferrini, A. Goodwillie, F. Nitsche, J. Bonczkowski, and R. Zemsky (2009), Global Multi-Resolution Topography synthesis, Geochem. Geophys. Geosyst., 10, Q03014, doi:10.1029/2008GC002332.

Salman, G., Abdula, I., 1995. Development of the Mozambique and Ruvuma sedimentary basins, offshore Mozambique. Sedimentary Geology 96 (1995), 7-41. Elsevier Science B.V. SSDI 0037-0738(94)00125-1.

Sweeney, J.J. and Burnham, A.K. Evaluation of a simple model of vitrinite reflectance based on Chemical kinetics. AAPG Bulletin, 74:1559-1570, 1990.

Thompson, K.F.M. and Dow, W.G. Investigation of Cretaceous and Tertiary kerogens in sediments of the Weddell Sea. In Barker, P. E, Kennett, J. P., et al., 1990. Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 113

Walford, H.L., White, N.J. and Sydow, J.C. Solid sediment load history of the Zambezi Delta. Earth and Planetary Science Letters 238 (2005) 49–63

Wygrala, B.P. Integrated Study of an oil field in the Southern Po Basin, Northern Italy. PhD thesis, University of Cologne, Germany, 1989.

5. Summary and Conclusions

This thesis is a pioneer scientific work elaborating some of the geodynamic aspects giving new insights into the geodynamic evolution of the Mozambique margin with respect to its formation and the petroleum system. Some open questions about the evolution of the East African margin are answered by providing an overview of the tectonic settings which is focused on the structural evolutionary processes of the northern Mozambique basin, development of the Davie Fracture Zone, and deformational tectonic mechanisms along the Rovuma deltaic system.

The interpretation of (1) aerial lava flows within the Zambezi Delta depression, and (2) a sequence of half-graben morphologies confining the syn-rift infill at the south-eastern Beira High, establishes a concept of the two-stages of Gondwana break-up (Figure 5.1). The presence of thick volcanics shed a light on plume driven rifting processes along the margin. These rocks are assigned to the episodic emplacement of magmatic material associated to the activity of the Angoche dyke swarms which are younger than the initial Karoo magmatism. The Rift stage 1 is understood as a plume driven rifting which occurred in coincidence with Karoo/Bouvet hotspot interaction at 182 ± 2 Ma. The lava flows and the Angoche coastal dykes are emplaced by the final stage of Rift 1 phase followed by the second rifting and break-up stage 2. Based on this fact, the crustal architecture of the Mozambique margin is formed by three compositions: the continental-transitional-oceanic crusts (Figure 5.2). The Lebombo-Limpopo monoclines form a boundary between the continental and the transitional crust, and the Angoche coastal dykes form the boundary between the transitional-oceanic crusts. However, the Beira High is a prominent isolated low gravity structure surrounded by higher values of gravity anomalies (Figure 5.2). The results from the seismic data interpretation show deformation in the eastern part by extensional tectonics with prominent imbricated half-graben morphologies (e.g. Figure 5.1). These rifts depict some episodic stages in which the Beira High was involved, initially attached to Antarctica during the initial rifting phase. However, later Rift 1 phase aborted to develop Rift 2 and became part of the African Plate and the associated break-up stage 2 (Figures 5.1 and 5.2). This supports the views that at least part of it has a continental origin.

The existence of oceanic crust is supported by interpretation of the onset of oceanic spreading at the eastern Beira High where the break-up unconformity lies over the basement near the location of the oldest sea-floor magnetic anomaly M26r (155.4 Ma). This anomaly gives the minimum time for the separation between the Mozambique basin and the conjugate Riiser Larsen Sea which is synchronous to opening of the Somali basin and the Rovuma basin along the Davie Fracture Zone between mid-Jurassic and Aptian time. The main sedimentary successions of the basins were accumulated and the modern continental margin was developed.

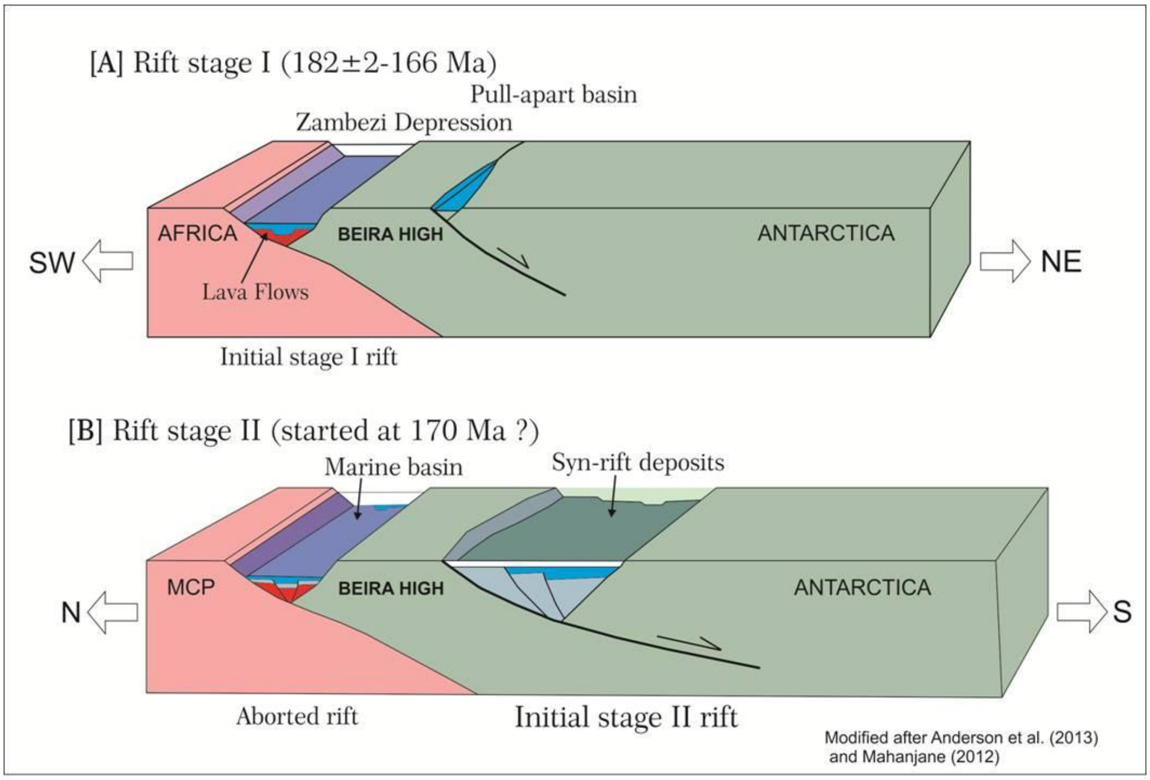


Figure 5.1 - The diagrams summarizing the rifting and break-up stages between Africa and Antarctica. [A] Initial rifting and NE motion maintained Antactica and Beira High in the same continental mass. Rift I is symmetrical graben in-filled by the thick volcanics; [B] the Beira High is rifted away from Antarctica during the southern motion and remains with the African Plate (Mahanjane, 2012). Key: MCP-Mozambique Coastal Plain.

The development of the Mozambique margin and opening of the Mozambique Channel evolved as a result of continent-continent drift from transform offsets into the oceanic fracture zones, namely Lebombo-Explora Fracture Zone and the Davie Fracture Zone. The East Gondwana Plate experienced dextral strike-slip motion along these transforms, developing a transform-related margin along the extent of the Davie Fracture Zone and a volcanic-related margin along the Lebombo-Explora Fracture Zone.

The Davie Fracture Zone underwent uplift and inversion in the Late Jurassic forming a compressional zone along the Angoche margin. Later it was reactivated by the extensional tectonics associated to the East Africa Rift System in the Oligocene-Miocene. Several depressions were formed, namely the Quirimbas, Nacala, Pemba and Mafia basins. At the early stage, the evolution of the Rovuma basin was controlled by the Davie transform, and became part of the rift-to-drift passive margin in the Late Cretaceous. In the mid-Miocene, deposition of the Rovuma Delta occurred, and was subject to intensive sediment loading and slumping along a shale detachment with the formation of a classic deep-water-fold-thrust-belt system. The architecture of the Rovuma Delta is basically a classic up-dip extensional region, which is linked to a down-dip arcuate region with asymmetric imbricate fans and ramp-flat geometries.

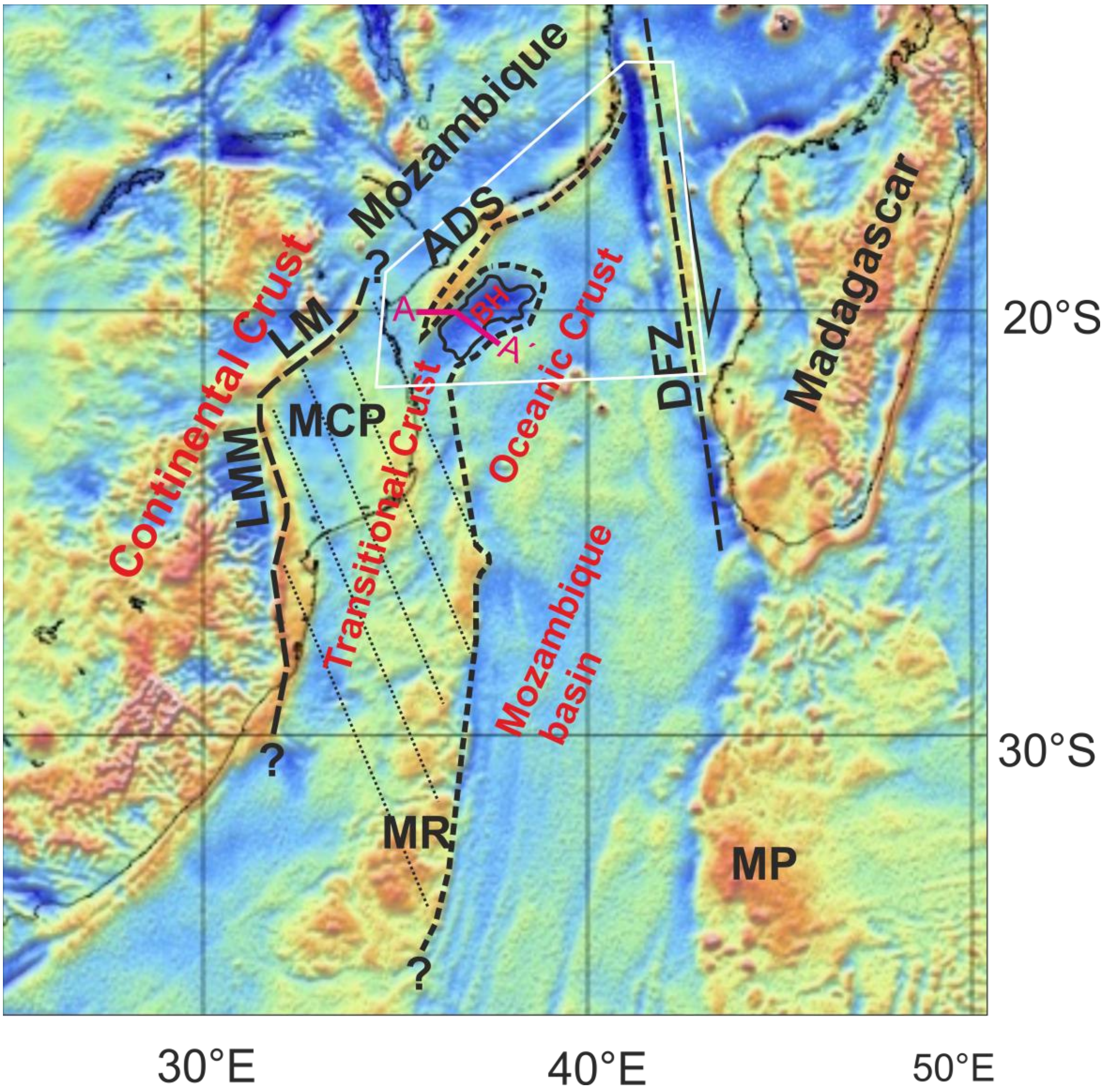


Figure 5.2 - Gravity anomaly map derived from satellite altimetry data (After Sanwell and Smith, 2009) shows crustal boundaries and composition proposed in this study. The white outline indicates the focused area. Keys: ADS- Angoche dyke swarms, BH- Beira High, DFZ - Davie Fracture Zone, MCP - Mozambique Coastal Plain; LMM - Lebombo Mwenezi monocline, LM - Limpopo monocline. A-A´ location of Profile 1 transecting Rifts I and II, and the Beira High (see section 4.1)

The 1-D and 2-D reconstruction model of the northern Mozambique basin show burial and thermal histories depicting stages of early maturation of the source rocks. That is explained by significant episodes of rapid deep burial of the Late Jurassic sediments and heat-flow enhancement during the opening of the oceanic basin. The Middle-Late Jurassic sediments were therefore sufficiently mature to generate hydrocarbons between Tithonian and Valanginian. Along the central axis of the Zambezi Delta depression, at the base of the basin depocentre, sediments passed through the oil and gas maturity windows already in the Early Cretaceous and became completely depleted (100% of transformation ratio) it the Late Cretaceous. It is unlikely that the deposition of suitable reservoir and seal rocks was not yet in place when the expulsion of hydrocarbons started in the basins. The simulation of the marine source rocks also show secondary cracking of oil to gas at an early stage of basin evolution (e.g. since the Barremian). Therefore, this suggests an alternative source of the gas reported in the Mozambique basin, generated by a generally oil-prone source rock.

The simulation models in the distal Zambezi Delta depocentre and Angoche area show a significant decrease of the sedimentation rate from the Aptian-Albian times onwards. The transformation ratio turns lower for the uppermost Jurassic and Early Cretaceous sediments, and keeps the source rocks active until the present time.

REFERENCES

Alconsult International 1996. The Hydrocarbon Potential of Mozambique. Part of ‘East Africa Regional Hydrocarbon Study’ for ENH on behalf of C.I.D.A.

Allen, P. A., and J. R. Allen, 1990, Basin analysis: Principles and Applications: Oxford, Blackwell, 451 p.

Anderson, L., Caillot, A. Gatter, L., Barrere, C., Grimmer, J., and Mahanjane, E.S., 2013. Rifting of the Zambezi Delta region, northern Mozambique Basin and its implications for a Jurassic marine source rock. Geological Society of Houston/Petroleum Exploration Society of Great Britain, London, 2013 September 11-12.

Bassias, Y., 1992. Petrological and geochemical investigation of rocks from the Davie fracture zone (Mozambique Channel) and some tectonic implications. Journal of African Earth Sciences, 15(3-4): 321-339.

Clive et al., 2008. Investigating Large Igneous Province Formation and Associated Paleoenvironmental Events: A White Paper for Scientific Drilling. Scientific Drilling, No. 6, July 2008doi:10.2204/iodp.sd.6.01.2008.

Coffin, M.F., and Rabinowitz, P.D., 1987. Reconstruction of Madagascar and Africa: Evidence from the Davie Fracture Zone and Western Somali Basin. Journal of Geophysical Research, Vol. 92, NO. B9, 9385-9406.

Coffin, M.F. and Rabinowitz, P.D., 1992. The Mesozoic East African and Madagascan Conjugate Continental Margins: Stratigraphy and Tectonics. In: J.S. Watkins, F. Zhiqiang and K.J. McMillen (Editors), Geology and Geophysics of Continental Margins, AAPG Memoir 53. The American Association of Petroleum Geologists, Tulsa, Oklahoma, U.S.A., pp. 207 – 240.

Coffin et al., 2006. Large Igneous Provinces and Scientific Ocean drilling status quo and a look ahead. Oceanography Vol. 19, No. 4, Dec. 2006.

Coffin, Millard F.; Olav Eldholm (February 1994). "Large igneous provinces: crustal structure, dimensions, and external consequences". Reviews of Geophysics 32 (1): 1–36. Bibcode:1994RvGeo.32.1C. doi:10.1029/93RG02508.

Courtillot, V., Jaupart, C., Manighetti, I., Tapponnier, P., Besse, J., 1999. On causal links between flood basalts and continental breakup. Earth and Planetary Science Letters 166, pp. 177-195.

De Buyl, M. & Flores, G. 1986 – The Southern Mozambique Basin: The Most Promising Hydrocarbon Province Offshore East Africa. Pp 399-425.

Droz, L. and Mougent, D., 1987. Mozambique Upper Fan: Origin of Depositional Units. The AAPG Bulletin V.71, No.11 (November 1987), P. 1355-1365, 13 Figs.

Duncan, R. A., Hooper, P. R., Rehacek, J., Marsh, J. S. & Duncan, A. R., 1997. The timing and duration of the Karoo igneous event, southern Gondwana. Journal of Geophysical Research 102, 18127–18138.

Exploration Consultant Limited (ECL) & Empresa Nacional Hidrocarbonetos (ENH), 2000. The Petroleum Geology and hydrocarbon Prospectivity of Mozambique. Volume 1. Instituto Nacioal de Petróleo, *Archives*.

Elburg, M. and Goldberg, A. Age and geochemistry of Karoo dolerite dykes from northeast Botswana, Journal of African Earth Sciences, Vol. 31. No. 314. pp. 539-554, 2000. ISSN 1464-343X, http://dx.doi.org/10.1016/S0899-5362(00)80006-8.

Eldholm, O., and M.F. Coffi n. 2000. Large igneous provinces and plate tectonics. Pp. 309–326 in The History and Dynamics of Global Plate Motions, M.A. Richards, R.G. Gordon, and R.D. van der Hilst, eds. American Geophysical Union Geophysical Monograph 121. American Geophysical Union, Washington, D.C.

Elliot, D. H. and Fleming, T. H., 2000. Weddell triple junction: The principal focus of Ferrar and Karoo magmatism during initial breakup of Gondwana. Geology 01/2000; 28(6):539-542. DOI:10.1130/0091-7613(2000)0282.3.CO;2.

Emmel, B. et al., 2011. Thermochronological history of an orogen-passive margin system: An example from northern Mozambique. Tectonics, 30(2): TC2002.

Franke, D., 2013. Rifting, lithosphere breakup and volcanism: Comparison of magma-poor and volcanic rifted margins, Marine and Petroleum Geology 43 (2013) 63-87, doi: 10.1016/ j.marpetgeo.2012.11.003.

Geoffroy, L., 2005. "Volcanic passive margins". C. R. Geoscience 337 (16): 1395–1408. Bibcode: 2005CRGeo.337.1395G. doi:10.1016/j.crte.2005.10.006.

Hinz, K. 1981. A hypothesis on terrestrial catastrophes. Wedges of very thick oceanward dipping layers beneath passive continental margins. Geol. Jahrbuch. E22 pp. 3-28.

Jokat, W., T. Boebel, M. König, U. Meyer, 2003. Timing and geometry of early Gondwana breakup, J. Geophys. Res., 108(B9), 2428, doi: 10.1029/2002JB001802.

Key, R.M. et al., 2008. Revised lithostratigraphy of the Mesozoic–Cenozoic succession of the onshore Rovuma Basin, northern coastal Mozambique. Journal African Earth Sciences, 111: 89-108.

Klausen, M. B., 2009. The Lebombo monocline and associated feeder dyke swarm: Diagnostic of a successful and highly volcanic rifted margin? Tectonophysics 468, 42-62.

Kreuser, T. 1995. Rift to drift evolution in Permian-Jurassic basins of East Africa. In: 'Hydrocarbon Habitat in Rift Basins'. Ed. Lambiase, J. J. Geol. Soc. Spec. Publ. No. 80 pp 297-315.

König, M., and Jokat, W., 2010. Advanced insights into magmatism and volcanism of the Mozambique Ridge and Mozambique Basin in the view of new potential field data. Geophysical Journal International, 180, 158-180.

Law, C., 2011. Northern Mozambique: True "Wildcat" Exploration in East Africa. Adapted from oral presentation at Forum: Discovery Thinking, at AAPG Annual Convention and Exhibition, Houston, Texas, USA, April 10-13, 2011. Search and Discovery Article # 110157 (2011). Posted June 20, 2011.

Ledesma, D., 2013. East Africa Gas – Potential for export, The Oxford Institute for Energy Studies, University of Oxford.

Leinweber, V. T., and W. Jokat (2011), Is there continental crust underneath the northern Natal Valley and the Mozambique Coastal Plains?, Geophys. Res. Lett., 38, L14303, doi:10.1029/2011GL047659.

Maende, A. and Mpanju, F., 2003. Geochemistry and source rock potential of East African Passive Margin. EAPC 2003, Nairobi, Kenya.

Magoon L. B. & Dow, W. G. 1994. The petroleum system. In: Magoon, L. B. & Dow, W. G. eds.: The petroleum system − from source to trap. AAPG Memoir 60, 3-24.

Mahanjane, E.S., 2012. A geotectonic history of the northern Mozambique Basin including the Beira High - A contribution for the understanding of its development. Marine and Petroleum Geology 36 (2012) 1-12.

Mahanjane, E.S and Franke, D., 2014. The Rovuma Delta deep-water fold-and-thrust belt, offshore Mozambique, Tectonophysics 614 (2014) 91–99. doi:10.1016/j.tecto.2013.12.017.

Mahanjane, E.S., D. Franke, D., Lutz, R., Winsemann, J., Ehrhardt, A., Berglar, K., and Reichert C. (in Review). Maturity modelling and petroleum system of the northern Mozambique basins, off Zambezi Delta and Angoche basins.

Mahanjane, E.S., (in review). The Davie Fracture Zone and adjacent basins in the offshore Mozambique Margin – a new insight for the hydrocarbon potential. Ms. Ref. No. JMPG-D-12-00292R2.

Mann, P., L. Gahagan, and M. B. Gordon, 2003, Tectonic setting of the world's giant oil and gas fields, in M. T. Halbouty, ed., Giant oil and gas fields of the decade 1990–1999, AAPG Memoir 78, p. 15–105.

Matchette-Downes, C., 2006. Petroleum potential of the Morondava Basin. Madagascar Promotional Meeting. Houston May 25th 2006.

McCALL, R. A., 1997. Implications of recent geological investigations of the Mozambique Channel for the mammalian colonization of Madagascar. Proc. R. Soc. Lond. B (1997) 264, 663–665.

McKenzie, D. 1978. Some remarks on the development of sedimentary basins. Earth and Planetary Science Letters, 40 (1978) 25-32.

Menzies, M.A., Klemperer, S.L., Ebinger, C.J., and Baker, J., 2002, Characteristics of volcanic rifted margins, in Menzies, M.A., Klemperer, S.L., Ebinger, C.J., and Baker, J., eds., Volcanic Rifted Margins: Boulder, Colorado, Geological Society of America Special Paper 362, p. 1–14.

Mubarak and Miriam et al., 2009. Basin and Petroleum Modelling. Oilfield Review Summer 2009: 21, no.2.

Nairn, A.E.M., Lerche, I. and Iliffe, J.E., 1991. Geology, basin analysis and hydrocarbon potential of Mozambique and the Mozambique Channel. Earth-Sci. Rev., 30: 81-124.

Pepper, A.S. and Corvi, P.J., 1995a. Simple kinetic models of petroleum formation. Part I: oil and gas generation from kerogen. Marine and Petroleum Geology, Vol. 12, No. 3, pp. 291-319, 1995.

Peters, Kenneth E., Leslie B. Magoon, Carolyn Lampe1, Allegra Hosford Scheirer, Paul G. Lillis, and Donald L. Gautier, 2007. Petroleum Systems and Geologic Assessment of Oil and Gas in the San Joaquin Basin Province, California. *Edited by* Allegra Hosford Scheirer. U.S. Geological Survey Professional Paper 1713. Chapter 12.

Rabinowitz, P.D., Coffin, M.F. and Falvey, D., 1983. The Separation of Madagascar and Africa. Science: 67-69.

Reeves, C., 2000. The Geophysical mapping of Mesozoic dyke swarms in southern Africa and their origin in the disruption of Gondwana. *J. Afr. Earth Sci., 30, 449-513*.

Reeves, C. , 2009. Re-examining the evidence from plate-tectonics for the initiation of Africa's passive margins. Geological Society of Houston/Petroleum Exploration Society of Great Britain, London, 2009 September 9-10.

Reeves, C. and Mahanjane, E.S., 2013. Mozambique and its role in the downfall of Gondwana. Geological Society of Houston/Petroleum Exploration Society of Great Britain, London, 2013 September 11-12.

Riley, T. R. & Knight, K. B., 2001. Age of pre-break-up Gondwana magmatism: a review. Antarctic Science 13, 99–110.

Roberts, E.M. et al., 2012. Initiation of the western branch of the East African Rift coeval with the eastern branch. Nature Geosci, 5(4): 289-294.

Ryan, W.B.F., S.M. Carbotte, J.O. Coplan, S. O'Hara, A. Melkonian, R. Arko, R.A. Weissel, V. Ferrini, A. Goodwillie, F. Nitsche, J. Bonczkowski, and R. Zemsky (2009), Global Multi-Resolution Topography synthesis, Geochem. Geophys. Geosyst., 10, Q03014, doi:10.1029/2008GC002332.

Salman, G., Abdula, I., 1995. Development of the Mozambique and Ruvuma sedimentary basins, offshore Mozambique. Sedimentary Geology 96 (1995), 7-41. Elsevier Science B.V. SSDI 0037-0738(94)00125-1.

Segev, A., 2002. Flood basalts, continental breakup and the dispersal of Gondwana: evidence for periodic migration of upwelling mantle flows (plumes). EGU Stephan Mueller Special Publication Series, 2, 171–191, 2002.

Sandwell, D. T., and W. H. F. Smith, 2009. Global marine gravity from retracked Geosat and ERS-1 altimetry: Ridge Segmentation versus spreading rate, J. Geophys. Res., 114, B01411, doi:10.1029/2008JB006008, 2009.

Svensen, H, Corfu, F., Polteau, S., Hammer, Ø., and Planke, S., 2012. Rapid magma emplacement in the Karoo Large Igneous Province. Earth and Planetary Science Letters 325–326 (2012) 1–9.

Sweeney, J.J. and Burnham, A.K., 1990. Evaluation of a simple model of vitrinite reflectance based on Chemical kinetics. AAPG Bulletin, 74:1559-1570, 1990.

Thompson, K.F.M. and Dow, W.G., 1990. Investigation of Cretaceous and Tertiary kerogens in sediments of the Weddell Sea. In Barker, P. E, Kennett, J. P., et al., 1990. Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 113.

Turcotte, D. L., and Emerman, S. H., 1983. Mechanisms of active and passive rifting. Tecronophysics, 94 (1983) 39-50.

Yilmaz, Ö., Seismic Data Processing, Book, Society of Exploration Geophysicists, 1987.

Acknowledgements

- I am grateful to the Instituto Nacional de Petróleo (INP) of Mozambique for funding this project. Dr. Christian Reichert and the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR – Federal Institute for Geosciences and Natural Resources) for the logistics and support during my research. I extend the gratitude for other colleagues from the BGR (Marine Seismic) at Hannover, namely Dr. Axel Ehrhardt, Dr. Rüdiger Lutz, Dr. Bernd Schreckenberger, Dr. Kai Berglar, Dr. Ingo Heyde, Dr. Christoph Gaedicke, Mr. Martin Block, Mr. Otto-Hans Bargeloh, Mrs. Sonja Breuer, all your advice and contributions for my pubications are highly appreciated and gratefully acknowledged.

- I gratefully acknowledge Prof. Dr. Jutta Winsemann for supervision and support during my stay in Hannover. Dr. Dieter Franke for the readiness for discussion and contributing to the publications, PD Dr. Udo Barckhausen is thanked for readiness to support and contributing to the thesis, Prof. Dr. Bernhard Cramer is thanked for time and review.

- I thank the editors and the reviewers of the Marine and Petroleum Geology, Tectonophysics, and Journal of Petrolum Geology for all their valuable contributions to my publications.

- I dedicate this thesis to the memory of my brother Samuel Mahanjane. To my children Chinyimu (7 years) and Manu Bhonghani (5 years) for their premature acceptance the challenge of life and being away for long months from papa, and to my wife Laura Nilza of being supportive.

- My deepest thanks and gratitude to all my family members, Bhava Amós Mahanjane and other brothers, sisters, nephews and nieces. To Vovo Neli for raising me with patience and love.

- Last but not least, I want to thank Laura (Naninha) Mahanjane and Anna Hacker for the kindly help with the text editing of my manuscripts.

"Action will remove the doubt that theory cannot solve"

Curriculum Vitae

Estevão Stefane MAHANJANE

Date of Birth:	07-03-1974
Place of Birth:	Maqueze (Alto-Changane), Mozambique
Nationality:	Mozambican

EMPLOYMENTS

06/2001 onwards	**Geoscientist/Explorationist** Exploration division, Instituto Nacional de Petroleo, Maputo-Mozambique
06/2012-06/2017	**Member of the Commission on the Limits of the Continental Shelf, the Scientific body under the United Nations Convention on the Law of the Sea** United Nations Headquaters, New York, The United State of America
01/2011-06/2014	**PhD Researcher** Gottfried Wilhelm Leibniz Universität Hannover, Institut Für Geologie
06/2007 onwards	**Teaching Assistant** Eduardo Mondlane University, Maputo-Mozambique

EDUCATION

2011	**PhD Candidate** Gottfried Wilhelm Leibniz Universität Hannover, Institut Für Geologie, Hannover, Deutscland
2002	**Bsc Honours Degree** University of Cape Town, South Africa
1994-1999	**Undergraduate student of geology** Eduardo Mondlane University, Maputo, Mozambique
1992-1993	**High school** Francisco Manyanga Secondary School, Maputo, Mozambique

Scientific publications

Mahanjane, E.S., D. Franke, D., Lutz, R., Winsemann, J., Ehrhardt, A., Berglar, K., and Reichert C. (submitted to Journal of Petroleum Geology). Maturity and petroleum systems modelling in the offshore Zambezi Delta depression and Angoche basin, northern Mozambique basin;

Mahanjane, E.S., in press. The Davie Fracture Zone and adjacent basins in the offshore Mozambique Margin – A New insight for Hydrocarbon Potential. Ms. Ref. No. JMPG-D-12-00292R1. http://ees.elsevier.com/jmpg/;

Mahanjane, E.S and Franke, D. 2014. The Rovuma Delta deep-water fold-and-thrust belt, offshore Mozambique, Tectonophysics 614 (2014) 91–99. doi:10.1016/j.tecto.2013.12.017;

Mahanjane, E.S., 2012. A geotectonic history of the northern Mozambique Basin including the Beira High – A contribution for the understanding of its development. Marine and Petroleum Geology 36 (2012) 1-12. doi:10.1016/j.marpetgeo.2012.05.007;

Mahanjane, E.S., 2013. Corrigendum to "A geotectonic history of the northern Mozambique Basin including the Beira High e A contribution for the understanding of its development" [Mar. Pet. Geol. 36 (2012) 1-12]. DOI of original article: http://dx.doi.org/10.1016/j.marpetgeo.2012.05.007;

Reeves, C. and Mahanjane, E.S., 2013. Mozambique and its role in the downfall of Gondwana. Geological Society of Houston/Petroleum Exploration Society of Great Britain, London, 2013 September 11-12. http://pesgb.org.uk/events/event-165/;

Anderson, L., Caillot, A. Gatter, L., Barrere, C., Grimmer, J., and Mahanjane, E.S., 2013. Rifting of the Zambezi Delta region, northern Mozambique Basin and its implications for a Jurassic marine source rock. Geological Society of Houston/Petroleum Exploration Society of Great Britain, London, 2013 September 11-12;

E.S. Mahanjane, M. Achimo, M. Block, N. Ott, S. Žarić, and C. Reichert, 2013. Lava flows interbedded in the sedimentary sequence of the southernmost Mozambique Basin – A challenge for the application of the Gardiner Formula. Third International Symposium on Scientific and Legal Aspects of the Regimes of the Continental Shelf and the Area. Beijing 22-23November, 2012;

Reichert, C., Neben, S., et. al., 2008. Cruise Report, BGR07. R/V MARION DUFRESNE CRUISES MD 163 & MD 164. PROJECT MOBAMASIS;

Mahanjane, E., 2002. "SEA LEVEL: Its influence on sedimentary processes and sedimentary facies distribution in the offshore Zambezi Delta (Mozambique)".Bsc Honours Thesis (UCT);

Mahanjane, E., Achimo, M., 1997. "A Contribution for knowledge of the Marine and continental sedimentary deposits in Massingir-Gaza", Southern Mozambique basin (scientific reserach).