East Africa: From Research to Reserves

13-15 April 2016

Corporate Supporters

Conference Sponsors

CONTENTS PAGE

PROGRAMME

Wednesday 13 April	
08.30	**Registration**
08.50	**Welcome**
	Session 1: Research in Geodynamics
09.00	**Keynote Speaker: Duncan Macgregor *(MacGeology)*** From Seeps to Success : The Evolution of Hydrocarbon Plays In East Africa
09.30	**Stewart Fishwick *(University of Leicester, UK)*** Lithospheric Structure of East Africa and Its Margins: Linking Deep Seismology to Tectonics and Basin Evolution
10.00	**Ken McDermott *(ION)*** Crustal Structure & Hydrocarbon Plays of the East African Margin Revealed: Insights from the Mega-Regional East AfricaSPAN Dataset
10.30	**Break**
11.00	**Jordan Phethean *(Durham University UK)*** Madagascar's Escape from Africa: New Constraints and Understanding for Plate Tectonic Reconstructions
11.30	**Colin Reeves *(Earthworks)*** Origins of the East Africa Margin: Prolonged Rifting Preceded Initiation of Transforms in the Kimmeridgian
12.00	TBC
12.30	**Lunch**
	Session 2: Regional Tectono-Stratigraphy and Provenance Studies
13.30	**Benjamin Palmer *(BG Group)*** Structural Evolution of the outboard Davie-Walu Trend Offshore Kenya and Northern Tanzania
14.00	**Eva Hollebeek *(Schlumberger)*** Unravelling the Tectonic History of the North Mozambique and Rovuma Basins Using Broadband Seismic Data to Understand the Correlation with Stratigraphy and the Potential Petroleum System Elements
14.30	**Amy Tuck-Martin *(Royal Holloway University of London, UK)*** Regional Tectono-Stratigraphy of East African Sedimentary Basins: Combining High Resolution Plate Kinematic Models, Plate-Scale Stress Simulations and Basin Fill Histories
15.00	**Break**
15.30	**Keynote Speaker: Pamela Sansom *(BG Group)*** Sequence Stratigraphic Scheme for the Jurassic-Neogene of Coastal and Offshore Tanzania
16.15	**David Johnstone *(ERCL)*** A Source to Sink Study of the Rovuma Basin, Mozambique
16.45	**Ross McCabe *(Chemostrat UK)*** Provenance within the Eastern Coast Of Tanzania from the Jurassic to Neogene Periods
17:15	**Ross McCabe *(Chemostrat UK)*** Elemental Chemostratigraphy of the Kilwa Group, Tanzania.
17.45	**Finish with Drinks Reception and Posters**

Thursday 14 April	
08.30	**Registration**
08:50	**Welcome**
	Session 3: Sedimentary Systems
09.00	**Anne McAfee *(Corelab)*** Tectono-Stratigraphic Evolution of the East African Coastal Basins: Observations and Insights from Rock-Based Regional Studies in Kenya, Tanzania and Mozambique.
09.30	**Bhavik H. Lodhia *(Imperial College London, UK)*** Uplift and Deposition of Sediment at Passive Margins: Examples from Africa
10.00	**Carlo Cazzola *(Total)*** Oligocene to Quaternary Turbidites and Contourites of the Zambezi and Angoche Basins South of the Mozambique Channel
10.30	**Break**
11.00	**Keynote Speaker: Ross Garden *(BG Group)*** Reservoir Quality and Producability of Deepwater Tanzanian Gas Reservoirs
11:45	**Fionnan Kearney Cunningham *(University College Dublin, Ireland)*** Large Volume Event Beds; Their Origin, Significance and Implications for the Development of the Mzia Field.
12.15	**Eleanor Stirling *(BP)*** Contourite Deposition over Time along the Offshore Tanzania Margin: Controls, Architectures, and Effects on Hydrocarbon Prospectivity.
12.45	**Lunch**
	Session 4: Petroleum Systems to Reserves
14.00	**Keynote Speaker: Glenn Rising *(Anadarko)*** Appraisal of Prosperidade Gas Field, Area 1 - Rovuma Basin, Northern Mozambique: 25 TCF of Gas Reserves and Growing
14.45	**Joseph Nicholson *(BG Group)*** Transforming Tanzania's Frontier Exploration Acreage into a Proven Hydrocarbon Province
15.15	**Fawad Chuhan *(Statoil)*** Tanzania Block 2 : From Discovery to Development
15.45	**Break**
16.15	**Niall Sayers *(BG Group)*** Linking Recent Gas Discoveries to Their Source Kitchens, Offshore Tanzania
16.45	**Kevin Dale & Markus Logering *(Sasol)*** The Pande Gas Fields Complex in the South Mozambique Basin, a Case History
17.15	**Jon Turner *(BG Group)*** Structure and Source Rock Potential of Syn-Breakup Mini-Basins, Offshore Tanzania and Kenya
17.45	**Finish with Wine Reception followed by Conference Dinner at The Cavendish Hotel, St. James'**

Friday 15 April	
08.30	**Registration**
08.50	**Welcome**
	Session 5: Frontier Opportunities
09.00	**Lindsay Davidson *(RPS Energy)*** Regional Geology and Hydrocarbon Potential of Deep Water Offshore SE Somalia
09.30	**Anongporn Intawong *(Spectrum Multi-Client)*** Hydrocarbon Prospectivity and Play Concepts Offshore Madagascar
10.00	TBC
10.30	**Break**
11.00	**Alice Butt *(Neftex)*** Exploring Subsurface Risk at Zambezi Delta: 3D Modelling Of Source Rock Maturity within a Regional Context
11:30	**John Fisher *(Genel Energy)*** Developing a Regional Geological Framework for the Horn of Africa
12.00	**Barry Wood *(Petroquest)*** Mkuranga-1: A sleeper Awakened
12.30	**Lunch**
	Session 6: Onshore rifts
13.30	**Christopher Scholz *(Syracuse University, USA)*** New Deep Basin- and Crustal-Scale Imaging of the Lake Malawi/Nyasa Rift: Constraints on Extension and Basin Evolution in the East African Rift
14.00	**Bastien Walter *(Univeristy of Lorraine, France)*** Structural, Petrophysical and Geochemical Investigations of Basement Oil Seeps from a Rift Border Fault System: Example of the Albert Graben (Uganda)
14.30	**Gion Kuper *(Tullow)*** Thermal History and Source Rock Facies Variation - Implications for Hydrocarbon Charge in the South Lokichar Basin, Kenya (EARS)
15.00	**Break**
15:30	**Peter Purcell *(P&R Geological Consultants)*** Mapping the Evolution of the East African Rift System – an Updating and Re-imaging
16.00	**Joshua Lukaye *(Directorate of Petroleum, Uganda)*** Geochemical Characterisation and Correlation of Crude Oil and Sediment Extracts from Two Oil Fields and Discovery Areas in the Albertine Graben, Uganda
16:30	**Robin Renaut *(University of Saskatchewan, Canada)*** Geothermal Processes and Evaporative Concentration: Contributors to the Formation of Lacustrine Source Rocks in the Saline, Alkaline Lake Basins of the Kenya Rift Valley
17:00	**Finish**

POSTER PROGRAMME

Yannis Bassias (Gemini Ressources) The Nature of the Crust Offshore East Coast Africa – When Geology and Seismic Meet Potential Fields in the Search for Hydrocarbons
Yannis Bassias (Gemini Ressources) Davie Fracture Zone - Scattered Island Connections in Mesozoic and Cenozoic
Matt Bolton (BG Group) Promoting an Interrelated Seismic Data Analysis Approach
Siebe Breed (CGG – NPA Satellite Mapping) Basement Control on Structure and Drainage in the East African Rift System
Amanda Gray (BG Group) Sequence Stratigraphic Framework of the Jurassic, Tanzania
Franck Eitel (The University of Yaounde) Contribution of the Geophysics to the Structural Study of the Continental Geology and Resource Exploration along CVL using GOCE Gravity Measurements
Daisy Lee (Chemostrat Ltd) Integrated Geochemical & Heavy Mineral Analysis of Rift Basin Sediments: A Case Study from the Lokichar Basin, Kenya
Kate Lloyd (BG Group) Shale Variability and Its Impact on AVA Offshore Tanzania
Joshua Lukaye (Directorate of Petroleum – Uganda) Development of a Coherent Stratigraphic Scheme of the Albertine Graben-Uganda
Doreen E. Mkuu (Southampton University) Thermal Maturity History of Mafia Deep Offshore Well, Southern Coastal Tanzania
Glyn Roberts (Spec Partners Ltd) An In-Depth Look at the Petroleum Potential of the Morondava Basin, Offshore Madagascar
Ahmad Shmela (University of Leeds) Investigation of Scaling Properties of Fault Populations in the Central Kenya Rift
Joanna Wallis (BG Group) Exploring the Noise in AVA Seismic Data

Oral Presentation Abstracts

(Presentation order)

Wednesday 13 April

Session One: Research in Geodynamics

Keynote Speaker: From Seeps to Success: The Evolution of Hydrocarbon Plays In East Africa

Duncan Macgregor[1] and Peter Purcell[2],

[1]*MacGeology Ltd, Reading, UK*
[2]*P & R Geological Consultants, Scarborough, Australia*

East Africa has emerged as one of the new and exciting petroleum provinces of the 21st Century. This success is, for the most part, a relatively recent event and comes after many decades of relatively unsuccessful exploration. This paper looks at the exploration play concepts that have both led and misled the search for oil and gas deposits in the region over those years.

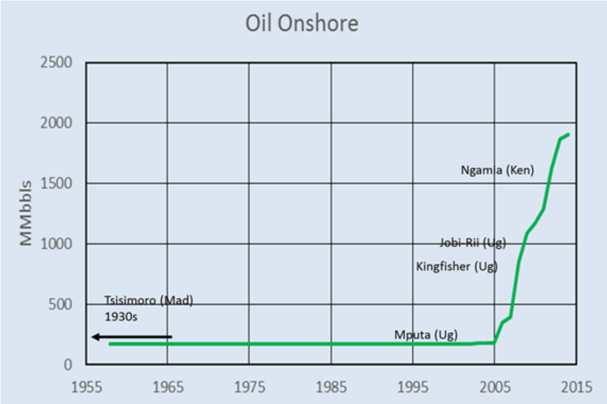
Onshore

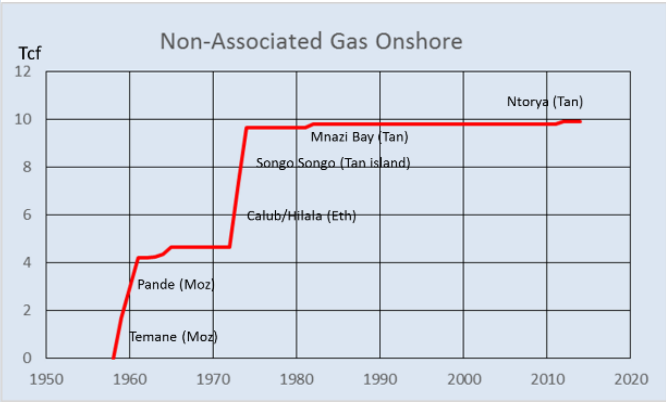
Exploration began in East Africa in the early 20th Century, based on drilling near oil seeps in Eritrea (Dahlac Island, 1930s), Madagascar (1930s) and Uganda (Lake Albert, 1938). The first deep well was the Butiaba Waki well on a small hill in Lake Albert in 1938, a well which was deep enough to penetrate near to mature lacustrine source rocks. The shallow Tsisimoro field in Mozambique was found at that time and for decades was the only proven subsurface oilfield in the region.

Systematic exploration commenced mid-Century. This early work was based on drilling four-way dip-closed structures, defined initially by geological mapping and gravity surveying, and by the 1960s, by seismic reflection surveys. Projection of plays from others basins of similar age heavily influenced exploration. Noteable failed campaigns include attempts by Sinclair and others in the 1950s and 1960s to extend Middle East carbonate plays into Somalia and eastern Ethiopia, several phases of drilling in the Anza Rift (a projected analogue of the Sudan rifts) ranging from the late 1950s to 2010s, efforts in the Kenyan and Tanzanian coastal basins initially driven by BP and Shell and over 40 wells, mainly in the 1960s and 1970s, close to the Mozambique shoreline.

These wells saw no more than oil shows, but gas was 'accidentally' found in a number of basins. The 5Tcf Temane and Pande fields of Mozambique were found as early as 1959 and 1961 and still represent the largest gas fields onshore east Africa. These fields took 45 years to commercialise. Other moderate sized gas discoveries were made at Calub in Ethiopia in 1973, still stranded, and Songo-Songo (1974) and Mnazi Bay (1982) offshore Tanzania, which, in retrospect, were the key pointers in petroleum systems terms to the gas potential of the deep offshore (see figure below).

Apart from the early seep-driven drilling in Lake Albert and an Amoco campaign in the 1980s, the East African Rift System was largely ignored until Shell's drilling of the Loperot well in the South Lokichar Basin in 1993, which failed however to flow to surface. This did however establish the presence of a petroleum system to be later confirmed by drilling of improved reservoirs in 2012. The eventual success in Lake Albert from 2006 onwards and thereafter in the Lokichar Basin was located in unusual downfaulted and fault sealed traps in the fields labelled below.

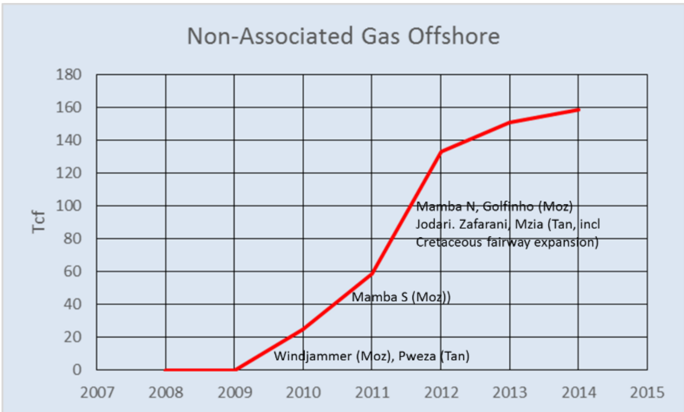




Offshore

Most wells offshore were also targeted at oil, including the ENI and Anadarko wells in the Rovuma Basin. To date, the only indicators are some small oil production from the Inhassoro well in Mozambique, which is on the shoreline and a small oil leg in the Sunbird well in Kenya.

The gas ‘boom’ of deepwater Rovuma and Tanzanian Coastal Basins is portrayed below. Volumes have exceed all expectations, partly due to the reservoir connectivity being much greater than predicted. Modern 3D seismic technology has clearly been the key to these massive discoveries in Tertiary and Cretaceous deepwater reservoirs, which lie mainly within stratigraphic and combination traps.



What have we learnt?

East Africa contains a wide variety of basins of different ages and it is clearly difficult to derive any simple ‘lessons learnt’ that are applicable across the whole region. However, some interesting observations can be made:

- As in other regions of the world, the regional source rocks are associated with rift and immediate post-rift phases. It is the thickness of overburden to these levels (or onshore, the past state of maturity prior to uplift) that dictates the predominant hydrocarbon phase and the overall gas-proneness of most fairways.
- Understanding the exploration legacy is key. Most discoveries had pointers towards them from early drilling in terms of discoveries that may have been uneconomic at that time, proven source rocks or columns which must have been charged from distant kitchens.

- The main successes group around kitchens that are active (sometimes highly active) at Present Day.
- Associated with this, the distribution of working trap types does not follow global paradigms. Fields in simple four way closures are rare in east Africa and instead we see a high stratigraphic element in the offshore traps and largest onshore gas fields, and unusual fault sealed and downthrown traps in the EARS.

Acknowledgements : the data for the creaming curves in this paper is extracted from various public domain sources for the older fields, IHS creaming curves for recent years published in a PESGB newsletter article (May 2015) and, by kind permission, data on recent drilling from Richmond Energy Consultants.

NOTES

Lithospheric Structure of East Africa and Its Margins: Linking Deep Seismology to Tectonics and Basin Evolution

Stewart Fishwick[1]**;** Ana Domingues[2]**;** Judith Sippel[3]; Carmen Gaina[4]; Magdalena Scheck-Wenderoth[3,5]; Joao Fonseca[2]

[1]*Department of Geology, University of Leicester*
[2]*Instituto Superior Técnico, Lisbon*
[3]*Helmholtz-Zentrum Potsdam Deutsches GeoForschungsZentrum GFZ, Section 4.4,*
[4]*Centre for Earth Evolution and Dynamics, University of Oslo*
[5]*RWTH Aachen, Germany*

Knowledge of the present-day structure of the lithosphere plays a key role in understanding the tectonic evolution of any region. In this context we present an updated surface wave tomography model covering both the continental part of East Africa and the oceanic margins.

Due to the path coverage, surface wave tomography provides the opportunity to recover detailed variations in seismic velocity within the lithosphere both in areas with, and those without, seismic stations; making it an ideal tool for investigating the broad regional structure. In this study, more than two decades worth of data from both permanent and temporary deployments of seismometers are included within the tomographic inversion. The resulting velocity model covers the uppermost mantle and is presented as a series of depth slices from 50 – 250 km depth.

In the continental interior the model at 75km depth shows strong correlations with the rift structure. Intriguingly, at 125km depth, there are areas of the rift system that appear to be underlain by faster velocities (and thus thicker lithosphere), which may play a controlling role in the nature of the basins in these regions. Offshore, fast velocities are observed at lithospheric depths (75km) beneath the central region of the West Somalian Basin. Between east Africa and Madagascar, regions of fast velocities are fragmented, and indicate that the evolution of deep lithospheric structure beneath the ocean is more complicated than simple models of lithospheric cooling based on the age of the ocean crust. In a focused study using ambient noise, detailed crustal structure of the Mozambique Coastal Plains is also recovered.

The tomographic models have also been used to estimate lithospheric thickness for the region. Two approaches can be taken: 1) a simplistic seismic proxy, such as the depth to a particular velocity contour, is taken as the lithospheric thickness; or, 2) converting velocities to temperature, and then attempting to estimate the depth to a particular isotherm. These estimates of lithospheric structure are then used as a priori information in combined isostatic and gravity modelling in order to recover variations in lithology and temperature across the greater Kenya Rift.

NOTES

Crustal Structure & Hydrocarbon Plays of the East African Margin Revealed: Insights from the Mega-Regional East AfricaSPAN Dataset

Ken McDermott[1]**,** Richard Haworth[1], Al Danforth[2], Katie-Joe McDonough[3], Jim W. Granath[3], Paul Bellingham[1]**,** Brian W. Horn[2]

[1]*ION, 1st Floor Integra House, Vicarage Road, Egham, Surry, TW20 9JZ, UK*
[2]*ION, 2105 CityWest Blvd., Suite 400, Houston, TX 77042-2839, USA*
[3]*ION E & P Advisors, Denver, CO 80203*

The offshore East African margin has proven a rich exploration province over the last 5 years, with over 130 Tcf of gas discovered to date as well as emerging liquids potential. However, fundamental questions remain regarding the structural and magmatic history and the impact these have on reservoir distribution and source maturation.

Integrated interpretation of regional seismic data from Kenya to Madagascar focussed on the most recently acquired data from the Comoros Archipelago. A regional play-based exploration framework was developed to address these questions. These Comorian seismic data demonstrate there is seismic evidence for sand-prone facies (deep water fans, splays, and channels) being present and the existing deep water Cretaceous and Paleogene plays identified in the Rovuma Basin, Mozambique and Tanzania extend eastward across the Kerimbas Graben into the Somali Basin. Stratal architecture and isopach mapping from 2D SPAN data reveal a N-S fairway trending toward Comoros which contain multiple aggradational channel/levee and lobe complexes 5-10km in width and up to 400m thick. These complexes appear to have higher accumulation rates than surrounding low-accumulation sediments, suggesting reservoir intervals overlain by sealing mudstones.

We present a refined structural element map delineating regions of continental, oceanic, and hybrid crust within the Somali Basin. The role of plate reorganisation and the development of the Comorian Large Igneous Province in the development of hydrocarbon plays, the identification of structural closures and the modelling of thermal history in the region are discussed. Evidence for multiple intrusive and extrusive magmatic episodes (Albian; Oligo-Miocene; Miocene – Recent) within the Somali Basin is presented and demonstrates that magmatism directly associated with the creation of the Comorian Archipelago is longer-lived than previously recognised from geochemical data – c. 28 Ma to present. The importance of long-lived magmatism is described with respect to regional heat flow and the development of a viable petroleum system within the Comorian region.

NOTES

Madagascar's Escape from Africa: New Constraints and Understanding for Plate Tectonic Reconstructions

Phethean, J.J.J., Biffi, P.G., Davies, R.J., Kalnins, L.M., McCaffrey K.J.W., van Hunen, J., *Durham University*

We present a new plate tectonic reconstruction for the drift of Madagascar away from East Africa using the new Sandwell and Smith gravity dataset. Detailed analysis of the free-air gravity anomaly, vertical gravity gradient, and horizontal derivatives of filtered gravity (used to enhance spreading lineaments from heavily sedimented ocean basins) allow us to identify the extinct mid-ocean ridge and associated spreading lineaments in the Western Somali Basin. Identification of the mid-ocean ridge segments provides a means to identify the basin's centre of symmetry, which can be compared directly to ocean magnetic anomaly interpretations for the Western Somali Basin. Interpretations of the basin's symmetry based on the M0 magnetic anomaly are found to be most reliable, and are therefore used in conjunction with the gravity-derived spreading lineaments to produce a temporally constrained plate tectonic reconstruction.

This reconstruction supports a tight fit for Gondwana fragments prior to breakup, and predicts that the continent-ocean transform margin lies along the Rovuma Basin, not along the Davie Fracture Zone (DFZ) as previously thought. This is supported by new seismic evidence for oceanic crust inboard of the DFZ, and changes the direction, position and style of the continental margin offshore Mozambique and Tanzania. The Tanzania Coastal Basins should be considered as an oblique, and likely segmented, rifted continental margin. We also show the DFZ to be a major ocean-ocean fracture zone formed by the coalescence of several smaller fracture zones during a change in plate motions as Madagascar escaped from Africa.

NOTES

Origins of the East Africa Margin: Prolonged Rifting Preceded Initiation of Transforms in the Kimmeridgian

Colin Reeves[1] Jon Teasdale[2] and E.S. Mahanjane[3]

[1]*Earthworks BV, Delft, The Netherlands;*
[2]*Shell International Exploration and Production, The Hague, The Netherlands;*
[3]*Institute National Petroleum, Mozambique*

We combine data from the Indian Ocean with geological information from Africa to interpret a simple but comprehensive plate tectonic model for the earliest disruption of Gondwana and hence the initiation of the east coast of Africa as a continental margin. Rifting, propagating from NE to SW, was initiated in Karoo times (Late Carboniferous to early Jurassic, 300-190 Ma) and continued - or resumed - following the outbreak of the Karoo mantle plume and the consequent Limpopo triple junction in Toarcian times (~180 Ma). Rifting and proto-ocean creation morphed into strike-slip movement along major offshore transforms only in Kimmeridgian times (~153 Ma). The change in mid-ocean spreading mechanism is illustrated in Figure 1.

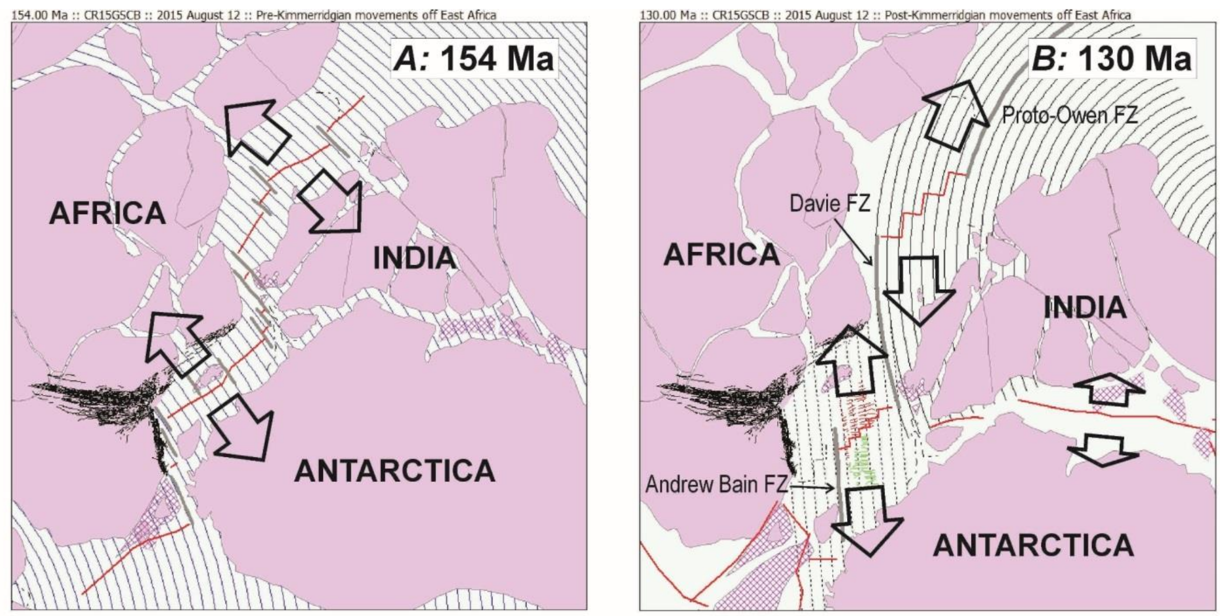


Figure 1. The Precambrian fragments of Gondwana shown in pink. ***A:*** The situation at 154 Ma with the pre-Kimmeridgian Euler pole for relative motion between East and West Gondwana shown by small circles (blue), indicating rifting propagating from NE to SW. ***B:*** the situation at 130 Ma with small circles around the post-Kimmeridgian pole for Antarctica versus Africa shown as dashed black lines and for India-Madagascar versus Africa motion as solid black lines. M-series marine magnetic anomalies for Africa shown in red and for Antarctica in green.

The data are consistent with East Gondwana (Antarctica, Madagascar, Greater India, Sri Lanka and Australia) being still intact as one fragment at 153 Ma. Conjugate marine magnetic anomalies off Mozambique and Dronning Maud Land (König and Jokat, 2010; Figure 2) define the subsequent movement of Antarctica against Africa. The movement of Madagascar against Africa after ~153 Ma is defined by the arc of the early Davie Fracture Zone (DFZ), initiated when a transform offset of about 1500 km joined the early mid-ocean ridge off Somalia with that off Mozambique. Keeping India and Madagascar intact as long as possible within these constraints requires slow opening of the early ocean between Greater India and Antarctica-Australia in the interval 153-127 Ma approximately. A ‘sidestep’ to the east in the motion of

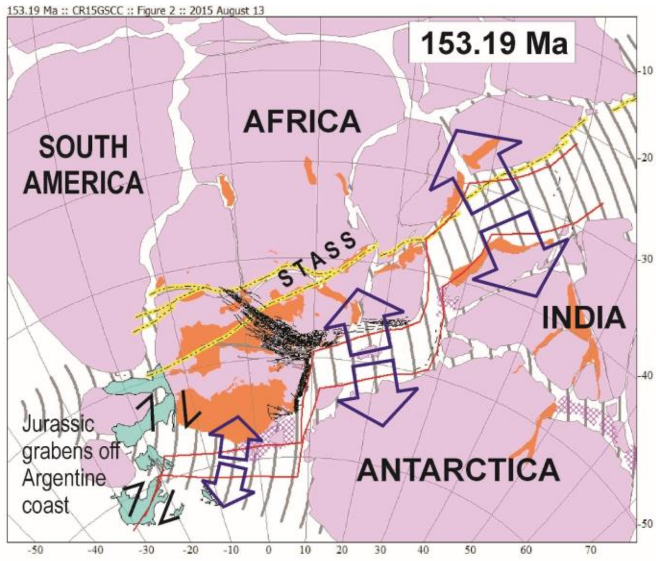


Figure 2. The Karoo rift and basin system (orange) in the context of the early (pre-153 Ma) opening between East and West Gondwana and the STASS. Euler small circles based on the interval pole 182.7-153.19 Ma shown as thick grey lines in the incipient ocean. Red lines following the margins were conjugate in the 'fit' position.

Antarctica against Africa is noted at the start of Aptian times (125 Ma), shortly after the youngest of the M-series magnetic anomalies was created. This event we equate with the migration of the ridge and transform system between Madagascar and Africa to a new location between Madagascar and India, initiating prolonged dextral transtensional strike-slip between these two fragments (until ~88 Ma and the outbreak of the Marion mantle plume).

For the East African margin, we predict that rifting with extension in directions close to NW-SE will predominate in pre-Kimmeridgian times. Thereafter, transform motion will take over within the ocean crust, leaving the pattern of faulting on the extended margins relatively undisturbed, inboard of the trace of the active DFZ. From the start of Aptian times and the demise of the DFZ, the East Africa margin should remain passive. Some reactivation of old fault lines and perhaps creation of new ones is to be expected with the outbreak of the East African Rift System in relatively recent times.

We envisage the southern trans-Africa shear system (STASS, Figure 2) being active during Karoo times, the resulting Karoo rifts being confined to lines of weakness following mobile belts separating the main Precambrian cratons of eastern and southern Africa. The observed Karoo rift system fits well with that expected for the pole of rotation between East and West Gondwana we determine for the pre-Kimmeridgian movements of these two fragments (Figures 1 and 2). But the outbreak of the Karoo mantle plume (~180 Ma, Toarcian) re-routed the principal and ultimately successful rupture south and east of Mozambique and the Kalahari craton. The lack of offset in the Okavango dyke swarm (178 Ma) testifies to the absence of strike-slip movement on the STASS since dyke emplacement.

Early relative movement between East and West Gondwana about a pole west of Patagonia also offers a plate-tectonic explanation for the coast-normal ‘Jurassic’ grabens off Argentina if dextral strike-slip along the future line of the South Atlantic Ocean is invoked with extension resulting on the South American side, both before and during initial Gondwana break-up (Figure 2).

An animation of the early development of the East African margin based on our model is to be found at www.reeves.nl/gondwana. A full animation of Gondwana dispersal may be found at the same web address, together with images based on the Geological Map of the World (2010) for the period 0-20 Ma at intervals of 2 myr. The Euler rotations for the model are to be published shortly.

Thanks to Alan Smith and Lawrence Rush (Cambridge Paleomap Servcies Ltd) for software and support and to the Commission for the Geological Map of the World for permission to

selectively digitize their world map. This is a contribution to IGCP-628, the new Gondwana Map Project.

NOTES

Wednesday 13 April

Session Two: Regional Tectono-Stratigraphy and Provenance Studies

Structural Evolution of the Outboard Davie-Walu Trend Offshore Kenya and Northern Tanzania

Benjamin Palmer, Chris Rowles, Verity Agar, Pamela Sansom, Matt Bolton and Jonathan Turner, *BG Group, 100 Thames Valley Park Drive, Reading, Berkshire RG6 1PT, UK*

The structural histories of the Northern Tanzania Coastal Basin and Offshore Lamu Basin have key controls on their exploration potential. These basins sits on the interaction of the East Africa transform margin, Anza failed rift and Somalia passive margin. The aim of this study was to define the major regional structural lineaments within these basins and the tectonic evolution of the Davie-Walu Trough. The Davie-Walu Trough is a localised prospective gravity low with significant sediment infill of c. 9 km with the Mbawa-1 gas discovery on its northern edge; it was previously interpreted as a half-graben, an extension of the Anza graben, which initiated in the Early Cretaceous. This study utilised 10460 km^2 of 3D seismic, 2D seismic acquired by Woodside and ION GXT, gravity and magnetic surveys and well control from four wells: Simba-1, Sunbird-1, Kiboko-1, Kubwa-1 and Mbawa-1 and suggested that the Davie-Walu Trough was a transtensional basin that initiated earlier in the Late Jurassic.

Subsidence initiated In the Early Jurassic by the NE-SW rifting between Kenya and Madagascar culminating in continental breakup in the Late Jurassic and transform motion between East Africa and Madagascar. The continental oceanic boundary was identified along the margin using gravity modelling in conjunction with the interpretation of long offset seismic data. Post breakup the transform motion is taken up by the, right lateral, N-S oriented Davie Transform fault which underlies the Davie-Walu Trough. It is suggested that the interaction of this transform fault with a divergent plate margin, as demonstrated by the Basile and Brun (1999) sand box experiments, generates the pull-apart basin and a significant amount of accommodation space. The highly deformed Jurassic stratigraphy observed on the eastern margin of the trough is linked to dextral shear along the horsetail splay rotating previous normal faults up to 80° causing local inversion. The Davie-Walu Trough underwent inversion and erosion in the Albian and the associated unconformity is overlain by a large scale Mass Transport Complex. Further inversion occurred in the Late Cretaceous linked to the change in pole of rotation of the African plate in the Santonian, and the rift between the Seychelles and India in the Campanian. In the Tertiary the trough is still in compression and forms a bathymetric high on the sea floor.

This study has significant implications re defining the deeper chronostratigraphy, basin modelling and gross depositional environment mapping for the area surrounding and including the Davie-Walu Trough.

NOTES

Unravelling the Tectonic History of the North Mozambique and Rovuma Basins Using Broadband Seismic Data to Understand the Correlation with Stratigraphy and the Potential Petroleum System Elements

Eva Hollebeek, Olivia Osicki, Tekena West, Sebabrata Sarkar, *Schlumberger*

Introduction

For a long time, the Mozambique basin was relatively underexplored, with a paucity of wells both in the onshore and the offshore. In recent years, large hydrocarbon discoveries have been made in the Rovuma basin (Figure 1). The hydrocarbon discoveries in Rovuma are one of the most exciting word wide exploration successes of recent years. The fields in the Rovuma basin are believed to contain approximately 180 trillion cubic feet of gas. Hydrocarbon discoveries in Tanzania and Kenya, as well as heavy oil discoveries on the conjugate margin in Madagascar also prove hydrocarbon potential on the East African passive margin. In this study, multiclient broadband long-offset seismic data is used to answer questions related to the paleotectonic development of the Mozambique and Rovuma basins. Understanding the timing of fault movement along major fault zones such as the Davie Ridge helps us to better understand the paleogeographic setting of the basin and the corresponding stratigraphic sequences that can be expected. This knowledge can be used to identify the petroleum system elements in the basin and to understand how they will vary through time and space. Interpretation of the seismic data aids the understanding of the location of the continent-ocean boundary and the corresponding location of potential synrift basins. With this knowledge, we can better pinpoint the location of synrift source rocks that are considered to be an important potential source rock in the basin.

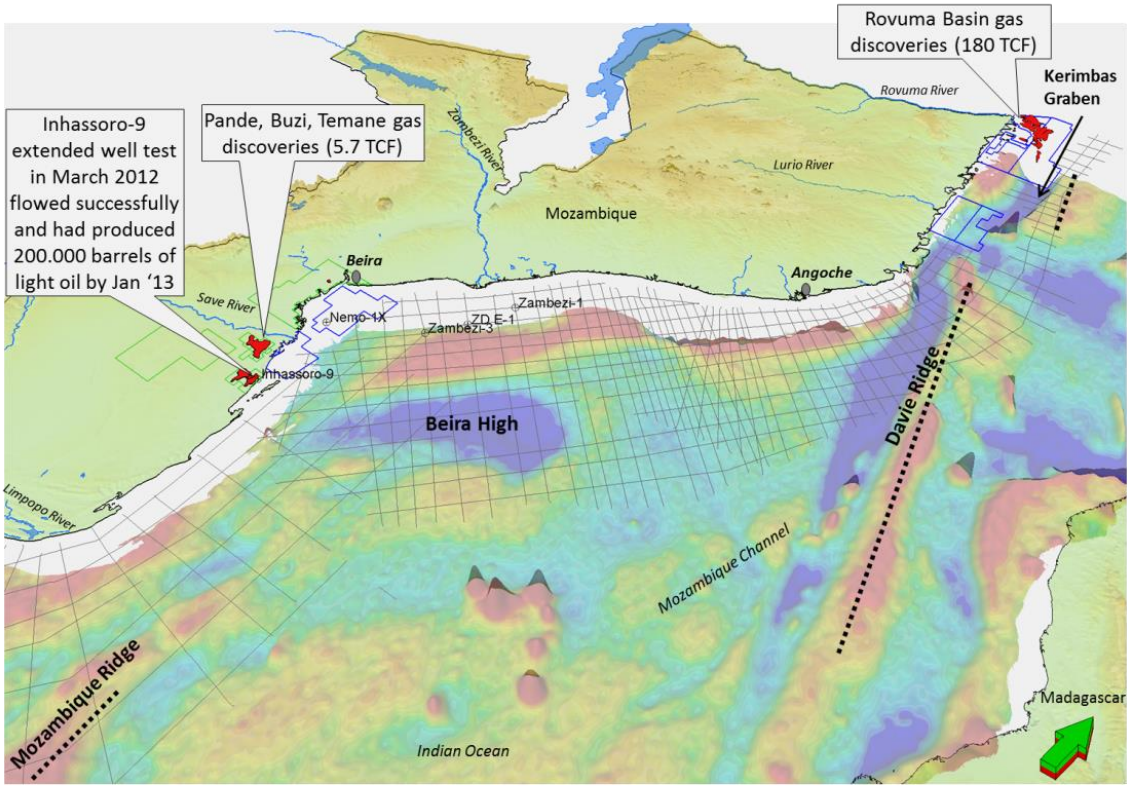


Figure 1: Overview of Mozambique offshore area with major structural elements annotated on free air gravity map. Hydrocarbon fields are in red. Current license blocks are in blue (for offshore) and in green (for onshore). Outline of the multiclient seismic data set acquired in 2013 is in grey.

Structural Framework

The hydrocarbon potential of the offshore Mozambique basin can be understood in terms of the tectonic history of the East African margin. The major tectonic events in the region influence the formation, uplift and subsidence of basins and therefore the environment of deposition. The margin formed by the breakup of supercontinent Gondwana in Triassic-Jurassic times. During this breakup East Africa separated from Madagascar, Antarctica, Australia and India. Rifting started with a phase of east-west extension in Triassic to Early Jurassic time. This phase was followed by a major phase of north-south rifting creating a proto-ocean between Madagascar and Kenya and Somalia (Reeves and de Wit, 2000). Madagascar moved south along the Davie Ridge, forming an anastomosing set of north-south trending shear zones, affecting the basin by localized compression and extension. On the seismic data, tectonic structures such as thrust faults, normal faults, full and half grabens and fold belts can be recognized. In the Zambezi delta, the Beira High can be identified on the seismic data. The Beira High is believed to be a remnant of continental crust that was left behind during rifting (Mahanjane, 2012). During the Neogene, the East African Rift system (EARs) formed, creating new rift structures as well as reactivating existing faults both in the onshore and in the offshore. The Davie Ridge is identified as the southern extension of the EARS to the north (Calais et al., 2006).

Regional Geology

Seven horizons are interpreted in the offshore Mozambique area, using 36.000 km of 2D long offset broadband multiclient seismic data and an additional 51.000 km of 2D multiclient broker data. The horizons represent the boundaries between the megasequences that can be interpreted across the offshore basin. The horizon interpretation is tied with three wells in the Zambezi delta: Nemo-1X, Zambezi-3 and ZDE-1. Gravity and magnetic data were used in this study to aid the basement and continent-ocean boundary interpretation. Our interpretation shows the spatial and temporal changes in stratigraphy and tectonic setting across the Mozambique and Rovuma basins. These variations can be correlated with the tectonic history of the basins and with the different petroleum system elements that can be expected in the basins.

The seismic interpretation confirms that isolated grabens formed during the initial stages of Gondwana breakup, when synrift sediments of terrestrial, lagoonal and lacustrine origin were deposited (Figure 2A). These sediments form the first potential source rock of the basin. As rifting continued, the basin developed into a marine environment with restricted conditions, which is also considered to be a good potential source rock interval. During the Cretaceous Period, Madagascar reached its present day position, and fault movement along the Davie Ridge ceased. Due to uplift of the East African craton in the Cenozoic Era, thick packages of clastic river-fed sediments were brought into the basin by large deltas, such as the Rovuma delta in north Mozambique. Thickness maps are generated to confirm these changes to the sediment deposition trends (Figure 2B). Passive margin sediments like turbidite systems and basin floor fans provide good potential reservoir rocks across the East African margin. The Rovuma discoveries have almost exclusively been made in these types of reservoirs of Cretaceous and Cenozoic age.

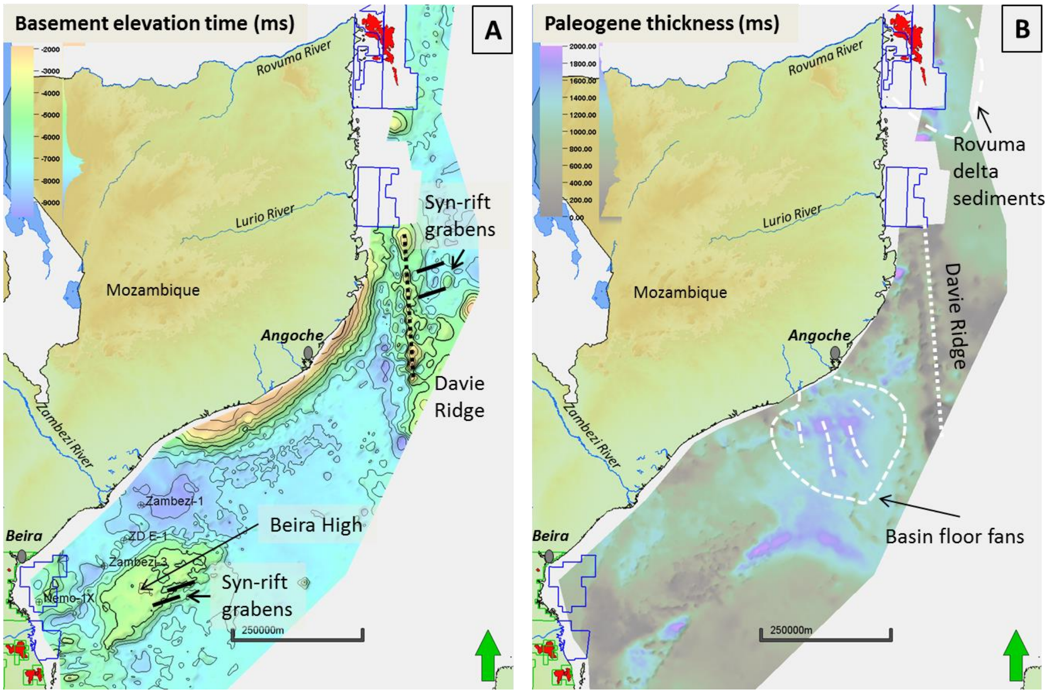


Figure 2. A: Basement elevation (in ms) to show the structural elements in the Mozambique basin, including synrift grabens, the Beira High and the Davie Ridge. B: Paleogene thickness map (in ms) showing increased sediment thickness in parts of the north Mozambique basin. Hydrocarbon fields are in red. Current license blocks are in blue (for offshore) and in green (for onshore).

Conclusion

Interpretation of seismic data from the offshore Mozambique and Rovuma basin has been used to correlate the tectonic history of the basin with the stratigraphic variations and corresponding petroleum system elements. The basins along the East African margin formed by a complex sequence of tectonic events related to the breakup of the super continent Gondwana. Many uncertainties remain related to the exact breakup configurations and timing of the different stages of the breakup. On the seismic data, tectonic structures such as thrust faults, normal faults, full and half grabens and fold belts can be recognized. The interpretation of these structures together with the interpretation of the sedimentary megasequences is used to increase our understanding of the paleotectonic development of the Mozambique and Rovuma basins. This information is used to analyse the petroleum system elements that can be expected offshore Mozambique. The synrift and sag phase sediments form good potential source rocks. The Cretaceous and Cenozoic clastic sediments deposited in the basin when the margin had transformed into a passive margin provide good quality reservoir rocks. The seismic interpretation results provide a better understanding of the stratigraphic and tectonic development of the much underexplored Mozambique basin.

References

Calais, E., Ebinger, C., Hartnady, C., Nocquet, J.M. (2006), Kinematics of the East African Rift from GPS and earthquake slip vector data. From: Yirgu, G., Ebinger, C.J. and Maguire, P.K.H. (2006), The Afar Volcanic Province within the East African Rift System. Geological Society, London, Special Publications, 259, 9-22.

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, 1-12.

Reeves, C. and 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.

NOTES

Regional Tectono-Stratigraphy of East African Sedimentary Basins: Combining High Resolution Plate Kinematic Models, Plate-Scale Stress Simulations and Basin Fill Histories

Amy Tuck-Martin[1], Dr Jürgen Adam[1], Dr Graeme Eagles[2], Dr Rob Govers[3]

[1] *Royal Holloway University of London, Egham, Surrey, UK, TW20 0EX*
[2] *Alfred Wegener Institute, Helmholtz Centre for Polar und Marine Research, Am Alten Hafen 26, 27568 Bremerhaven, Germany*
[3] *Utrecht University, Heidelberglaan 2, Utrecht, NL.*

Introduction

The sedimentary basins of East Africa and West Madagascar formed during the rifting and breakup of Gondwana in the Mid-Jurassic. In recent years, significant hydrocarbon discoveries have made the area attractive to petroleum exploration. In support of this activity, a better understanding of the margin-scale tectono-stratigraphic framework of the region is required, which integrates a consistent plate-kinematic model with individual basin fill histories.

In this study, we present a new comprehensive plate kinematic model of the Northwest Indian Ocean using finite rotation poles generated by a method of visual fitting and iterative joint inversion of magnetic isochron and fracture zone data [2,3]. The model has been correlated with the tectono-stratigraphic subsidence and stretching history of the East African sedimentary basins. The formation of marginal sedimentary basins has been controlled by changes in the plate boundary forces in different tectonic stages. For the quantitative analysis of the paleo stress field we use the plate kinematic model to approximate the first-order tectonic stress field based on plate motion and the nature and geometry of the plate boundaries.

Plate-Kinematic Model, Basin History and Derived Stress Field

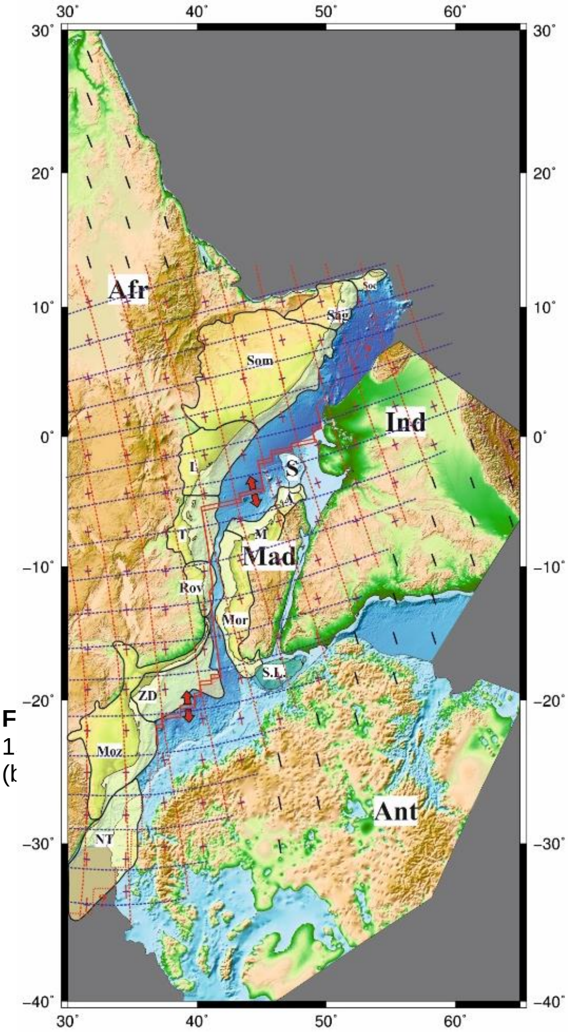
The plate-kinematic model identifies four phases of spreading, from the Jurassic to the present, preceded by intracontinental 'Karoo' rifting episodes in the late Carboniferous to late Triassic.

The first phase (183-133Ma) began with continental rifting and subsequent seafloor spreading in a predominantly NW – SE direction that separated Madagascar/India/Antarctica from Africa. Syn-rift sediments aged ~180 to ~170 Ma, and breakup unconformities (~171Ma) have been recognised in most of the East African sedimentary basins. By 169Ma syn-rift sedimentation had ceased in all basins and full marine conditions had been established. During rifting, maximum horizontal stresses trended perpendicular to the plate-kinematic vector, and parallel to the rift axis. After breakup, this changed drastically with the initiation of a spreading ridge and the onset of the drift phase.

Phase two began with boundary relocation at approximately 133Ma when spreading in the West Somali Basin ceased and the spreading axis relocated to the south, separating Madagascar/India and Antarctica. This change caused moderately high subsidence rates in the Somali, Lamu, Morondava, Mozambique and Rovuma [4]. The orientation of the plate divergence vector and the maximum horizontal stress however did not change markedly.

During phase three (89-61Ma), the initiation of the Mascarene Ridge separated India from Madagascar which led to renewed tectonic activity in the sedimentary basins of western Madagascar in the form of wrench faulting and compressional folding [1]. Coincident with this was a period of rapid subsidence in the East African basins and continued thick, deep water sediment deposition. The initiation of the Mascarene Ridge caused a dramatic change in the orientation of SH max. from N–S to ENE–WSW.

In the fourth phase (61Ma-present), the Carlsberg Ridge propagated south to form the Central Indian Ridge, separating India from the Seychelles and the Mascarene Plateau. The ridge-push related maximum horizontal stresses in the sedimentary basins became progressively outweighed by local gravity-driven NE-SW maximum horizontal stresses trending parallel to the margin. These stress regimes are caused by sediment loading and extensional collapses of thick sediment wedges predominantly controlled by margin geometry and amplified by the development of the East African Rift System in the Oligocene. Coeval with the development of the EARS was increased subsidence in the Lamu, Rovuma and Mozambique basins [4].



F
1
(t

Dynamic Stress Modelling

The kinematically derived regional stress maps (Fig. 1) are based on plate motion vectors driven by boundary forces. This is effective at predicting first order stress fields but does not work where there are lateral variations in topography and density. Our plate model is used as input to quantify the forces acting on the African plate and calculate the resultant regional stress field at important tectonic stages. We assume that the plate is in mechanical equilibrium, (i.e. not accelerating or decelerating) for this the torques arising from edge forces, lithospheric body forces and mantle tractions are required to cancel out. Edge force torques are generally well constrained by boundary geometry and relative motion, and lithosphere body forces can be estimated when the thickness and density structure of the Lithosphere are known. These “known” torques provide some constraint on the poorly understood mantle traction torques [5,6].

We anticipate the numerous tectonic changes in the NW Indian Ocean to produce a temporal change in the torque of forces acting on the East African margin. In order the maintain balance the other forces will have to change too, this can be used to revaluate timings of boundary changes in comparison to the plate model and basin history. Particular events expected to have major change on the torque balance and stress field are; complete detachment of South America and the subduction zone on its western edge, initiation of the Mascarene ridge at the Eastern boundary, and continental collision on the northern boundary.

Summary

Our study successfully integrates an interpretation of paleo-stress regimes constrained by the new high resolution plate-kinematic model, with qualitative dynamic stress simulations and basin history to produce a margin scale tectono-stratigraphic framework that highlights the important interplay between plate tectonics, boundary forces and basin formation.

References

[1] Clark, D. N. (1998) Review of the exploration potential of Madagascar, Houston Geol. Soc. Bull., v. 40, pp. 23–29.

[2] Eagles, G. & Hoang, H. H. (2014) Cretaceous to present kinematics of the Indian, African and Seychelles plates, Geophys. J. Int., v. 196, pp. 1-14.

[3] Eagles, G. & Wibisono, A. D. (2013) Ridge push, mantle plume and the speed of the Indian plate, Geophys. J. Int., v. 194, pp. 670-677.

[4] Janssen, M. E., Stephenson, R. A. & Cloetingh, S. (1995) Temporal and spatial correlations between changes in plate motions and the evolution of rifted basins in Africa, GSA Bulletin, v. 107(11), pp. 1317-1332.

[5] Warners-Ruckstuhl, K. N., Govers, R. & Wortel, R. (2012) Lithosphere-mantle coupling and the dynamics of the Eurasian Plate. Geophys. J. Int. v. 189(3), pp: 1253-1276

[6] Warners-Ruckstuhl, K. N., Meijer, P. T., Govers, R. & Wortel, M. J. R. (2010) A lithosphere-dynamics constraint on mantle flow: Analysis of the Eurasian plate, v. 37(18)

[7] Z. Zhou, Y. Tao, S. Shujun & W. Ding (2013) Hydrocarbon potential in the key basins in the East Coast of Africa, Petrol. Explor. Develop, v. 40(5), pp. 582-591.

Keynote Speaker: Sequence Stratigraphic Scheme for the Jurassic-Neogene of Coastal and Offshore Tanzania

Pamela Sansom, *BG Group, 100 Thames Valley Park Drive, Reading, RG1 6PT*

A new sequence stratigraphic framework, spanning the post break-up Jurassic to Neogene succession for coastal and offshore Tanzania, is presented here, which relates the onshore/nearshore stratigraphy to the much more complete succession offshore.

Prior to the onset of the recent phase of deep water drilling, the sequence stratigraphy of coastal and offshore Tanzania was known only from outcrop, onshore and nearshore wells, shallow boreholes and un-calibrated 2D seismic data in the deep water areas. The addition of data from 16 deep water offshore wells, together with the acquisition of large volumes of 3D seismic data, has transformed understanding of the stratigraphy and architecture of the Tanzanian offshore basin.

Seismic stratigraphy, coupled with an extensive well biostratigraphic database, has revealed that the post-rift succession comprises a number of unconformity-bound stratigraphic sequences, which can be grouped into 8 megasequences (MS), on the basis of recognition of key bounding unconformities and marked changes in depositional style and slope architecture.

The Lower-Middle Jurassic deposits of the rift basins, which record the rifting and separation of Madagascar from Africa, are assigned to megasequence J1, and are not addressed here. Marine transgression in the upper part of MS J1 is characterised by the deposition of shallow-marine carbonates and associated siliciclastics of Bajocian-Bathonian age, which overstep the syn-rift deposits onto basement in some areas. In Block 1, folding and inversion of the syn-rift deposits occurred prior to the widespread Callovian marine transgression, which marks the base of MS J2 (Callovian-Tithonian) and accompanied the subsequent southward drift of Madagascar along the Davie Fracture Zone. Any remaining intra-basinal highs were drowned during the deposition of MS J1, forming one connected basin across the onshore and offshore areas. MS J1 can be divided broadly into three parts, though biostratigraphic resolution is generally low. Stacked, progradational fluvio-deltaic and shallow marine sequences developed during MS J1a (Callovian-Oxfordian), in the Mandawa Basin, extending into the inboard part of the offshore area. MS J2b is characterised by backstepping of these systems and overall transgression, which culminated with widespread mudstone deposition in the Kimmeridgian. Resumption of fluvial-deltaic progradation is recorded in the Tithonian in some onshore and near-shore wells and characterises MS J2c. However, the extent of these systems is currently difficult to establish, due to differential Base Cretaceous erosion and uncertainty in dating and separating these deposits from similar overlying Lower Cretaceous facies. Offshore, MS J2 is characterised seismically by low amplitude, continuous parallel reflectors, which are capped by the incisional Base Cretaceous Unconformity which defines the base of MS K1.

Megasequence K1 (Berriasian-Aptian) is the least well resolved of the megasequences, due to limited well penetrations offshore for seismic calibration, and poor biostratigraphic dating. Onshore and nearshore wells record thick successions of marginal to shallow marine siliciclastics, with uncertain and commonly conflicting Late Jurassic to Neocomian age interpretations, due to the effects of poor diagnostic microfossil recovery, potential for extensive reworking of Late Jurassic palynomorphs into the Early Cretaceous and the uncertainty due to caving in dominantly cuttings-derived biostratigraphic datasets.

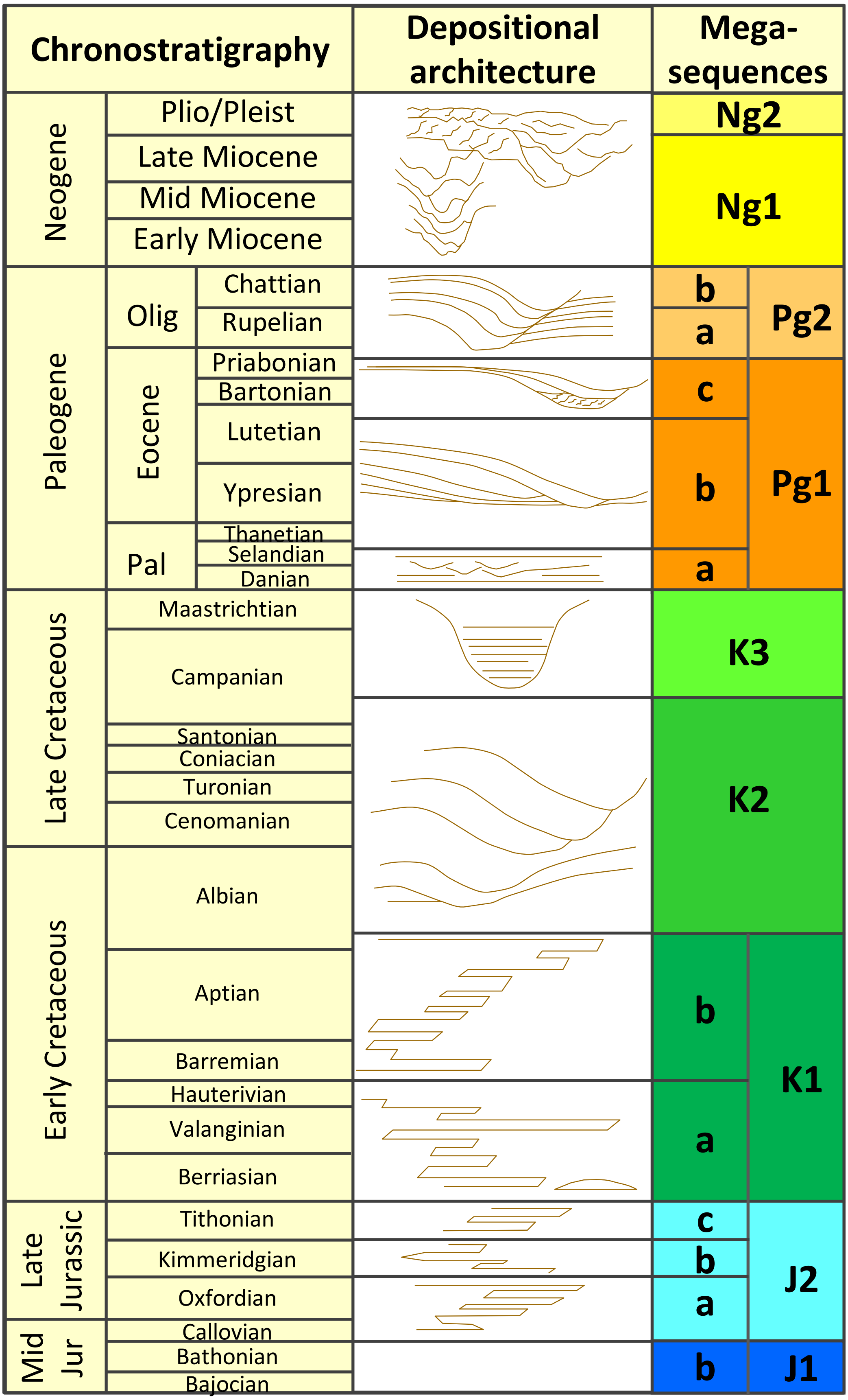


Fig. 1. Sequence stratigraphy and depositional architecture of offshore Tanzania

Offshore, the base of MS K1 is defined by the Base Cretaceous unconformity. This is overlain by a wedge of higher amplitude, variably continuous reflectors which onlap the Base Cretaceous surface. Limited offshore well control and biostratigraphic calibration suggest significant depositional breaks in the Late Berriasian, Late Valanginian and within the Hauterivian, and imply the existence of significant unconformities in the onshore succession. MS K1 comprises a succession of basin-thickening wedges, and is divided into two parts (MS K1a and b) by a prominent regional reflector. In Block 1, two channel systems are defined at the base of MS K1a by incision of the Base Cretaceous surface into the Upper Jurassic, and feed an expanded wedge of probable Early Berriasian sediments. A more prominent and continuous reflector within MS K1a may represent the middle Valanginian unconformity. The age of the prominent reflector separating MS K1a and b is uncertain, and may be either Early Barremian or Early Aptian age. Onshore, the Barremian-Aptian succession is again poorly biostratigraphically calibrated. It is capped by a prominent regional unconformity separating Early Albian outer-shelf shales and marls of MS K2 above from older, shallower marine deposits of MS K1 below. A model is proposed comprising basinward shifts in the Early Barremian, Early Aptian, and Late Aptian-earliest Albian, with transgression and relative highstand conditions in the Late Barremian and latter part of the Early Aptian. Published biostratigraphic calibration of 3 wells from onshore northern Tanzania indicates that ?Early Aptian transgression was followed by a prolonged period of highstand progradation throughout much of the Late Aptian, followed by a major basinward shift no older than the latest Aptian, exposure and erosion of onshore areas, and formation of the unconformity defining the top of MS K1.

The major relative fall in sea level recorded in the onshore wells resulted in the progradation of shallow marine sandstones into the offshore area and possible fan deposition in the deeper parts of the basin, characterised by a typically “stripy” seismic facies. Core from the shallow marine part of this sequence in Block 1 yielded an Early Albian age for the upper part of this sandstone package. This Late Aptian-earliest Albian wedge is interpreted as recording progradation during falling sea level. The MS K2 sequence boundary is picked at the top of this package offshore and at the prominent unconformity below Early-Mid Albian shales onshore.

The K2 Megasequence (Early Albian-Early Campanian) records a pivotal change in the architecture of the Tanzanian margin. Major transgression occurred in the Early Albian, resulting in rapid deepening of the basin and establishing the channelized slope environment which persists to the present day. MS K2 records the development of a thick, muddy slope, characterised by the presence of long-lived slope valley systems, which show a consistent southerly migration and asymmetric stacking pattern, and increasing divergence from the W-E depositional trend of earlier sequences. The slope was increasingly differentiated into mounded overbank areas separating sandy slope valley systems during this time, and seismic geometries suggest the increasing influence of bottom currents on the slope architecture. It is suggested that the magnitude of the Albian transgression pushed the depositional systems far to the west, and that the contourite drifts had time to become established before strongly erosive channel systems advanced, so that the slope channels became captured, amalgamated and deflected by the sediment drifts. The equivalent MS K2 shallow-marine systems have been subsequently eroded, but relative falls in sea level are suggested by the consistent occurrence of sandy channel systems and associated slope fan deposits in the Late Albian, Mid Cenomanian, Early Turonian, Late Coniacian and Early Santonian. The basin appears to have been tectonically stable during MS K2, with the slope architecture controlled by autocyclic depositional processes, bottom currents and sea level fluctuations.

The setting changed again in the Middle Campanian, when more highly incisional systems widened out the slope valleys, creating large, symmetrical canyons following the template set by the MS K2 systems. These large canyons are a particular feature of the Tanzanian slope, and suggest a period of uplift of the African margin, resulting in bigger, more erosive flows. This resulted in the formation of a regional Mid-Campanian unconformity, which defines the base of MS K3 (Mid Campanian-Maastrictian). MS K3 records the complete infilling of these canyons in Mid-Late Campanian times, by backstepping, ponded sheet-systems, comprising high-density turbidity and hybrid flow deposits. This culminated in widespread marl deposition in the Late Campanian to Maastrictian, with only minor reactivation of the canyon systems in the Maastrictian in inboard areas.

The Base Tertiary unconformity, although not strongly incisional on the slope, clearly marks another major change in depositional style at the base of Megasequence Pg1 (Paleocene-Eocene). MS Pg1 is divided into three parts based on changes in depositional style and unconformities recorded in offshore well data. MS Pg1a (Danian-Selandian) records the re-establishment of slope channel systems and a return to W-E flow directions, and comprises relatively unconfined terminal and distributary fan systems and associated thin debris flow deposits. The high-density turbidite deposits are medium to coarse grained and commonly gravelly, indicating rejuvenation of sediment source areas and hinterland uplift. Condensed marly claystones were deposited away from the depositional fairways. Onlap and pinch-out of MS Pg1a in the northern part of Block 4 suggests tectonic uplift of the Mafia Arch at this time. The Danian part of MS Pg1a is also largely absent onshore, where Selandian deposits overlie the Maastrictian on the Base Tertiary unconformity.

More confined and incisional systems evolved in MS Pg1b (Thanetian-Lutetian). Channel deposits sit in the toesets of large, muddy overbank wedges and show a marked asymmetry due to consistent southerly lateral migration, again indicating the interplay of turbidity current and bottom current processes. Individual channel systems erode the southerly side of the previous system as they migrate, resulting in climbing, compound unconformities on the leading edge of the channel fairways, so that seismic correlation across the complexes is very difficult in the absence of well control. Incision appears to increase through the Early Eocene, and channels locally cut out MS Pg1a and incise down into the Maastrictian in the axes of the channel belts. This leads to a highly laterally variable and complex stratigraphic architecture across the slope, with sedimentary units being very thick in one location and virtually absent in another. Condensed marl deposition continued to characterise overbank areas away from active channel complexes. Thick mass transport deposits also characterise this unit in Block 4, possibly suggesting increased slope instability and tectonic activity in this area. The architecture differs from MS K2 in that channel systems maintained a westerly flow direction and did not become amalgamated. It is suggested that the coastline was closer at this time and the slope steeper, resulting in the establishment of erosive channels with a coarse grained sediment load prior to the build-up of the sediment drifts.

The base of MS Pg1c (?late Lutetian-middle Priabonian) is defined by a consistent depositional break in the offshore wells, where the uppermost part of the Lutetian appears to be absent beneath Bartonian-Priabonian deposits. However, this unit is relatively thin compared to the resolution of cuttings-based biostratigraphy, and therefore poorly resolved. It is suggested that this was a time of tectonically-driven remodelling of the slope, which is supported by the presence of two straight, highly incisional channels in Block 1 and a significant unconformity and onlap onto the Chaza high, suggesting movement on the Seagap Fault. Seismic indicates that MS Pg1c is thicker in some areas and contains slope valleys plugged by mass transport deposits, but these areas are not calibrated by well control.

Megasequence Pg 2 spans the Oligocene, and is characterised by the increased entrenchment of the slope channel systems and increased angle of climb of the turbidite-countourite complexes, which build up into thick sequences of laterally-stacked channel complexes separated by extensive overbank drifts characterised by highly laterally continuous seismic reflectors. Upslope-migrating sediment waves are also seen on some overbank areas in Block 4 at this time. The base of MS Pg2 is interpreted as mid Priabonian age, as the upper Priabonian appears to be conformable with the basal Rupelian in wells away from erosional channel axes and in onshore data from Tanzania Drilling Project boreholes. There is a shift to a more vertical aggradation pattern at the base of the Chattian, marked by increased incision of the channel complexes and also the initiation of new slope canyon systems.

The onset of significant deltaic progradation marks the base of the Miocene Ng1 Megasequence in onshore and nearshore areas, accompanied by the development of inboard troughs as the East African Rift system extended into the Tanzania coastal area. The Miocene is unconformable on Oligocene and Eocene sediments in onshore/nearshore areas. Offshore, the base of the Miocene channel complexes is highly incisional, but there may be no significant unconformity in overbank areas, so that the surface can be difficult to map seismically without well control. The Middle-Late Miocene part of MS Ng1 is unconstrained biostratigraphically (above first cuttings returns), but is characterised by the onset of major slope failures in both Blocks 1 and 4, resulting in plugging and disruption of the slope channel systems. A renewed phase of slope failure and extensive fan deposition is represents the Pliocene-Recent Ng2 megasequence, and numerous deep canyons still characterise the slope today.

The changing anatomy of the Tanzanian margin resulted from changes in slope angle, sediment supply rates and sediment grade that occurred in response to tectonic, eustatic and oceanic circulation drivers. The architecture at any one time reflects the dominance of certain drivers over others. Plate-scale drivers include progressive break-up of Gondwana, changes in rotation of the African plate, and evolution of the East African rift system, whilst the extent of the Seagap Fault and persistence of drainage routes such as the paleo-Rufiji and paleo-Rovuma systems exerted more local influence. Detailed calibration of the evolution of the Tanzanian offshore stratigraphy and comparison with adjacent areas of the margin will aid further differentiation between plate-scale and local drivers and dating of major tectonic events.

NOTES

A Source to Sink Study of the Rovuma Basin, Mozambique

David Johnstone[1], Inga Sevastjanova[2], James Bowkett[1], Matthew Gelsthorpe[1], Paul Markwick[2],

[1]*ERCL*
[2]*Getech Group plc, UK*

The present study examines the link between the different morphological elements of the Rovuma Basin (hinterland catchment, shelf, slope, and basin floor) in order to better understand reservoir presence and quality through time. This also provides an opportunity to test some of the common concepts of source to sink studies, which relate variations in sediment flux to morphological and sedimentological evolution of an erosional-depositional system (Sømme et al., 2009).

The Rovuma Basin is approximately 400 km long by 160 km wide, covering an area of 64,000 km2 and is centered on the Rovuma River Delta. At the present day, sediments are shed into the Rovuma Basin from five principal rivers, Rovuma, Messalo, Montepuez, Lurio and Mecurburi, with catchment areas ranging from 10,248 km2 to 162,807 km2. The present day bathymetry shows a well-defined shelf-slope and basin floor with a series of slope channels (Figure 1).

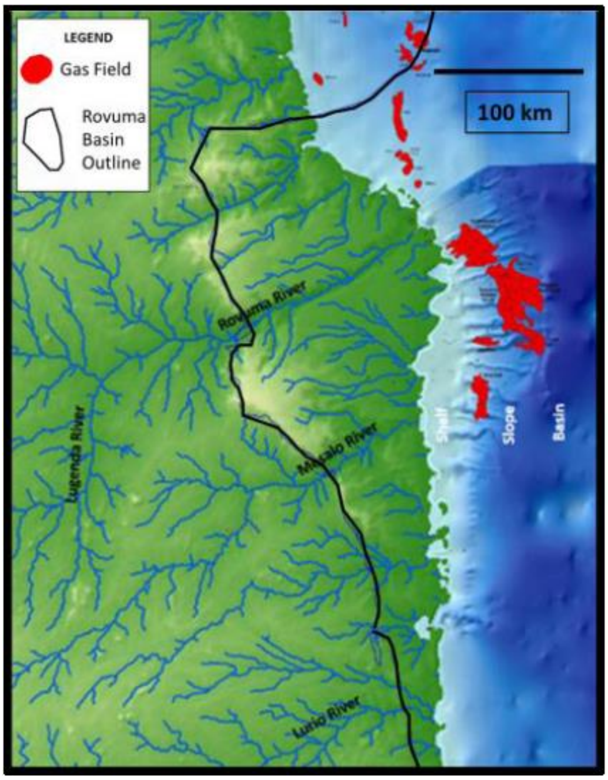


Figure 1. Location of the Gas discoveries and present day bathymetry of the Mozambique portion of the Offshore Rovuma Basin.

ERCL have been working together with INP (Instituto Nacional de Petróleo) in Mozambique to interpret recently released data in the Rovuma Basin. In parallel, Getech have completed a series of regional studies on the drainage basin history of East Africa and this presentation links these two different, but complementary, studies.

The offshore Rovuma Basin has, since 2006, seen a number of gas discoveries in Cenozoic slope channels and fans of Paleocene, Eocene and Oligocene ages. Other Upper and Lower Cretaceous targets have been tested but without the same success. The seismic expression of these fans is shown in Figure-2. These channel and submarine fan sands have been the focal point of exploration in the Rovuma Basin, leading to several large discoveries by Anadarko and ENI, in Mozambique. Current recoverable reserve estimates for the Mozambique Rovuma Basin are around 140-180 TCF. The Tanzanian portion of the Rovuma Basin has also seen a number of discoveries over a similar time period, though the reserves are an order of magnitude smaller, at around 20-30 TCF of gas.

Biostratigraphic data are sparse but, where available, indicate major depositional breaks in the Early Cretaceous (Late Aptian to Early Albian), Late Cretaceous to Early Paleogene, and Mid-Eocene to Oligocene. These are regional events and are also seen in adjacent basins including the equivalent transform margin in Madagascar. These events are also linked to distinct sediment input with Paleocene, Eocene and Oligocene slope and channel fan sandstones, with excellent quality, being widely distributed across the offshore area.
RMS amplitude extractions highlight the location and geometry of these reservoirs, and their feeder channels, from the top Paleocene to present day. These fans have areas from 12 km2 up to approximately 150 km2. There is an increase in sediment delivery through the Oligocene, with a consequent increase in the fan size. Lower sedimentation rates through the Miocene, result in more confined and linear reservoir units, which have a much smaller lateral and distal extent. Generally these fans and channels appear to overlie each other through the Cenozoic, with little evidence of major shifts in the location of the sediment entry points.

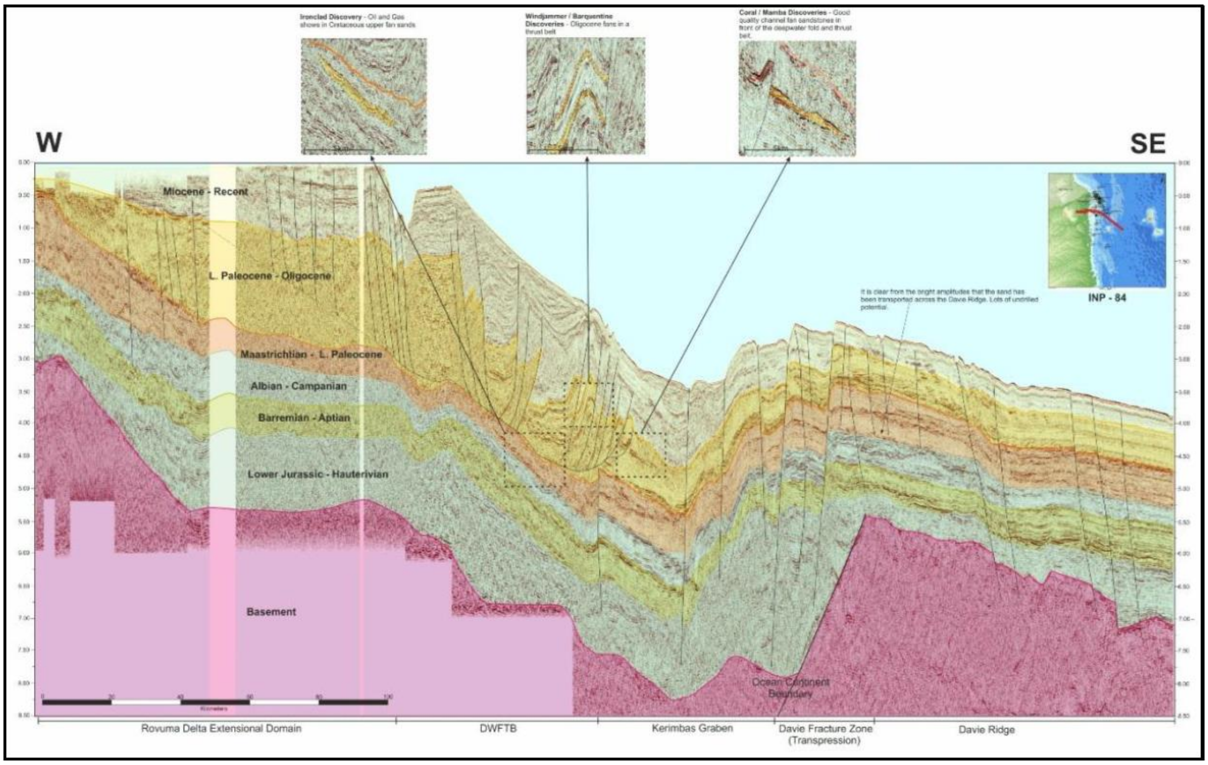


Figure 2. Regional seismic line across the Rovuma Basin, showing the different play types and high amplitude reservoir sands.

Getech's drainage and landscape analysis suggests that most rivers feeding sediments into the Rovuma Basin are mature. The limits of their catchments were definitely established during the

Early Cretaceous. This may even have been earlier, during the latest Jurassic, after the intrusion and extrusion of the Chilwa Volcanic System in southern Malawi. This interpretation is consistent with the published apatite fission track (AFTA) and (U-Th)/He data from the crystalline basement of Mozambique. These data record two periods of rapid cooling due to uplift during the Mesozoic, 1) Early to Late Jurassic and 2) Early to Late Cretaceous. These were followed by persistent slow denudation from Late Cretaceous to Paleogene/Neogene, with a localised Paleogene reheating event along the eastern margin of the Lurio Belt (Daßinnies, 2006). A long-lived drainage network implies that fluctuations in sediment supply to the Rovuma Basin offshore are more likely to be the consequence of changes in climate and relief, rather than changes in the river network.

References

Daßinnies,M.Ch., 2006. The Phanerozoic thermo-tectonic evolution of northern Mozambique constrained by 40Ar/39Ar, fission track and (U-Th)/He analyses. Universität Bremen, PhD Thesis, 268 pp.

Sømme,T.O., Helland-Hansen,W., Martinsen,O.J., Thurmond,J.B., 2009. Relationships between morphological and sedimentological parameters in source-to-sink systems: a basis for predicting semi-quantitative characteristics in subsurface systems. Basin Research 21, 361-387.

NOTES

Provenance within the Eastern Coast Of Tanzania from the Jurassic to Neogene Periods.

Tom Stone[1], **Ross McCabe[1]**, Dr Pamela Sansom[2]

[1]*Chemostrat Ltd, Unit 2 Ravenscroft Court, Buttington Cross Enterprise Park, Welshpool, Powys, SY21 8SL, UK*
[2]*BG Tanzania, 100 Thames Valley Park Drive, Reading, Berkshire, RG6 1PT, UK*

The N-S trending offshore basins of Tanzania developed in response to the breakup of Gondwana and have been active sedimentary basins since the Permo-Triassic. The region has been subject to considerable interest following several high-profile gas discoveries in the last decade, which has led to an increase in geoscientific work conducted in the area. Chemostrat Ltd have been involved in a series of regional provenance studies to better understand the development of the sedimentary system in Tanzania and how provenance evolved over time and space to help understand the locations and volume of coarse clastic sediment in the offshore areas.

Detrital zircon U-Pb geochronology is a powerful technique used for studies of sand and sandstone provenance. It has been successfully employed in siliciclastic sediments for mapping reservoirs in the basins, tracing sedimentary pathways, recording denudation histories and dating volcano-magmatic events. This approach identifies characteristic detrital zircon age spectra, compares them with those from other stratigraphic units in the basin and matches them with potential sediment source areas.

The onshore basement geology of East Africa reveals a complicated history with several distinct geological terranes developed. The main terranes proximal to the basin are the Tanzanian Craton, Ubendian-Usagaran Belt and Irumide Belt, with all three being subject to overprinting by the Mozambique Belt. From thorough review of available literature as well as geochronological dating of basement by Chemostrat Ltd, five key terranes are identified for evaluating the detrital zircon spectra. These terranes are as follows:

- 400-700 Ma: Mozambique Belt Granulite Facies Metamorphism
- 700-1200 Ma: Irumide Belt & other rocks related to the breakup of Rodinia
- 1200-1550 Ma: Kibaran/Karagwe and Ankole Belt
- 1600-2100 Ma: Ubendian-Usagaran Belt
- 2400-2900 Ma: Tanzanian Archean Craton

As these terranes are situated in distinctly separate parts of East Africa, tracing regional sedimentation patterns is more effective with detrital zircon U-Pb geochronology than with other provenance techniques, which struggle due to the lithological and mineralogical complexity of the mobile belts.

Using the published information on the ages of the hinterland, sand-prone successions from wells both onshore and offshore have been analysed across Tanzania to determine provenance and map out provenances shifts within the sediments from the Jurassic to the Neogene periods.

From reviewing the detrital zircon data from the sediments, several different drainage systems are apparent, making it possible to understand where wells shared a similar drainage basin and where changes in provenance occur. To the south, the provenance seems to have been limited to the Masasi Spur and Northern Mozambique, whilst further north the situation appears more complicated, with sediments being routed variably through the Selous Basin and/or the Mafia Trough. The lack of Kibaran/Karagwe and Ankole Belt zircons throughout the successions suggests that at no point did the catchment for these sediments extend beyond the western branch of the East African rift system.

A key finding from this study has been a major change in provenance that roughly coincides with the Cretaceous-Paleogene boundary, with a shift in provenance interpreted as an increase in the amount of sediment originating from the northwest of Tanzania, likely caused by intracontinental tectonism and an ongoing marine transgression in East Africa.

NOTES

Elemental Chemostratigraphy of the Kilwa Group, Tanzania.

Ross McCabe[1,2], Dr Christopher Nicholas[2]

[1]*Chemostrat Ltd, Unit 2 Ravenscroft Court, Buttington Cross Enterprise Park, Welshpool, Powys, SY21 8SL, UK*
[2]*Trinity College, Dublin, College Green, Dublin 2, Ireland.*

The Kilwa Group currently comprises five clay-dominated formations deposited between the Early Cretaceous (Albian) to Late Paleogene (Oligocene) Epochs in the Mandawa Basin, south eastern Tanzania. The various lithostratigraphic units were deposited in a mid to outer shelf setting across a passive margin. The Kilwa Group have been the subject of detailed scientific research by the Tanzanian Drilling Project (TDP) for nearly 15 years. In that time, numerous publications have been produced that deal with the lithostratigraphy, biostratigraphy, stable isotope stratigraphy and sedimentology of the group, as penetrated by over 40 shallow cores. Despite the wealth of work, the formations of the Kilwa Group are not clearly defined based on the characteristics of the primary lithology.

Presented here is a comprehensive chemostratigraphic examination of 27 TDP cores that cover the Kilwa Group in its entirety. Chemostratigraphy involves the characterisation and correlation of sedimentary successions based on variations in bulk-rock elemental composition. The key elements and element ratios employed in any chemostratigraphic study model mineralogical variations that, themselves, are controlled by variations in climate, environment, provenance and diagenesis. The analytical resolution of the inorganic geochemical data is such that even the most subtle of mineralogical variations can be detected in apparently uniform sedimentary successions.

Approximately 1500 core samples, collected at 1m spacing, have been subjected to inductively coupled plasma (ICP) optical emission spectroscopy (OES) and mass spectrometry (MS) analysis, with high-resolution data being acquired for fifty elements. The objectives of the study have been to:

1) To test the lithostratigraphic definition of the Kilwa Group based on the chemical characteristics of the primary lithology.

2) Understand the mineralogical (and therefore, geological) controls on the data

3) Proposed amendments to the lithostratigraphic model based on the chemical data

Using the inorganic geochemical data, the Kilwa Group has been divided into (in order of resolution) four chemostratigraphic sequences, five chemostratigraphic packages and six chemostratigraphic units. The key elements that define the various chemostratigraphic zones are; Th, Zr, Ti, Sc, K, Rb, Na, Mg, Ca and Mo, which, themselves, are interpreted to model variations in heavy minerals, feldspars, clay minerals, carbonates and authigenic minerals. The variations in the inorganic geochemistry of the Kilwa Group claystones reflect temporal changes in climate, environment and sediment provenance within the Mandawa Basin and whilst the main chemical signatures can be broadly linked to the five lithostratigraphic formations, subtle revisions are proposed to the existing lithostratigraphic model.

The results of the study highlight the efficacy of bulk-rock chemostratigraphy as a tool for basin modelling, both at a regional and local scale. Additionally, the results highlight the need for a comprehensive and formally-defined lithostratigraphic model for the entire Tanzanian coastal margin that draws upon as many different scientific disciplines as possible.

NOTES

Thursday 14 April

Session Three: Sedimentary Systems

Tectono-Stratigraphic Evolution of the East African Coastal Basins: Observations and Insights from Rock-Based Regional Studies in Kenya, Tanzania and Mozambique.

Anne McAfee, *Core Laboratories Integrated Reservoir Solutions, UK.*

Our initial rock-based regional study of the Tanzanian Coastal Basin highlighted the importance of deep-seated structural features in controlling the lateral distribution of sands, carbonates and shales across onshore and shallow water offshore blocks, particularly during deposition of the Karoo and Lower Cretaceous succession. More recent follow-up geological studies in Kenya, Uganda and Mozambique, combined with additional well datasets from Tanzania, have provided us with a wider regional perspective of the Indian Ocean Margin as a whole, offering insights into the large-scale regional tectonic elements which controlled sedimentation patterns during the highly complex Cretaceous and Tertiary periods of margin evolution.

The main focus of recent and ongoing, highly successful, exploration campaigns on the East African Margin has been within the deepwater offshore basins. It is therefore easy to overlook the importance of studying the onshore and shallow-water coastal regions which, in addition to hosting important hydrocarbon reserves (e.g. Songo Songo; Pande-Temane), formed the 'staging area' for sediments deposited further offshore. Inboard parts of the margin also provide access to basement-involved structures which are usually deeply buried and highly overprinted in the more distal offshore blocks. Detailed and systematic evaluation of all geological datasets from onshore and coastal wells is therefore particularly useful in providing clues to the tectonic evolution of the East African Margin, where oblique-trending transpressional and transtensional Cretaceous and Tertiary structures intersected and overprinted deep-seated Karoo extensional structures, during multiple phases of reactivation and adjustment of the structural architecture.

The main consequence of Karoo rifting was the creation of a horst and graben topography; a branching system of topographic highs and lows which appear to have continued to strongly influenced sedimentation patterns throughout a prolonged 'rift transition phase' from the Upper Jurassic to the Barremian. Fluvial-deltaic systems were established within the main axial-trending structural lows (e.g. Dar es Salaam Platform, Tanzania), while locally, thick sequences of wave-winnowed sands were trapped within fault-bounded terraces along the paleo-shoreline (e.g. Songo Songo Field).

Data from both the coastal and interior basins provide evidence of a major change in both structural style and drainage patterns during the Albian – Cenomanian, apparently triggered by tectonic uplift of the hinterland, which led to deep incision of the basin margins. Although this mid-Cretaceous interval is thin and truncated in many onshore and shallow-water wells, core data provides evidence of significant forced regression at this time, which led to preservation of sand-filled incised valley and shelf-edge canyon systems. This regressive episode was followed by a prolonged transgressive phase during the Late Cretaceous which led to widespread deposition of marine shelf and slope shales, although significant deep marine sands were deposited at a number of locations during a significant Campanian regression (e.g. Mafia, offshore Tanzania and Pomboo, offshore Lamu Basin), possibly in response to Santonian uplift and rejuvenation of sediment source regions at this time.

The Early Tertiary marked the start of a major regression in the northern part of the Tanzanian Coastal Margin, apparently in response to rapid and substantial uplift along the eastern margin of the Kenya Dome. This uplift event preceded the initiation of the EARS. During the Paleocene – Early Eocene sediment supply exceeded subsidence rates, resulting in rapid outbuilding of a fluvio-deltaic lobe across the northern margin of the Dar es Salaam Platform in Tanzania at this time. From Mid Eocene to Pliocene times, sedimentation patterns along the coastal margin became extremely complex due to rapid and pronounced changes in the configuration of the basin architecture, in response to evolution of the East African Rift System. Observations from well log and rock data suggest that differential transpressional movements on ‘transform-related’ structures such as the Seagap Trend (Tanzania) and the Davie-Walu Fault system (Kenya) led to creation of a series of (N & NNE-trending) offshore topographic ridges which became sites for carbonate platform accumulations, while adjoining rapidly subsiding troughs accumulated thick successions of deep marine shales and sands. Southward propagation of the East African Rift System also appears to have resulted in reactivation of significant Precambrian basement lineaments (such as the NW-trending Aswa Shear Zone) resulting in rapid switching of sand and carbonate depocentres during the Late Tertiary, as seen in the Pemba-Zanzibar region, offshore Tanzania and in the Lamu Embayment in Kenya.

In contrast to the strong (N and NNE-trending) Karoo rift and offshore transform-related faults observed along the Kenyan – Tanzanian coastal basins, sedimentation patterns in the Mozambique Basin appear to be very strongly controlled by oblique ENE-trending structures, parallel and sub-parallel to the prominent offshore ‘Beira High’ trend. When viewed in a greater regional context these ‘Beira-trend’ lineaments appear to correspond to strike-slip or transform fault zones along the southern edge of the ‘Ruvuma Microplate’. Repeated transtensional and transpressional displacement on these deep-seated lineaments led to multiple episodes of uplift on regional topographic highs (e.g. Beira High, Inharrime High) which formed preferential sites for carbonate deposition along the coastal and offshore parts of the Mozambique Basin. Inboard of these regional highs, rapid subsidence led to creation of major depocentres, which locally filled with ponded sands where the offshore highs obstructed basinward transport of sediment sourced from the western basin margin. Systematic mapping of facies trends shows that these oblique-trending lineaments exerted a strong control on the location of sand, carbonate and shale depocentres throughout the Late Cretaceous and Tertiary evolution of the Mozambique Basin.

NOTES

Uplift and Deposition of Sediment at Passive Margins: Examples from Africa

Bhavik H. Lodhia, Gareth G. Roberts, Al Fraser, *Department of Earth Science and Engineering, Imperial College London*

It is generally accepted that histories of sedimentary flux at passive margins contain information about uplift and erosion histories onshore. Inversion of drainage inventories for uplift histories suggests that we might be able to quantitatively link long-term uplift onshore and delivery of sediment to passive margins. We use an inventory of 14601 river profiles in Africa to invert for Cenozoic histories of uplift and predict erosion rates. We test our model by comparing predicted rates of sedimentary flux to our measurements of solid-sediment flux offshore Mauritania-Senegal and the Mozambique Channel. The drainage inventory was extracted from the 3 arc second SRTM dataset. The stream power erosional model was calibrated using independent observations of marine terrace elevations and ages. Solid sedimentary flux was measured from decompacted isopach volumes mapped using dense 2D seismic reflection and well data. Our preliminary results suggest that we can close the loop between Cenozoic uplift onshore and efflux to west and east Africa's passive margins. Calculated uplift and erosion is staged and suggests that African topography was rejuvenated during the last ~30 Ma.

Keywords: *sedimentary flux, uplift, erosion, inverse model, Cenozoic, passive margins*

NOTES

Oligocene to Quaternary Turbidites and Contourites of the Zambezi and Angoche Basins South of the Mozambique Channel

Olga Kurnosova and **Carlo Cazzola**, *TOTAL, 2 place Jean Millier La Defense 6, 92078 Paris*

The studied area is located between the Mozambique continental margin and the Davies ridge that corresponds to the western boundary of the Madagascar continental crust.

The oceanic currents in the Mozambique Channel are presently dominated by a train of large anti-cyclonic eddies (diameters >300 km) that reach the channel bottom and propagate southward, leading into the Agulhas Current off the east coast of South Africa.

The tertiary Zambezi deep sea fan of the Mozambique Channel is a turbidite system whose internal architecture was controlled by erosional and depositional features linked to the contourites.

Seismic evidences indicate that deep oceanic currents start to have strong influence on the sedimentation since late Eocene. Reinforcement of oceanic currents is probably associated with global reorganization of oceanic circulation due to simultaneous closing of Thethys and Panama seaways and opening Drake and Tasmanian seaways.

The study consisted of separating out time-depositional units based on detecting and picking unconformities or changes in seismic patterns.

Inside the depositional sequences the main depositional elements (turbidite channel belts, turbidite fans, contourite channels, contourite drifts and mass-transport deposits) were identified from seismic reflection characteristics and then mapped.

Several types of contourite drift were observed. They can be classified according to the nomenclature proposed by Rebesco et al. (2014). Plastered drifts, separated drifts, detached drifts were observed. In addition contourite dunes were observed to the east of the Beira High (Fig. 1). Such type of deep water dunes have almost no analogue described in the literature except, perhaps, for the barchan dunes described by Viana (2007) and Mutti et al. (2014) on the eastern margin of Brazil.

Since the late Eocene and during the Oligocene changes in the seafloor topography produced by erosion or deposition induced by strong bottom currents lead to the re-adjustment of the sediment accommodation space. In particular, the formation of a huge contourite drift elongated in E-W direction (Fig. 1), led to the individualization of two sub-basins (Zambezi and Angoche). During the Miocene the turbidites derived by the Zambezi delta were deflected to the NE by the submarine relief, channeled into previously excavated contourite channels and deposited into the Angoche basin whose outlet to the south was blocked by the giant contouritic ridge formed during the Oligocene.

In the late Miocene the Angoche basin was completely filled and turbidites could overflow from the dam formed by the giant contouritic ridge and spill over into the open basin to the south, forming the Zambezi Valley which remains the feeder of the main Zambezi fan nowadays.

At the end of the Pliocene the structural depression located NW of the Beira high was filled by the Zambezi prograding slope sediments thus allowing the following turbidites to spill into the basin located to the east. This basin was completely filled during the Pleistocene.

The study allowed to highlight the differences, in terms of seismic facies and geometry, between channels formed by turbidity currents and channels excavated by deep oceanic currents and to assess the interaction between gravity flows and thermohaline bottom currents.

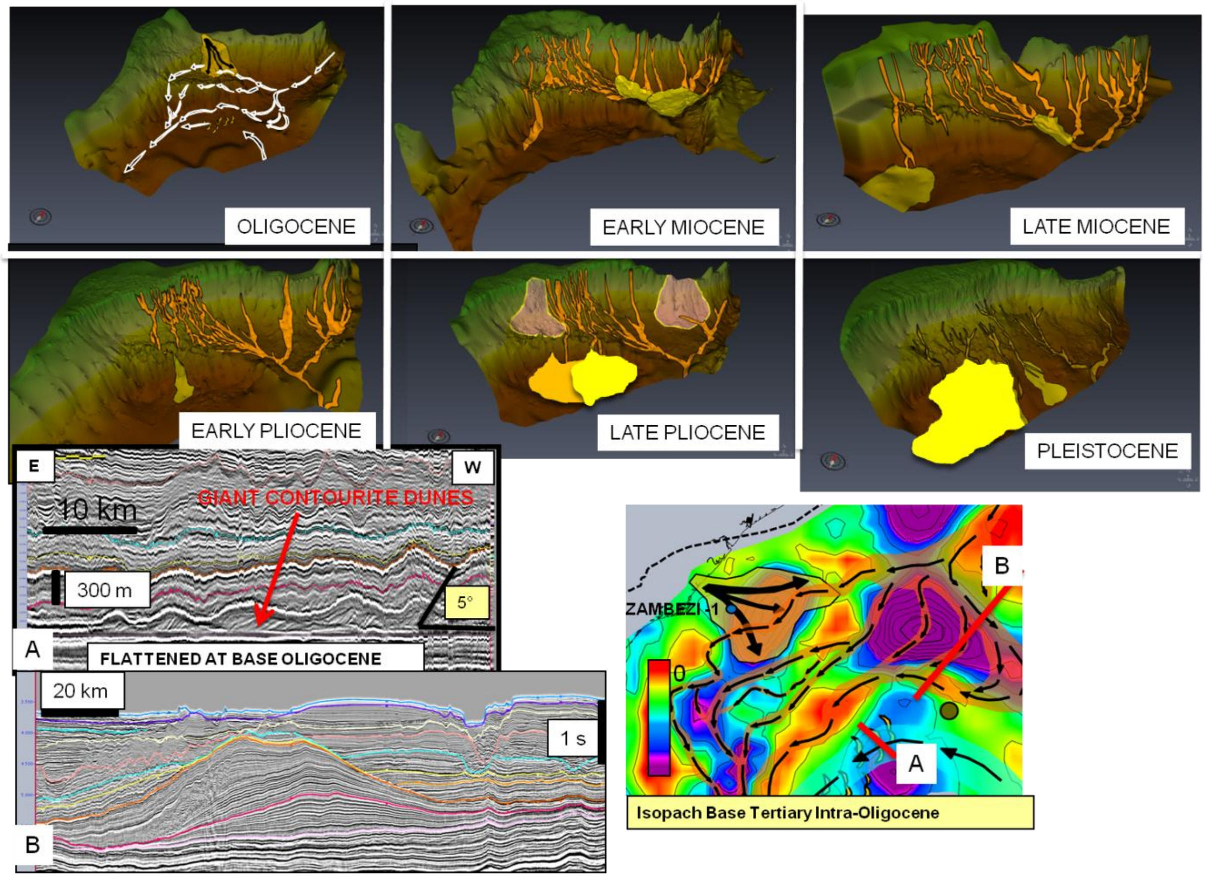


Fig. 1. Sedimentary evolution of the western margin of the Mozambique channel From Oligocene to Pleistocene and seismic sections showing giant contourite dunes (A) and detached contourite drift (B).

References

Mutti, E., Cunha, R.S., Bulhoes, E., Arienti, L.M. , Viana, A. R., 2014. Contourites and Turbidites of the Brazilian Marginal Basins Search and Discovery.

Rebesco,M., Hernández-Molina, F.J., Van Rooij, D.,Wåhlin, A., 2014. Contourites and associated sediments controlled by deep-water circulation processes: state of the art and future considerations. Mar. Geol. 352, 111–154.

Viana, A.R., Almeida, W., Nunes, M.C.V. & Bulhões, E.M., 2007. The economic importance of contourites. In: A.R. Viana & M. Rebesco (eds), Economic and Palaeoceanographic Significance of Contourite Deposits: 1-24 London: Geological Society Special Publication 276

NOTES

Keynote Speaker: Reservoir Quality and Producability of Deepwater Tanzanian Gas Reservoirs

Ross Garden, *BG Group*

Significant gas discoveries have been made in deepwater offshore southern Tanzania since 2010 in continental slope gravity flow deposits of Aptian to Miocene age. Sands were deposited in a variety of slope settings including canyon fills (cf. the Jodari field), amalgamated channel complexes (cf. the Pweza and Chaza fields), channel-lobe transition successions (cf. the Chewa field), levees (cf. the Fulusi and Mkizi fields) and intraslope basin fills (cf. Mzia). Examples of many of the depositional settings can be seen on the existing sea floor where canyon heads extend into the river mouths bypassing the narrow present day carbonate shelf. While simplistically reservoir quality can be considered at the pore scale, the key to understanding the complexity of the development of deep water reservoirs comes from integrating this information with the reservoir architecture. As well costs, design and water management are fundamental drivers of project economics it is important to understand the interplay of reservoir thickness and heterogeneity, hydrocarbon column thickness, aquifer size and distribution in addition to reservoir properties. It is only once these aspects are accounted for can the subtlety of reservoir quality be fully appreciated.

In southern offshore Tanzania, the majority of the gas bearing sands discovered to date were deposited in large scale canyon incisions or as channel complex fills and comprise amalgamated, high density turbidite deposits. Debrites and mass transport complex deposits are common within the parts of some incisions and at channel and canyon margins. Locally these mudrock-prone deposits form intra-reservoir seals. Internal and external levee deposits are locally preserved in channel complexes and comprise heterogeneous reservoirs of muds and thin-bedded high quality sands. In contrast to the canyon and channel complex deposits, the Upper Cretaceous Mzia field comprises a heterolithic succession of sands deposited within a transtensional pull-apart basin along the sinistral strike-slip Seagap fault.

Texturally the Tertiary and Cretaceous sands are moderately mature, fine to coarse grained and moderately to moderately well sorted. However, compositionally they are immature plagioclase-rich arkoses to sub-arkoses. Heavy mineral analysis is consistent with derivation from the Precambrian metaigneous rocks, granulite metasedimentary rocks of the Mozambique belt in southern Tanzania and northern Mozambique. The geothermal gradients across the south Tanzanian margin are high, but as most Tertiary reservoirs are at relatively shallow depths below mud line and diagenesis is generally not a major impact on reservoir quality. However, in the deeper Cretaceous reservoirs quartz cementation becomes increasingly significant with depth.

Unsurprisingly reservoir properties in most of the reservoirs are primarily controlled by grain size with sorting and clay content having secondary impact. Localised carbonate cementation as doggers is common and in more deeply buried, clean sandstones well developed quartz overgrowths have a degradational effect on porosity and permeability. In consequence the prediction of porosity is relatively well constrained in reservoirs dominated by clean, high density turbidite sands. However, things are somewhat different where deposition is from event beds transitioning between turbulent and laminar flow conditions. In these hybrid beds, clay content and distribution can vary considerably. In these sands, clay is present in a variety of forms; mudclasts, silty to very fine grained bed caps, and as dispersed pore-filling and lining clay in intergranular pores. Pore-filling clays are commonly chloritised and retain significant porosity albeit in micropores. In consequence the distribution of chloritic pore-filling clays significantly impacts water saturation and absolute and relative permeability.

NOTES

Large Volume Event Beds; Their Origin, Significance and Implications for the Development of the Mzia Field

Kearney-Cunningham, F.[1], Baker, R.[1], Garden, R.[1], Haughton, P.[2]

[1]*BG Group, 100 Thames Valley Park Drive, Reading, Berkshire RG6 1PT UK, UK*
[2]*UCD School of Geological Sciences, University College of Dublin, Belfield, Dublin 4, Ireland*

Mzia is a giant gas field located in the Ruvuma Basin within the Block 1 licence, offshore Tanzania. The discovery well, Mzia-1, was drilled in 2012 and encountered deep-marine sandstones of Cretaceous age; subsequently a further two appraisal wells have been drilled and partly cored. The reservoir consists of a number of offset-stacked turbidite sequences that were deposited in a confined basin setting. The reservoir was initially divided into Upper, Middle and Lower units, the latter further subdivided into four intervals (Lower Sand 1-Lower Sand 4). This presentation concerns the Lower Sand 2 (LS2), the thickest and most volumetrically significant of the sandstone units in the field.

Six categories of event bed have been identified in the LS2 on the basis of their expression in core. Bed types 1 and 4 represent high- and low-density turbidites respectively and bed types 5 and 6 represent differing styles of hybrid event bed. Bed types 2 and 3 are mud clast-rich beds and are interpreted to record the onset of flow transformation from a high-density turbidity current to a hybrid flow. These beds are interpreted to have been deposited beneath spatially and temporally complex flows fluctuating between more turbulent and more cohesive dominated flow regimes. Type 4 beds account for 75% of the total bed count in the cored intervals and are on average 0.19 m thick. The remaining bed types are, on average, in excess of 1.5 m thick, and account for over 50% of the total LS2 thickness. The understanding of the processes that led to the deposition of these beds, termed large volume event beds (LVEBs) on account of their thickness, and their lateral variability on a bed scale has important implications for future reservoir development.

The LVEBs are interpreted to have been deposited from flows that were initially high-density turbidity currents with the resulting bed type controlled by the equilibrium state of the feeder slope and/or basin floor during deposition. The equilibrium state of the system is interpreted to have controlled the amount of mud-clast entrainment via substrate erosion ultimately controlling end-member bed character in conjunction with topographically induced flow constriction and expansion and interactions with the confining basin margins.

A newly proposed well correlation of the LS2 interval has been developed which suggests a down-dip and marginal transition from high-density turbidites and mud clast-rich beds to hybrid event beds and low-density turbidites. Based on the results of this correlation, a higher abundance of high-density turbidites and mud clast-rich beds are predicted in more proximal settings with a progressive transition marginally and distally to hybrid event beds and low-density turbidites.

NOTES

Contourite Deposition over Time along the Offshore Tanzania Margin: Controls, Architectures, and Effects on Hydrocarbon Prospectivity

Carole Decalf[1], **Eleanor J. Stirling[2]**, and Jake Hossack[3]

[1]*BP America, 200 Westlake Park Blvd, Houston, TX 77079, USA.*
[2]*BP EOC Ltd, 8 Novinskiy Blvd., Moscow 121009, Russian Federation*
[3]*BP UK, retired.*

Introduction

The East African margin has proved to be a prolific gas province, with a series of giant fields discovered since 2007. One of the reasons for this exploration success is the thick, stacked, high net-to-gross sandstone reservoirs within the Cretaceous and Tertiary sedimentary sections in the offshore. These sands entered the basin as turbidite flows, and were strongly influenced both by slope topography and structure, and by contourite currents flowing along the margin. The resulting mixed-process deposits can contain higher concentrations of good quality sands, which can be excellent reservoirs. Understanding the controls on these contourite-turbidite deposits is critical to predict where and when they occur. The tectonic history of the margin, the structuration of the slope, and the erosional and depositional topography created by the turbidite and contourite currents themselves, all play a significant role in controlling currents and deposits. This paper gives examples of observed contourite-turbidite distribution patterns and architectures in offshore Tanzania on 2D seismic. We describe the deposits over time and we discuss the factors controlling sand distribution. This work is based on a limited data set, and should be tested against more comprehensive data sets along this margin and in other mixed contourite-turbidite systems.

Regional Tectonic Setting and Slope Structuration

Along the present-day East African margin, contourites are formed by deep cold thermo-haline waters flowing north-eastwards from the Antarctic to the Indian Ocean. In the geologic past, such currents could only begin when a through-going marine connection between the pole and the equator was formed by continental break-up and spreading along the East African margin. Initial rifting started in the Jurassic between 183-170 Ma, followed by N-S sea-floor spreading from 168-120 Ma, which occurred in three offset ocean basins: the Weddell Sea, and the Mozambique and Somali oceans. Complete marine connection only occurred when the southward drift of Madagascar ceased at 120 Ma. However, thermo-haline flow of contourites was only possible after the mid-ocean ridges of the three connected oceans cooled and subsided to 3-4 km water depth, which seismically we estimate to have occurred around the Albian-Aptian at ~112 Ma. The strength of contourite currents must have varied through Cretaceous-Tertiary times, driven by climatic variations of hothouse and glacial conditions. Most active currents are to be expected with the initiation of Antarctic glaciation in the Oligocene. Also key sea-floor spreading events at 145 Ma, 130 Ma and 90 Ma would have impacted current geometries as the South Atlantic, Antarctic, and South Indian oceans formed to create the present ocean geography.

Numerous structural lineaments related to the tectonics of the margin, of which the Davy Fracture Zone (DFZ) is the most significant, are orientated roughly parallel to the present-day coastline, and represent strike-slip movement along the margin. Turbidite flows are often captured and diverted by these margin-parallel features, while the contourites currents tend to flow parallel to them. Seismic images of depositional architecture show that the contourite currents prevailing during the Cretaceous and early to mid-Tertiary flowed from north to south – the opposite direction to modern-day contourites.

Contourite Depositional Architectures

Along the offshore Tanzania margin, Lower and Mid-Cretaceous deposition is highly impacted by volcanism. In the northern part of the margin, sills obscure the seismic character making it difficult to identify any seismic facies. Overall, the seismic facies of the Aptian to Santonian package are moderate to high amplitude semi-continuous reflectors with few channel-like forms. The Tanzania Outer High locally acted as a barrier and experienced no deposition. Basinward, the seismic becomes dim with more-or-less parallel continuous reflectors. Several discrete contourites have been observed in this section and could be described as mounded drifts, following Faugeres *et al.*'s 1999 classification.

The Upper Cretaceous section (Santonian to Top Cretaceous) shows parallel continuous seismic reflectors in the southern part of the margin. Deposition appears well behaved, with some local transparent (muddy) wedge shapes separated by bright reflectors (hiatal surfaces). These wedge-shape drifts migrate upslope and form a very large (250 x 170km) contourite zone. The Outer High is again a major control on deposition, with sediments thinning over it; chaotic seismic facies east of it suggest debris flows and slumps originated from it.

The Tertiary section of the Tanzanian offshore comprises interleaved turbidite, contourite, and mixed-influence deposits. Elements identified on 2D seismic include large stacked incised slope channels, smaller channels incising the lower slope, channelized sheet facies (fan lobes), migrating contourite channels and associated contourite drifts, inter-channel parallel continuous facies representing quieter background hemipelagic deposition, and abyssal plain pelagics and contourite sheets.

The contourite drifts fall into four main categories, using Faugeres *et al.*'s classification scheme (1999): 1) separated drifts (upslope migration); 2) confined drifts; 3) channel-related drifts (down-current migration); and 4) abyssal sheet drifts, which exhibit striking wavy or ripple-like migrating seismic architectures. There are also many areas of mixed-influence deposits where turbidity and contourite currents combine to create erosional and depositional architectures that show characteristics of both processes.

We observed the evolution of turbidite channels downslope from purely erosional large stacked channel systems (typically >2km wide, >100m deep), to mixed aggradational and erosional channels with asymmetric levees, to smaller channels with low-relief levees and associated sheets. The main differences between typical turbidite systems and these East African mixed-influence systems are: the asymmetry of the levees, which form predominantly on the southern side of the channels, since contourite currents sweep the plumes of finer sediment southwards; and the progressive diversion of the channels themselves from a west-east (downslope) orientation to northwest-southeast and even north-south directions.

The reworking and diversion by contourites of the turbidite-supplied sediments serves to winnow away the finer-grained components of the flows. This results in concentrated stacked sandy facies and adjacent drifts of muddy/silty facies (based on seismic facies). In this way, very high net-to-gross potential reservoirs are developed and seals for them are provided by adjacent and subsequent contourite drift deposits. Mapping of slope structures and understanding turbidite-contourite interactions allows predictions of where these good quality sands can be found.

NOTES

Thursday 14 April

Session Four: Petroleum Systems to Reserves

Keynote Speaker: Appraisal of Prosperidade Gas Field, Area 1 - Rovuma Basin, Northern Mozambique

Glenn Rising, Alrik Thiriet & Scott Munsell**,** *Anadarko Petroleum Corporation*

Area 1 Partnership
ENH (Empresa Nacional de Hidrocarbonetos, E.P.)
Bharat Petro Resources
Mitsui & Company
Oil India Limited
ONGC Videsh (The International Petroleum Company of India)
PTTEP
AMA1 (Anadarko Mozambique Area 1)

Anadarko Mozambique Area 1 (AMA1) and the participants in Area 1 have drilled a total of 43 wells including the original Windjammer 2bp1 discovery well which reached total depth in February of 2010. Anadarko and the participants in Area 1 have drilled 11 successful exploration wells and 26 successful appraisal wells which will develop in excess of 75 TCF of recoverable natural gas reserves within Area 1. The largest and highest quality natural gas field in Area 1, the Prosperidade Field, was defined by the discoveries of the Windjammer, Barquentine, Lagosta, and Camarao exploration prospects. Over time, it became evident that Area 4 discoveries of Mamba North, Mamba South and Mamba Northeast drilled by eni were in pressure communication with the large Prosperidade Field in Area 1. The Prosperidade – Mamba Straddling Reservoir Complex has expected recoverable reserves in excess of 25 TCF within Area 1. The field will be developed in a coordinated effort with each area developing 2 LNG trains to produce 12 TCF of natural gas. Additional development of the Prosperidade – Mamba Fields beyond the first four trains will be developed as a unit with a Joint Unit Operator.

A passive margin subsidence during the Tertiary (2.6 – 65 mya) created accommodation space which allowed the Rovuma Delta to prograde seaward and deposit up to 5000 m of sediment. The sediments were deposited as deltaic sands on the shelf and as turbidities in the deep water. The deepwater turbidities sands of the Oligocene and Eocene are the reservoirs which will be produced in the Prosperidade – Mamba complex. Gravity-driven delta deposits resulting from uplift and sedimentation have produced a classic linked system of deformation. The deformation is characterized by numerous listric growth faults both onshore and in shallow water. This compressional fold belt is linked by a regional detachment layer downdip in the deepwater section. The Rovuma basin had seen limited activity prior to Anadarko and eni drilling campaigns. The nearest hydrocarbon discovery was Agip's Mnazi Bay discovery in Tanzania from the Miocene and Oligocene age formations. The Mnazi Bay discovery is located 80 km northwest of the Windjammer discovery.

Geophysical interpretation of Area 1 for the original exploration drilling program utilizing a 3,370 km2 3-D seismic survey which was shot in 2008 and later reprocessed in 2011 after the original natural gas discovery. In 2014, eni and Anadarko jointly reprocessed a seismic data set from Area 1 and Area 4 to develop high-quality time and depth volumes that tied all the wells within the area of interest. The primary geophysical volume used for mapping the thick high-quality turbidite gas sands is the Far Angle Stack Volume, which is rotated 90 degrees. The survey is rotated 90 degrees so the top of the sand and the base of the sand are at the zero crossing. Forward modeling of Vp, Vs and Rho data illustrates a class II AVO response within the natural gas saturated Oligocene and Eocene sands. The increase in amplitude with offset in the gas sands allows the Far Offset Volume to highlight the gas sands which can be calibrated to the wells with offset synthetic seismograms.

The original Windjammer discovery tested four play types, (1) a stratigraphic trap in the shallow Miocene section, (2) a faulted four-way closure in the Oligocene on the hanging wall section above the thrust fault, (3) a low-relief combination structural stratigraphic trap in the Oligocene outboard of the thrust fault, and (4) a combination structural stratigraphic trap in the Paleocene. Three of the four play types proved to be natural gas productive in the Windjammer discovery. The Miocene stratigraphic trap was water bearing. The largest natural gas reservoir in the area was discovered on the low-relief combination structural stratigraphic trap in Oligocene outboard of the thrust faults. The Barquentine, Lagosta and Camarao exploration wells all targeted this play type. The turbidite section within this play type is very homogenous and is structurally simple due to the lack of faults which intersect the interval. Wells from this section have encountered up to 170 m of natural gas pay within the Oligocene Upper Reservoir. The Oligocene Upper reservoir is interpreted to have been deposited as a turbidite channel on the toe of the slope and as large fans on the basin floor. The basin floor fans are confined by large mass transport complexes which form barriers to the south allowing the channel / fan complexes to stack vertically. The Oligocene Upper turbidite system is a very high net-to-gross system with the average net to gross sand being 80 percent in the Area 1 wells. The average porosity for the Oligocene Upper reservoir is 20.5 percent and average permeability for the Oligocene Upper ranges between 100 and 200 md.

Anadarko has taken whole cores from three wells within the Prosperidade Field. A total of 765 m of core was recovered from the three wells. A wide range of depositional facies have been cored and analyzed. The reservoir facies are classified into three major facies, (1) a fine gained highly laminated turbidite, (2) a medium-to- coarse grained sand-rich poorly sorted turbidite, and (3) a conglomeratic – coarse-to-very-coarse matrix supported turbidite. The conglomerates are associated with the initiation phase. The medium to coarse-grained sand makes up more than 80 percent of the rock volume and is associated with the growth phase. The fine-grained sand is associated with the retreat phase of sedimentation.

An extensive well-testing program was performed by the Area 1 partnership during the appraisal drilling phase of the field. Three wells were drill stem tested. Six separate drill stem test were completed. Four of the drill stem test were in the Oligocene Upper and one each in the Oligocene Lower and Eocene. The tests were for an extended time ranging from five to seven days in duration. Each of the six drill stem test flowed natural gas at rig constrained rates of from 85 to 110 mmcfpd. Each of the drill stem test had minimal drawdown throughout the test. Observation wells were perforated and pressure gauges were installed to evaluate the communication from one well to the other. In the Oligocene Upper in the Barquentine area, communication was seen in both of the observation wells with a maximum distance of 4.8 km. In the Lagosta area in the Oligocene Upper, communication was recorded between the drill stem tested well, Lagosta #2 and the observation well, Lagosta #1 at a distance of 7 km. The six positive drill stem test gave the Area 1 partners confidence the three straddling reservoirs of the Prosperidade – Mamba Field were highly productive and well connected.

Complex 3-D earth models and reservoir simulation models have been constructed to evaluate the sand distribution, facies distribution, property distribution and the flow characteristics from each of the straddling reservoirs. Reservoir simulation models demonstrate the high-quality, homogenous reservoir can be drained with minimal wells. The average well in the simulation model produces in excess of a ½ Tcf (500 Bcf) natural gas.

NOTES

Transforming Tanzania's Frontier Exploration Acreage into a Proven Hydrocarbon Province

Joseph Nicholson, *BG Group*

Introduction

BG Group entered Tanzania in June 2010 attracted by the possibility of large frontier exploration plays and sizeable licence blocks covering deep to ultra-deep water close to several recent discoveries. A material recoverable hydrocarbon presence was postulated to be possible in multiple play types with multi-TCF gas potential. This would support BG Group's desire to connect organic exploration success with BG Group's LNG supply business.

Tanzania was also identified as a stable and progressive country favourably positioned to provide excess gas production via LNG shipments to the Indian or Asia Pacific markets. These conditions effectively identified the East African coast as an Exploration 'hot spot' with vast potential.

BG Group farmed-in to Ophir Energy's equity position in Southern Tanzania's offshore blocks 1, 3 and 4 in June 2010 and subsequently took operatorship in July 2011.

This paper will focus on the exploration activity that has been conducted in blocks 1 and 4 providing examples of the diverse trap types that have been tested, the range of geological ages penetrated with the drill bit and different geological facies identified either through drilling or seismic observation.

Emphasis will also be placed on some of the challenges encountered and technological enablers that have been deployed to safely deliver the activities described in a remarkably short timeframe of five years.

Deployed Technology

From a subsurface perspective, the volume of seismic data collected and provided for analysis has been substantial. The AVA characteristics of gas sands in southern Tanzania, similar to many deepwater settings, are well suited for quantitative interpretation techniques utilising pre-stack information. Selvage and Edgar (2013) describes the geophysical techniques deployed to enable parallel streams of analysis. These rock physics characteristics have allowed rapid identification of prospectivity culminating in compressed timelines from data receipt to exploration well. In the example of the Taachui-1 wildcat well, the exploration borehole commenced drilling nine months after receipt of the seismic data for initial interpretation.

Amplitude analysis has also played a key role in developing BG Group's understanding of the key structural lineament named the Seagap fault. This structural feature running parallel to the Tanzanian coast plays an influential role in the development of hydrocarbon accumulations in the offshore. Figure 1, as described by Camila França (2012), identifies sinistral motion along the Seagap fault offsetting an earlier deepwater channel.

The volume of 3D seismic data has also confirmed one of the key significant geotechnical challenges for hydrocarbon production offshore Tanzania. This is the presence of giant seabed canyons. The prevalence of offshore canyon systems occurring beneath the sea surface provides a technological challenge both in terms of placing pipeline export routes to connect the discovered gas to market but also from a geoscience perspective providing complex seismic imaging problems requiring careful and well thought through handling of the geophysical data collected.

Numerous technological firsts have been achieved during the past five years of offshore operations including the extraction of the first deepwater core offshore Tanzania, the first walkaway VSP and from a risk mitigation perspective the first implementation of downhole H2S analysis. This deployment of key technologies has continued in 2015 with the acquisition of broadband seismic data to better identify and delineate potentially gas bearing reservoirs.

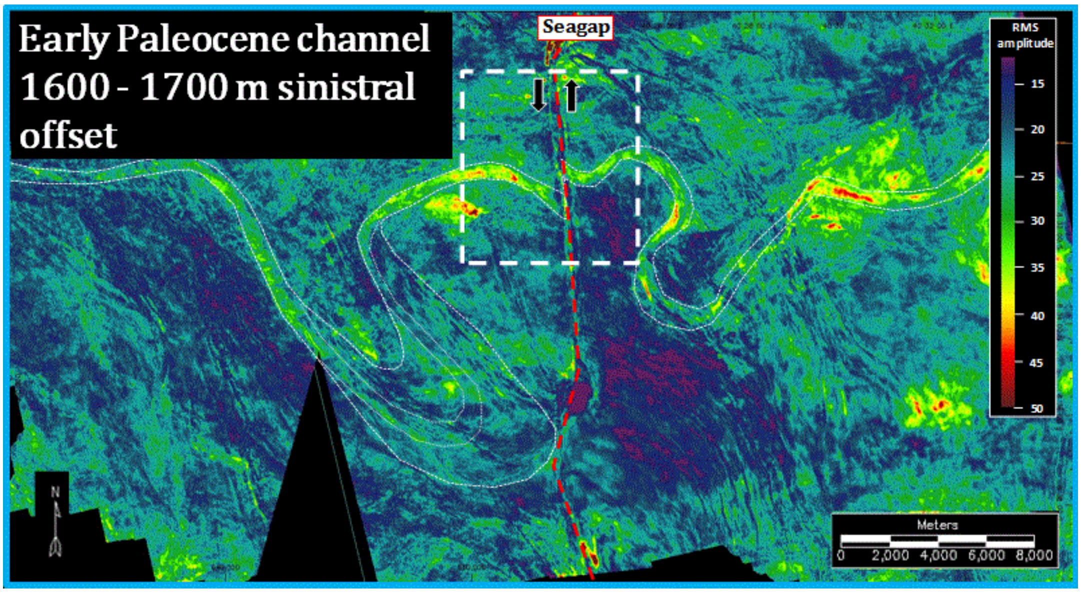


Figure 1 Evidence for sinistral movement along the Seagap Fault zone. Presented by Camila França at the Geological Society East Africa conference (2012)

Conclusions

The last five years has seen a transformation of the Tanzanian petroleum story from a “hot spot” of frontier exploration potential to a proven hydrocarbon province holding ~16 TCF of gas spread across multiple plays. BG Group and its partners have been instrumental in this transformation. As operator, BG Group has deployed numerous technologies to enable the safe delivery of an exploration and appraisal campaign. This activity has delivered sixteen wells with a 100% success rate of encountering hydrocarbons.

Acknowledgements

Block 1 & 4 JV partners (BG Group, Ophir Energy plc., Pavilion and TPDC)

Previous BG Group co-workers including J. Argent, R. Blight, T. Glover, C. França, P. Sansom, M. Bolton, A. Raiment and J. Selvage.

References

França, C., 2012, 3D Seismic interpretation and Tectonic history of the Seagap fault zone, Offshore Tanzania, East Africa: Petroleum Province of the 21st century, Geological Society, London

Sansom, P., 2012, Insights from the First Deep Water Core, Offshore Tanzania, East Africa: Petroleum Province of the 21st century, Geological Society, London

Selvage, J.I. and Edgar, J.A., 2013, Rapid Screening of Pre-stack Seismic for Hydrocarbon Prospectivity, 75th EAGE Conference & Exhibition.

Selvage, J.I., Korsmo, Ø., Jones C.E. and Rønholt, G., 2014, Unifying Tomography & Pre-stack Anomaly Detection in PreSDM to Correct for Near Surface Channels in Exploration Settings, 76th EAGE Conference & Exhibition.

NOTES

Tanzania Block 2 - From Discovery to Development

Fawad Chuhan, Timothy John, Sabina Solymar, *Statoil*

Introduction

Statoil was awarded Block 2 in 2007 as operator and in 2010 ExxonMobil Exploration and Production Tanzania Limited became its partner with 35%. The first 3D seismic data was acquired in 2009 covering the area around the Sea Gap strike slip fault system and its associated pop-up structures and pull-apart basins. A total of 8 discoveries have been made during the drilling campaign from 2012 to 2015. In addition to the discovery wells, the drilling campaign included several appraisal wells and one DST. The discoveries in Tanzania Block 2 are located some 100km offshore Tanzania at a water depth of approximately 2500m.

Theory

The geological setting has persisted since at least the Jurassic, depositing deep water turbidite systems through time. At present day, the sea floor still shows evidence of a highly erosive system creating steep canyons, contributing to challenging development solutions.

Discoveries have been made in Cretaceous, Paleogene and Miocene stratigraphic levels. Deposition has been strongly influenced by tectonic activity along the Sea Gap strike slip fault system. Presence of pop-up highs, pull-apart basins, development of faults and possibly mounding affected the accommodation space and guided the reservoir deposition. Despite many similarities, the discoveries all have their individual challenges, including facies distributions and reservoir properties.

Several of the discoveries are now being evaluated for development but are at different maturity levels. The understanding of the discoveries is being matured through comprehensive geological and geophysical work as well as dynamic understanding based on simulated reservoir models. The full value chain development project is expected to comprise gas extraction through subsea wells and a subsea production system to an onshore LNG plant.

NOTES

Linking Recent Gas Discoveries to Their Source Kitchens, Offshore Tanzania

Niall Sayers, *BG Group, Thames Valley Park, Reading, RG6 1PT*

To date, BG Group and its partners have discovered ~16 TCF total gross resource of dry gas in offshore Tanzania blocks 1 and 4. Other discoveries along the East African margin have also been overwhelmingly dominated by gas, which at first pass is at odds with published interpretations of an oil-prone source for the area. Geochemical analysis of the gases, associated condensates and cuttings from BG wells have been integrated with regional studies, seismic interpretation and basin modelling to provide insights into the nature of the dominant offshore source rock, its maturity, and processes affecting the hydrocarbons post-expulsion.

The dominant source rock is interpreted to lie in the Lower-Mid Jurassic (syn-rift to early post-rift) section, although erosional remnants of underlying Permo-Triassic Karoo basins possibly contribute locally, as do plant material-rich Palaeocene-Eocene sections where sufficiently mature. The Jurassic source-prone section is uplifted and exposed in places onshore – notably the Mandawa Basin – but as yet unpenetrated offshore of Tanzania. However, the hydrocarbons in BG's Tanzania discoveries indicate a highly mature source with potential marine affinities, tentatively typed to oil extracted from Lower Jurassic shales in the Mandawa Basin. Basin modelling, calibrated with observations from gas and condensate geochemistry, links the discoveries to the discontinuous source kitchens interpreted on seismic, and illustrates contrasting migration pathways leading to their emplacement.

NOTES

The Pande Gas Fields Complex in the Mozambique Basin, a Case History.

Kevin Dale, Ian Hutchinson & **Markus Logering.** *Sasol Exploration & Production International*

Acknowledgements:
Partners Companhia Moçambicana de Hidrocarbonetos (CMH) and The International Finance Corp. World Bank Gp. (IFC) : liaison with specialists at Empresa Nacional de Hidrocarbonetos (ENH) and Instituto Nacional de Petroleo (INP) – plus the Sasol E & P technical teams and their contract support specialists (too numerous to mention individually) in Maputo, Johannesburg and London.

1. INTRODUCTION

The Pande area gas fields lie in the Mozambique Basin, about 550 km north northwest of Maputo and about 1,300km southeast of the prolific Rovuma Basin. The giant [2] gas field complex consists of three separate accumulations: Pande, Temane and Inhassoro gas fields; these were discovered in 1956, 1961 & 1965 respectively. Currently estimated proven full-field Ultimate Recovery (SEC 2014) is 3,000 bcf gas and 11 MMbbl oil (Inhassoro Field is not yet reported at SEC).

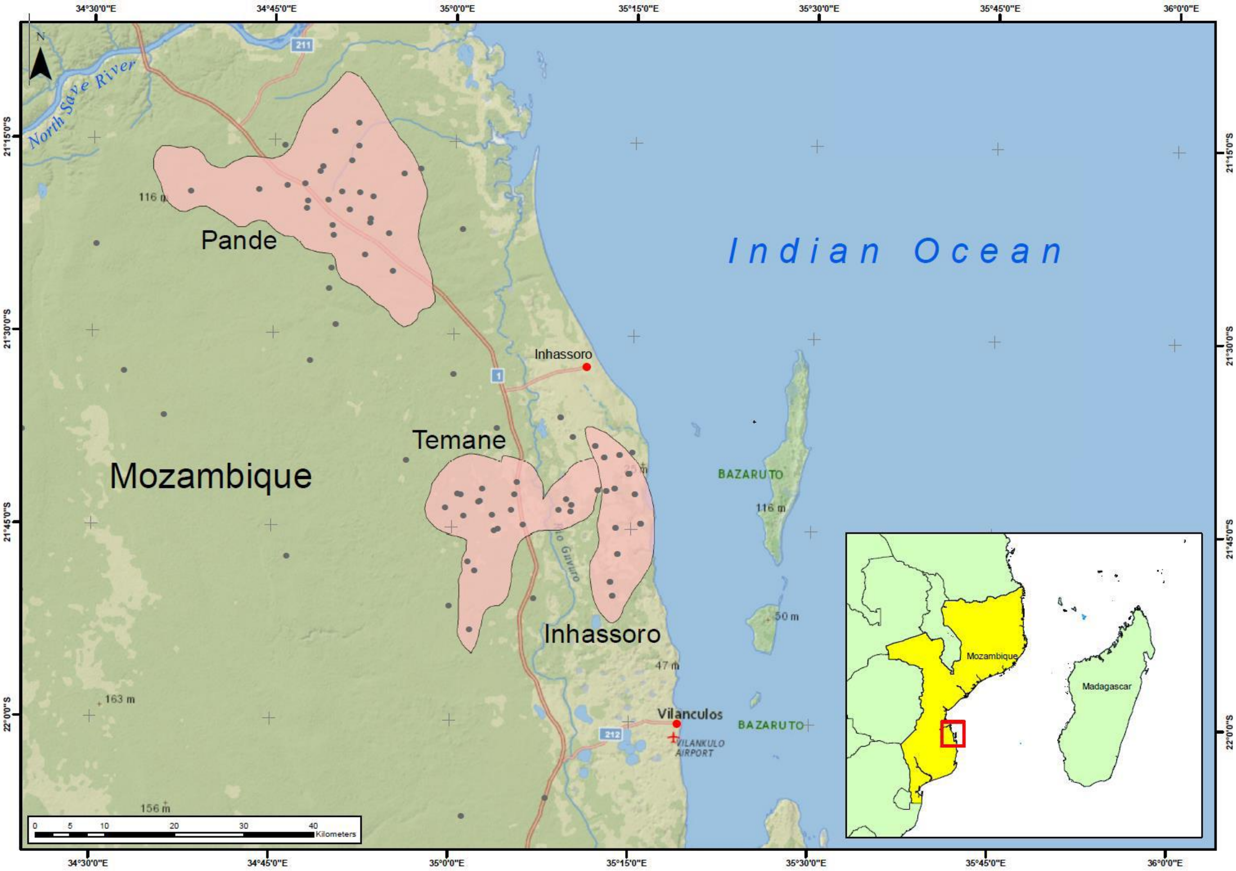


Figure 1 : Location Map

2. THE BASIN

The Mozambique Basin was formed in the oceanic void created by the rifting of the African and Antarctic plates during the late Jurassic. The steeply dipping volcanic hills of the Lebombo – Sabe Monocline which form the western and north-western margin of the basin, mark the onset of this rifting event and are tightly dated at 183 ±1 Ma [1]. Sedimentary fill of the basin is divided into the Cretaceous ‘Limpopo’ and the Tertiary ‘Zambezi’ deltaic super-cycles.

3. THE DATABASE

Sasol has an extensive database of seismic, well and production data (132 wells around 65,000km of 2D and 4,000km2 of 3D). Taking on-board a new geodynamic model for the Mozambique Basin from Gondwana rifting and with the assistance of expert sequence stratigraphers, our teams have subdivided the Jurassic – Cretaceous sediments into a series of classic second-order sedimentary cycles, integrating 2D & 3D seismic, well and biostratigraphic data. Upper Cretaceous gross depositional environment maps, developed from the sequence stratigraphy and well control, show that the basin fill exhibits a facies transition, from continental clastics in the west through shallow shelf sediments in the gas fields area, giving way to deeper marine deposits offshore.

4. EXPLORATION HISTORY

The fields were originally discovered by Gulf Oil, and have seen subsequent operatorships by: ENH, Arco, and Enron. However, due to challenging commercial conditions and their location in a relatively remote area of Africa, they remained undeveloped ‘stranded gas’. During that period, the Pande-4 appraisal well infamously blew-out in 1965 and it took until 1967 to kill the well. Overall the Temane Field saw six appraisal wells and the larger and slightly more complex Pande Field saw seventeen appraisals.

In 2000, Sasol became an equity holder and eventually took on operatorship. Sasol has brought its technology and downstream market to turn-around the previously stranded gas, creating a valuable asset for Mozambique. In December 2003 the Temane field was brought on-stream via a 865 km 24” pipeline across the border to industrial customers in South Africa. This was followed by the Pande Field in May 2009. A key customer is Sasol’s giant gas-to-liquids plant at Secunda, which converts the previously stranded gas into higher value synthetic diesel and naphtha.

The Pande Field has a very subtle surface anticlinal nose. However, most exploration has been via the identification on 2D seismic of gas-bearing sands from high-amplitude single-cycle, often shingled, prograding and retrograding reflectors. There are also examples of false positive amplitude anomalies. Petrophysical interpretation has proved challenging as the reservoir sands are fine grained, sometimes thinly bedded and occasionally have low-resistivity pay.

5. SOURCE ROCK

The hydrocarbons encountered in the Pande and Temane Fields are predominantly dry gas; where condensate is found CGR’s are typically +/- 6bbls / MMscf [4]. The Inhassoro Field by contrast has a light oil-rim of around 10 metres. Research using analytical data and modelling suggests the geochemical character of the hydrocarbons can be explained by: (a) variable maturity of the source rock, and (b) migration from a kitchen to the north-east of the fields. To date the source rock has not been penetrated by any well. However integrating all available geological, sequence stratigraphic and geochemical data into a 3D thermal model has suggested the source horizon lies in the Neocomian Lower Domo Shale [3].

6. RESERVOIR

The fields in the complex are subtle, low-relief stratigraphic traps, formed by the up-dip pinch-out of relatively thin-bedded, easterly-dipping lower shore-face to shallow-shelf sand bodies. The main reservoir sands are of Maastrichtian-Palaeocene age. Cleaning and coarseningupward cycles are evident from wireline logs. Heavy bioturbation is reported from core. Several sand bodies within the sequence have proven to contain and sometimes produce hydrocarbons. Multiple stacked reservoirs, however, are rare. Porosities and permeabilities reported in the main reservoirs are good, typically around 25% and frequently over 500 md, but reservoir facies and quality can rapidly deteriorate both laterally and vertically. The Pande Field produces from the youngest sandstone level in the lower Grudja Formation, known as the G6 while the Temane Field produces from the stratigraphically older G9 level. The interbedded shales are significantly thicker than the sandstone reservoirs in this relatively low net-to-gross system.

7. COMMERCIAL SUCCESS

The Mozambique Basin is not a world-class petroleum province. There is a lean and enigmatic source rock, silty and thin-bedded reservoirs and a lack of structural relief / traps. While the petroleum geology has proven challenging, Sasol's unique position as a large African integrated E&P company has enabled the investment of time and resources to fully utilise all the G&G information in the basin and bring hydrocarbons, previously abandoned by several multi-nationals, into commercial production. Going forward, Sasol intends to leverage this local knowledge and expertise to maximise the value of this basin for all stakeholders.

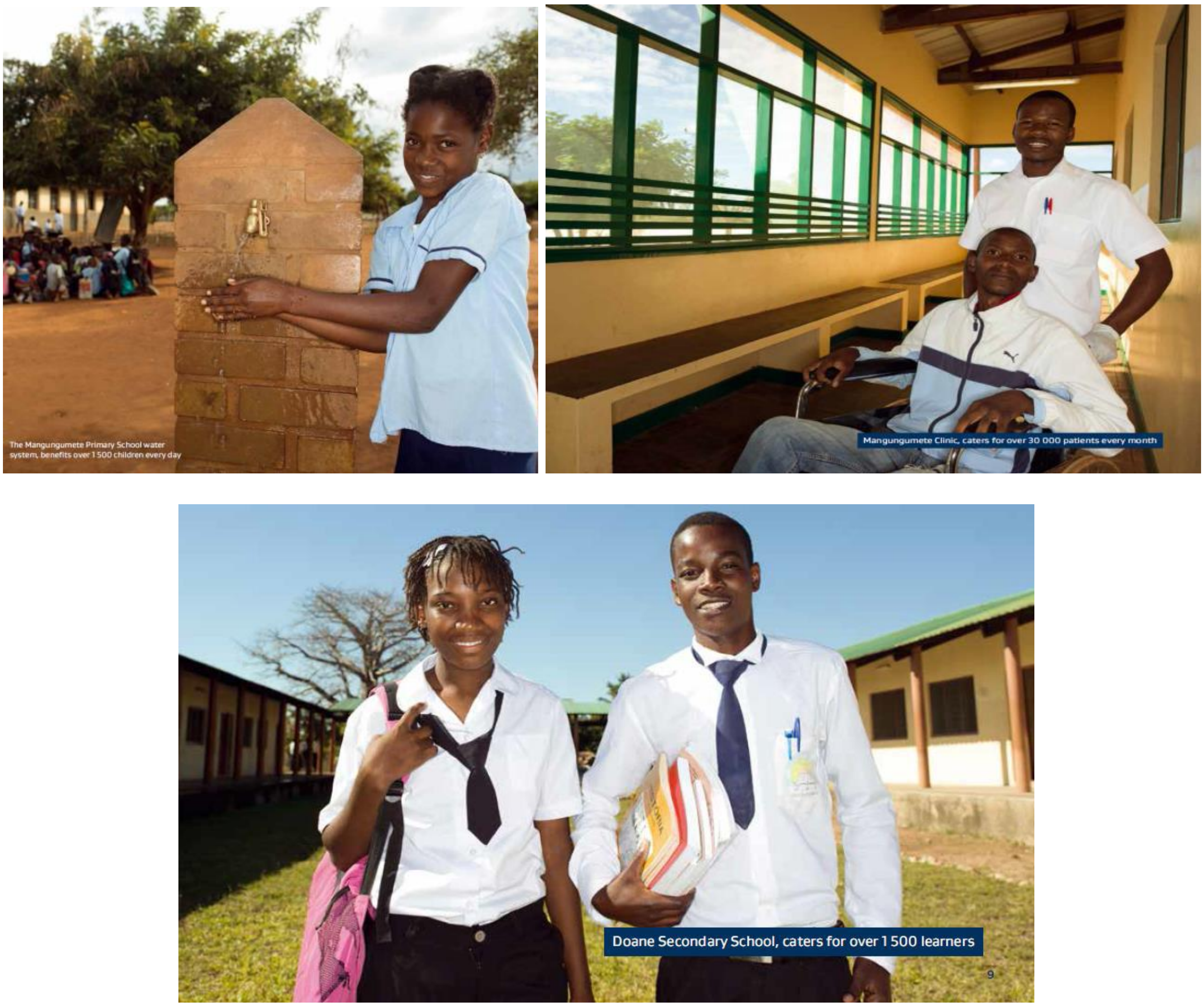


Figure 2 : Sasol In Mozambique, shared and sustainable value for communities

8. REFERENCES

DALE, K.J. & KUSIAK, J. (2015) The Pande Gas fields Complex in the Mozambique Basin, a case history. Extended Abstract The 14th HGS/PESGB Conference on African E&P 'Always Something New Coming Out of Africa' September 2015 Conference BDC London.

[1] DUNCAN, R.A. ,et al. (1997) The timing and duration of the Karoo igneous event, southern Gondwana: Journal of Geophysical Research: Solid Earth, 102 (B8), pp. 18,127-18,138. 1997.

[2] HALBOUTY, M.T. (2001) Search and Discovery Article #20005 (2001), presentation at Symposium, Giant Oil and Gas Fields of the Decade 1990-2000, AAPG Convention, Denver, CO, June 5, 2001.

[3] LOEGERING M.J. ,et al. Integration of isotube analysis, fluid inclusion stratigraphy and basin modelling in the Mozambique Basin, First EAGE Eastern Africa Petroleum Geoscience Forum 16-19 November 2015. Dar es Salaam, Tanzania.

[4] QUAM, S., DURKAN, R., JONKER, A., MITCHEV, S. (2008) Exploration and Development of the Temane / Pande / Inhassoro Complex Mozambique. Presentation to the Global Pacific Africa Oil Conference in Cape Town 2008.

Figure 3 : Despite the challenging petroleum geology and commercial situation, the project has delivered considerable value for stakeholders

Driving sustainable development over the last decade

In line with creating social value, helping society achieve an improved standard of living is one of Sasol's key business objectives within the various operating entities in Mozambique. Creating social value is fundamental to our business. Society needs healthy, competitive companies to create jobs, buy local goods and pay taxes, while corporations need vibrant communities which offer a market for goods and services.

Over the past ten years, Sasol and our partners' corporate social responsibility (CSR) initiatives have prioritised people-centred, needs-driven capacity building and the sustainable development of communities. Over 150 projects are reaching beneficiaries in three provinces along the NPG.

This table outlines the key interventions based on a study conducted in 2011

Focus area	Count	Actual costs (US $)	%	Largest population	%
Agriculture	9	259 629	2.27%	5090	1.14%
Education	47	5 992 564	52.48%	40 004	8.98%
Health	19	2 010 723	17.61%	175 125	39.30%
Job Creation	10	107 252	0.94%	446	0.10%
Other	13	1 670 144	14.63%	86 459	19.40%
Water	56	1 378 226	12.07%	138 462	31.07%
Grand Total	**154**	**11 418 538**	**100.00%**	**445 586**	**100.00%**

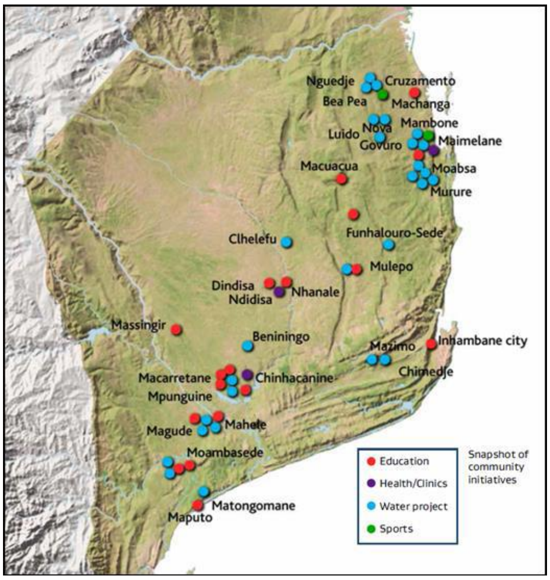


Figure 3 : Despite the challenging petroleum geology and commercial situation, the project has delivered considerable value for stakeholders

NOTES

Structure and Source Rock Potential of Syn-Breakup Mini-Basins, Offshore Tanzania and Kenya

Jonathan Turner & Alan Foum, *BG Group, Thames Valley Park, Reading RG6 1PT, UK*

We have mapped the pre-Cretaceous structure of the Tanzania and Kenya margins in an effort to understand the distribution of potentially source rock-bearing mini-basins that developed during Indian Ocean breakup. These margins are bounded by major coast-parallel fault zones – the transcurrent (i.e. intracontinental) Seagap Fault and transform Davy Fault - that accommodated overall right-lateral sense breakup and obliquely divergent early spreading from c.160 million years ago. Following breakup – the creation of a new throughgoing plate boundary - transform margins undergo a finite period during which opposing margins are conveyored past one another across a central rift. It comprises a mosaic of embryonic ocean basins and highly stretched continental crust offset across crustal-scale Riedel shear zones. These mini-basins form before full drift conditions are established and before the opposing margins become separated by a continuous arm of oceanic crust. The consequent restricted circulation in the central rift creates favourable conditions to preserve organic-rich mudstones, the primary objective of this study. The Seagap Fault defines the eastern limit of coal-bearing Karoo facies and crustal thickness maps based on a gravity inversion method indicate that it marks an abrupt increase in stretching factor. Further east, the zone between the Seagap and Davy structures is characterized by highly thinned (and likely intensely intruded) 'transitional' crust within which we map numerous half-graben containing syn-kinematic reflector packages of probable Middle Jurassic age. These half-graben are essentially pull-apart basins and are bounded by oblique-slip faults related to Jurassic transform motion. Right-stepping bends on the Seagap Fault served to focus transpressional strain, consequently the Jurassic mini-basins are often strongly inverted within crustal–scale flower zones. To the north, the array of basement structures that accommodated the dying out of the Seagap and Davy faults, and the kinematics of displacement transfer to the onshore rift system, will also be discussed.

NOTES

Friday 15 April
Session Five: Frontier Opportunities

Regional Geology and Hydrocarbon Potential of Deep Water Offshore SE Somalia

Lindsay Davidson, Tom Arthur, Geoff Smith, Simon Tubb, *RPS Energy, UK*

This presentation discusses the geological insights revealed by a regional 20,000km 2D seismic survey acquired offshore SE Somalia in 2014 by Soma Oil & Gas. This was the first seismic to be acquired over most of the survey area hence the basin configuration and hydrocarbon potential of the deep water region had previously been largely unknown. The 2014 survey extends some 1200km along the SE Somalia coast and to 200km offshore in water depths of up to 3500m, as shown in Figure 1. Only one direct tie can be made to an offshore well, Meregh-1, while indirect ties are also made to Pomboo-1 and DSDP-241. Given the limited available well control it follows that significant uncertainty remains in the stratigraphic age dating of the depositional units mapped in the basin.

Regional analogies, particularly from Madagascar, demonstrate the likely presence of hydrocarbon source rocks of Permo-Triassic (Karoo) and Early to Mid Jurassic age in the Somali Basin. Late Jurassic and Mid Cretaceous sources are also possible.

The separation of southern Somalia from Madagascar began with rifting in the Early Jurassic, with later oceanic spreading from Mid Jurassic through to Aptian time. The Early Jurassic rifting was partly coincident with the more extensive Karoo rift systems, following a SW-NE trend sub-parallel to the present day coast. However, when ocean spreading began later in the Jurassic the opening movement re-orientated to a N-S direction as evidenced by the E-W magnetic striping in the ocean crust separating Somalia from Madagascar. During the Aptian the ocean spreading ceased in the greater Somali basin when the ridge jumped to the east of Madagascar to separate that continental fragment from India.

The Davie Ridge transform fault system formed the western boundary of the greater Somali basin during ocean spreading, while the Dhow Ridge transform served as the eastern edge. Other dextral transforms lying between these two major fault zones also offset the ocean-continent boundary as shown in Figure 1. Subsequent to the Aptian cesation of spreading the region was affected by several episodes of tectonic adjustment relating to oceanic spreading further to the east and to the initiation of the East African Rift system in the Tertiary.

Three major basins are identified in the deep offshore area, Jubba Deep, Mogadishu Deep and Mid Somalia High (Figure 1), each with distinctive geological characteristics. These basins are interpreted to overlie stretched continental crust, with a continent ocean boundary tentatively identified to the SE of the Soma 2D survey.

Jubba Deep Basin

The characteristic ferature of the Jubba Deep Basin is the presence of Mid Cretaceous to Tertiary clastic deltaics of at least 8km thickness, probably derived from the paleo Jubba and Shabeelle rivers. This Cretaceous delta underwent spectacular gravity collapse in the Paleocene to form the Kismaayo Thrust Belt, some 350 x 200km in extent, where nearshore extensional faulting is balanced by toethrusts in the distal region. The detachment slip plane lies within Mid Cretaceous shale which mobilised to form diapirs in the centre of the system where it represents a potential source rock. A second gravitational collapse, the Baraawe Thrust Belt, occurred in the Late Tertiary, mainly involving Tertiary deposits.

The toethrust region in the outer part of the Kismaayo Thrust Belt contains particularly attractive targets for hydrocarbon exploration with large trapping structures which have been in place since the Early Tertiary and seismic evidence for deep marine fan and channel sand systems. Analogies may be drawn with the Niger Delta and the Rovuma Basin in Mozambique.

Jurassic rift and post rift deposits are present in the Jubba Deep although deeply buried over much of the basin area. Potential source rocks in the Jurassic are modelled to be in the gas window at present day in the deep water areas, and post-mature further inshore. If source rocks are present in the Mid-Cretaceous mobile shales these would largely be in the oil window at present day.

Mogadishu Deep Basin

The Mogadishu Deep basin contains a thick sedimentary succession from syn-rift Early Jurassic through to Cretaceous and Tertiary. A tie is made to the shelfal well Mergeh-1 but seismic indicates significant changes in thickness and depositional character of many of the sedimentary units between the shelf and the deep basin. Deep marine Cretaceous and Early Tertiary sands may form potential reservoirs. Post-rift structuring in the basin is dominated by a series of Early Tertiary WSW-ENE trending wrench faults. These produce some extensive structural closures with the potential for large volume hydrocarbon traps. Tertiary and Cretaceous volcanics are present in the basin with one localised volcanic centre together with more widespread minor sills and extrusives.

Mid Somalia High

Crustal stretching was less severe over the Mid Somalia High resulting in a relatively thinner sedimentary section compared to the two other basins. Early Jurassic rift faulting is well imaged on seismic and the restricted syn-rift fill provides good potential for hydrocarbon source rocks at moderate burial depths modelled to remain in the present day oil window. Rotated fault blocks provide structural closures with potential for Karoo and Early Jurassic syn-rift sandstone reservoirs.

The rifting was followed by widespread carbonate platform deposition in the Mid to Late Jurassic. Large areas of carbonate reef and shoal development are very well imaged on seismic and these provide attractive hydrocarbon reservoir targets particularly where located on the crests of rotated fault blocks. Mixed carbonate and clastic deposition followed in the Late Jurassic to Early Cretaceous and this may also contain reservoir facies.

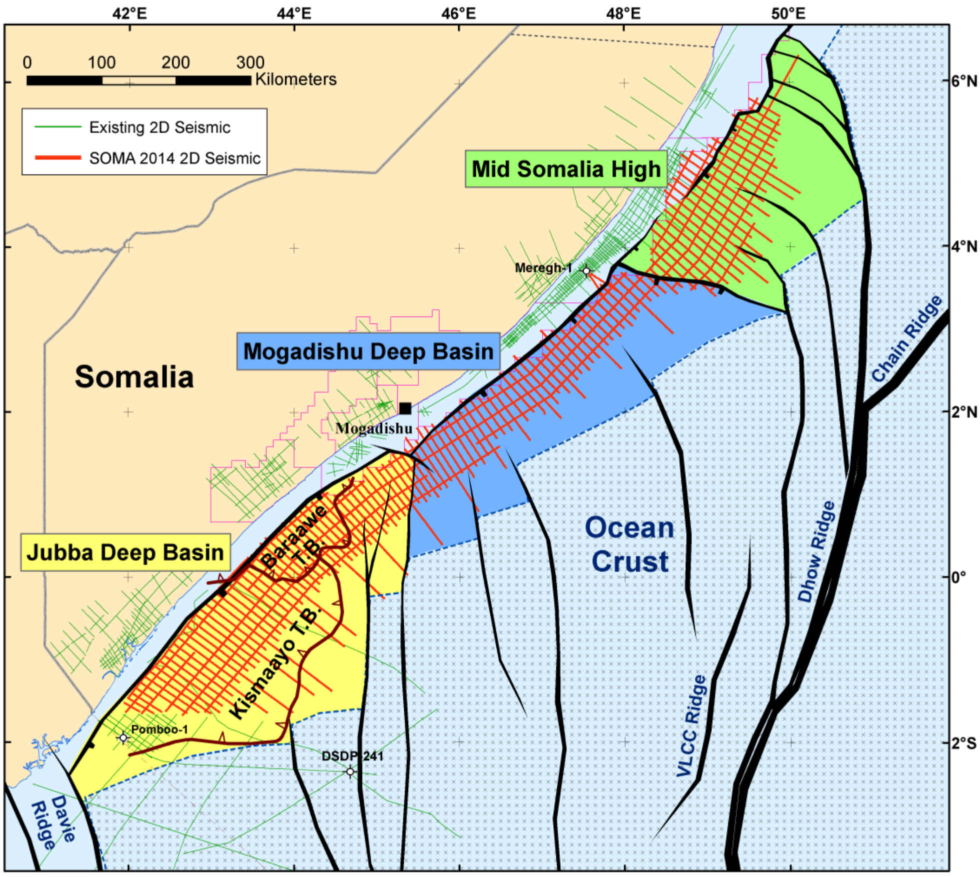


Figure 1: Seismic basemap and basin configuration of deep water SE Somalia

NOTES

Hydrocarbon Prospectivity and Play Concepts Offshore Madagascar

Anongporn Intawong and Karyna Rodriguez, *Spectrum Multi-Client UK, Dukes Court, Duke Street, Woking, Surrey, GU21 5BH, United Kingdom*

Madagascar remains largely under-explored and is still a frontier exploration province. Despite this, many hydrocarbon play types have been widely identified on seismic data in western offshore Madagascar, such as tilted fault blocks, inverted and strike-slip associated structures, carbonate build-up, complex large salt-related structures, and channel and basin floor fan stratigraphic plays (Figure 1). As part of this study we present an example of hydrocarbon prospectivity in north-east Madagascar from evidence observed on the Spectrum reprocessed 2D dataset.

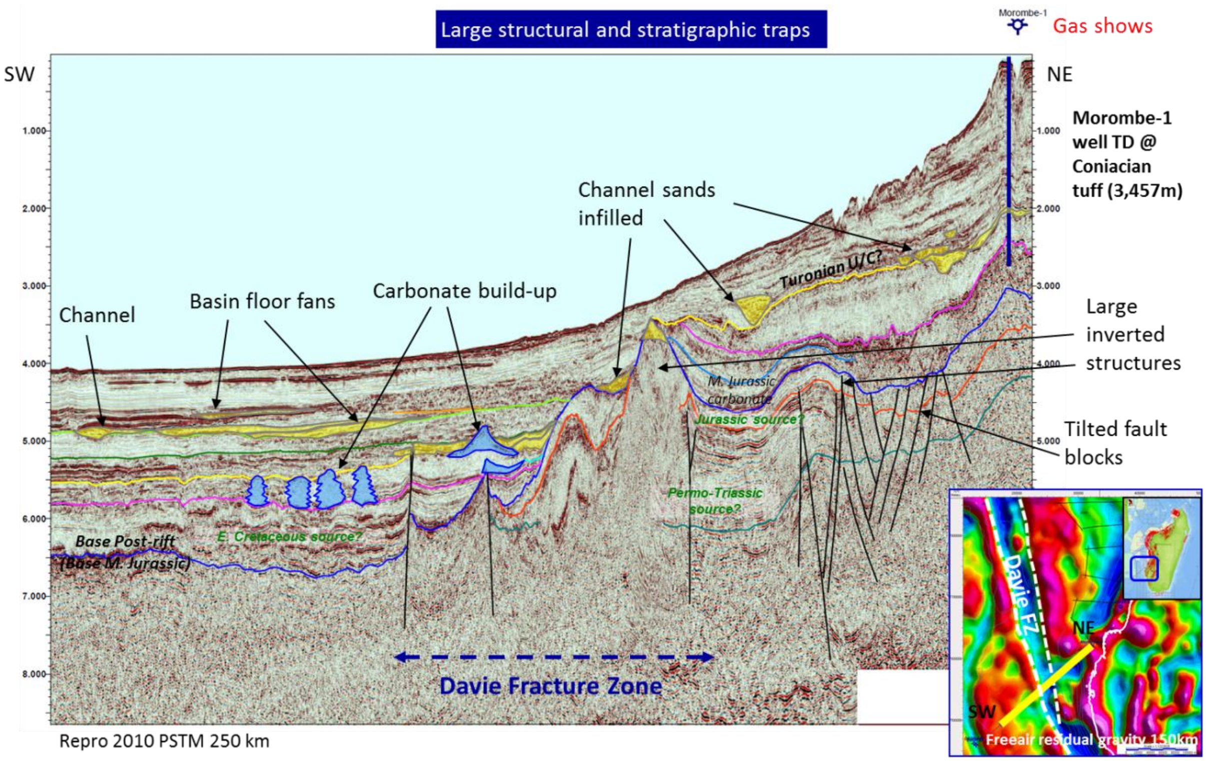


Figure 1: Numerous large structural and stratigraphic plays offshore Morondava Basin identified on Spectrum reprocessed 2D PSTM seismic. The line was reprocessed in 2010 and has a line length of 250 km. An inset figure illustrates the Davie Fracture Zone exhibiting on a Free Air residual gravity anomaly.

The north-east coast of Madagascar margin is characterised by narrow restricted sedimentary basins developed along the coastline, demonstrated as NW-SE trending gravity low areas on Bouguer gravity (inset figure in Figure2). These narrow basins are likely to be infilled by Late Cretaceous to Recent sediments deposited during the initial rifting of Madagascar and Seychelles/India in Santonian (88 ma) (Storey et al., 1995) which is related to the Marion mantle plume centred in southern Madagascar (Hammond et al., 2012).

Only one exploration well has been drilled in this area offshore Madagascar; Ile Saint Marie-1 was drilled in 1973 by Tenneco to test a Free Air gravity low within the narrow half-graben structure. The well has a TD of 1,770 m and has oil shows from 1,725 m to TD within an interval of weathered sandstones and limestones of continental sediments overlaying slightly weathered and fractured gneiss and quartzite. The oil section is seen within a slightly wedged syn-rift package on Spectrum reprocessed seismic data (Figure 2). Based on stratigraphic logs, the well encountered unknown age shallow marine sediments in the first 975 m before reaching unknown age continental sediments to TD at metamorphic basement. This wedged syn-rift section is possibly developed during the transpressional rifting stage over eastern Madagascar and Seychelles/India.

The Marion thermal event is one of the major thermal episodes and has been identified by an AFTA (Apatite Fission Track Analysis) study in the Seychelles conjugate margin to eastern Madagascar (Waples and Hegarty, 1999). Therefore, the Marion plume possibly also plays an important role in hydrocarbon generation in the eastern Madagascar basin that would result in source rocks experiencing higher temperatures than is commonly expected, leading to higher levels of maturity and hydrocarbon generation.

The petroleum prospectivity and play concept of the eastern Madagascar margin remains poorly understood. A simple fault block rotation within syn-rift half-graben play has been recognized on the reprocessed 2D seismic data within the elongate geometry of the coastal narrow bay in the north-east of the island (Figure 2). These findings, together with traced evidence of an active petroleum system may bring the eastern side of Madagascar to the list of potential exploration areas in East Africa.

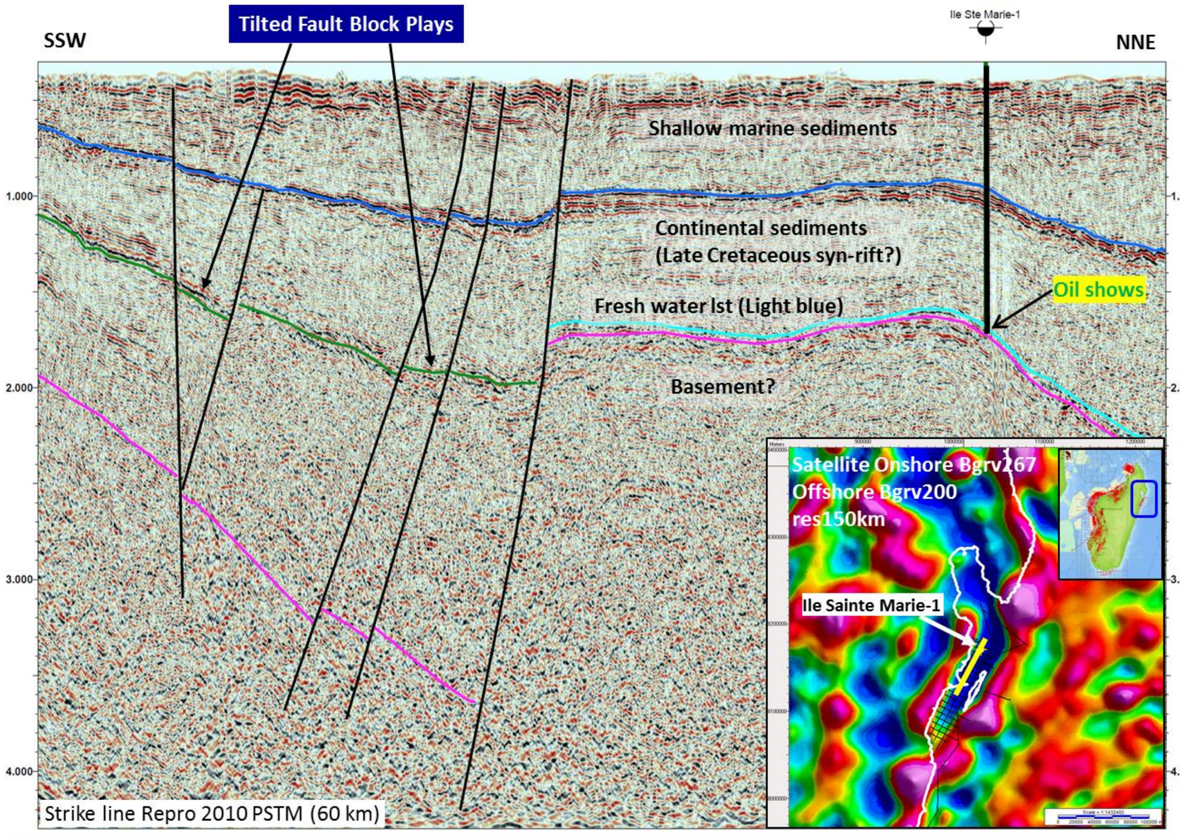


Figure 2: Ile Saint Marie-1 oil shows displays on a SSW-NNE oriented strike line of Spectrum reprocessed 2D PSTM seismic in the eastern Madagascar margin. An inset figure demonstrates gravity low areas on Bouguer gravity (in blue) in relation to the 2D reprocessed seismic survey (in black).

References

Hammond, J.O.S., Collier, J.S., Kendall, J., Helffrich, G., and Rumpker, G., 2012. Plume scar in the mantle lithosphere beneath the Seychelles revealed by seismic imaging. Earth Planet. Sci. Lett., 355-356, 20-31.

Storey, M., Mahoney, J-J, Sauder, A.D., Duncan, R.A, Kelly, S.P., and Coffin, M.F., 1995. Timing of hot-spot related volcanism and the breakup of Madagascar and India. Science, 267, 852-855.

Waples, D. W., and Hegarty, K., 1999. Seychelles thermal history, hydrocarbon generation traced. Oil & Gas Journal: International petroleum news and technology. 97(21), 78-81.

NOTES

Exploring Subsurface Risk at Zambezi Delta: 3D Modelling Of Source Rock Maturity within a Regional Context

Alice Butt, *Halliburton*

With Mozambique's 5th licensing round bringing a spotlight onto new areas with exploration potential, the need to comprehend the regional geology along the east coast of Africa is of critical importance. Following regional scale source rock quality analysis and maturity screening it has been identified that areas with increased sediment influx after the rifting of Gondwana have contributed to the gas abundance in the region, specifically offshore Tanzania. Is a similar situation to be expected in the Zambezi Delta Basin with total sediment thicknesses of c.10km?

The Pande and Temane fields to the south of the Zambezi Delta produce dominantly gas with a few oil legs sourcing the Inhassoro field. However, due to an unusually low geothermal gradient in the basin the maturity screening results are optimistic showing greater oil potential for both Jurassic and Cretaceous source rocks. Possible analogues, such as the Rovuma basin, point towards a success in updip pinchout traps, though similar prospects drilled on the Direct Hydrocarbon Indicators of the Grudja Formation closer to the shore of the Zambezi Delta have been dry. This is due to the fault network extending south from the East Africa Rift system and influencing the seal integrity, demonstrating that care is needed when evaluating the data within a regional geological context.

With this in mind the Beira High, thought to be an isolated fragment of continental crust further offshore, could create a unique scenario and hold the long searched for major oil field. The structural high formed during the complex rifting and movement of Antarctica away from Africa during Early to Middle Jurassic and consequently developed various play components that may be exploited.

Here, a detailed 3D depth model of the Zambezi Delta and Beira High is presented, with an analysis of the source rock distribution and maturity (Figure 1) to locate the working kitchen and determine its potential as a source for traps on the Beira High. The model has been constructed from the assimilation and interpretation of limited publically available data (Figure 2), therefore further data collection and integration would be necessary to give a holistic assessment of the risk. Nevertheless, the work enables initial constraints to be made on the hydrocarbon source, which is currently speculative for the producing fields in the area, and allow a discussion of frontier play ideas.

So, from a first glance the Zambezi Delta Basin appears to be similar to other basins along the East Africa margin, however there is much more going on in the subsurface that needs to be accounted for. Shifting the focus to the furthest reaches of the Zambezi Delta is now ever more possible due to the ability to drill deepwater wells and the newly acquired licence blocks should present some interesting results in the current round of exploration.

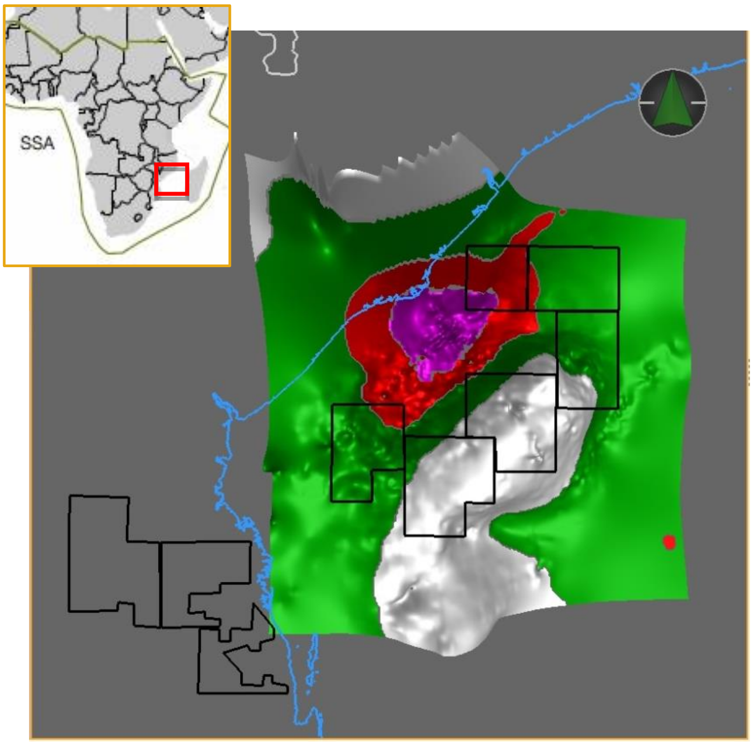


Figure 1. Present day maturity results, assuming continuous coverage of a Late Jurassic source rock at 20°C/km geothermal gradient.

- Immature
- Oil
- Gas
- Over mature

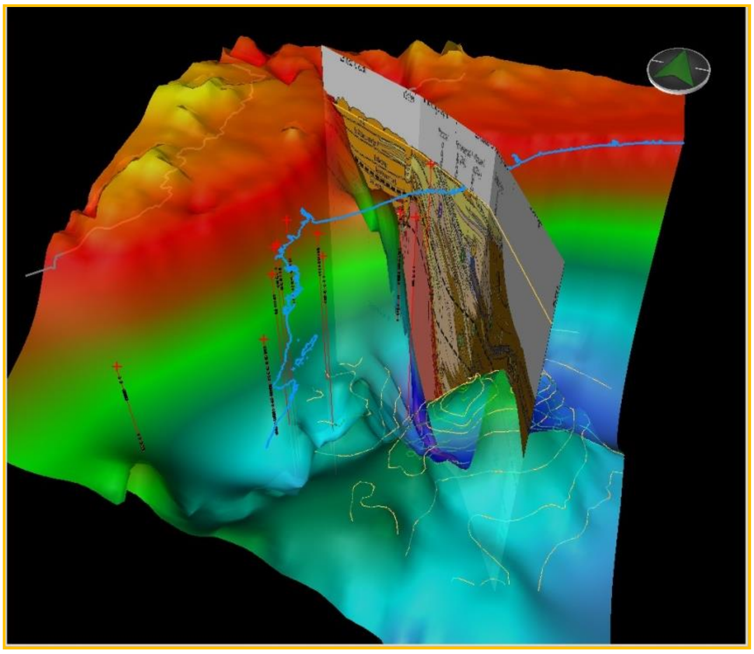


Figure 2. Zambezi Delta basin and Beira high updated depth to basement surface with well tops, contour data and play cross section.

NOTES

Developing a Regional Geological Framework for the Horn of Africa

Fisher, J.A., *Genel Energy, 1 Grafton Street, London, W1S 4FE*

Genel has been actively exploring the Horn of Africa since August 2012 when it was awarded a 75% operated interest in the SL-10-B and SL-13 licences of onshore Somaliland. Shortly after in November 2012 Genel acquired a 50% interest in the adjacent Odewayne license followed by the acquisition of a 40% non-operated interest in the Adigala Block onshore Ethiopia from New Age in August 2013. In total Genel has an acreage position of over 60,000km2, of which 40,000km2 lie in Somaliland.

Genel's strategy in acquiring this acreage position was to chase Cretaceous through to Triassic objectives developed within Mesozoic rift basins which share some analogies to the prolific Marib-Shabwa & Sayun-Masila oil provinces of Yemen. The area is very much under-explored, particularly in Somaliland where political instability limited previous exploration efforts.

In Somaliland the legacy onshore seismic database is limited and well data points are few and far between. Whilst progress is being made towards the acquisition of new onshore seismic Genel has been developing its understanding of the regional tectono-stratigraphic framework through a combination of airborne gravity and magnetics, reconnaissance geological fieldwork and structural setting analysis. The presence of all of the key play elements together with a working petroleum system has been documented from offset wells, reconnaissance fieldwork as well as active seeps which were the focus of a 2015 geochemical survey.

This paper presents the results of this new regional analysis and highlights the exploration potential in these underexplored Mesozoic rift basins.

NOTES

Mkuranga-1: A sleeper Awakened

Barry G. M. Wood (DPhil), *PetroQuest International Ltd.*

The Mkuranga-1 well onshore Tanzania tested 19.4 mmcfg/d from Upper Cretaceous sandstones during January 2007. This discovery broke a 25-year country history of 18 failed exploration attempts by both the majors and independents. The story is one of dogma stunting progress and how new ideas can hold the secret to success and must be championed.

Not taking into account the many wells drilled along the East African coast from Somalia to Mozambique, in Tanzania alone over 25 exploration wells had been drilled beginning in 1956 with the partnership of Darcy-Shell drilling a true wildcat Mafia-1 on Mafia Island based solely on the recognition of a raised block of Miocene carbonates and a strong gravity anomaly. Over the next 51 years only 2 discoveries were made, Songo Songo-1 in 1974 and Mnazi Bay-1 in 1982 both by Agip. Not an encouraging picture. The question was therefore, why did the consortium of Maurel et Prom, PetroQuest and Hollick believe they could do better.

Mistakenly considered to be a passive continental margin, the East African coastal belt's hydrocarbon systems have defied interpretation. Further, while it is now recognized that the margin actually deformed under compressional and shearing forces since at least the mid to late Jurassic, targets are still difficult to map as multiple shear directions are present that need to be understood in the light of the African continent intermittently rotating counterclockwise while moving north. Between each period, namely the late Jurassic to Neocomian, the Upper Cretaceous to Eocene and the Oligocene to the Present, the continent folded, fractured and rotated under a constant force from the southeast. Taking rotation into account, the final piece of the puzzle, together with arching and shearing, new maps for each interval revealed a new picture.

The Mkuranga-1 well was drilled in an area named the Bigwa Embayment, an area thought to have simply collapsed during coastal stretching and therefore never drilled. The nearest offset wells, drilled on the elevated margins of the embayment, were Kisaware-1, 23km NW, drilled in 1976 by Agip and Ruaruke North-1, 60km south, drilled in 1984 by Shell. Both were dry. In fact, the well was drilled on the newly recognized NE plunging Bigwa Arch, itself cut by generally north oriented shears to form four-way closed compressional structures. Aside from cross cutting of the arch setting up traps, the arch focused migration of gas from the deeper areas to the northeast completing the petroleum system.

The well was drilled in 78 days with testing continuing for another 61 days. Three zones tested gas while logs indicated an untested fourth gas interval. Leaving aside the geological challenges, physical constraints presented a task in itself due a lack of infrastructure. These challenges were met and success followed.

NOTES

Friday 15 April

Session Six: Onshore Rifts

New Deep Basin- and Crustal-Scale Imaging of the Lake Malawi/Nyasa Rift: Constraints on Extension and Basin Evolution in the East African Rift

Christopher A. Scholz[1], Donna J. Shillington[2], Tannis McCartney[1], Natalie N. Accardo[2], Patrick Rafiki Chindandali[3], Godson Kamihanda[4]

[1]Syracuse University, Syracuse, New York, USA 13244
[2]Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964
[3]Geological Survey of Malawi, Zomba, Malawi
[4]Geological Survey of Tanzania, Dodoma, Tanzania

1. Background

The Lake Malawi (Nyasa) rift occupies the southern extension of the western branch of the East African Rift System (EARS)(Fig.1), from the Rungwe Volcanic Province in southern Tanzania south approximately 600 km, to the Shire River outlet of Lake Malawi. Comprised of three main rift segments defined by ~150-200 km-long border faults, it is the main southern expression of the EARS. Lake Malawi is one of the world's largest and oldest lakes and has likely persisted in its present form since the Miocene. With a modern water depth of ~700 m, the lake's stratified water column helps preserve organic matter in deep-water sediments; given rapid rates of fault-controlled subsidence and the thick sedimentary section, it is likely that the rift preserves a working hydrocarbon system.

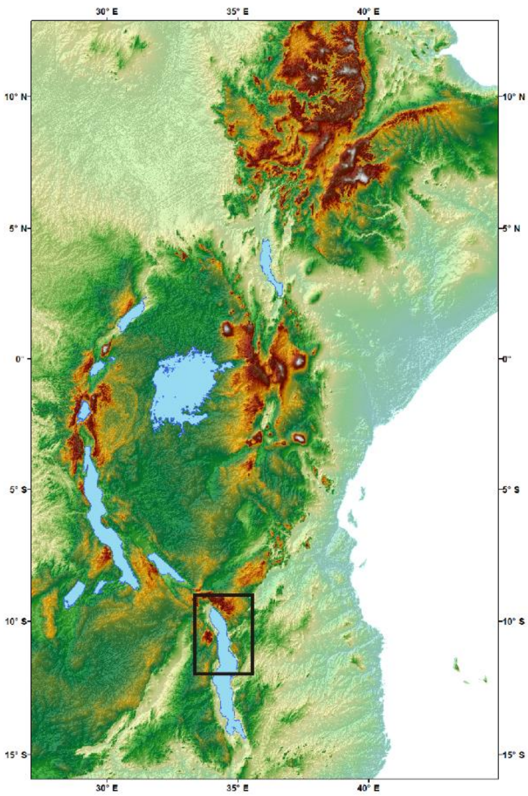


Figure 1. Digital elevation model of the East African Rift System (EARS), with the study area in northern and central Malawi/Nyasa rift outlined. The study area encompasses the northern and central basins of the lake, which contain the thcikest, and presumably oldest rift sections in this part of the EARS.

2. SEGMeNT Project

In February-April 2015 an international team conducted an offshore-onshore basin- and crustal-scale active-source seismic experiment in the Lake Malawi (Nyasa) rift. Funded by the U.S. National Science Foundation, collaborators from the USA, Malawi and Tanzania collected ~2000 km of multichannel reflection (MCS) and wide-angle reflection and refraction data in the rift. The goals of the study are to assess the influence of magmatism in early rifting, and compare and contrast magmatically-active, and apparently amagmatic rift segments. The SEGMeNT project incorporates various observational methods, including active and passive seismology (onshore and offshore), magneto-telluric profiling, as well as geochemical surveys and analyses. Wide-angle seismic data were recorded using onshore seismometers and offshore by 35 long- and short-period Ocean Bottom Seismometers sourced from the U.S. national instrument pool. This presentation focuses on the multichannel reflection seismic data acquired in the offshore parts of the study area.

3. Offshore Data Collection and MCS Imaging

In order to acquire new “marine” seismic reflection data on the lake, a 62 m container vessel operated by the Malawi Shipping Company was temporarily converted into a geophysical survey ship. An array of between 2 and 6 Sercel “G-Guns” were used as the seismic source, which varied in size from 2500 in3, for long-offset crustal-scale refraction and wide-angle reflection lines, to 1500 in3 for most MCS reflection profiles, to 500 in3 for select high-resolution basin-scale profiles. The digital seismic streamer deployed from the vessel had a maximum offset of 1500 m, and provided 60-fold maximum CMP coverage.

4. Data Processing and Key Observations

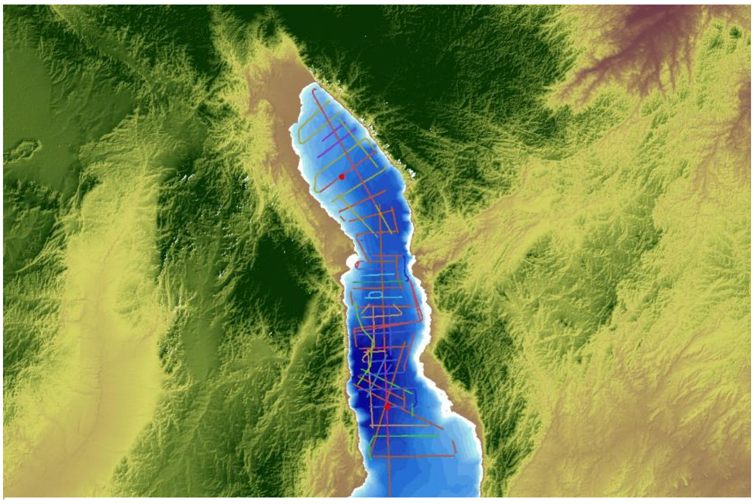


Figure 2. Digital elevation model of the Malawi rift illustraing asymmetric half-graben morphology and uiplifted rift shoulders; lake bathymetry (maximum depth = 700 m); positions of all shots fired during the 2015 SEGMeNT active source sesmic experiment (colored lines indicate all refraction and MCS reflection shots); locations of two scientific drillholes (red dots).

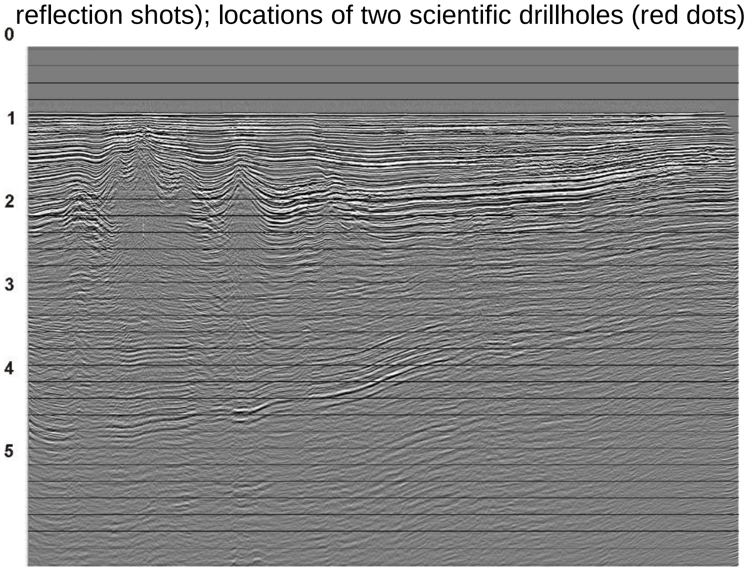


Figure 3. New SEGMent project migrated profile – Lake Malawi. Image from Central Basin showing pre-rift basement reflections and mud diapirs. Processing by T. McCartney, Syr. Univ. doctoral candidate.

Data were acquired in the northern two rift segments of the Malawi/Nyasa rift, in the central and northern basins of the lake, with a nominal line spacing for MCS profiles of ~4-8 km (Fig. 2). Extensive negotiations and advance planning were carried out in order to allow seamless data collection across the entire lake, and near international boundaries, for instance in the lake’s northern basin. The close collaboration between the Geological Surveys of Malawi and Tanzania, is credited with enabling this rift-wide survey. MCS data processing is now underway, with primary parameter testing completed, and production processing, including multiple removal and post-stack migration progressing rapidly. Following initial interpretation work, Pre-Stack Depth Migration will be applied to all MCS data sets. The large active source deployed for this survey allows for exceptionally deep imaging for this basin; the extensive onshore and ocean-bottom seismometer deployment in this experiment will permit the development of a high-fidelity velocity model for the basin. Initial observations include a complex array of shallow fault-related folds extending across the central part of rift; a series of deep seated mud diapirs in the main depocenter in the Central

Basin of the lake (Fig. 3); and clear images of pre-rift basement at two-way travel time depths of 5 s or more in several localities. This thick section occurs adjacent to a scientific drilling project drill site that sampled high-Total-Organic-Carbon proto-source rock; accordingly we interpret the presence of a working hydrocarbon in the Lake Malawi/Nyasa rift.

NOTES

Structural, Petrophysical and Geochemical Investigations of Basement Oil Seeps from a Rift Border Fault System: Example of the Albert Graben (Uganda)

Bastien Walter, Yann Hautevelle, Yves Géraud, *UMR-CNRS 7359 GeoRessources, ENSG - University of Lorraine, 2 rue du Doyen Marcel Roubault, 54518 Vandoeuvre-les-Nancy Cedex, France*

Introduction

The northern segment of the western branch of the East African Rift System (EARS) consists in a complex graben system over 700 km, composed of several basins progressively trending from NNE-SSW to NE-SW, from the Kivu Lake to the Albert Lake up to the North (Chorowicz, 2005). Due to their organic-rich sediment fillings, these lacustrine basins are known for their hydrocarbon resource potential, especially the Albert Lake (e.g. Lirong et al., 2004; Abeinomugisha & Kasande, 2009; Karp et al., 2012). This graben system developed since Miocene, with rare occurrences of magmatic events, propagates through Archaean and Proterozoic magmatic and metamorphic basement rocks. The rift locus was controlled by pre-existing Proterozoic lithospheric suture belts, playing as a mechanical weakness zone between the two stable Precambrian Tanzania and Congo cratons (Ebinger, 1989; Morley, 2010; Link et al., 2010).

Unconventional hydrocarbon basement reservoirs are nowadays frequently described in extensive tectonic settings, corresponding generally to fault-bounded basement structural highs, flanked by sedimentary rocks within a basin (e.g. Landes et al., 1960; P'an, 1982; Petford & McCaffrey, 2003; Trice, 2014). The porosity-permeability system of such reservoir is provided by brittle structures, ranging from seismic scale faults to sample scale fractures and cracks, and by altered rock layers, both resulting of a combination of different tectonic, hydrothermal or supergene weathering events.

This paper investigates fluid circulation zones within the basement footwall of the eastern border fault of the Albert Lake, on the Ugandan shore (Fig. 1a). This flank of the Albert full-graben is bounded by the Toro-Bunyoro fault system, antithetic to the major SE-dipping Bunya fault, located on the Congolese shore of the lake (Karp et al., 2012). The significant throw of the Toro-Bunyoro fault system develops an eastern rift shoulder at about 1300m elevation whereas that of the lake is at 618m (Chorowicz, 2005). This fault system is composed of a ENE-trending transfer zone between two 100-km long steeply NW-dipping NE-trending faults.

This work presents a structural and petrophysical characterization of the fault zone architecture along the lake and we provide information about recent fluid circulations, especially at two sites where hydrocarbon (HC) material was sampled and analysed. We investigate the fault and fracture networks and the rock matrix properties to estimate the reservoirs capacities of such fault zones and the oil seeps are analysed to get information about the HC source and transport.

Structural and petrophysical characterization of the Albert Lake main fault architecture

Field analysis of the basement fabric and AMS measurements show good correlations with the orientation of the rift main structures and of the dominant fracture sets. This observation confirms the strong control of inherited structures on the rift-related brittle structures development, already described at larger scale (e.g. Katumwehe et al., 2015).

From several sites along the main fault, a classical fault architecture is identified from structural and microstructural observations, consisting in a 10-20m thick heavy strained, cataclastic fault core and a larger damaged zone (Fig. 1b). Overall thickness of the fault zone all along the scarp appears to be about 200-300m. Values observed in the fault zone are ranging from 5 fractures per meter up to 50 fractures per meter. The strong lithological heterogeneities encountered in the basement (e.g. granitic gneiss, micaschist) control the fracture density and a relationship with the distance to the fault core appears to be secondary. Nevertheless, the distance to the fault plays a role on the orientation of the different fracture sets between the compartments. Out of the fault zone, many different fractures sets are identified, interpreted as various inherited structures while in the fault zone the organization of the fracture network becomes simpler with one dominant fracture set. This fracture pattern change towards the fault core is interpreted as a result of the syn-rifting cataclasis development, which erased previous rock fabric and structures, leading to the development of a post-cataclasis fault-related fracture network.

Regarding the petrophysical properties (porosity, permeability, P-waves propagation velocity), measurements on samples taken both in the fault core and in the damaged zone show variations relative to the properties of the protolith samples. At the rock matrix scale, grain size reduction associated to the cataclasis development in the fault core induces a rock strain-hardening phenomenon, characterized by a decrease of porosity and permeability properties and an increase of the P-waves propagation velocity. On the contrary, the increase of porosity and permeability identified within the damaged zone is interpreted as a result of cracks development associated to the fault strain. These petrophysical measurements of the rock matrix of the different samples suggest that the fault core might represent a fluid barrier, whereas the damaged might play a role of fluid conduit with high transfer properties, as well as a potential storage volume.

Therefore, we suggest that because of these structural and petrophysical variations, such fault compartments in basement rocks have to be considered separately for reservoir understanding.

Structural and organic chemical characterization of two basement fault oil seeps

Oil seepages were identified at two sites located along the Toro-Bunyoro fault system footwall. On both sites, the basement rocks consist of granitic gneiss and fluid resurgences occur exclusively at intersections between main faults and secondary oblique ones. Hydrocarbon (HC) is generally found as fracture fillings or is part of the matrix in basement fault breccia facies (Fig. 1c, d).

The first site (Kabyosi site) is located along the N70-80° transfer zone of the Toro-Bunyoro fault system. Several HC seepages are identified at intersections between transfer zone-parallel ENE-faults and NNE-structures (Fig. 1e). These intersections form circulation zones of about 10m thick, consisting of fracture corridors surrounding cataclastic bands soaked of HC. The second site, located further north along the rift parallel fault scarp, close to the Kibiro village, has already been described for its geothermal potential (e.g. Natukunda, 2010). Hot springs, sulphur deposits and HC seepages are identified at intersection between the main N50° rift-border fault and other NNE- and NW- secondary faults.

The organic extracts of HC samples of these two sites have been fractionated by liquid chromatography in order to recover aliphatic, aromatic and a polar fractions for each sample.

The molecular composition of these fractions has been determined by gas chromatography-mass spectrometry.

Kabyosi HC samples have a rather unusual molecular signature. Indeed, some standard compounds of crude oil are here absent (e.g. n-alkanes, acyclic isoprenoids. The molecular composition of these samples is mainly characterized by the presence of some C27, C28 and C29-hopanes. C30-hopanes are only recovered in low abundance and homohopanes (>C30-hopanes) are absent. All these molecular features indicate that the oil, which has migrated through the fault network, has been intensively biodegraded. Indeed, acyclic compounds like n-alkanes, pristane and phytane are the first to be consumed by microorganisms. The large predominance of hopanoids, which originate from bacteria, is a further argument concerning the biodegradation. Kibiro HC samples are similar to the previous ones with a total lacking of n-alkanes and acyclic isoprenoids, as well as the predominance of hopanes, suggesting also biodegradation processes that affected the oil after its migration in the fault network.

Because of the intense biodegradation, which has deeply altered the initial molecular signatures of these asphalt samples, we cannot get any clear information about the source(s) of these oils. However, the structural location of these HC seepages and the presence of oil resource within the Albert Lake strongly suggest a lacustrine origin. The basement footwall appears to be connected through these fault intersections to the basin source rock and/or to a sedimentary reservoir.

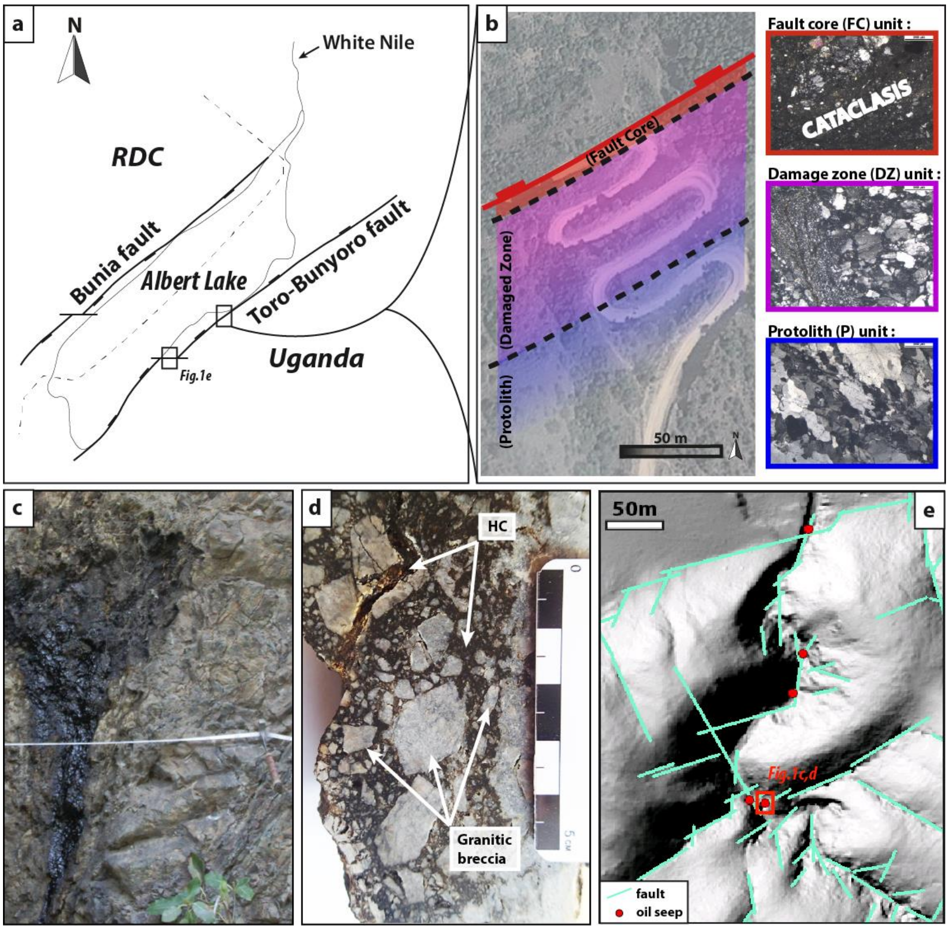


Fig.1: a) General map of the study area. b) Fault zone compartments identified by (micro)structural facies recognition. c) Oil seep within the core of a fault zone in granitic basement rocks. d) Granitic breccia with HC infillings sampled in a basement fault zone. e) Map showing the structural location of the oil seeps relative to the lineament structures.

References

- Abeinomugisha, D., Kasande, R., 2012. Tectonic control on hydrocarbon accumulation in the intra-continental Albertine graben of the East African rift system. In Gao, D. (Editor), Tectonics and sedimentation: Implications for petroleum systems. *AAPG Memoir* **100**, 209-228.

- Chorowicz, J., 2005. The East African rift system. *Journal of African Earth Sciences* **43**, 379-410.

- Ebinger, C. J., 1989. Tectonic development of the western branch of the East African rift system. *Geological Society of America Bulletin* **101**, 885-903.

- Karp, T., Scholz, C. A., McGlue, M. M., 2012. Structure and stratigraphy of the Lake Albert Rift, East Africa: Observations from seismic reflection and gravity data. In Baganz, O. W., Bartov, Y., Bohacs, K., Nummedal, D. (Editors), Lacustrine sandstone reservoirs and hydrocarbon systems. *AAPG Memoir* **95**, 299-318.

- Katumwehe, A. B., Abdelsalam, M. G., Atekwana, E. A., 2015. The role of pre-existing Precambrian structures in rift evolution: The Albertine and Rhino grabens, Uganda. *Tectonophysics* **626**, 117-129.

- Landes, K. K., Amoruso, J. J., Charlesworth, L. J., Heany, JR. F, Lesperance, P. J., 1960. Petroleum resources in basement rocks. *Bulletin of the AAPG* **40** (10), 1682-1691.

- Link, K., Koehn, D., Barth, M. G., Tiberindwa, J. V., Barifaijo, E., Aanyu, K., Foley, S. T., 2010. Continuous cratonic crust between the Congo and Tanzania blocks in western Uganda. *International Journal of Earth Sciences* **99**, 1559-1573.

- Lirong, D., Jianjun, W., Dingsheng, C., Xuefeng, R., Rubondo, E. N. T, Kasande, R., Byakagaba, A., Mugisha, F., 2004. Geological conditions and petroleum exploration potential of the Albertine graben of Uganda. *Acta Geologica Sinica* **78** (4), 1002-1010.

- Morley, C.K., 2010. Stress re-orientation along zones of weak fabrics in rifts: An explanation for pure extension in “oblique” rift segments? *Earth and Planetary Science Letters* **297**, 667-673.

- Natukunda, J. F., 2012. Geology of Kibiro, Katwe and Buranga geothermal prospects of Uganda. *Proceedings of the 4th African Rift Geothermal Conference*, 21-23 November 2012, Nairobi, Kenya.

- P’an, C. H., 1982. Petroleum in basement rock. *AAPG Bulletin* **66** (10), 1597-1643.

- Petford, N., McCaffrey, K., (Editors), 2003. Hydrocarbons in crystalline rocks. *Geological Society, London, Special Publica*tions **214**.

- Trice, R., 2014. Basement exploration, West of Shetlands: progress in opening a new play on the UKCS. In Cannon, S.J.C., Ellis, D. (Editors), Hydrocarbon exploration to exploitation West of Shetlands. *Geological Society, London, Special Publictions* **397**, 81-105.

NOTES

Thermal History and Source Rock Facies Variation - Implications for Hydrocarbon Charge in the South Lokichar Basin, Kenya (EARS)

Gion Kuper and Raingard Haberer, *Tullow Oil plc., United Kingdom*

In recent years the East African Rift System (EARS) has revealed high petroleum potential with the discovery of significant resources in previously underexplored basins. The EARS divides into a western branch ‑ a young continental rift ‑ and an eastern branch representing a failed, mature rift system [3].

Tullow Oil has been at the forefront of hydrocarbon exploration in the EARS. Following a successful campaign in the young Albertine Rift in Uganda, the company expanded its interests by focussing on the eastern branch, acquiring a strong acreage position with partners Africa Oil Corp. in Kenya and Ethiopia.

The new exploration campaign initially targeted the South Lokichar Basin, where a single well had already been drilled in 1992. This well proved the existence of a working petroleum system, but suggested issues with trapping and charge mobility. The first new well in the basin, Ngamia-1, was a significant discovery, opening a major new play along the western bounding fault. Further discoveries followed in quick succession revealing a highly prospective basin with high overall charge volumes.

The South Lokichar Basin has been identified as the oldest rift basin in a string of EARS basins in the Lake Turkana area. The geology and structural development of these basins has been comprehensively described in Morley et al. [3, 4], Tiercelin et al. [6], and Macgregor [2], among others. Both the occurrence of source rock and its thermal evolution are strongly influenced by the structural development of the basin. The extent and rate of crustal thinning over time determine the heat flow history, although sedimentation and erosion rates have important transient influence. The rate of basin opening also affects the potential for the development of rift lakes and the deposition of rich lacustrine source rocks.

In the South Lokichar Basin three source rock horizons have been identified. The most prolific source rock is the Miocene Lokone Shale. At the Loperot-1 well in the eastern part of the basin, the Lokone Shale has been reported to be very rich in organic matter (TOC up to 17%). The most prospective intervals have a very high oil potential with Hydrogen Index >700 mg/gTOC [5]. In addition, the older Loperot Shale and the younger Auwerwer Shale also show very good source rock potential, each representing a separate phase of lake development in the basin. The source rocks in the basin show a general lacustrine Type I kerogen, which is highly oil-prone, but distinct source differences can be identified that impact on the type and volume of hydrocarbons expelled.

Understanding source facies variations, identifying access to charge and determining reservoir conditions, oil quality and charge preservation are shown to be essential aspects of recognising and drilling the most prospective accumulations. Unlocking the basin therefore requires a detailed understanding of the geochemistry of the source rock and its thermal evolution.

Based on advanced geochemical biomarker and stable carbon isotope analyses of source rock samples and oils, we are able to differentiate between three lacustrine source rock sub-facies within the Lokone Shale. The results allow an estimate of the relative amount of input from green algae, cyanobacteria and terrestrial plants into the organic matter in the source rocks. The three specified lacustrine sub-facies are: 1) a central deeper water lake facies with algal contribution only, 2) a shallow near-shore lake facies with both cyanobacterial and algal contributions, and 3) a coastal and river run-off facies with added contribution of terrestrial organic matter.

The thermal history of the basin was reconstructed in a comprehensive petroleum systems model. The model encompasses the most recent understanding of basin development, integrating the results of the extensive drilling campaign (e.g. bottom hole temperatures, thermal maturity data). A new apatite fission track analysis study commissioned by Tullow Oil and performed at Trinity College Dublin added key understanding of the thermal evolution [1]. The model also integrated the different source rock sub-facies identified, allowing a more accurate prediction of hydrocarbon potential and character.

The modelling results reveal source rock maturation and hydrocarbon generation upon burial under elevated rifting heat flow, influenced by later rift flank uplift in an intricate interaction of factors influencing the heat flow history. It is possible to map out where recent expulsion provides an additional drive to charge in the fields and where uplift stopped expulsion early. In addition, a map can be produced indicating the depth of the biodegradation risk boundary based on the palaeo-pasteurisation principle [7]. The basin model therefore provides valuable insights in the variation of prospectivity across the basin beyond general maturity, generation and migration evaluation. It reduces risk and uncertainty related to charge quality and producibility.

Detailed evaluation of the thermal history and source rock facies allows us to identify the most prospective areas for exploration in the South Lokichar Basin. By identifying commonalities, as well as key differences with the Albertine Rift and other EARS basins in our portfolio, it also allows us to better assess the prospectivity of unexplored rift basins.

References

[1] N. Cogné, “Thermal Evolution of the South Lokichar Basin: Fission Track Analyses on Wells Etuko-1, Loperot-1, Ekales-1, Ngamia-1 and Twiga South-1,” Tullow internal report, Trinity College Dublin, p. 23, Ireland, 2014.

[2] D. Macgregor, “History of the Development of the East African Rift System: A Series of Interpreted Maps through Time,” Journal of African Earth Sciences No. 101, pp. 232-252, 2015.

[3] C.K. Morley, D.K. Ngenoh, and J.K. Ego, “Introduction to the East African Rift System,” in C.K. Morley (Ed.), Geoscience of Rift Systems−Evolution of East Africa, AAPG Studies in Geology No. 44, pp. 1–18, 1999.

[4] C.K. Morley, W.A. Wescott, D.M. Stone, R.M. Harper, S.T. Wigger, R.A. Day, and F.M. Karanja, “Geology and Geophysics of the Western Turkana Basins, Kenya,” in C.K. Morley (Ed.), Geoscience of Rift Systems−Evolution of East Africa, AAPG Studies in Geology No. 44, pp. 19–54, 1999.

[5] M.R. Talbot, C.K. Morley, J.-J. Tiercelin, A. Le Hérissé, J.-L. Potdevin, B. Le Gall, “Hydrocarbon potential of the Meso-Cenozoic Turkana Depression, northern Kenya. II. Source rocks: quality, maturation, depositional environments and structural control”, Marine and Petroleum Geology 21, pp. 63–78, 2004.

[6] J.-J. Tiercelin, J.-L. Potdevin, C.K. Morley, M.R. Talbot, H. Bellon, A. Rio, B. Le Gall, and W. Vétel, "Hydrocarbon Potential of the Meso-Cenozoic Turkana Depression, Northern Kenya. I. Reservoirs: Depositional Environments, Diagenetic Characteristics, and Source Rock - Reservoir Relationships," Marine and Petroleum Geology No. 21, pp. 41-62, 2004.

[7] A. Wilhelms, S.R. Larter, I. Head, P. Farrimond, R. di-Primio, and C. Zwach, "Biodegradation of oil in uplifted basins prevented by deep-burial sterilization," Nature No. 411, pp. 1034-1037, 2001.

NOTES

Mapping the Evolution of the East African Rift System – An Updating and Re-Imaging

Peter Purcell[1] and Duncan Macgregor[2]

[1]*P & R Geological Consultants, Scarborough, Australia*
[2]*MacGeology Ltd, Reading, UK*

Our knowledge of the tectonic development of the East African Rift System (EARS) is constantly improving, as new work provides new data and insights, and our constructed images of the evolving rifting and magmatism must be regularly re-imagined. For example, the recent identification of Oligocene and Late Miocene sediments in the Rukwa Rift has necessitated a change to earlier perceptions of the rifting pattern and development in southern Tanzania, suggesting less a simple north-to-south propagation and more a lattice-like expansion from several nodes. Depicting the progressive development of rifting in the EARS involves both geological and artistic choices and challenges. Do we plot the rift at the time of initial downwarping and faulting, for instance? Or at the time of main rifting? Or both? How do we illustrate that in map form? How do we distinguish between what is known (or thought to be known) and what the authors might consider to be reasonable projections. The series of maps of the EARS presented here, combining work by the authors, are an updating and re-imaging of the maps presented by Duncan Macgregor to the Geological Society of London at the East Africa conference in 2012 and published in 2015.

Much of the pattern of Phanerozoic rifting in eastern Africa has been controlled by the underlying Proterozoic fabric, and the EARS has developed partly as a new lithospheric rupture within that fabric and partly as a reactivation of earlier rifting. The progressive development of the EARS is shown on a series of map depicting the rift at various times from the Permian to the present. The main focus is on the Cenozoic rifting which commenced about 35-30 Ma in the Gulf of Aden and Afar in the north, the Rukwa area in the south and, centrally, the Turkana area in northwest Kenya. This rifting was preceded by extensive volcanism in the northern areas but with little volcanism in the south. The paucity of magmatism associated with the Western Branch of the EARS is a marked difference to the voluminous volcanism that occurs along the Eastern Branch. Rifting intensified in the period c12-8 Ma and by 5 Ma was continuous from Afar through Ethiopia and Kenya into Tanzania. Rift activity in EARS is arguably at an historical peak at the present time.

NOTES

Geochemical Characterisation and Correlation of Crude Oil and Sediment Extracts From Two Oil Fields and Discovery Areas in the Albertine Graben, Uganda

Joshua Lukaye[1], Micheal Okello[1] and Geoffrey Abbot[2]

[1]*Petroleum Exploration and Production Department, Uganda*
[2]*Newcastle University, UK.*

This study analysed crude oil and source rocks from two oilfields (Mputa and Kingfisher) and two discovery areas (Turaco and Ngassa) in the Albertine Graben, Uganda. It aimed to assess the source rock potential and maturity, characterize the sedimentary depositional environments using specific biological marker compounds and consequently, establish the genetic link between the oils and the source rocks.

Bulk geochemical analysis of source rocks from the sampled wells in the two discovery areas show that they are characterised by total organic carbon (TOC) content in the range 0.57-2.87%, S2 and production potential (PP) in the range 7.44-8.24 (mg HC/g rock) and 7.54-8.75 mg HC/g rock respectively with Tmax and hydrogen index (HI) ranging between 451-457.5 0C and 287.1- 820.4 (mg HC/gTOC) respectively indicating that they are mature oil-prone source rocks with good potential to generate oil. Source rocks from sampled wells in the two oil fields display very low TOC, S2 and PP with Tmax and HI in the range 428-255 0C and 88.2-414.3 (mg HC/gTOC) respectively, consistent with mature oil-prone source rocks with limited or no potential to generate oil.

The aliphatic and aromatic hydrocarbon distributions of the oils and sediments have been described and contrasted in the search for diagnostic features among their biological marker distributions. The aliphatic hydrocarbons for all the oils are dominated by n-alkane compounds in the range nC12-nC32, Pr/Ph ratio of 3.0, CPI of 1.3, high C29 regular steranes, abundance of C30 αβ hopanes relative to C29 norhopane. They also show dominance of 9-methyl phenanthrene, low abundance of the C31 (22R) homohopane with C32 22S/(22S+22R) hopane ratios that are in range 0.56 - 0.57. These data indicates that the oils are from the same family and were derived from a mature mixed algal/terrigenous source rock deposited under anoxic to sub-oxic conditions.

The source rocks from the Kingfisher and Mputa wells are characterised by a unimodal n-alkane distribution, relatively low pr/ph ratios, high C27/C29 regular sterane ratio with C32 22S/(22S+22R) hopane ratios that are in range 0.56 - 0.57 while source rocks from Turaco and Ngassa wells are characterised by a bimodal n-alkane distribution, high pr/ph ratios of 6.39 and 4.32 respectively. The data shows that source rocks from Kingfisher and Mputa wells are mature and of algal source facies deposited under anoxic to sub-oxic conditions while the Turaco and Ngassa source rock are mature and of predominantly terrestrial source facies deposited under oxic conditions.

Comparison of biomarker distributions in the oils with biomarker distributions in the source rocks show no correlation between the oils and the source rocks hence, none of the source rocks was responsible for the expulsion of the oils.

Keywords: Organic matter, crude oil, biomarkers, source facies, steranes, terpanes, maturity, oil-oil and oil-source rock correlation, Albertine Graben, Uganda

NOTES

Geothermal Processes and Evaporative Concentration: Contributors to the Formationof Lacustrine Source Rocks in the Saline, Alkaline Lake Basins of the Kenya Rift Valley

Robin W. Renaut[1], R. Bernhart Owen[2], Jean-Jacques Tiercelin[3] and John K. Ego[4]

[1] *Dept. Geol. Sci., Univ. Saskatchewan, Saskatoon SK, S7N 5E2, Canada*
[2] *Dept. Geography, Hong Kong Baptist Univ., Kowloon Tong, Hong Kong*
[3] *UMR 6118 CNRS Géosciences Rennes, Université de Rennes 1, Rennes, France*
[4] *National Oil Corporation of Kenya, AON Minet House, PO Box 58567 - 00200, Nairobi, Kenya*

Most lacustrine petroleum source-rocks in East African rift basins develop in two hydrological settings: (1) large, relatively stable, hydrologically open lake-basins ('overfilled') with moderate to high rates of planktonic organic-matter accumulation – such lakes may be deep and stratified (thermally meromictic) with little sediment-mixing; and (2) hydrologically closed ('underfilled'), chemically stratified, saline alkaline lakes with oxygenated surface waters (mixolimnion) and anoxic bottom waters (monimolimnion). The latter lakes have high organic productivity, but typically have unstable limnological regimes. Under favourable conditions, however, saline alkaline rift-lakes generate high-quality source rocks. Two factors – evaporative concentration and geothermal fluid inflow – combine to create ideal conditions for accumulation and preservation of planktonic organic matter in offshore muds.

The modern, saline alkaline lakes of the Kenya Rift consist of shallow ephemeral lakes (Nakuru, Elmenteita, Logipi), stratified (Bogoria) and polymictic (Nasikie Engida) perennial saline lakes, and a hypersaline pan (Magadi). All are variably recharged by hot (~35–98.5°C) alkaline Na-HCO3 springs and runoff, and have exceptionally high microbial productivity. The microbiota in these lakes, dominated today by Arthrospira fusiformis, attracts a large avifauna including lesser flamingos, which consume, recycle and introduce nutrients (P, N) that help to maintain very high aquatic productivity (Fig. 1A).

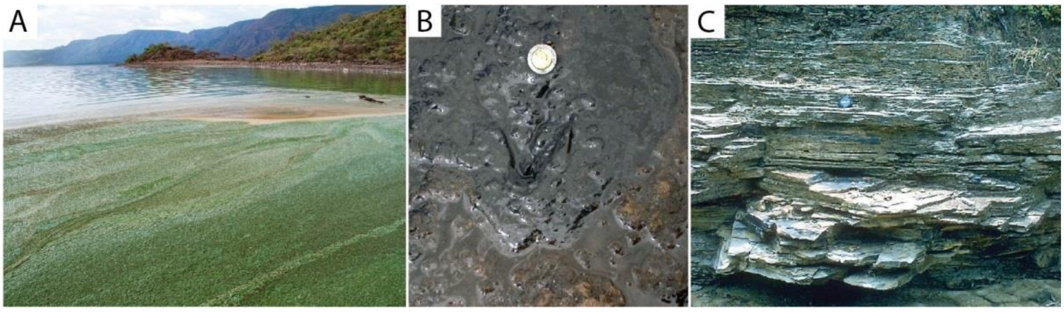


Figure 1. **A.** Plankton scum (*Arthrospira fusiformis*) on the surface of Lake Bogoria. **B.** Organic-rich gelatinous muds, disturbed by digging, north Nasikie Engida. **C.** Miocene laminated zeolitic shales, Ngorora Formation, Member C, Tugen Hills, west of Lake Baringo.

Evaporation increases lake salinity (from ~20 to >320 mg l-1 TDS), decreases water volume, and, while excluding many organisms, allows adapted plankton to thrive. Preservation potential of this microbial organic matter varies with lake type. Organic matter in the ephemeral (playa) lakes is oxidised rapidly upon exposure or is recycled, but perennial saline lakes are more likely to preserve organic matter in their muddy sediments. The stratified (periodically meromictic) regime of Lake Bogoria, only 10–12 m deep, has enabled lacustrine organic-matter preservation (1–6% TOC: mainly Type 1) in anoxic lake-centre muds and oozes below a fluctuating shallow (5–6 m deep) chemocline. At Nasikie Engida (<1.2 m deep) organic matter is poorly preserved because of periodic mixing and oxidation, but some survives in buried bedded nahcolite-trona evaporites and in offshore muds and siliceous gels (up to 4% TOC)

(Fig. 1B). Even Lake Magadi, a saline pan with bedded trona, has cm-scale layers with preserved microbial remains that accumulated during episodes of high productivity when the expanded lake was relatively dilute. Some of that microbial organic matter (1–4% TOC) survives in evaporites and zeolitic muds that are now immersed in anoxic interstitial hypersaline brine below the modern lake.

A common factor in all these saline lake basins is a reliable supply of carbon, some perhaps originating from geothermal fluids of $Na-HCO_3-(CO_3)$ composition. The hot springs that provide those fluids discharge along faulted lake-shorelines and from vents on lake floors. They supplement bicarbonate ions in dilute inflow waters (rivers, groundwaters) derived from silicate mineral hydrolysis during chemical weathering of volcanic rocks. Deeper volcanogenic CO_2 might also contribute to the high organic productivity in the Kenya Rift lakes, and provide a nearly constant HCO_3^- supply that also contributes to trona precipitation in Lake Magadi. In contrast, hypersaline lakes with either chloride or sulfate as their dominant anion are frequently less productive.

Geothermal sources of lake recharge that are deeply sourced (from >1 km depth) with long residence time respond more slowly to short- to medium-term climate variations than recharge waters controlled by surface and near-surface hydrology. Lakes Bogoria, Nasikie Engida, and Magadi all depend strongly on geothermal inflow. About 35-40% of the annual recharge at Lake Bogoria, and up to ~80% of the annual recharge at both Nasikie Engida and Lake Magadi originates from alkaline hot-spring fluids. At Lake Magadi, most modern hot-spring inflow evaporates rapidly and precipitates trona. In contrast, perennial Lake Bogoria and Nasikie Engida shrink and become shallower when the climate becomes drier, but still retain saline, alkaline surface water. Consequently, organic matter in their offshore sediments has a higher preservation potential than, for example, that of lakes Nakuru and Elmenteita, which have much lower hydrothermal recharge and periodically undergo complete desiccation. Geothermal fluids help to preserve organic matter during periods of climate change on timescales up to thousands of years. Nasikie Engida remains a perennial lake only because of its geothermal recharge. Without sustained hot-spring inflow the lake would desiccate rapidly, most of its microbial organic matter would be rapidly oxidised, and the clay minerals in its offshore muds would undergo early rapid zeolitisation.

Favourable conditions for preserving petroleum source rocks in saline, alkaline rift lakes occur in relatively deep (>10 m), steep-sided faulted basins with small drainage basins that receive enough hydrothermal inflow to maintain lake water when the climate becomes more arid. Planktonic organic matter, suitable for generating types I and II kerogen, forms in shallow oxygenated waters during humid periods and is deposited offshore in anoxic muds, often below a chemocline. Small catchments limit coarse sediment supply and the macrovegetal organic influx that would generate type III kerogen. If the climate becomes drier after a humid period when organic-rich muds accumulated, saline hydrothermal fluids may then dominate the annual lake recharge. The lake might shrink in surface area and depth but, with steep faulted margins, would maintain surface water that would limit subaerial exposure and reduce organic matter oxidation.

Evapoconcentration of alkaline brines after periods of organic mud sedimentation may lead to precipitation of bedded evaporites or cherts. Chert and evaporites are both effective caprocks. Bedded cherts form because silica solubility decreases when lake-water temperature falls (cooling of geothermal fluids) or when the pH of the lake brine decreases abruptly by several triggers (e.g., during magadiite precipitation). High geothermal gradients in active rift-basins, in turn, promote maturation of earlier, lacustrine microbial organic-matter.

Member C of the Miocene Ngorora Formation (Tugen Hills, W Baringo) is a series of lacustrine, zeolitic organic-rich shales that are silicified near the top of the unit (Fig. 1C). Lake Magadi contains laminated carbonaceous mudstones (High Magadi Beds) capped by trona evaporites, and older organic mudstones interbedded with Pleistocene cherts (Green Beds). A decrease in water temperature and (or) pH potentially created caprocks overlying alkaline, lake-mudstone sequences rich in planktonic (Type 1) organic matter.

Stratified saline, alkaline lakes fed partly by geothermal fluids provide highly favourable conditions for source-rock generation in continental rifts. Those potentially productive intervals nonetheless are more limited in lateral extent and thickness than those of large, open, freshwater lakes that have lower organic-productivity. Climate, tectonics, bedrock, and their combined influences on hydrology and hydrogeology, are fundamental controls on generation of lacustrine source rocks in the East African Rift.

NOTES

Poster Presentation Abstracts

The Nature of the Crust Offshore East Coast Africa – When Geology and Seismic Meet Potential Fields In the Search for Hydrocarbons.

Yannis Bassias[1], Glyn Roberts[2], Trond Christoffersen[2]

[1]*Gemini Ressources SAS,*
[2]*Spec Partners Ltd. Contact*

Introduction

Based on the work the authors have undertaken in the Central Mozambique Channel Basin (CMCB) (Bassias et.al 2015, Roberts et.al 2013) and observations made by others (e.g. Mahanjane 2012, 2014) on the geology of offshore East Africa, this paper examines some of the assumptions regarding the nature of the crust (Continental-Transitional-Oceanic: COB) and their identification and location. Our study investigates the reliance placed on the interpretation of magnetic striping for the identification of oceanic crust and the creation of paleogeographic reconstructions and other geological models. Our observations are based on seismic data examples (Fig 1 & 2) from the CMBC and an analysis of the methodology used in the identification of magnetic striping (Figs. 3). We discuss the validity of some of these models and conclude by suggesting that there is continental/transitional crust in areas that have previously been regarded as being made up of oceanic crust. The implications in the search for hydrocarbons are obvious and we believe this approach can be extended to other parts of offshore East Africa.

Observations from our Study Area

According to our interpretation, the COB in the southern part of the Mozambique Channel developed further south from the volcanic cluster of Bassas da India and Europa. To the north Cretaceous, volcanics with continental alkaline affinities crop out on the crests of the Davie Ridge and in some cases were emplaced or altered above sea level (Bassias 1992).

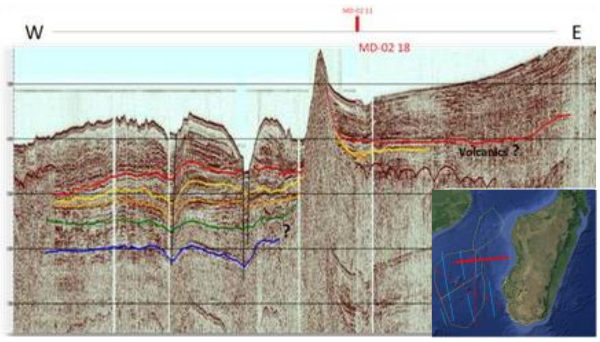


Fig. 1. To the east of the CMCB Pre-Tertiary igneous activity affected the area. This volcanic setting extends further south to the southern edge of the Morondava basin where the Davie Ridge weakens and sinks. The presence of similar volcanic activity has been documented onshore Madagascar.

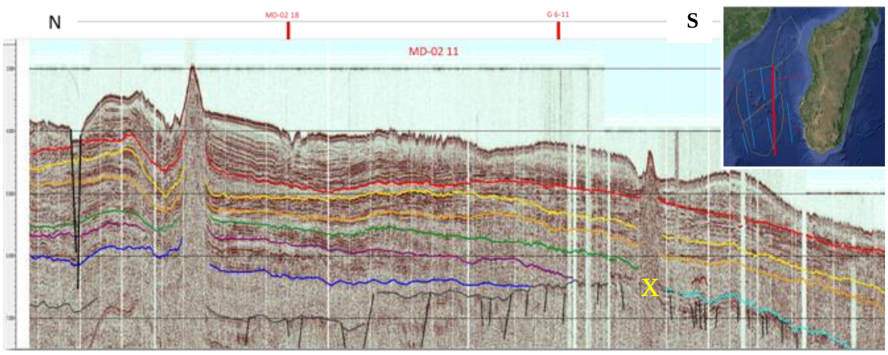


Fig. 2. The Mesozoic part of the sedimentary pile seems to be absent in the southern part of the section. The marker in light blue (and X in yellow) indicates the presence of a probable area of transition to oceanic crust.

Work by a few authors (e.g Raillard 1990, Leinweber et.al 2013 and Ferriday and Firpo 2015) has suggested spreading anomalies and oceanic crust to extend northwards to the Rovuma basin and in some cases even onshore through all of the CMCB (Fig. 3A). However, using a data driven, rather than model driven approach, the authors have seen no convincing evidence of spreading anomalies in the central and northern parts of the Mozambique channel (i.e. between 23 degrees south and 17 degrees south). A comparison of figures 3B and 3C illustrates this. Here we see that the Earth Magnetic Anomaly Grid EMAG2 (Maus et al., 2009) data with neutral gridding shows no evidence of spreading anomalies in the CMCB study area (black polygon), while evidence of spreading anomalies can be seen to the south of the study area (Fig. 3B). When applying directional gridding to the EMAG2 data, as in the published Earth Magnetic Anomaly Map, spreading anomalies are introduced into our study area without sufficient support in actual data (Fig. 3C). The EMAG2 map was published with an explicit health warning concerning the influence of the embedded crustal age model and the directional gridding on the map's appearance. Accordingly, other geological and geophysical data need to be considered to address the nature of the crust. In addition to seismic, this can include gravity. For example satellite gravity data shows that the Beira High is associated with a negative gravity anomaly, while in the central part of the study area, a possible Jurassic depo-centre (yellow dashed outline) shows some correlation with a gravity low that could represent the proto Zambesi delta (Fig. 3D) (Bassias et al., 2015).

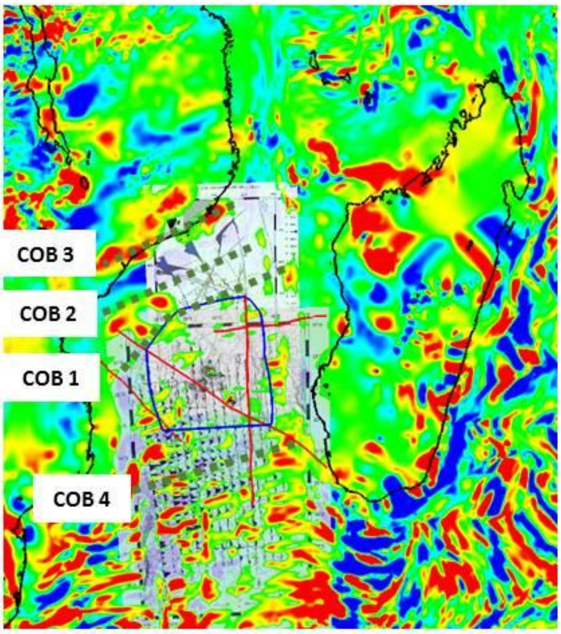


Fig 3A. Approximate locations. COB 1: Raillard 1990, COB 2: Leinweber et.al 2014, COB 3: Ferriday 2015, COB 4: The authors 2015.

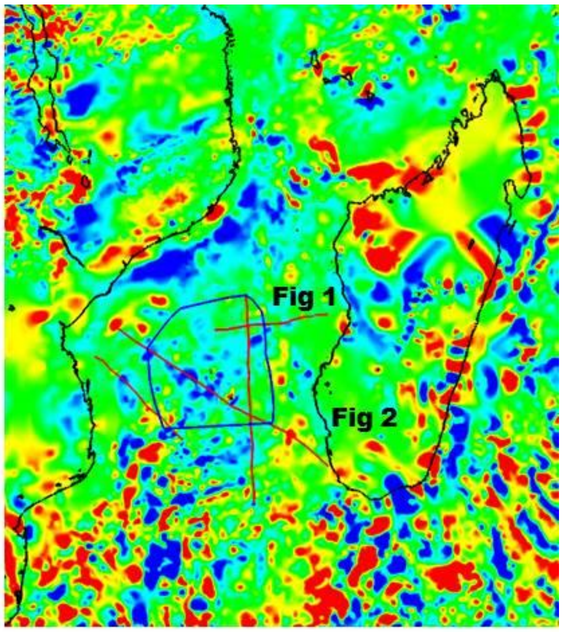


Fig 3B. EMAG2 data set with neutral gridding.
Seismic lines from figures 1 and 2 in red.

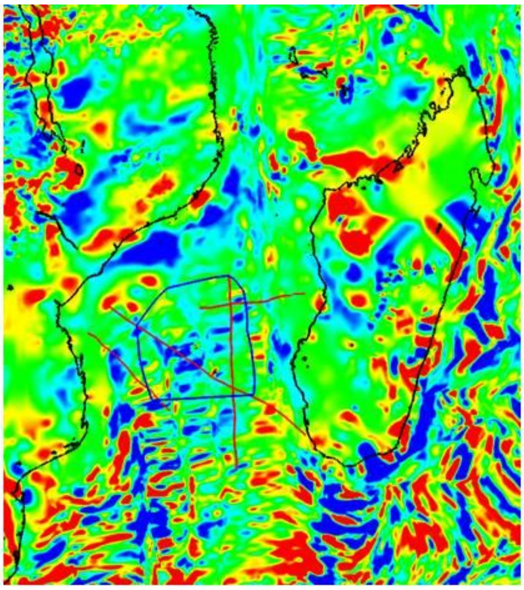


Fig 3C. EMAG2 data from the published global "seafloor-spreading"-map with directional gridding.

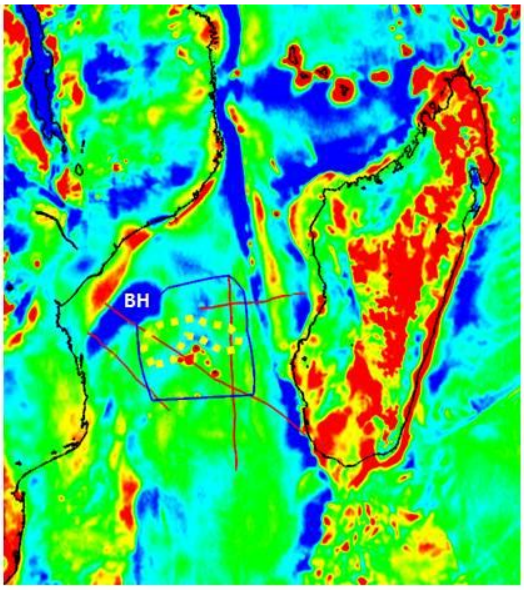


Fig 3D Satellite gravity data from Sandwell et al 2014. BH = Beira High. Dashed yellow is outline of possible Jurassic depo-centre from seismic.

References

Bassias Y., Christoffersen T. and Roberts G. (2015). The petroleum potential of the Central Mozambique Channel between Madagascar and Mozambique. PESGB/HGS: African Geology Meeting, Poster session and extended abstract, London, September 2015.

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 and the Middle East, Volume 15, Issues 3–4, October–November 1992, p. 321-339.

Ferriday T. and Giacomo Firpo (2015). Gravity modelling of the Beira High, Angoche and Rovuma margins, Mozambique. PESGB/HGS: African Geology Meeting, Poster session and extended abstract, London, September 2015.

Leinweber V., Klingelhoefer F., Neben S., Reichert C., Aslanian A., Matias L., Heyde I., Schreckenberger B., Jokat W. (2013). The crustal structure of the Central Mozambique continental margin — Wide-angle seismic, gravity and magnetic study in the Mozambique Channel, Eastern Africa, Tectonophysics, 599, p. 170-196.

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

Mahanjane, E.S (2014). The Davie Fracture Zone and adjacent basins in the offshore Mozambique Margin – new insights for hydrocarbon potential. Mar & Pet Geol 57, p. 561-571.

Maus et.al., 2009 Maus, S., U. Barckhausen, H. Berkenbosch, N. Bournas, J. Brozena, V. Childers, F. Dostaler, J. D. Fairhead, C. Finn, R. R. B. von Frese, C. Gaina, S. Golynsky, R. Kucks, H. Lühr, P. Milligan, S. Mogren, D. Müller, O. Olesen, M. Pilkington, R. Saltus, B. Schreckenberger, E.Thébault, and F. Caratori Tontini (2009), EMAG2: A 2-arc-minute resolution Earth Magnetic Anomaly Grid compiled from satellite, airborne and marine magnetic measurements, Geochem. Geophys. Geosyst., Vol. 10, N° 8, p.1-12.

Roberts G.F. Christoffersen T. et al., (2013). New insights on the prospectivity of the Morondava Basin, Offshore. Madagascar, based on new seismic data. Poster paper, 12th PESGB/HGS Conference on African E & P. London, Sept 2013.

Sandwell et al, (2014). Science 3, October 2014.

Davie Fracture Zone - Scattered Island connections in Mesozoic and Cenozoic

Yannis Bassias, *Gemini Ressources SAS*

The geological evolution of the Davie Fracture Zone (DFZ) is observed here under the combined spectrum of tectonics and depositional environments in search of paleogeographic conditions supportive for the presence of islands in the Mozambique Channel during Mesozoic and Cenozoic. A large number of core and dredge samples from the DFZ identified since the 80s a sheared continental basement that underwent high pressure / low temperature metamorphism, then unconformably overlain by limestones, basalts and carbonate oozes, suggesting that a marine sedimentary environment was definitely established since Miocene (Leclaire et al. 1989). It appears that parts of the DFZ were (or remained) above sea level during Early Cretaceous transpression and later in mid-Eocene times when a westwards compression coming from the Central Indian ridge spreading affected Madagascar and the DFZ. Today the Fracture zone is a Ridge that rises from the floor of the Mozambique Channel at 2500 mbsl to around 500 mbsl in some places (Fig. 1).

<u>Lower Cretaceous transpression:</u> The southwards movement of Madagascar along the Davie Fracture zone (Heirtzeler and Burroughs 1971, Segoufin 1978, Rabinowitz et al. 1983) was related with a transpression regime resulting in folding/faulting, uplift and erosion of continental crust (Bassias 1992). It produced tectonic movements which raised the sea-bed and flooded the lowlands. With the emergence of coastal shallows a series of scattered islands could emerge during that time, like in ancient Europe during Middle Jurassic.

<u>Mid-Cretaceous eustasy:</u> The presence of islands across the Mozambique Channel due to mid-Cretaceous eustatic reduction in sea level has probably amounted to a few hundred meters (Haq et al. 1987). A reduction of a few hundred meters would reveal few islands and narrow the channel only slightly. However, the combined effects of tectonic activity, sediment accumulation / compaction and eustasy on accommodation changes can be important on a regional scale with rates varying from several meters to tens of meters per million year (myr). The Cenomanian–Turonian interval (100–90 myr) was repeatedly punctuated by large and rapid sea-level drops, the reasons of which are still poorly understood (Janetschke et al. 2015). The sea-level falls were of high-magnitude and short duration (tens of meters in less than 100 kyr) resulting in "absolute" rates of sea-level change in the order of 150–1000 mr/myr. These sea-level falls, resulted in the development of depositional sequences and unconformities have been reported on several continental margins. Similar unconformities were mapped on seismic lines of the DFZ flanks (Bassias and Bertagne, 2015).

<u>Late Cretaceous basalts:</u> Basalts with alkaline affinities were emplaced along the fracture zone under hypabyssal and in some cases subaerial conditions (Bassias and Leclaire, 1990). The crustal thickness between Africa and Madagascar seems to have inhibited the emplacement of huge volumes of magma along the fracture zone and underplating of magma probably contributed to uplift (Bassias, 1982). Basalts were emplaced after cessation of the southwards movement of Madagascar, apparently at a time of relaxation when India separated from Madagascar at around 83 Myr (Segoufin and Patriat 1981).

<u>Eocene uplift:</u> Basaltic breccia with reworked angular and rounded clasts were amply dredged at the northern and southern part of the DFZ. They are cemented in a Middle and Upper Eocene (49-37 Myr) carbonate matrix indicating that areas of the Mozambique Channel were subject to shallow water to subaerial erosion (Leclaire et al. 1989; Bassias and Leclaire, 1990).

This erosion was explained as a result of compression due to the change of spreading rates in the Indian ocean during Middle Eocene (50-43 My). It corresponds to the time of increase of the E-W spreading rates of the Central Indian Ridge that followed the rapid northwards migration of the Indian plate (Patriat and Segoufin 1988). It is proposed that some of the old NW-SE transfer dextral faults crossing the Mozambique channel were reactivated to sinistral under compression. The amplitude of this compression and uplift is registered on E-W seismic lines across the DFZ (Fig.2).

<u>Miocene-Pliocene gap:</u> Miocene bioclastic limestones and breccia from the crests of the ridge are locally karstified, fractured and directly covered by younger Pleistocene chalks. Fault controlled tilting, emersion and erosion being present along the ridge during Miocene-Pliocene record an important stratigraphic hiatus which might be related with a large tectonic activity and/or emersion after the global marine regression in mid-Oligocene (Leclaire et al, 1989) and during the general epeirogenic african uplift and east african rift development (Mougenot et al., 1986, Chorowitz et al, 1987). Faulting observed on E-W seismic lines, brings the western flank of the crystalline edifice to a total vertical displacement of 2 seconds (twt) that favoured the development of channel filled sandstones west of the ridge (Fig.2).

<u>Conclusion:</u> Parts of the DFZ were or remained above sea level during Early Cretaceous transpression and later due to the Eocene reorganization of the Indian ocean ridges affecting Madagascar and the DFZ. Emersion was the result of long term intermittent uplift and eustasy combinations through Mesozoic and Cenozoic. The ridge subsided definitely from Late Miocene times in the middle of the Mozambique Channel.

<u>Implications for the biodiversity:</u> In the Middle Eocene the circum-Antarctic current between Australia and Antarctica disrupted ocean currents worldwide and caused global cooling, shrinking the jungles, restricting the tropics to the equator and induced extreme seasonal changes in areas beyond the tropic lines. The presence on Madagascar of several terrestrial mammalian groups with poor dispersion capacity across wide water barriers led several authors (McCall, 1997; Masters, 2006; Godinot, 2006; Tattersall, 2008) to suggest the existence of land-bridge connections between Africa and Madagascar (during mid-Eocene to early Miocene (47-26 Myr), rather than assuming the rafting hypothesis on mats (Simpson, 1940; Jolly et al. 1984; Paulian, 1984; Krause, 2003; Rabinowitz and Woods, 2006; Yoder and Nowak, 2006; Ali and Huber, 2010). The presence of a series of small Mesozoic-Cenozoic scattered islands in the middle of the channel, as demonstrated in this paper, combined with the Paleogene eastward Mozambique paleocurrent and wind circulation should favour the migration of mammalian groups from Africa to Madagascar.

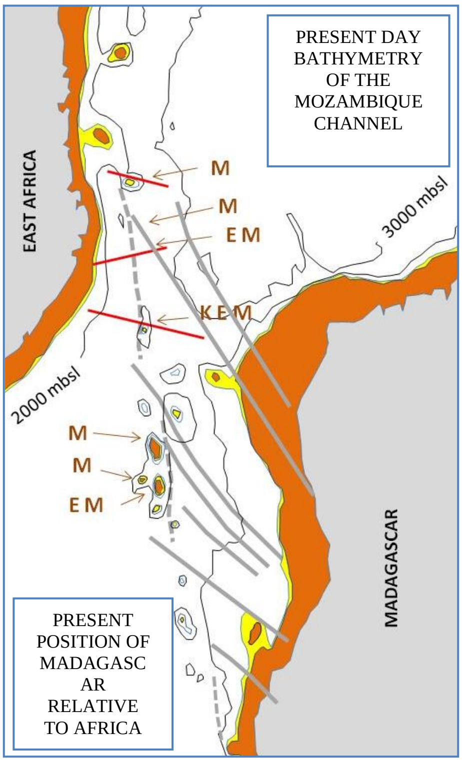


Fig. 1. Contours from 0-1000m in orange, from 1000-1200m in yellow. K, E, M indicate Cretaceous, Eocene and Miocene emersion - erosion detected from dredges. Seismic lines of figure 2 in red. Sketch of NW-SE sinistral reactivated faults in grey.

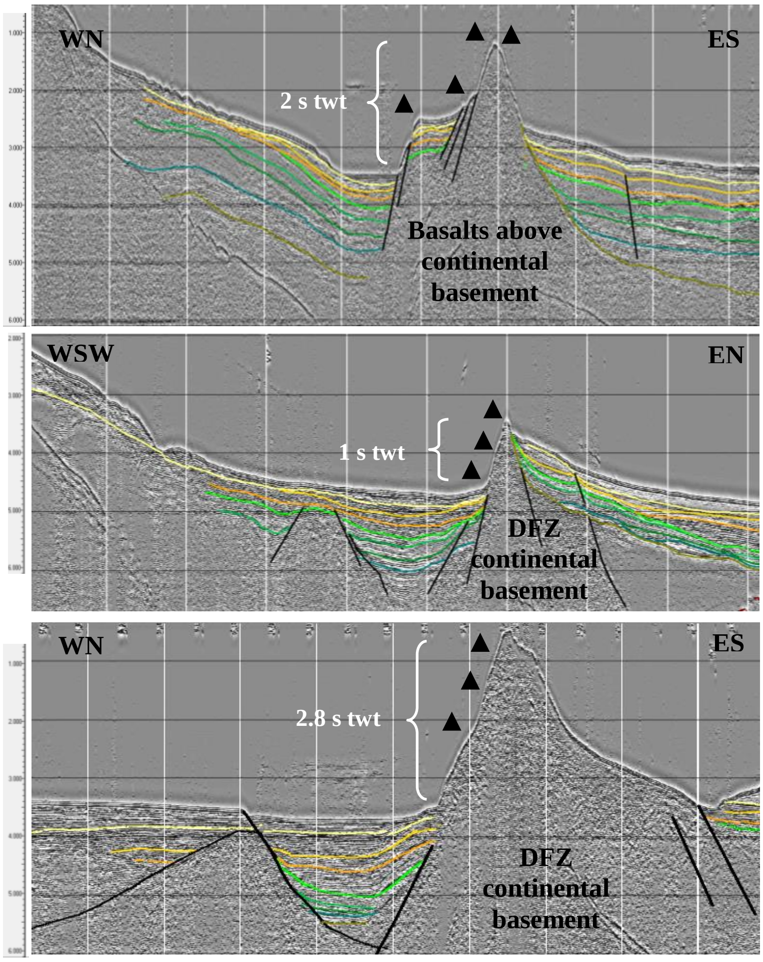


Fig. 2. Dredge samples location on the Davie Ridge.

REFERENCES

Ali JR and Huber M., 2010. Mammalian biodiversity on Madagascar controlled by ocean currents. Nature 463, 653-657

Bassias Y., Leclaire L., 1990. Crystalline basement and intraplate mesozoic magmatism of the Davie Fracture Zone. Neues Jaarbuch fur Geologie und Palaontologie Mh., 2, 67-90.

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 and the Middle East, Volume 15, Issues 3–4, 321-339.

Bassias Y., Bertagne R., 2015: Study updates uplift-erosion correlation, Davie fracture zone. Oil & Gas Journal, Sept. 7, 2015, 54-67.

Chorowitz J., Le Fournier J., Vidal G., 1987. A model for rift development in Eastern Africa, Geological Journal, 22, 495 - 513.

Godinot, M. 2006. Lemuriform origins as viewed from the fossil record. Folia Primatol. (Basel) 77, 446–464.

Heirtzler J.R., Burroughs, R.H., 1971 : Madagascar's paleoposition: New data from the Mozambique Channel. Science, 174, 488-490.

Janetschke N., Niebuhr B., Wilmsen M., 2015: Inter-regional sequence-stratigraphical synthesis of the Planerkalk, Elbtal and Danubian Cretaceous groups (Germany): Cenomanian -Turonian correlations around the Mid-European Island. Cretaceous Research 56 (2015), 530-549.

Jolly, A., P. Oberlé, R. Albignac. 1984. Key Environments: Madagascar. Pergamon Press, Oxford. Published in collaboration with the International Union for Conservation of Nature and Natural Resources by Pergamon Press,.

Krause, D.W., 2003. Late Cretaceous vertebrates of Madagascar: a window into Gondwanan biogeography at the end of the Age of Dinosaurs. In: Goodman, S.M., Benstead, J.P. (Eds.), The Natural History of Madagascar. University of Chicago Press, Chicago, 40–47.

Leclaire L., Bassias Y., Clocchiatti M., Segoufin J. 1989. La ride de Davie dans le Canal de Mozambique: approche stratigraphique et géodynamique.- C.R. Acad. Sci. Paris, 308, II: 1082-88; Paris.

Masters, J. C., de Wit, M. J. & Asher, R. J. 2006. Reconciling the origins of Africa, Indiaand Madagascar with vertebrate dispersal scenarios. Folia Primatol., Basel, 77, p.399–418.

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

Mougenot D., Recq M., Virlogeux P. at Lepvrier C., 1986. Seaward extension of the East-African rift. Nature, 321, 599- 803.

Patriat, P., Segoufin, J. 1988. Reconstruction of the Central Indian Ocean. Tectnophysics 155, 211–234.

Paulian, R., 1984. Introduction to the mammals of Madagascar. In: Jolly, A., Oberle, P., Albignac, R. (Eds.), Madagascar. Pergamon Press, Oxford.

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

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

Segoufin J., 1978. Anomalies magnétiques mésozoïques dans le bassin de Mozambique. C. R. Acad. Sci. Paris, 287, (D), 109-112.

Segoufin J. et Patriat P., 1981. Reconstruction de l'Océan Indien occidental pour les époques des anomalies M-21, M-2 et M-34. Paléo-position de Madagascar. Bull. Soc. Géol. France, XXIII, 6, 603-607.

Simpson, G. G., 1940. Mammals and land bridges. J. Wash. Acad. Sci. 30, p. 137–163.

Tattersall, I. 2008. in Elwyn Simons: A Search for Origins, Eds: Fleagle, J. G. & Gilbert, C. C., p. 397–408, Springer.

Yoder A.D.,Nowak M.D., 2006. Has Vicariance or Dispersal Been the Predominant Biogeographic Force in Madagascar? Only Time Will Tell, Annu. Rev. Ecol. Evol. Syst., V. 37, 405–31.

Promoting an Interrelated Seismic Data Analysis Approach

Matt Bolton and James Selvage, *BG Group*

Introduction

Early in the exploration of offshore Tanzania seismic amplitude analysis indicated the importance of using pre-stack seismic data for prospect identification. This led to the acquisition of large 3D seismic datasets that needed to be analysed to compressed schedules – to take advantage of drilling rig availability. Therefore, we require techniques that streamline the analysis of large amounts of data and are flexible enough to overcome technical challenges and to incorporate new data. In this abstract we look back at the technological advancements in processing, pre-stack seismic data analysis and global interpretation that enable the extraction of greater geological information from 3D seismic data.

Method - Processing

The main seismic processing challenges in offshore Tanzania (Selvage et al., 2014) are considered to be:

(1) Complex water bottom multiple from deep channel incisions

(2) Diffracted multiples from bright shallow channels

(3) Potential for large lateral velocity contrasts associated with shallow channels

Challenge (3) requires pre-stack depth migration (PreSDM). However, tackling challenges (1) and (2) were the main focus because it was not known at the outset how extensive the shallow channel systems were or whether they were located above potential prospects. This meant that pre-stack time migration (PreSTM) processing was undertaken, but in parallel the impact of challenge (3) was assessed by finding whether shallow channel systems overlaid amplitude-versus-angle (AVA) anomalies. Performing this assessment on large 3D volumes required the use of pre-stack seismic data analysis and global interpretation.

Method - Pre-stack seismic analysis

Hindering the direct interpretation of pre-stack seismic data is its unwieldy data size and reduced signal-to-noise ratio relative to the full-stack. In many circumstances this means that pre-stack seismic data is overlooked until interpretation of the full-stack is completed and zones of interest are defined. Figure 1 (left) shows the components of a framework to preliminarily screen pre-stack seismic data for AVA anomalies (Selvage and Edgar, 2013), which helps focus further processing and generates products that are used in both traditional and global interpretation methods. The framework enables the extractraction of anomalous amplitudes as geobodies (Figure 1 right) to aid geological interpretation.

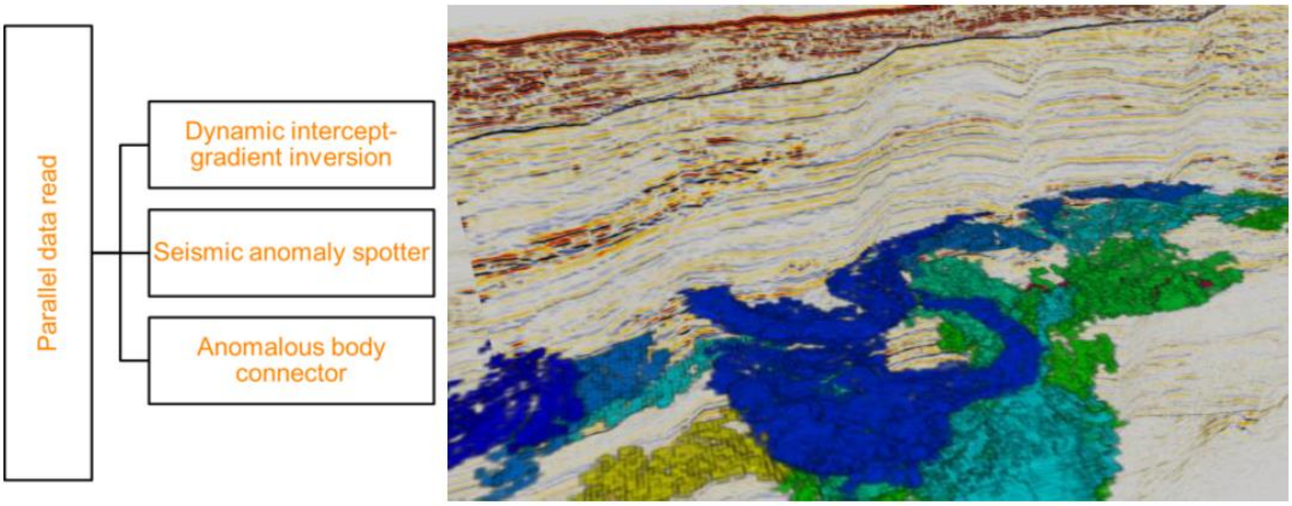


Figure 1 A framework to preliminarily screen large seismic volumes for AVA anomalies (left). Each component runs in parallel on a Linux cluster environment and can be used to extract geobodies (right).

Method - Global interpretation

A global interpretation method (Pauget et al., 2009) was used to integrate the products derived from processing and pre-stack seismic analysis into a seismically derived geological model (Figure 2). This significantly accelerated the process of interpreting sand prone systems within a seismic sequence stratigraphic framework, because depositional geomorphologies can be visualised in high fidelity aiding interpretation of sand distribution, architecture and facies. The seismically derived geological model is easily updated when new data become available (Bolton et al., 2014).

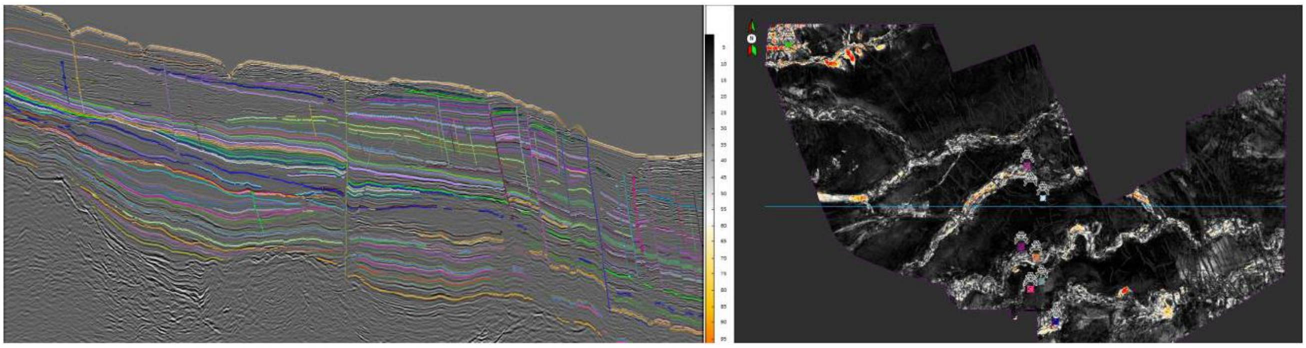


Figure 2 A seismically derived geological model was created from the 3D seismic and used to visualise depositional geomorphologies.

Integrating pre-stack and global interpretation technologies provides an array of seismic interpretation methodologies for geoscientists to explore more efficiently. One such example is reviewing pre-stack derived attributes simultaneously on stratigraphically consistent surfaces through the entire volume which can reveal amplitude differences which require further investigation (Figure 3).

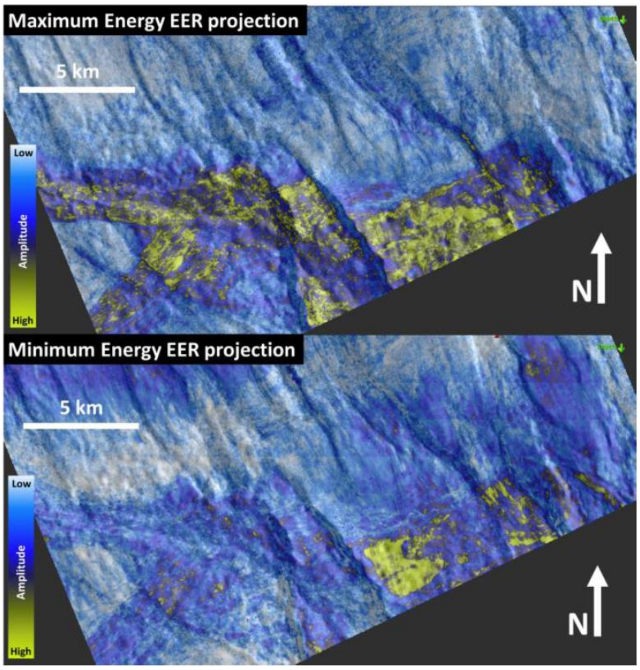


Figure 3 Simultaneous comparison of Pre-Stack 3D seismic attributes using Global Interpretation stratigraphic horizon extractions. EER maximum energy is computed to best highlight lithological variation, whilst EER minimum energy highlights anomalous fluid AVA behaviour in the 3D seismic data.

Conclusions

Too often seismic processing, pre-stack analysis and interpretation are treated as sequential and separate stages. In offshore Tanzania the compressed schedules necessitated a more interrelated cycle whereby each stage is evolving based on the results of data analysis. This required the collaboration of skilled specialist teams in development of enhanced workflows, the development of parallelised computer algorithms and increased computing power accessible by a greater proportion of geoscience professionals. Ultimately, this approach enabled the correct drilling decisions to be made in a short timeframe and should be adopted regardless of the schedule.

Acknowledgements

Block 1 and 4 JV partners (BG Group, Ophir Energy plc, Pavilion Energy) and Tanzania Petroleum Development Corporation (TPDC).

References

Bolton, M., Selvage, J.I. and Durot, B, 2014, Enhanced 3D seismic interpretation workflows key to gas exploration success, offshore Tanzania, 3rd Young Earth Scientists (YES) Congress 2014.

Pauget, F., Lacaze, S., and Valding T., 2009, A Global Approach to Seismic Interpretation Based on Cost Function Minimization, SEG 2009 Annual Meeting.

Selvage, J.I. and Edgar, J.A., 2013, Rapid Screening of Pre-stack Seismic for Hydrocarbon Prospectivity, 75th EAGE Conference & Exhibition.

Selvage, J.I., Korsmo, Ø., Jones C.E. and Rønholt, G., 2014, Unifying Tomography & Pre-stack Anomaly Detection in PreSDM to Correct for Near Surface Channels in Exploration Settings, 76th EAGE Conference & Exhibition.

Basement Control on Structure and Drainage in the East African Rift System

Siebe Breed, Rowan Edwards, Diana Necea, Mark Broadley, Mike Oehlers, *CGG – NPA Satellite Mapping*

The East African Rift System (EARS) is presently deforming under the main phase of rift development, a time of active faulting and deposition of syn-rift sediments, which locally form quality source, reservoir and seal rocks. A number of the Neogene rifts that belong to the EARS are found in areas that have evidence of previous rifting phases, most commonly Karoo (Late Carboniferous – Middle Jurassic), and Cretaceous - Paleogene rifts (Macgregor, 2015). The currently active rifts, (where present in combination with sediments and structures related to the previous phases of rifting), are ideal locations for hydrocarbon traps to form.

As most basins in the EARS are currently underexplored or even unexplored, the amount and quality of the data available for the region is generally very low. However, satellite data is available over the whole of East Africa. CGG's NPA Satellite Mapping have used Landsat 8 OLI optical data (15m resolution) and SRTM1 DEM data (30m resolution) to create a contiguous geological map (1:200.000 scale) over Kenya, Uganda, Tanzania, Rwanda, Burundi, Malawi and parts of Ethiopia, Mozambique and DRC. This interpreted dataset, in combination with an analysis of current day drainage anomalies, allows for a quick overview of several aspects of the individual rift basins, including:

- What is the nature of the structures commonly found around these basins, and what is their orientation? What role does the basement play in the evolution of these structures?
- What is the evidence of previous phases of rifting in and around the Neogene EARS basins, and how do these phases interact with each other?
- Where do the rivers enter the rift basins, and deposit the sediments that they carry with them?
- How big are the areas that these rivers drain, and which lithologies are exposed at surface within these drainage basins?
- Where does evidence of active source rocks exists, based on seepage data?

Rifts are generally environments of low stress, (compared to compressional and strike-slip environments). Therefore it is unlikely that new faults will form where there are established pre-existing zones of weakness in the area that can be reactivated. The nature and orientation of these weaknesses is controlled by the structure of the basement. In the EARS it is very clear that the zones of rifting are located in areas of previous intense deformation (many Precambrian and Palaeozoic "Belts", as well as areas active during previous phases of rifting), and are focussed between the Cratons in mobile zones that are present throughout East Africa. In more detail, the regional structural basement grain around individual rift basins gives an indication of the local pre-existing weaknesses that controls the orientation of the faults and fault blocks within the basins. These structures can have a major influence on the formation of structural traps. Where multiple rift phases are present, structures and reservoirs from one phase can be charged by active source rock from another age (which currently finds itself in the oil or gas window). This allows multiple play types to develop.

The location and orientation of relay ramps, accommodation zones and transfer faults, boundary faults and flexural margins, all largely controls the sediment input into the rift basins. This is critical for the distribution of potential reservoirs, source rocks and seals. Sedimentation has a major impact on the prospectivity of individual basins and sub-basins. But if there is no direct evidence (from drilling, good quality seismic, etc.), indirect indications are available to determine what to expect in the subsurface. NPA Satellite Mapping has undertaken detailed geological mapping to build a model of what the subsurface can look like, in the East African rift basins.

Anomalies in the present-day drainage system indicate changes during the past millions of years, during the Neogene rifting activity in the EARS. In combination with information on the sediment provenance, explorers can determine where to find good quality reservoir rocks, in areas where no other data is available. This exploration method provides a relatively low-cost method of screening individual rift basins, and focusing the more expensive follow-up exploration methods (Airborne Gravity Gradiometer, seismic acquisition, drilling).

By integrating the results of NPA's Global Offshore Seepage Database, a database of active seepage, in the rift lake basins, the existence of charge and migration can be re-risked using another economic screening method.

Macgregor, D., 2015, History of the development of the East African Rift System: A series of interpreted maps through time. Journal of African Earth Sciences 101, p 232-252.

Sequence Stratigraphic Framework of the Jurassic, Tanzania

Amanda Gray, Pamela Sansom, *BG Group, 100 Thames Valley Park Drive, Reading, RG6 1PT*

Successful exploration offshore Tanzania has continued to prevail in recent years and yet the precise spatial distribution and stratigraphic position of the regional source rock is poorly constrained. The Tertiary is believed to be widely immature, the Cretaceous has largely been ruled out for effective source potential, and the distribution of Jurassic potential source rocks remains poorly understood.

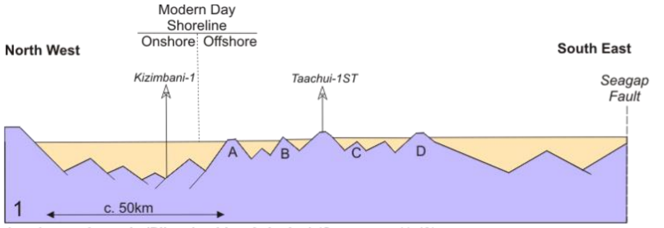
This poster aims to present a sequence stratigraphic framework for the Jurassic in Tanzania and present a schematic basin evolutionary model for the Tanzanian margin during the Jurassic. This framework provides a context for understanding the spatial and stratigraphic distribution of source potential in the Jurassic.

This scheme is based on the correlation of 20 wells from the onshore coastal basins, 1 offshore well (Taachui-1ST) drilled by BG Group in Block 1, the Tendaguru Hill outcrop in Tanzania, and 9 sedimentary logs from outcrop in the Morondava Basin, Madagascar.

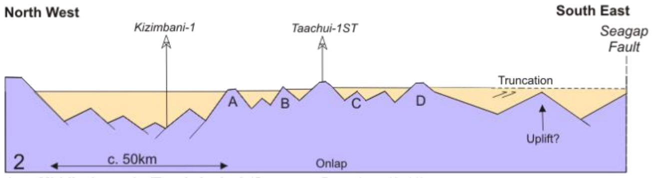
10 Jurassic sequences have been identified and described; named J1-J10. The succession captures the evolution of the basin from continental syn-rift sediments, to a carbonate platform, to an open marine setting, which can also be defined as 3 tectonic settings: syn-rift, “transitional” and “post-rift”.

Seismic interpretation shows that between “transitional” to “post-rift” (between sequences J5-J6; Bathonian-Callovian) significant deformation is expressed throughout the basin, as orthogonal stretching switches to a transform margin, resulting in an extensive unconformity. However, the term “break-up unconformity” has intentionally not been used, as it infers processes associated with a simpler passive margin setting. Tanzania is not a simple passive margin; instead it is a basin with a complex mode of formation and continued structural influence through time. Seismic interpretation suggests that transtensional and transpressional movement on the Seagap Fault initiated in the early Middle Jurassic. Lower Jurassic syn-rift sediments were confined to evolving sub-basins, “transitional” sequence distribution was also controlled by exposed basement highs and a large inversion structure on the Seagap fault appears to have restricted the basin during Upper Jurassic. Therefore an element of restriction has impacted stratigraphic distribution throughout the Jurassic. This may have created favourable conditions for source rock deposition on numerous occurrences during the Jurassic. For the spatial distribution of a Jurassic source rock to be fully understood than a detailed study of the sub-basins must be completed.

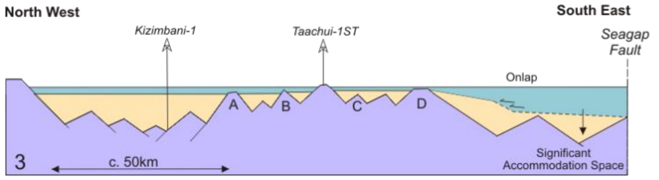
Attached is a figure “Schematic Basin Evolution of the Tanzanian Margin during the Jurassic”.



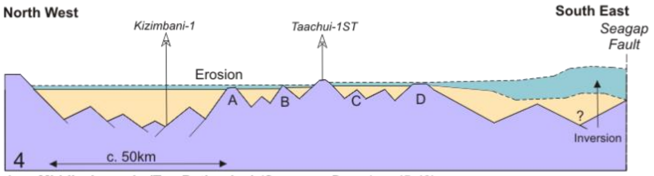
Age: **Lower Jurassic (Pliensbachian-Aalenian)** (Sequences J1-J3)
Tectonics: Syn-Rift
Depositional Environment: Continental/Restricted Marginal Marine/Shallow Marine
Note: Two large sub-basins seperated by several mini-basin around the Taachui High.



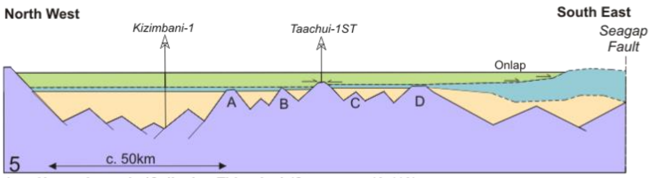
Age: **Middle Jurassic (Top Aalenian)** (Sequence Boundary J3-J4)
Tectonics: End of Syn-Rift
Note: Erosion of sub-basin in south east (truncation observed on seismics) . Erosion not evident in rest of basin from current study.



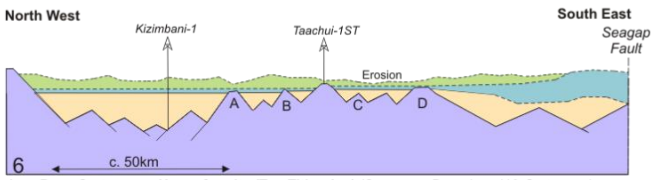
Age: **Middle Jurassic (Bajocian-Bathonian)** (Sequences J4-J5)
Tectonics: Transition Phase (?) with *transtensional* movements on Seagap Fault
Depostional Environment: Carbonate Platform/Siliclastic Shallow Marine
Note: Thick sequence deposited in the south east sub-basin suggesting significant increase in accommodation space. Onlap character observed in seismic. Thin carbonates observed in onshore wells.



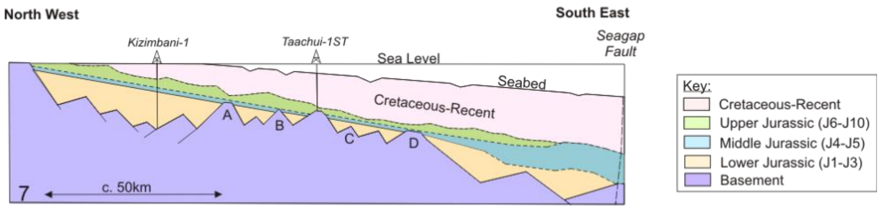
Age: **Middle Jurassic (Top Bathonian)** (Sequence Boundary J5-J6)
Tectonics: End-of-Transition Phase (?) with *transpressional* movement on Seagap Fault
Note: Inversion of thick sequence in south east, and inferred erosion throughout basin.



Age: **Upper Jurassic (Callovian-Tithonian)** (Sequences J6-J10)
Tectonics: Post-ritft/Sag Phase
Depositional Enviornment: Shallow-Deep Marine
Note: Onlap onto inverted high observed in seismic character.J6 shoreface sands onlap Taachui basement high



Age: **Base Cretaceous Unconformity (Top Tithonian)** (Sequence Boundary J10-Cretacous)
Tectonics: Post-ritft/Sag Phase
Note: Deep erosion throughout basin, often rugose. Inverted left high exposed.



Age: **Modern Day**
Tectonics: Passive Margin with minor movements on Seagap Fault
Depositional Environment: Deep Marine
Note: Basin has tilted seaward and thick overburden has been deposited.

Contribution of the Geophysics to the Structural Study of the Continental Geology and Resource Exploration along CVL using GOCE Gravity Measurements

Kemgang Ghomsi Franck Eitel[1], Nguiya Sévérin[2], Nouayou Robert[1], Ngatchou Heutchi Evariste[1], Tokam Kamga Alain Pierre[3]

[1]*Department of Physics, Faculty of Science, The University of Yaounde I, Yaounde, Cameroon*
[2]*Industrial Engineering Faculty, University of Douala, Douala, Cameroon*
[3]*School of Geosciences, University of Witwatersrand, Witwatersrand, South Africa*

Broad plateaux, narrower swells and volcanism occurring from ~45 Myr ago to the present characterize the geology of northern and central Africa. The GOCE gravity field is globally homogeneous at the resolution of about 50km or better allowing for the first time to analyze tectonic structures on the continental scale (Figure 1). Geologic correlation studies propose to continue the tectonic lineaments across continents to the pre-breakup position. Tectonic events that induce density changes, as metamorphic events and magmatic events, should then show up in the gravity field. Two gravities profiles derived from the Bouguer gravity map of Adamawa plateau, perpendicular to the anomaly associated with the uplift shows a broad negative and an axial positive Bouguer anomaly. These profiles are used the logarithmic power spectrum technique to obtain detailed images and corresponding source depths as well as certain lateral inhomogeneity of structure density. The broad negative and central positive anomalies beneath the Adamawa uplift are interpreted as a consequence of lithospheric thinning (27.5 - 35 km) and crustal thinning (3.67 – 11.5 km), respectively. Compared to the Kenya dome, the Adamawa uplift may be in an early stage of continental rifting, along the site of a pre-existing basement weakness, the Central African Shear Zone

(CASZ). These focus areas are particularly rich in mineral resources. Density variations produce heat and increase pressure on the rocks in the boundary areas and we have observed it along the Cameroon Volcanic Line (CVL). The gravity field is an excellent proxy for the borders of the continental fragments, due to the existing density variations. Here seemingly unconnected geologic units associated with rich mineral findings correspond

to continent-wide lineaments identified by GOCE. The outcrops are linked to the much larger and deeper crustal inhomogeneity that presumably contributed to the differentiation of the minerals. Our area is located to the north of the Congo Craton, and straddles the countries of Cameroon, Central African Republic, Gabon, Democratic Republic of Congo and Congo.

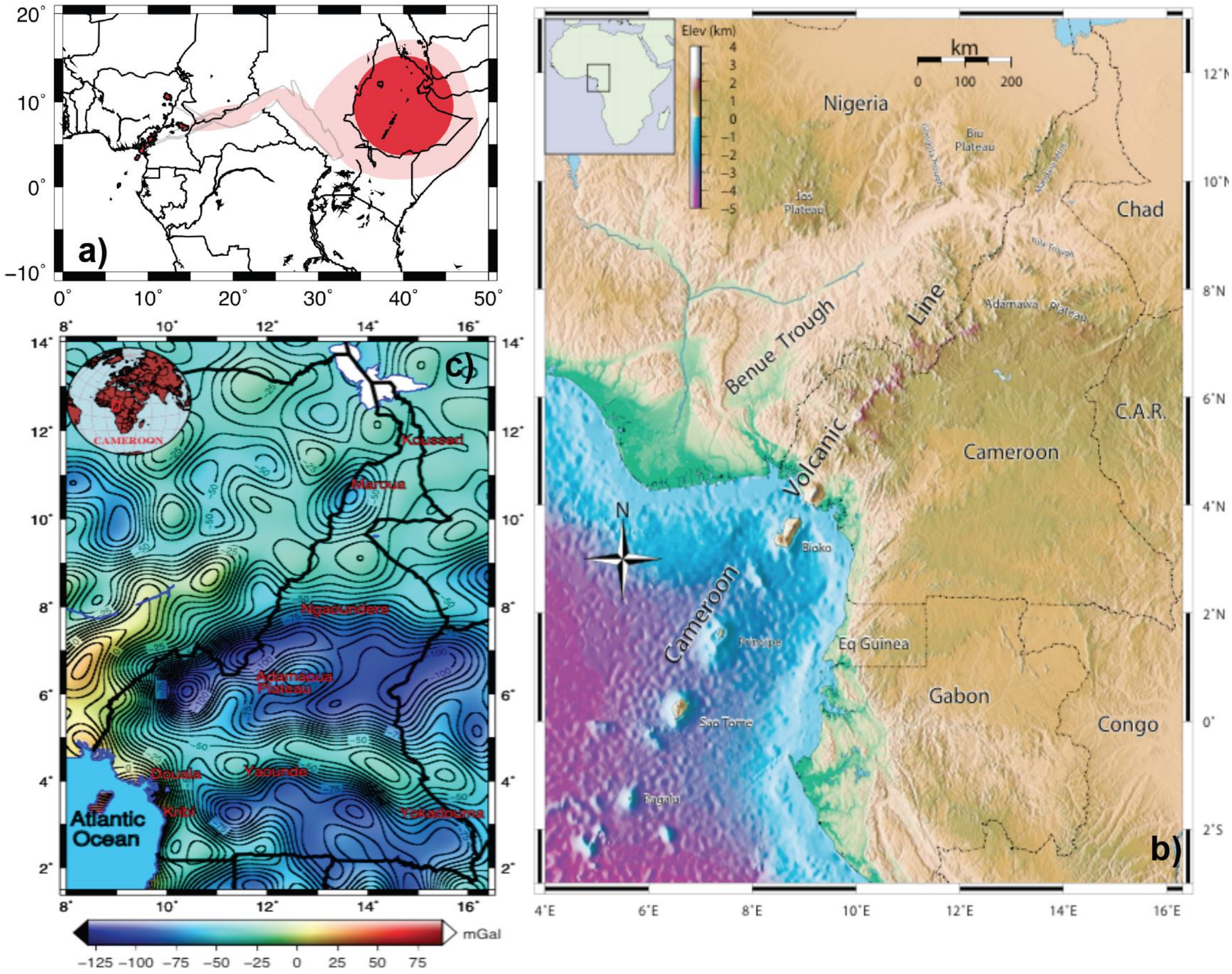


Figure 1 : a) Proposed models for the CVL formation flow from Afar [after Ebinger and Sleep, 1998]; b) Central Africa Topographic Map (the seamount to the southwest of Pagalu may or may not be a part of the CVL); c) Bouguer gravity Map of Cameroon issue from GOCE gravity data.

Integrated Geochemical & Heavy Mineral Analysis of Rift Basin Sediments: A Case Study from the Lokichar Basin, Kenya.

Daisy Lee[1], Tom Stone[1], David Pickering[2]

[1]*Chemostrat Ltd, Unit 2 Ravenscroft Court, Buttington Cross Enterprise Park, Welshpool, Powys, SY21 8SL, UK*
[2]*Tullow Oil Plc, Building 9, Chiswick Park, 566 Chiswick High Road, London, W4 5XT, UK*

The Lokichar Basin of north-west Kenya is a N-S trending extensional half graben structure that developed during the latter half of the Cenozoic Era (upper Paleogene and Neogene Periods) in response to the onset of the East African Rift System (Tiercelin et al. 2004). The Lokichar Basin has recently been host to a number of high-profile oil discoveries, which has stimulated an increase in geoscientific work conducted in the region. Chemostrat Ltd has been working with Tullow Oil on a multidisciplinary study, incorporating; inorganic geochemical, heavy mineral and geochronological data to better understand the stratigraphy and sediment provenance of the Lokichar Basin.

Bulk rock inorganic geochemical data has been used to define stratigraphic correlations in the petroleum industry for decades. Chemostratigraphy relies upon recognising changes in elemental concentrations through time and making geological interpretations based upon these variations of key elements. A chemostratigraphic model is developed for the Lokichar Basin, which compromises five chemostratigraphic sequences, four chemostratigraphic packages and three high resolution chemostratigraphic units. The key chemostratigraphic zones are defined by variations in elements including; Ti, Nb, Ta, Cr, Fe, K, Rb, Na and P, which, themselves, are interpreted to be controlled by heavy minerals, clay minerals and feldspar minerals. Based on the results, the inorganic geochemical data is interpreted to reflect temporal and lateral variations in environment, weathering and sediment provenance within the Lokichar Basin.

The interpretations drawn from the inorganic geochemical data are enhanced by the results of automated heavy mineral analysis (by Raman spectroscopy) and by U-Pb analysis of single detrital zircon grains in key chemostratigraphic horizons. When used in conjunction with each other, these methodologies provide an additional level of insight into the depositional history the Lokichar Basin and clearly highlight which chemostratigraphic sequences are influenced by changes in sediment provenance and which ones are influenced by changes weathering patterns.

Shale Variability and Its Impact on AVA Offshore Tanzania

Lloyd, Kate L., *BG Group*

The Amplitude versus Angle (AVA) response of an overburden-siliciclastic reservoir interface is fundamentally a function of the contrast in elastic properties between the two units. An observed change in the AVA response can be caused by variation in both the properties of the reservoir and the properties of the overburden, as well as saturated fluid changes. An offshore Tanzanian dataset of nine wells within Block 1 was used to study the effect of overburden shale variability on AVA response.

Elastic parameter (Vp, Vs, and ρ) rock physics depth trends were generated to produce a regional shale trend with which to compare identified petrophysically categorised shale intervals within the area. Intervals of normally compacted shale overburden were categorised by the geological stratigraphical interpretation, seismic character, mineralogy and elastic parameters, and compiled into shale 'types' observed within the region. Three key shale types were identified: Hemipelagic shale, Calcite-rich shale and Silty shale. Where sufficient data supported, elastic parameter rock physics depth trends were defined for different shale types using a sonic transit time derived normal compaction equation.

Vp, Vs, and ρ values were extracted from the rock physics depth trends at reservoir depth, and used in half-space modelling to evaluate the AVA response of the different shale overburdens capping a typical soft Tertiary brine filled sand, at the same depth. A fluid substitution using Gassmann's equation was performed to assess the change in AVA response for a gas-saturated equivalent sand. The Intercept (I) and Gradient (G) values for the Hemipelagic and Calcite-rich shale overburden displayed on an AVA crossplot give a consistent separation from one-another for both the brine- and gas-saturated sands. The fluid-consistent separation is interpreted to be a result of the overburden lithology variability dominating the AVA response.

The modelled brine-saturated interfaces plot close to the trajectory of the seismically derived minimum energy chi angle, which corresponds to the offshore Tanzania background shale trend, while by contrast the gas-sand-shale interfaces plot with a significant perpendicular distance (Chi-Perpendicular) for both overburden shales. In addition, at this depth, the different overburden shales are observed to plot at varying distances from the origin along trend (Chi-Parallel) – the Hemipelagic shale overburden has a larger I and G value for both brine and gas filled sands than the Calcite-rich shale. This overburden lithology dependent range of Chi-Parallel distances can lead to a different AVA class interpretation for these shale-sand interfaces. Shale overburden properties are interpreted to impact identification of reservoir AVA class response.

Development of a Coherent Stratigraphic Scheme of the Albertine Graben-Uganda

Joshua Lukaye[1], Tonny Sserubiri[1], Wilson Tumushabe[1] and David Worsley[2]

[1]*Directorate of Petroleum – Uganda, Plot 21-29 Johnstone Road, Entebbe, Uganda 256*
[2]*PRW Consulting, Saetre, Norway.*

The Albertine Graben is one the most petroliferous onshore rifts in Africa. It forms the northernmost termination of the western arm of the East African Rift System. Its surface exposures were first studied by Wayland (1925), O'Brien (1939), and Pickford et al. (1993) among others. Pickford et al. (1993) especially developed the basic stratigraphic framework of the graben which was later modified by the Government geoscientists and international oil companies using subsurface data. The stratigraphic units were however not fully and formally described, and have been used informally in different and often confusing ways. The current study therefore aims to solve this challenge by establishing a coherent stratigraphic scheme for the entire graben through an integral study of surface and subsurface data.

The study involves precise description of the type and reference sections for various formations both in exposure and in the wells; and has therefore led to the development of lithostratigraphic columns of some basins in the Graben. The approach reveals that the Semliki area south of Lake Albert has the most complete sedimentary succession in the graben, spanning the period from middle Miocene (ca 15 Ma) to Recent. It also reveals that platform deposits which form a small fraction of the thickness of the basinal succession represent a highly condensed sequence which only saw deposition at times of Lake highstand. The developed models suggest that in the Kaisotonya area, the southernmost subsurface deposits which also represent a condensed sequence pass northwards over a major down-stepping fault into the much more complete succession, only seen in deep wells. It's coastal and river valley exposures in the northern plain display only a fraction of the complete succession.

Thermal Maturity History of Mafia Deep Offshore Well, Southern Coastal Tanzania

Doreen E. Mkuu, *Ocean & Earth Science, Southampton University, National Oceanography Centre Southampton, SO14 3ZH, UK.*

The Coastal Basin of Tanzania is an important hydrocarbon province in Tanzania. Organic petrology, thermal maturity and burial histories are as yet little known for most of the source rocks in the basin.

Organic petrological analysis of acid-macerated organic residues from samples from the Mafia Deep Offshore well in southern Tanzania has been undertaken to identify the maceral components. This has been combined with vitrinite reflectance (%Ro) and spore colour index (SCI) analyses, with the aim of evaluating the hydrocarbon potential of the source rocks and determining maturation levels within this well.

The sediments beneath Mafia Island were deposited in a marine/deltaic environment. Vitrinite macerals mainly of telinite are dominated together with inertinite components of semi-fusinite form. Lesser amounts of exinite components such as sporonite and cutinite are also present.

Data show a general increase of vitrinite reflectance with depth from 0.4 to 3.9 %Ro through the depth of 300m to 5600m of section which indicate a thermal maturity level that encompasses the entire oil and gas window. The spore colour index (SCI) changes progressively from dark yellow to orange and brown to dark brown. SCI values range from 3-4 within the shallower depths (300m ‑ 800m) and >6 for greater depths (2000m ‑ 5600m) which reflect maximum deeper burial.

The Mafia Deep well shows that it is full of type III kerogen which has potential for gas generation. The results of both %Ro and SCI show a full maturity range from light hydrocarbon generation to dry methane gas. The gas window is from approximately 1500m (Lower Paleocene) through to 4200m (Lower Cretaceous).

Keywords: Coastal Basin; Mafia Deep well; Source Rock; Vitrinite; Spore Colour; Maturity Level.

An In-Depth Look at the Petroleum Potential of the Morondava Basin, Offshore Madagascar.

Glyn Roberts[1], Trond Christoffersen[1], Shi Kuitai[2], Xu Jingwei[2], Xu Wenshuai[2]

[1]*Spec Partners Ltd;*
[2]*BGP Multi Client*

The authors give an update to their previous papers (*) on the Petroleum prospectivity of the Morondava Basin, Offshore Madagascar.

These works are based on an analysis of a ~13,000 line km long offset 2D Multi-Client seismic survey (BGP/TGS MAD-13 survey) acquired in 2013 in the offshore part of the Morondava Basin by BGP under the jurisdiction of the government authority OMNIS; and in preparation for a new International Bid Round.

The previous papers presented initial observations on the hydrocarbon potential of the Basin and its relationship with the neighbouring areas.

Evidence from the dataset shows large (e.g 20 x 80 km wide) sandbodies of both Tertiary and Cretaceous age; fluvial channels of Cretaceous to Tertiary age; Tertiary (gas filled) reefal features and larger (e.g 30 to 40 km wide) platform carbonate reefs of Cretaceous age (as identified and described in Roberts et al 2015); drape-over plays; gas escape structures with large regional seals; basin floor fans; horsts/grabens of Jurassic/Permo-Triassic age and toe thrust plays of Cretaceous age.

Prospects occur in the Coastal Platform area and at the foot of its slope; east of the Davie Ridge (ie onlap from the east); and west of the Davie Ridge in the Kerimbas Graben where we see large basin floor fans and thrust faulting (Roberts et al 2014, Tyrrell et al 2014).

This update is based on further work on the data in the depth as well as time domains.

It will address questions concerning both oil and gas potential and be illustrated by seismic sections showing the various different plays in the Basin.

Note: papers referred to in (*) above:

Morondava Basin, Offshore Madagascar – New Long Offset Seismic Data highlights the Petroleum Prospectivity of this Emerging Frontier Basin. Roberts, GF; Christoffersen, T and Weining, H. P*oster presentation at the AAPG Annual Convention and Exhibition, Pittsburgh, Pennsylvania, May 2013*

New Insights on the Prospectivity of the Morondava Basin, Offshore Madagascar, based on New Seismic Data. Roberts, GF; Christoffersen, T and Weining, H. *Poster Presentation: PESGB/HGS Africa Conference, London, Sept 2013.*

Further Insights on the Prospectivity of the Morondava Basin, Offshore Madagascar, based on New Seismic Data. Roberts,GF, Christoffersen,T, Weining, H and Zhang, K. *Poster Presentation at the PESGB/HGS Africa Conference, Houston, Sept 2014.*

Morondava Basin, Offshore Madagascar – Observations from Modern Seismic Data on the Nature and Hydrocarbon Potential of its Cretaceous Reefs. G.F Roberts, T.C Christoffersen and Jingwei, X. *Poster presentation at the PESGB/HGS 2015 Africa Conference, London. Sept 2015.*

Other references:

M.Tyrrell. Regional Setting and Prospectivity of the offshore Morondava Basin, Madagascar, seen in the newly acquired MAD13 2D dataset. PESGB/HGS Africa Conference, Houston, Sept 2014 and Poster Presentation at PETEX, London, November 2014.

M. Tyrrell, X. Jielai, S. Kuitai, P. Conn and P.Chandler. A new oil play in East Africa. GeoExpro, Vol 11, No 6, p 46-50, December 2014.

Acknowledgements:

Omnis (Office des Mines Nationales et des Industries Stratégiques, Madagascar): www.omnis.mg
BGP and TGS: JV partners, Morondava (MAD-13) 2D Multi-Client seismic survey.

Investigation of Scaling Properties of Fault Populations in the Central Kenya Rift

Ahmad Shmela, Douglas Paton, Richard Collier, *Basin Structure Group, School of Earth and Environment, University of Leeds*

The present work quantifies fault scaling properties of selected fault populations in different rift segments within the central Kenya rift in order to characterize any patterns of fault growth and distribution of extensional strain along this part of the rift. 500 surface faults have been mapped from topographic surface generated from Digital Elevation Model DEM. Three fault populations with varying trends have been defined as zone1 (NNE), zone2 (NNE to NNW) and Zone3 (NNW). The wide scale range of fault size populations in this study (lengths 272m – 86243km, displacement 11 - 1561m), permits detailed quantitative assessment of the scaling properties of faults and fault related strain. The relationship between fault length and throw exhibited well-defined power-law distributions in the three zones. Two cross-sections were made at each zone to estimate heave related strain and throw related strain in each zone, these estimations showed a general increase of strain northward before it drops in the northernmost transect. Estimations of power-law exponent (fractal dimension) of fault throw population in the three zones exhibited a decrease of the fractal dimension value with the increase of strain, which indicates an increase of fault size towards the north. Profiles of throw distribution for isolated fault segments in zone2 reveal an increase of fault length while the displacement is limited. Isolated fault segments in zone 3 however, showed a growth in displacement while lateral propagation is hinder. Plots of spatial strain distribution along the rift axis indicated a transition from distributed deformation of faulting to a more localized deformation of faulting. The transition between these faulting regimes is attributed to an increase in linkage maturity of fault systems. Variations in strain accommodation and fault orientation in the three zones with respect to extension direction can be attributed to reactivation of Proterozoic, regional-scale NW-SE and NS trending ductile/brittle shear zones underlying the Kenya rift.

Exploring the Noise in AVA Seismic Data

Joanna Wallis, *BG Group Plc*

Understanding the angle versus amplitude (AVA) response of prospects identified in seismic data over the Tanzania coastal basin significantly derisks them prior to drilling, and allows more detailed mapping of facies distributions and internal structure of gas discoveries when moving into the appraisal phase.

As exploration in Tanzania has progressed, we have started to test the limitations of our ability to use AVA to differentiate water and gas. Ultimately, these limitations are dictated by our ability to anticipate the properties of the reservoir rock and overburden, and whether amplitude variation due to the subsurface can be distinguished from noise in the angle gathers.

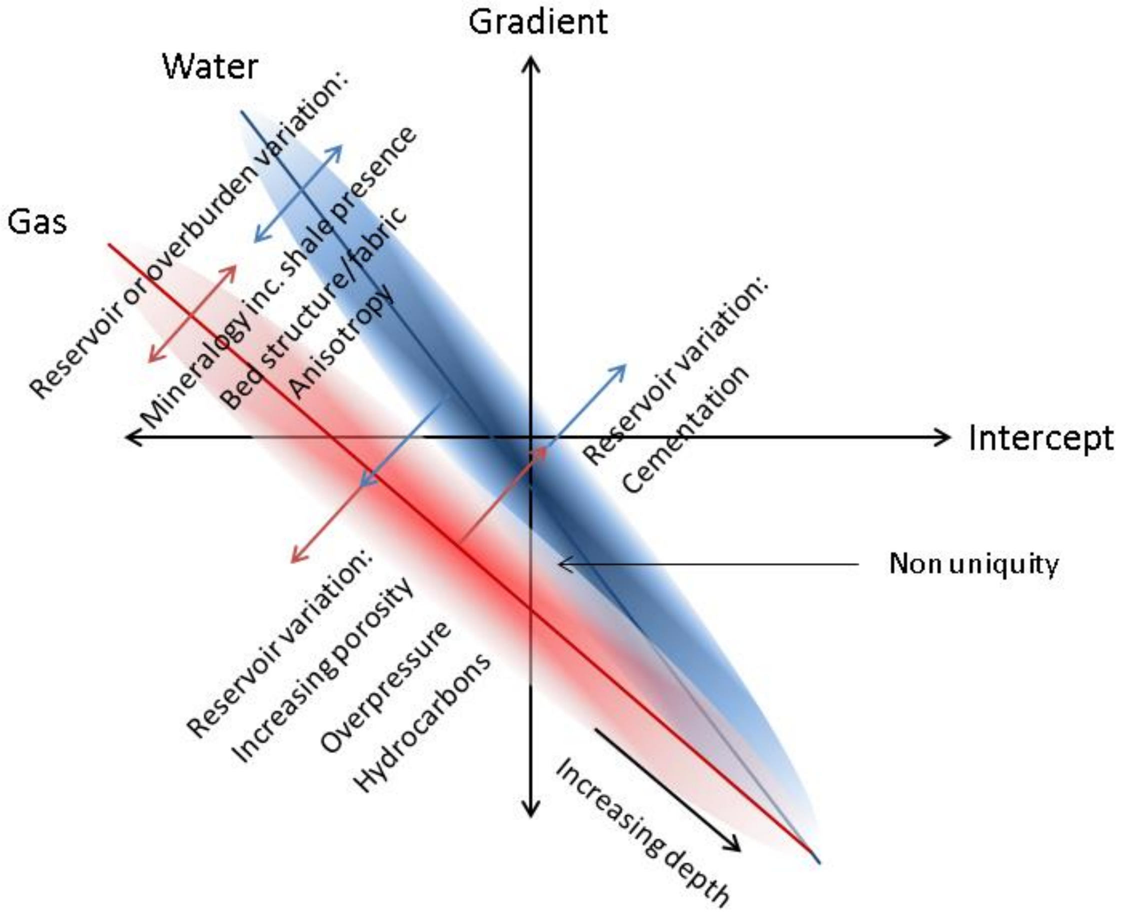
Extended elastic reflectivity (EER) projections of the seismic data based on linear characterisations of the AVA response in terms of intercept and gradient allow the most anomalous and exceptional sands to be identified. The contrast in AVA response between gas and water bearing sands is greatest in relatively uncompacted or high/preserved porosity (e.g. due to overpressure) sands as the fluids form a greater proportion of the bulk volume of the fluid saturated reservoir rock.

The primary control on the contrast in AVA response is therefore effective stress (or burial depth), due to its impact on porosity. Simple models utilising compaction trends derived from velocity and density data illustrate the progressive non uniqueness of the response of gas and water bearing sands with increasing depth/effective pressure as the trends converge in the intercept-gradient cross plot space.

There is significant scope for false responses where the elastic properties of the reservoir and/or overburden deviate significantly from the values predicted by a simple depth model. This is particularly due to data bias, as initial wells inevitably target the best, most anomalous sands. However, there is potential to enhance the separation where the response becomes non unique if the properties of the reservoir and overburden can be further constrained.

Secondary controls that may cause the elastic properties of the reservoir or overburden to deviate from the long wavelength depth trend, and consequently induce false responses, include overpressure, mineralogy, bed structure and fabric, presence of hydrocarbons and anisotropy. Alternatively, assumptions made by the model may be invalid.

This study focusses on identifying whether overpressure causes a significant risk of false positive responses in offshore Tanzania, and the degree of overpressure required, and investigates the complex relationship between shale content and effective porosity, identifying the situations in which a gas bearing sand may yield a false negative response.


Gradient
Water
Gas
Intercept
Reservoir or overburden variation:
Mineralogy inc. shale presence
Bed structure/fabric
Anisotropy
Reservoir variation:
Cementation
Non uniquity
Reservoir variation:
Increasing porosity
Overpressure
Hydrocarbons
Increasing depth

Burlington House
Fire Safety Information

If you hear the Alarm

Alarm Bells are situated throughout the building and will ring continuously for an evacuation.
Do not stop to collect your personal belongings.
Leave the building via the nearest and safest exit or the exit that you are advised to by the Fire Marshall on that floor.

Fire Exits from the Geological Society Conference Rooms

Lower Library:
Exit via Piccadilly entrance or main reception entrance.

Lecture Theatre
Exit at front of theatre (by screen) onto Courtyard or via side door out to Piccadilly entrance or via the doors that link to the Lower Library and to the main reception entrance.

Piccadilly Entrance
Straight out door and walk around to the Courtyard or via the main reception entrance.

Close the doors when leaving a room. **DO NOT SWITCH OFF THE LIGHTS**.

Assemble in the Courtyard in front of the Royal Academy, outside the Royal Astronomical Society.

Please do not re-enter the building except when you are advised that it is safe to do so by the Fire Brigade.

First Aid

All accidents should be reported to Reception and First Aid assistance will be provided if necessary.

Facilities

The ladies toilets are situated in the basement at the bottom of the staircase outside the Lecture Theatre.

The Gents toilets are situated on the ground floor in the corridor leading to the Arthur Holmes Room.

The cloakroom is located along the corridor to the Arthur Holmes Room.

Ground Floor Plan of the Geological Society, Burlington House, Piccadilly