The Petroleum Group would like to thank BP, Desire, FOGL and RockHopper for their support of this event:
South Atlantic Petroleum Systems

Exploring Mesozoic Gondwana break-up basins

6 – 7 November 2007

Tuesday 6 November 2007

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The Argentina-Uruguay segment of the South Atlantic margin consists of three distinct tectonic provinces (Fig. 1):

a) The Austral Basin sits in a tectonic corner and is partly a foreland basin of the N-S trending Andean chain, but its southern sector forms part of the Scotian-South America transform plate boundary. The South Scotian Fold belt extends along this transform zone from Tierra de Fuego eastwards along the South Scotian Plate Boundary for 2000 km. A thick sedimentary pile (5-10 km) developed in the western part of the fold and thrust belt and this was folded and thrusted in the late Cenozoic. Good source rocks are predicted in the fold and thrust belt, as rich oil-prone Upper Jurassic source rocks have been found at outcrop in Tierra del Fuego, in the DSDP 330 well east of the Falkland Islands (where TOC averages 5% over a 200m thick interval) and in the Outeniqua Basin in South Africa. Very large anticlinal four-way dip closures are present. However, Cenozoic reservoir quality is perceived to be a problem as much of the sedimentary source area was Andean volcanics. High quality seismic data has recently been acquired over several large blocks in both Argentina and the Falklands sectors, but no wells have been drilled in the deep offshore area of this foldbelt to date.

b) The South Atlantic continental margin extends for approximately 1,500 km from Uruguay to the Agulhas-Falklands Fracture Zone, but there has been no exploratory drilling in the deepwater (1000+m). The outer part of the margin is dominated by several seaward-dipping reflector sequences which reach up to a total width of 100 km (E-W), and 5-6 km in thickness. It is not clear whether these sub-aerial basaltic sequences are partly erupted on extended continental or oceanic crust. Narrow-rifted grabens have been imaged on sparse seismic data which may contain Early Cretaceous syn-rift lacustrine source rocks. Presence of these source rocks has not been confirmed in Argentina. However, the AK-1 well on the conjugate margin of South Africa lies opposite to the Colorado and Salado Basins, suggesting a source may be present (Fig. 2). Oil shows were encountered in the Cruz del Sur-1 well in the outer Colorado basin, but this oil may be sourced from the Palaeozoic. Thick Cretaceous and Cenozoic sediment piles have been deposited along the shelf edge in Uruguay and at various other points along the margin (e.g. outer Colorado basin), which may have buried potential Aptian source rocks deep enough to be mature. Recent exploratory activity is focussed on the outer Colorado Basin, where Cretaceous and Tertiary turbidites are predicted, and where late faulting has provided fluid migration pathways from the syn-rift source rocks.

c) A series of E-W trending internal rifts are present within the broad Argentine continental shelf, which opened up in Late Jurassic to Early Cretaceous times (San Julian, San Jorge, Colorado, Salado, Rawson-Valdeza, Fig. 1). The San Jorge Basin has a prolific source rock in the Early Cretaceous and many oil and gas fields have been discovered in shallow water. The San Julian Basin has been drilled by one well which did not encounter any good source rock in the volcanic and red bed dominated syn-rift fill. The Rawson-Valdez Basin has only been drilled by one well, which also did not find any evidence of source rock presence. However, these basins contain several isolated half-graben that can have very variable syn-rift fill and isolated lacustrine source rocks may be developed (equivalent to AK-1) which so far have not been drilled.
Offshore Exploration in Argentina is still in a very early stage with no wells drilled in water depths greater than 1000m. Most exploration has focussed on the Austral and San Jorge Basins, where there are proven hydrocarbon reserves, but the vast areas of the rifted Atlantic margin, and the South Scotian fold and thrust belt have still to be tested.

Fig. 1 Map fo the Argentina Offshore showing the internal rifts (light green), seaward-dipping reflectors (purple striped area) and large crustal arches with pink anticline symbols. Yellow dotted line marks the edge of the seaward dipping reflectors and may coincide with the landward edge of normal oceanic crust.
Fig. 2. Map showing the fit of Argentina and S. Africa with the main source rock occurrences.
The Palaeogeographic and Palaeoclimatic Context for Exploration in the South Atlantic

Jim Harris¹, Rob Crossley¹, Nick Stronach¹, Tim Hudson, Paul Markwick¹,², Frank Richards¹,³, Dan Burggraf² John Suter², Brad Huizinga², Samir Ghazi², Paul Valdes⁵, Roger Proctor⁶, (1) Fugro-Robertson Ltd., Llandudno, N. Wales (2) ConocoPhillips, Houston, TX, USA (3) currently GETECH, Leeds, UK (4) currently Helix RDS, Aberdeen, UK (5) University of Bristol, UK (6) NERC Proudman Oceanographic Laboratory, Liverpool, UK

Some of the main uncertainties for exploration in frontier basins are the presence of source rocks and reservoirs. To provide an objective, process based, predictive methodology focused on these problems, global palaeogeographic reconstructions underpinned by data were coupled with state-of-the-art palaeo-Earth systems modelling (HadCM3 palaeoclimate model). Palaeotectonics and palaeoenvironments maps for six Mesozoic - Cenozoic time slices were prepared and a new method relating topography and bathymetry to plate tectonic environments was used as the basis for palaeo digital elevation models (DEMs). These were gridded in GIS and used to provide the topographic and bathymetric boundary conditions for coupled ocean-atmosphere general circulation models (GCMs), and a barotropic model to simulate palaeotides. The compilation of the base maps is based on a global database of palaeoenvironmental and lithofacies data, the legacy of over 25 years of petroleum geological studies and an equally extensive source rocks database. These data include climate proxies that were used to test the veracity of the modelling results. Here this work is used to provide an understanding of the evolving palaeogeography and palaeoclimatic context for exploration in the South Atlantic.
Exploration of the deep water plays of Argentina can still be considered as immature but certainly remains one the most important frontier areas to be explored in South America.

The Argentine platform is particularly wide and extends to more than 400 km away from the shoreline and the slope has water depths ranging from 200 to 4,000 meters. We chose to present petroleum systems from two different basins, the Colorado basin located offshore the Buenos Aires province and the Malvinas basin between Tierra del Fuego and the Malvinas islands.

Some wells were drilled over the last three decades proving the existence of working petroleum systems through oil shows and well tests but the hydrocarbons found were not in enough quantity to be commercially viable. Different 2D seismic campaigns were shot over the years which helped to delineate one specific area in each of these two basins. Over these areas, 3D seismic campaigns were acquired very recently by RepsolYPF and its partners, which helped to refine plays definition and identify new ones. Multidisciplinary approaches were applied to constrain facies distribution and reservoir presence, assess location of generative source rocks, and estimate the hydrocarbon expulsion, migration, entrapment and preservation.

The formation of the two basins are most probably related to the Gondwana break up followed by a generalized thermal subsidence period starting during the Cretaceous and that ultimately reached the present day passive margin configuration in the Colorado basin. Seismic data clearly shows that the Colorado basin was subject to a second tectonic event reactivating the normal faults during late Cretaceous-early Cenozoic that were further sealed by basal Tertiary sediments. During Late Cretaceous and Tertiary times, the southern part of the Malvinas basin has been shaped by the interaction between South America, Antarctica and Scotia plates. This led to a fold and thrust belt developed essentially during Oligocene and Lower Miocene forming the southernmost limit of the Malvinas foreland basin.

The main reservoir targets are Cretaceous sandstones in Colorado basin and Tertiary sandstones in Malvinas basin. Jurassic and Cretaceous potential source rocks were identified in both basins through well data and seismic analysis. It is not so obvious that Gondwana breakup and Scotia plate formation played a crucial role in the source rock maturation. Local volcanism might also be evoked. Migration of hydrocarbons can not be entirely explained by flow through a fault plumbing system and migration through fine grained sediments needs to be assumed.

Even though the exploration risk and costs involved in these frontier basins is high, a success would bring an important change in the hydrocarbon potential of the region. The exploration challenge is now focused to understand the economic viability of the potential petroleum systems defined in the area.
Palaeogeographic reconstructions of the Falklands: Permian to Present

Phil Richards  
British Geological Survey

Most palaeogeographic reconstructions of the Falklands and the southernmost South Atlantic in general are based on onshore work, with little attention paid to offshore data, yet these offshore datasets are essential to constrain the reconstructions of the region. Extensive exploration surveys acquired in the North Falkland Basin and Falkland Plateau Basin over the past 10 years facilitate the identification of evolving sediment supply patterns and basin evolution.

Some palaeogeographic reconstructions made on the basis of onshore work differ markedly from those proposed by offshore workers. The most notable of these differences concerns the nature of the Falklands micro-plate. Onshore workers have traditionally envisaged the Islands as a rotated micro-plate – although the size of the rotated plate and the timing of rotation have often been disputed amongst these workers – whilst many offshore workers, both in print and privately, subscribe to the fixed plate model for the evolution of the Falklands. The new Permian to Jurassic reconstructions discussed in this paper show that it is possible to reconstruct a regional palaeogeographic origin for the Falklands without resorting to subsequent rotation, whilst still honouring the onshore data that has been used to substantiate rotation. However, whilst offshore data all point to an origin for the Falklands without micro-plate rotation, new data emerging from the onshore dyke swarms (Stone et al. this volume) indicate that if micro-plate rotation did occur, that it might now be possible to use the various dykes to pinpoint and constrain its amount and timing. The nuances of the rotation versus non-rotation argument are not yet resolved fully.

New seismic data from the Falkland Plateau and South Falkland Basins are illustrated to show the differing evolution of those basins compared to the North Falkland Basin. Jurassic and Cretaceous fan and delta systems are differentiated and related to changes in source areas on the Falklands Plateau and beyond. The tectonic system changed in the mid Cenozoic, with the inception of over-thrusting from the southwest along the Falkland Thrust/North Scotia Fault, leading to the development of a foreland basin to the south of the Falklands and associated deltaic deposition in the North Falklands Basin.
The Malvinas Basin is a Jurassic rift basin located in the South Atlantic Argentine shelf, between Tierra del Fuego and Malvinas Islands (fig. 1). It presents a NNW-SSE elongated shape of approximately 350 by 150 km with a sedimentary fill that ranges from 2 to 8 km. To the west, north and east, the basin is surrounded by Paleozoic pre-rift terranes, which to the east are exposed on the Malvinas Islands, while to the west they conform the Rio Chico High, a positive structural relief between the Malvinas Basin and the hydrocarbon prolific Austral Basin in southern Argentina. To the south, the basin ends abruptly against the Burdwood Bank, a structural high lying in shallow water, and the North Scotia Ridge.

The consortium Repsol-YPF and Pan American Energy has been granted by the Argentine authorities with the permission to explore the blocks CAA-40 and CAA-46. Old 2D seismic lines have been reprocessed as well as a 2300 km² 3D survey was acquired during the summer 2004/5. A number of 17 wells have been drilled by other companies since 1979, in the western lying shallow sector of the basin.

The tectonic evolution of the basin started in the Jurassic with rifting processes associated to the Gondwana break up. During the Cretaceous a generalized thermal subsidence (sag) caused a regional marine ingression. At around the Cretaceous-Tertiary boundary, a process of transtensional deformation took place originating the beginning of a foreland basin phase. The basin tilts and the NE flank is uplifted. Strike slip and direct faulting occurs in the south sector. At the Upper Eocene, a transpressive regime took over. The south sector of the basin was uplifted by faulting and folding with an E-W alignment, constituting an Andean orocline.

Seismic and well data show that the stratigraphic column of the Austral Basin is also developed beyond the Rio Chico High resulting the Malvinas Basin a continuation of that one (fig. 2). Almost all the seismic reflectors can be followed from one basin to the other through the sector south of Rio Chico High.

The occurrence of an active petroleum system has been documented by the oil obtained from wells in the western sector of the basin (Figueroa et al., 2005). Biomarkers of the recovered oil show a good correlation with the Lower Cretaceous marine shales. This source rock has a regular to good generating potential with values of TOC between 1 and 3% wt. and HI near 400 mgHC/gTOC (Nevistic et al., 1999). Continental Jurassic shales, proven source rock in the Austral basin, could also be present in this basin being part of a speculative petroleum system. Upper Cretaceous (Maastrichtian) as well as Eocene shales could be interpreted as belonging to hypothetical petroleum systems. In addition to hydrocarbon generation, sea bottom cores have provided gas samples which were interpreted as having a thermogenic origin (Figueroa et al., 2005).

A basinwide seismic-stratigraphic model and well data were the basis for building a petroleum system model of the basin. This suggests that at deeper positions of the basin the expulsion of oil could have started as early as Eocene times and continues today at shallower positions. Cretaceous and Tertiary reservoirs are likely to present the same quality as they show in the Austral basin.

The Austral and Malvinas basins seem to be a unique and single basin separated partially by the Rio Chico High (fig. 3). This is supported by seisms and well data. Being the stratigraphy almost the same, it is very encouraging that this analogy could also be valid when regarding commercial hydrocarbon accumulations.
Potential Petroleum Systems in the Malvinas Basin, Offshore Argentina. (continued)

Fig. 1. Location map of Malvinas Basin showing contours of sedimentary thickness (in seconds), water depth (in meters), exploration blocks and drilled wells (modified from Figueroa et al., 2005).

Fig. 2. Chart showing the petroleum systems main elements and tectonic stages.

Fig. 3. Compose tracing on seismic lines showing eastern Austral Basin, the Rio Chico High and northwestern Malvinas basin (trace is shown on fig. 1; modified from Galeazzi, 1996).

References


Source rocks and petroleum systems offshore South Africa: an overview

David van der Spuy
Petroleum Agency SA

Exploration for oil and gas has been conducted for more than 30 years offshore South Africa. There is production of gas and more modest production of oil, both from the Bredasdorp Basin. While production is currently limited to that basin, there have been discoveries and shows in all the basins offshore. Deeper water remains to be explored, stimulating expectations of future commercial discoveries and further production.

There are three major basins offshore South Africa, corresponding roughly to the west, south and east coasts. These are the Orange, Outeniqua and Durban basins respectively. The Outeniqua Basin, to the south of the country, is made up of a number of inner sub-basins, viz. The Bredasdorp, Pletmos, Gamtoos and Algoa basins, and a large outboard basin, the Southern Outeniqua Basin. This paper looks at the source rocks and petroleum systems documented and postulated to date in all South Africa’s offshore basins.

The Orange Basin off the west coast has a number of source rocks and proven petroleum systems. A Hauterivian oil petroleum system has been proven in the synrift graben fill, where a borehole intersected oil-bearing lacustrine sandstones and oil prone lacustrine source rocks with very high organic contents and hydrogen indices. Further synrift petroleum systems may be active in the main synrift basin to the west of the medial hinge line (van der Spuy, 2002).

In the drift succession, early Aptian and Barremian source rocks form a component of two proven petroleum systems in the Orange Basin, originally identified by Jungslager (1999). Gas from these source rocks is stratigraphically trapped in aeolian sands of Barremian age, while gas and condensate is also stratigraphically trapped in Albian and Cenomanian fluvial sandstones. The presence of oleanane in a condensate sample suggests some terrestrial component to the kerogen (Moldowan et al, 1994) while C30 steranes confirm the largely marine nature of the source (Peters & Moldowan, 1993). Recent discoveries indicate that this system may involve multiple source rocks.


The Outeniqua Basin comprises a number of en echelon sub-basins of South Africa’s southern offshore. The Bredasdorp Basin is the western most of these. Wet gas and oil prone shales occur in the late Valanginian to late Barremian succession. Sandstones within the synrift and post rift to early drift may contain gas or condensate and gas, derived from these source rocks.

The early Aptian was a period of regional sediment starvation and anoxia in the southern Atlantic. An oil prone claystone was deposited in the basin at this time. It can be very thick and occurs over a large areal extent. The organic material is largely Type II with a Type I component. Davies (1996 and 1997). Davies has shown this source rock to be the source of oils found in early and mid-Cretaceous reservoirs throughout the basin.

There is evidence that the source rock intervals that occur in the Bredasdorp Basin are also developed in the greater Southern Outeniqua Basin. Gas has been discovered in early drift sandstones and burial history studies in this large basin show that the early Aptian is sufficiently mature over large areas to have generated and expelled oil.
Source rocks and petroleum systems offshore South Africa: an overview (continued)

In the Pletmos Basin, there is some evidence of source development in the synrift succession but drilling has not been deep enough to intersect major source rocks. Oil, wet gas and dry gas prone shales have been intersected in sequences deposited over major unconformities, associated with the transition from rift to drift, the early drift and the upper Cretaceous.

In the Algoa basin, thick oil and gas prone potential source rocks have been intersected in the synrift and gas prone source rocks in the drift. The oldest known source rocks offshore South Africa are Kimmeridgian in age and occur in the southeast Gamtoos Basin. Oil, wet gas and dry gas prone source rocks are present in both the synrift and early drift successions.

The Durban Basin to the east of the country is under explored and no source rocks have yet been intersected. However, local increases in total organic content within shales, minor gas shows and fluorescence indicate that petroleum systems are at work in this basin also.

References:


Investigations on post-rift hydrocarbon systems in the offshore Congo and Orange Basins, West African Margin

Gesa Kuhlmann(1), Zahie Anka(1), Selwyn G. Adams(2), Curnell J. Campher(3), Rolando di Primio(1), Magdalena Scheck-Wenderoth(1), Dave van der Spuy(3), Brian Horsfield(1),

(1) GeoForschungsZentrum Potsdam, Germany
(2) University of the Western Cape (UWC), South Africa
(3) Petroleum Agency SA, South Africa

The passive continental margins of western Africa have accumulated large amounts of Tertiary and Cretaceous sediments and developed important petroleum provinces. Among these sedimentary depocentres, the Congo deep-sea fan and the Orange Basin constitute two of the main sedimentary basins.

In the Congo Basin more than 19,000 km of seismic profiles from the ZaiAngo project have been interpreted showing that the Tertiary Congo deep-sea fan is much broader and thicker than formerly estimated. It has been prograding since the Oligocene and not only extends hundreds of kilometres across the continent-ocean transition, but also contains an enormous volume of sediments of at least 0.7 Mkm$^3$. The main depocenter is located basinwards at the base of the present-day slope, on the Aptian oceanic crust. 3D petroleum system modelling has been carried out in order to evaluate the effects of the onset and further progradation of the Congo fan on source rock maturation and hydrocarbon generation. The model extends from the base of the slope to the ultra-deep oceanic domain (ca. 200,000 km$^2$). First results indicate that a distal upper-Cretaceous unit could be a good source rock candidate. The basinward progradation of the fan during the Miocene is a key parameter increasing the potential source rock maturation rate.

In the Orange Basin approximately 6,000 km of 2D seismic data has been interpreted showing the shift of the main Cretaceous and Tertiary depocentres from east to west. Gas leakage features are widespread within the present day basin and have been mapped in detail together with sedimentary and tectonic structures. Within the study area of exploration blocks 3 and 4, massive gas chimneys occur towards the eastern part where strong erosion was active since the Tertiary but no faulting occurred. A second area with more diffuse gas leakage through the sedimentary column appears together with subvertical faulting within the Cretaceous succession. Towards the east, where the main Tertiary depocentre developed no gas leakage has been observed. To test the generation, maturation and migration potential of the present day hydrocarbon system a 3D petroleum systems model has been built. Initial results show that the Aptian/Albian source rocks of the eastern and middle study area are already overmature while an assumed Cenomanian/Turonian source rock is still immature.

Only at the outer western part of the area both source rocks are actively generating hydrocarbons at present day. This implies an active kitchen area generating hydrocarbons in the outer part of the basin with subsequent migration along stratigraphic horizons towards the leakage sites in the inner part of the basin. Further modelling will constrain the migration pathways, timing and duration of the events and lead to a basin-scale quantification of thermogenic gas into the hydrosphere and atmosphere as a function of geologic time.
Kerogen Kinetics and Source Rock Maturation In The Kwanza Basin of Southern Angola

R. Burwood¹ and M. J. Cope²
¹ E & P Geochemical Advisory, Guildford GU1 3PE, United Kingdom.
² Sound Oil plc, Leatherhead KT22 9HD, United Kingdom.

The Kwanza Basin is known for the occurrence of multiple and hybrid petroleum systems based on at least six recognized contributory source formations of Neocomian to Eocene age (Burwood, 1999). These contributory sources display a wide range of organofacies variation and, as such, possess quite markedly different formation-specific kerogen kinetic characteristics. With the additional complication of source regimes separated by the widespread Aptian evaporites, the maturation and charge chronology to Pre- and Post-Salt reservoirs can be quite difficult to understand.

In such complex systems, the use of intrinsic kerogen kinetic parameters in maturity modeling and the derivation of petroleum yield and transformation measures can greatly facilitate the understanding of the charge history of a basin. Moreover, the adoption of this approach places less reliance on global vitrinite reflectance-defined generation thresholds, isopleths, and contouring control for end-member kerogen types. As such this reduces, if not obviates, uncertainties inherent with poor or unrepresentative vitrinite datasets.

Activation energy parameters (\(E_a, A\)) and transformation threshold temperatures (\(G_{T_{max}}\)) as determined by the Rock-Eval 5/Optkin/Kinwin procedures are presented here for several Kwanza Basin candidate source formations. Application of these data to a suite of well control points allows the development of a maturation chronology for the onshore and nearshore tracts of the basin. Paleogeographic reconstructions of source facies distribution and seismic data control for burial regime allow extrapolation of the maturation model into the deeper offshore, giving a fuller prospectivity evaluation of these areas.
Overview of Falklands Petroleum Geology: what, where, when, and what next?

Phil Richards
British Geological Survey

Falklands offshore exploration started in 1993 with a series of spec seismic surveys, and progressed to the first licence awards in 1996, with 14 companies in five groups committing to 10,000 Km of seismic acquisition and six wells in the North Falkland Basin. At the time this was considered the most prospective, as well as being the shallowest water area. All six wells were drilled in a single campaign during 1998, using a shared rig and supply base, in a fast-track approach to exploration. While the wells were generally a technical successes and mostly encountered hydrocarbons, none were commercially viable, although two petroleum systems were proven and live oil flowed to surface in one well. Unfortunately, the end of drilling coincided with the 1998 down-turn in the oil price and the subsequent retrenchment of worldwide exploration, so that the enticing finds in the North Falkland Basin were not followed up at that stage.

Exploration tailed off until 2002, when the start of new “Open Door” licensing in the Falkland Plateau and South Falkland Basins led to a new phase of more widespread data acquisition. There was also a resurgence of interest in the North Falkland Basin in 2004, with the shooting of new 3D surveys to begin the testing of otherwise overlooked plays, and the first new licensing in the basin for 8 years.

The new licences and attendant resurgence in activity in all of the basins surrounding the Islands have led to the acquisition of significant amounts of seismic and CSEM data, with plans for a new drilling campaign in place as soon as a suitable rig or rigs become available. The talk will outline the recent data acquisition, detail the new plays and targets now under consideration, and evaluate the potential for success in the next drilling phase.
The North Falkland petroliferous basin - implications from recent 2D, 3D and electromagnetic surveys.

Dave Bodecott, Rockhopper Exploration plc

The NFB is about to undergo its second phase of exploration drilling. There are two proven source rocks, one of which is world class and thought to be mature for oil generation and expulsion. Additional source rock facies are expected to be present in other currently undrilled areas of this predominantly lacustrine Atlantic rift basin. The Late Jurassic to Early Cretaceous Syn-rift phases of basin development are largely unexplored. Reservoir potential is varied and proven from well, 2D and 3D seismic data, encompassing alluvial, deltaic and fan sandstone facies. Reservoirs are interbedded with lacustrine shale sequences.

The interaction of the earlier Palaeozoic and later Cretaceous rift structural trends has generated structural closures, sometimes affected by late inversion. The high relief basement architecture has contributed to plentiful sand sources and major hanging wall structures and sediment build-ups in deep sub-basins.

Recently acquired electromagnetic and 3D geophysical surveys give strong encouragement to drill the untested structural closures and sub-source rock fan plays, located in modest water depths.
The offshore extension of the Andean Fold Belt trend, South Falkland Islands

Bruce Farrer and Howard Obee

The offshore extension of the Andean Fold Belt trend, orientated east-west, is located approximately 150 km south of the Falkland Islands. Early Jurassic extension of the southern margin of the Falkland massif was followed by the development of a passive margin sequence. Early Cretaceous sediments were eroded from the Falkland massif and debouched via delta systems into the developing basin. Rising sea levels during the late Cretaceous eventually drowned the early Cretaceous shelf. During the late Cretaceous to early Tertiary lithosphere loading created a foreland basin. The Magallanes basin, located to the west, initiated first following closure of the Rocas Verdes back arc basin. Plate loading slowly migrated to the east forming the Malvinas basin and sequentially leading to the development of the South Falkland Foreland Basin. The subsequent opening of the Scotia Sea to the south of the foreland basin created a northward compression that slowly inverted the foreland basin forming the major folds and thrusts observed today. Source rocks are interpreted to be present throughout the area sharing a common origin with source rocks identified on the Maurice Ewing Bank, the Cape Basin, Weddell Sea and the Magallanes Basin. Thermal modelling predicts both oil and gas phases. The presence of significant gas hydrates is interpreted from a well developed Bottom Simulating Reflector on seismic data. Combined play elements are in place, highlighting an exciting untested fold belt play fairway.
The break-up of Gondwana during the Late Triassic to Middle Jurassic and the subsequent formation of the Weddell Sea created an extensive continental margin. This extended from the Magallanes Basin in Argentina, across the Mavlinas Basin through the East Falklands Basin and linked with the now considerably displaced Outeniqua Basin of South Africa. The transgression of the coastline of the Weddell Sea across this margin commenced no latter than the Callovian and probably terminated during the Cenomanian to Turonian. The seismic expression and geology of the resultant transgressive wedge is controlled in each of the main basins by the interaction of sediment supply derived from the adjacent continental margin, basin subsidence and eustacy. These variations have had a fundamental control on the hydrocarbon prospectivity of each basin.

The Middle Jurassic to Lower Cretaceous transgressive fill of the East Falklands Basin, and in particular the Fitzroy sub-basin, is described and illustrated with recently acquired 2D seismic data. The gross stratigraphic architecture of the Fitzroy sub-basin is contrasted with the other basins forming part of this continuous and productive hydrocarbon trend. Examples of the key play types and trapping styles within this extensive transgressive wedge are illustrated and described.
Southern Africa as a model for the subducted portion of northern India?

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It is widely recognized that our appreciation of natural systems can be greatly enhanced by examining analogues. In this presentation, I will show that several major tectonic features in the southern South Atlantic which formed during the break-up and separation of Africa and South America have almost perfect analogues in the form of northern Greater India and its conjugate margin, western Australia. During the early stages of opening (an interval of ~25 m.y.) the South Atlantic and SE Indian Ocean systems operated as dextral “scything” transform faults (Fig. 1), with effectively identical Euler pole radii.

Elements common to the “inner-wall” blocks (South Africa and Greater India) include:
- Sharp ocean-continent transition across the fault scarps.
- Continental slivers adjacent to the faults.
- Perched grabens on the trailing corners.
- Extended rifting margins on the trailing edges (e.g. western South Africa).

Elements common to the “outer-wall” blocks (South America-Falkland Plateau-Maurice Ewing Bank and Zenith Plateau-Wallaby Plateau-western Australia) include:
- Narrow ocean-continent transition across the fault scarps.
- Tectonically thinned continental “tails” portions of which appear “boudinaged”.
- Continental slivers adjacent to and along-strike from the transform fault scarps.
- Extended rifting margins on the trailing edges (e.g. eastern South America).
- Possibility for large-scale vertical-axis rotations (e.g., Falklands).

I contend (and will in part demonstrate) that attempts to understand the petroleum prospectivity of the SW Atlantic region would benefit greatly from comprehensive literature and data-surveys of the western Australia-SE Indian Ocean region, and the Antarctic margin which once abutted eastern India. Also, outcrop studies of the Hauterivian-Aptian (132–110 Ma) shelf sequences in the central and eastern Himalaya might provide insights into the rift basins that formed offshore southern South Africa during the Early Cretaceous.

![Fig. 1. Development of a dextral scything transform fault.](image-url)
Contourites and Petroleum Systems, Northern Namibian Continental Margin

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The study of contourites can have an important, if indirect bearing on key elements of the petroleum system, that is often poorly appreciated in deepwater exploration methodologies. This presentation documents the role of contourites in the deposition of source, reservoir and seal lithologies, and in stratigraphic trap formation, using offshore Namibia as a type example.

Significant marine source rocks were deposited along the northern Namibian margin during the Aptian and around the Cenomanian-Turonian boundary, the former in an isolated and relatively stagnant basin, and the latter in an environment that included bottom currents flowing along linear moats. Organic matter from the second phase was preserved probably because the circulating bottom waters that created the observed moats were oxygen deficient. These bottom currents subsequently strengthened, resulting in increased ventilation and the deposition of giant, elongate contourite drifts overlying the Cenomanian-Turonian source rock. Sandy contourites have been widely recognised globally and have the potential to form deepwater reservoirs. Contourites have greater potential as semi-regional seals, the most effective of which are provided by laterally extensive sheeted drifts.

To summarise the main petroleum system elements of contourite depositional systems, we present a type example of a ‘contourite’ prospect from the northern Namibian margin, consisting of a Campanian turbiditic sand unit, reworked by contour currents into a mounded contourite drift. The sand was deposited on a gently convex surface that had been shaped by earlier contourite deposition, creating a four-way dip-closed trap. The sand body is sealed by thick unit of contouritic clays. Charge from Aptian or Cenomanian-Turonian source rocks is the major risk. The most likely migration route is probably from underlying Upper Jurassic or Lower Cretaceous lacustrine syn-rift deposits via numerous normal faults that intersect the contourite mound.
Sequence Stratigraphy of the South Atlantic margin: Global Comparisons


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Sharland et al., (2001; 2004) demonstrated the occurrence of 65 synchronous late Precambrian – Phanerozoic Maximum Flooding Surfaces (MFS) across the Arabian Plate. Ongoing work, incorporating the stratigraphy of North Africa, the western former Soviet Union, South-East Asia, South and Central America and North America and the Arctic now demonstrates the occurrence of further 1st, 2nd and 3rd order surfaces and intervening sequence boundaries. These surfaces may be correlated across all studied regions and sedimentary basins.

Each MFS and its associated sequence boundary (SB) are defined in a reference section. This is a location with good sedimentological and/or wireline log evidence for an MFS or SB that is supported by biostratigraphical evidence. The biostratigraphy also provides constraints on the correlation of these surfaces to occurrences in other locations.

Given the clear synchronous nature of these surfaces between basins of differing subsidence and sedimentation rates, a global eustatic origin is probable. It can be demonstrated that the Neftex sequence stratigraphic model, originally developed in the Middle East, can be successfully applied to the stratigraphy of the South Atlantic margin.

For example chronostratigraphic/sedimentological data from the Campos Basin (Rangel et al., 1994) shows a good correspondence with major transgressive and regressive events recognized in the Arabian Plate model of Sharland et al., (2001, 2004). As a further example the K90 SB picked at the base of the Nahr Umr in Oman can be identified in the Coban Formation of Guatemala (Fourcade et al., 1999), the Ariri Formation of the Pelotas and Santos Basins (Dias et al., 1994, Pereira & Feijo 1994), and the Muribeca Formation of the Sergipe Basin (Carvalho et al., 2006)

There are profound hydrocarbon exploration and production implications for the application of the sequence stratigraphic model that we have developed. The model provides a precise and reliable framework for correlation and mapping and the subsequent identification of petroleum system elements, such as lowstand reservoirs and transgressive source rocks.

References


Petroleum potential of the Weddell Sea: the South Atlantic’s forgotten margin.

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The Weddell Sea is a large embayment between East and West Antarctica. To the north, it bounds the oceanic Scotia plate across a strike-slip boundary, and the oceanic parts of the South American and African plates across spreading ridges. It has rifted margins to the south and east; the nature of its western margin (with the Antarctic Peninsula microplate is speculative. It has been cited as a potentially rich petroleum basin and has been the subject of (mostly poorly informed) debate and political controversy. This paper reviews the development of the sedimentary basins in the Weddell Sea region in the context of Jurassic-Cenozoic breakup of Gondwana and outlines current knowledge of the elements of potential petroleum systems.

The relevant knowledge of the region can be summarised under five headings. First, all seismic survey conducted offshore Antarctica have been for scientific purposes; the most detailed has a mean line spacing of more than 5 km, also no petroleum exploration wells have been drilled, so there is no prior knowledge of the subsurface. Second, although there are extensive black shale deposits of Late Jurassic-Early Cretaceous age with high TOC, no oil or gas seeps have been found, so we have no indications of a working petroleum system. Third, there is abundant evidence that sandstones in the region are highly volcaniclastic, with low porosity and permeability. Fourth, only one potential regional seal unit has been identified. Fifth, there is no neotectonic activity, a state of affairs that could go back as far as 50 Ma, so there are no young structures to provide traps.

In conclusion: no serious oil or gas exploration has been conducted in the Weddell embayment; the petroleum potential is unproven (but likely to be low). Coupled with the difficulties of working in the harsh environment, it is unlikely that any exploration will occur in the future.
The three-dimensional lithospheric structure of the Falkland Plateau region

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The Falkland Plateau extends eastwards from the South American continental shelf between the Mesozoic oceanic crust of the Argentine Basin to the north and Cenozoic crust of the Scotia Sea to the south. An initial estimate of crustal thickness variation across this region was made by assuming local isostasy and allowing for upper mantle temperature contrasts calculated on the basis of the observed heat flow on the plateau and a cooling model for the adjacent oceanic lithosphere. Differences between observed and calculated gravity anomalies over this model can be linked to departures from local isostasy, particularly near the margins of the plateau, which were accommodated by using 3D gravity inversion to adjust the depth to Moho. A reference level was selected for the Moho which provides a good fit with the majority of the available seismic determinations, but it was not possible to match all such determinations. In particular, a model that provides a reasonable estimate for oceanic crustal thickness beneath the Argentine Basin and Scotia Sea predicts a crustal thickness beneath the Falkland Plateau Basin that is significantly larger than previously inferred from limited deep seismic evidence. Two alternative explanations are: (i) that the Moho beneath the basin is supported at an anomalously shallow depth by low-density upper mantle, or (ii) that the deepest layer detected by the available seismic data is high-velocity lower crust rather than upper mantle. The second explanation is favoured on the basis of a comparison with the results of deep seismic experiments over the conjugate Filchner Block of Antarctica, where a high-velocity lower crustal layer has been detected and interpreted to indicate igneous underplating beneath extended continental crust. Underplating also appears likely on the basis of the position of the Falkland Plateau Basin in relation to the Karoo–Ferrar magmatic province at the time of extension. Continental crust is inferred to be continuous beneath the northern part of the Falkland Plateau, as tilted fault blocks have been imaged by seismic surveys across this region and there are consistent magnetic and flexural anomalies associated with the continent-ocean boundary. Flexural modelling of the southern margin of the plateau, based on departures from local isostasy predicted by the 3D model, indicates lateral variations in strength, with the strongest lithosphere beneath the Falkland Plateau Basin and weaker lithosphere beneath the southern sides of the Falkland Platform and Maurice Ewing Bank. This may indicate oceanic basement beneath the southern part of the Falkland Plateau Basin, although an alternative explanation is that the strength has been conferred by the thinning of relatively weak continental crust and its replacement in the lithospheric column by relatively strong underplating and lithospheric mantle.
Structure and HC potential of the volcanic margin off Argentina/Uruguay, South Atlantic

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The passive continental margins of the southern South Atlantic are one of the prospective future oil provinces. On the shelf hydrocarbon exploration and partly production is successfully taking place since years. The Federal Institute for Geosciences and Natural Resources, Germany (BGR) has investigated the passive continental margins offshore Argentina and Uruguay since the early 90ties. Numerous marine geophysical surveys have meanwhile established a databasis of more than 25000 km of regional multi-channel reflection seismic lines accompanied with magnetic and gravity profiles.

These data document that the Early Cretaceous South Atlantic continental break-up and initial sea-floor spreading were accompanied by large-scale, transient volcanism emplacing voluminous extrusives, manifested in the seismic data by huge wedges of seaward dipping reflectors (SDRs). These deeply buried and 60-120 km wide SDRs were emplaced episodically as suggested by at least three superimposed SDRS units. Distinct along-margin variations in the architecture, volume, and width of the SDRs wedges correlate with large scale margin segmentation. We identify at least four domains bounded by the Falkland Fracture Zone/Falkland Transfer, the Colorado Transfer, the Ventana Transfer and the Salado Transfer. The individual transfer zones may have acted as barriers for propagating rifts during the SDR emplacement phase, selectively directing rift segments in left stepping patterns along the western South Atlantic margin. The rift segments are offset systematically in a left stepping pattern along the western South Atlantic margin. Albeit we found extensive variations in the architecture, style and extent of the seaward dipping reflector sequences a general trend is that the largest volumes are emplaced close to the proposed transfer zones and the width of the SDRs wedges decreases northward within the individual margin segments.

Numerical basin modelling has been conducted to investigate the maturity development of the sedimentary organic matter of the deepwater area (>2 km water depth) offshore Argentina. Besides the recent structure, the most important input data comprise a detailed stratigraphic scheme, the lithology of the sedimentary rocks as well as different heat flow scenarios. As source rock we propose the excellent Lower Cretaceous marine source rocks that were drilled at several locations throughout the South Atlantic (DSDP leg 40 site 361 in the Cape Basin offshore South Africa; San Jorge Basin, Argentina; DSDP leg 75 site 530 in the Angola Basin). In general, sediment thicknesses at the Argentine continental margin range between one and only few kilometres. Thus maturity of the sedimentary organic matter is generally low. However, three local depocenters were mapped with a significantly thicker sediment cover ranging from 4 – 6 km thickness. In these areas Cretaceous to Middle Tertiary sediments are overlain by Late Tertiary contourites/turbidites (Oligocene and younger). These contourites intervals can reach thicknesses up to 3 km and allow the Aptian sediments to reach maturities suitable for the formation of hydrocarbons.
Structure and HC potential of the volcanic margin off Argentina/Uruguay, South Atlantic (continued)
Structure and HC potential of the volcanic margin off Argentina/Uruguay, South Atlantic (continued)
A new suite of Falklands dykes: implications for the evolution of the Falkland Islands

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The Siluro-Devonian to Permian sedimentary sequence of the Falkland Islands is cut by over 400 dolerite dykes that have been previously grouped into two main but intersecting swarms: one trending NE-SW (the "north-south" swarm) located mainly in West Falkland; and one trending broadly WNW-ESE (the "east-west" swarm) and entirely confined to the south of West Falkland and its outlying islands. The dykes were confirmed as Early Jurassic by Ar-Ar dates of 190±4 Ma and 188±2 Ma. Palaeomagnetic data from the dykes has been cited in support of the rotational tectonic model for the Falklands microplate, which envisages its derivation, during the break-up of Gondwana, from a position adjacent to the SE coast of South Africa.

An aeromagnetic survey flown during 2004 by Falkland Gold and Minerals Ltd has clearly identified three discrete sets of linear magnetic anomalies interpreted here as separate dyke swarms. These are:

- a partly radial pattern of dykes (about 80 degrees of arc can be seen) centred to the SW of West Falkland. This includes the WNW-ESE orientated dykes (the "east-west" swarm of earlier accounts) although some of the more prominent dykes within this swarm (with more E-W orientations) appear to cut across the general radial pattern. These dykes are all normally magnetised.
- a series of NE-SW trending dykes present in both West and East Falkland (the "north-south" swarm of earlier accounts); the full extent of these dykes in East Falkland is demonstrated for the first time. Most of these dykes are reversely magnetised.
- a distinctive N-S (swinging northwards to NW-SE) set of approximately 40 dykes, spaced across both East and West Falkland, that produce discrete linear magnetic anomalies unrelated to those from the other swarms. The discovery of this previously unrecognised, N-S dyke swarm has important implications for the evolution of the Falklands microplate and for the extensional histories of the surrounding offshore sedimentary basins. Most of the N-S dykes are reversely magnetised in the east, but show both normal and reversed polarities in the west of the archipelago.

Most of the newly identified N-S magnetic anomalies do not correspond with visible dykes at outcrop, but we have located and sampled dolerite dykes that are unequivocally associated with N-S, linear aeromagnetic anomalies at Teal Creek and in Pony’s Pass Quarry, both localities in East Falkland. Precise Ar-Ar (plagioclase) dates were obtained from the N-S dyke at Pony’s Pass Quarry and a NE-SW dyke at Port Sussex, also in East Falkland. The Ar-Ar date obtained at Port Sussex is 177.8±1.5 Ma (Toarcian). It is based on good plateau results and establishes the NE-SW swarm as probably younger than the Radial Swarm, which has dates in the range 186-194 Ma. In a regional context, the new Ar-Ar date is closely aligned with the c. 180 Ma peak of Karoo magmatism in South Africa. A precise Ar-Ar age of 122.1±0.9 Ma (early Aptian) was obtained from the Pony’s Pass Quarry N-S dyke. The Ar-Ar plateau is well constrained and the Cretaceous age is considered to be robust.

The compositions of the various Falklands dykes assist our differentiation of three dyke swarms. New data supports published work to confirm that:
Cretaceous dykes discovered in the Falkland Islands: implications for regional tectonics in the South Atlantic (continued)

- the Radial Swarm in the south of West Falkland consists of olivine dolerites with a subordinate clinopyroxene ferromagnesian phase.
- the NE-SW dykes comprise dolerites with two ferromagnesian minerals – clinopyroxene and altered orthopyroxene.
- the newly-identified N-S dykes comprise glassy dolerites with only clinopyroxene in the ferromagnesian phase. The geochemical compositions of the two N-S dykes sampled from East Falkland (Teal Creek and Pony's Pass) are effectively identical to each other, and distinct from those of dykes within the NE-SW and radial swarms. Major oxides exemplify the differences with the N-S Cretaceous dykes being high in Fe and Ti but low in Al and Mg relative to dykes from the Jurassic swarms.

1 The Aptian, N-S orientated dykes onshore are of similar age to the oldest oceanic crust recognised from the abyssal plains of the Argentine Basin north of the Falklands-Aghulas Fracture Zone. There, marine magnetic anomaly M4 (c. 130 Ma) has been recorded although somewhat earlier ocean opening is indicated by its distance from the continent-ocean boundary, and by the earlier Mesozoic anomalies (up to M11) on the conjugate margin. It is therefore conceivable that Aptian dyke emplacement on the Falklands was driven by the initiation of sea-floor spreading in the South Atlantic during the early separation of South America and South Africa. The onshore Aptian dykes are parallel to N-S extensional faults recognised throughout the North Falkland Basin and as local features along the western margin of the Falkland Plateau Basin. The North Falkland Basin rifted from the late Jurassic onwards, until the early Cretaceous, and the regional, east-west stress-system responsible was probably also exploited by the onshore dykes.

2 There is a prevalent view that the Falkland Islands lie on a microplate that was rotated by up to 180° during its break-out from Gondwana. This model derives largely from onshore geology and is difficult to reconcile with the history of offshore basin expansion in the South Atlantic. Support for the rotational model was provided by the palaeomagnetic results obtained from a NE-SW, early Jurassic dyke on West Falkland so, if rotation has occurred, it happened after about 178 Ma. Our discovery and dating of the N-S dyke swarm, intruded at about 122 Ma and linked to the rifting of the North Falkland Basin, places an absolute minimum age on the time available for rotation. A definitive test of the rotational model might now be possible through a comparison of the palaeomagnetic characteristics of the Jurassic and Cretaceous dyke swarms, intrusion of which must have respectively preceded and followed any microplate rotation.

Falkland Gold and Minerals Ltd are thanked for making available data from their 2004 aeromagnetic survey. This abstract is published by permission of the Falkland Islands Government and the Executive Director, British Geological Survey (NERC).

3 Key References


Cretaceous dykes discovered in the Falkland Islands: implications for regional tectonics in the South Atlantic (continued)


The Santos and Campos passive margin basins resulted from the Cretaceous break-up of continental Gondwanaland. South Atlantic plate-margin reconstruction models propose uniform; east-west extension and symmetric rift-basin evolution is inferred with conjugate West African passive margin basins. By inference half-graben development and planar faults would characterise the structural style of the Santos and Campos syn-rift basins. Regional PSDM 2D-seismic interpretation and the integration of potential fields data has revealed, important new rifted margin structural relationships previously obscured by Aptian-age evaporite sequences.

The Campos basin is dominated by simple half-graben and continuous coast-parallel fault segments. In contrast, the Santos Basin is characterised by rhombo-chasmic grabens and en-echelon fault arrays. As a consequence more complex rift-basin evolution has occurred and contrasting syn-rift fill history is inferred for both basins. Along-strike variation of the rifted margin is thought to be primarily constrained by the response of the brittle upper crust to extensional reactivation of pre-existing upper crust weakness. This fundamental mechanical crustal anisotropy is inherited from Archaean deformation zones associated with the pre-rift continental crust terranes of Gondwana. Contrasting crustal rheology would then differentiate deformation styles in the Santos and Campos Basins, with the Santos Basin evolution more consistent with oblique extension and asymmetric rifting. However and in addition, during initial extension, differential thermal perturbation at the base of the lithosphere has imparted contrasting crustal heat flows to both basins and has had a primary influence on brittle versus more ductile rift-kinematics. The new interpretation challenges a simple uniform stretching symmetric rift model for the basins and can explain the paradox of along-strike variation in tectonic versus thermal-sag subsidence patterns observed. Reconstruction of the continent/ocean boundary, along the Brazilian margin and consideration of conjugate West African margin basins demonstrates compelling asymmetry between the Santos and Benguela basins, whereas a more symmetric relationship exists between the conjugate Campos and Kwanza basins. This is consistent with a more complex rift margin evolution. The structural expression of the transition from attenuated continental crust to oceanic crust in the Campos and Santos Basins is clearly distinctive, and is related to the primary rifting mechanism and crustal response inferred for each. The interpretation that the conspicuous intra-basinal Sao Paolo Plateau/ridge as a stranded continental crustal boundary suggests that the loci of oceanic crust formation in the Santos Basin may have experienced an episodic basinward translation as a response to more ductile whole crust deformation influenced by elevated lithospheric thermal stress. The Cabo-Frio Arch structurally partitions contrasting Campos and Santos syn-rift basin architectures and the new interpretation has fundamental implications for the respective syn-rift petroleum systems.
NOTES
Lithospheric extension of the Espirito Santo Basin – Petroleum Systems Implications

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Interpretation of regional 2D-PsTM (pre-stack time migrated) seismic data from the Espirito Santo Basin reveals the presence of a sub-horizontal, “intra-crustal” seismic reflection. The mapped seismic reflection deepens basinward below the extended continental crust and is mapped landward of the oceanic crust. It extends some 1.5-5.0 seconds two-way-travel time beneath the interpreted base syn-rift unconformity. High-angle extensional faults do not extend below this continuous seismic event indicating its significance as an important mechanical discontinuity. Because of its regional extent this seismic reflection is proposed to be an important rheological interface that would mark either the vertical transition to a more ductile lower crust or may represent the crust – mantle boundary. In essence, the seismic data may have imaged, the reflection moho or alternatively has recorded the fossilization of a “palaeo-moho” within the attenuated continental crust. The rift extension factor “Beta” is importantly dependent on whichever of the above alternative hypotheses is confirmed. A two-layer crust model is however preferred to explain the origin of the intra-crustal seismic reflection. The acoustic interface highlights the presence of anomalous velocity and density regions within the highly extended continental crust below a brittle upper crust, possibly particular to hyper-extended non-volcanic passive margins. The whole crust response to Neocomian age extension of the South Atlantic margin is evidenced by differential “necking” of the lithospheric mantle. Mechanical anisotropy within the whole crust has constrained the distribution of basement fault trends in response to regional crust extension that lasted circa 20 million years. In addition along-strike variability in post-rift subsidence patterns suggests that extension of the lower crust and lithospheric mantle appears inconsistent with a simple uniform extension model sensu Mackenzie, (1978). Differential or depth dependent stretching and or decoupling of the upper crust from the lower crust may account for the apparent asymmetry in post-rift and syn-rift basin subsidence patterns and this would necessarily introduce significant complexity when describing the maturation of important syn-rift source rocks. Petroleum systems models would need to account for these alternative rift-related deformation mechanisms and the associated temporal constraints imposed by contrasting heat-flow anomalies during divergent margin evolution. Two basement fault trends are apparent and determine the distribution of fault-related syn-rift depocentres. The extensional faults segment the basin into two discrete thermo-structural provinces that reflect crustal and lithospheric mantle heterogeneity. Two end member rift models have been traditionally proposed to explain the mechanism by which continental crust is thinned by extension. Whether we infer a modified simple shear or a pure shear mechanism, there is no unique solution that adequately accounts for all geological and geophysical observations along passive margins. The northern Espirito Santo Basin has responded via a more uniform, pure shear extension model, whereas the southern Espirito Santo Basin has formed in a manner more consistent with simple shear deformation styles. In addition the interpreted presence of rift-related volcanics within the northern Espirito Santo basin syn-rift sequence is thought here to reflect the contrasting rift-related deformation mechanisms. The correspondence of volcanic seismo-facies with the region of maximum “necking” of the whole crust suggests that igneous extrusives would dominate the facies preserved within the northerly early syn-rift basin fill. The interpretation of along-strike co-existence of contrasting rift mechanisms has profound implications for presence, effectiveness and maturation of syn-rift source rocks associated with South Atlantic break-up. Basin models should necessarily embrace these sensitivities and an awareness of these observations will impact the exploration of the Espirito Santos Basin and other South Atlantic Margin basins.
Mapping crustal thickness and the ocean-continent-transition in the Santos and Campos Basins, Brazilian South Atlantic

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We have applied the techniques of 3D gravity inversion and 3D flexural backstripping to BP’s regional mapping of a large segment of the Brazilian South Atlantic continental margin. 3D gravity inversion is used to predict depth to Moho and to map crustal thickness. 3D flexural backstripping is used to map stretching/thinning factors across the continental margin and from this derive maps of crustal thickness independent of those derived from the gravity inversion. The maps of stretching factor are fed back into the 3D flexural backstripping to produce a 3D palaeobathymetric history for the Santos/Campos margin, from the mid-Cretaceous to the present-day.

The modelling techniques used include the isostatic consequences of:
• lithosphere thermal perturbation during Cretaceous continental breakup
• volcanic addition to the crust during the breakup process
Both are critically important to the geodynamic analysis of any continental margin.

A long-standing question concerning the tectonic evolution of the Brazilian margin has been the age of the Aptian salt sequence relative to the age of continental breakup. Seismic data alone do not allow us to distinguish whether the salt was deposited as part of the syn-breakup sequence or whether it is the basal part of the post-breakup sequence. Our analysis of the subsidence history of the base salt horizon shows that the salt almost certainly cannot be part of the post-breakup sequence. We believe the salt to have been deposited rapidly during the breakup process itself. A syn-breakup age for the salt allows most of the Santos/Campos margin to be floored by thinned continental crust (rather than oceanic crust). A post-breakup origin for the salt would require all but the coastal strip of the Santos/Campos margin to be floored by oceanic crust. A post-breakup age for the salt also means that the results of the gravity inversion and the flexural backstripping cannot be reconciled with each other.

A key sensitivity issue in predicting the crustal structure of the Santos/Campos margin is the amount of volcanic addition assumed to have occurred during continental breakup. For both the gravity inversion and the flexural backstripping we have tested sensitivity to:
• no volcanic addition, a “rift basin” model
• a maximum 7km of volcanic addition, a so-called “non-volcanic margin”
• a maximum 10km of volcanic addition, a so-called “volcanic margin”
We believe the Campos margin is best considered to be a “non-volcanic margin”, while the Santos margin is almost certainly a “volcanic margin”. This has considerable implications for heat-flow history.

Both the gravity inversion and flexural backstripping indicate that in the SW Santos Basin we have identified a segment of highly-stretched, perhaps even oceanic, crust. This is probably a failed breakup basin (c.f. the Rockall Trough in the North Atlantic), indicating that continental separation originally attempted to occur much closer to the present-day Brazilian coast than was ultimately the case.
Rift related petroleum systems of West Africa and East Africa

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The continental margins of both West and East Africa were created from rifting, however West Africa rifting was both younger and less complex than that of the break up margin(s) of Eastern Gondwana and that has lead to the development of families of oils with different petroleum geochemical characteristics.

Early rifting on both margins led to the initial development of fluvial lacustrine conditions; however these conditions persisted for far longer over a far more extensive area and were considerable older in East Africa. The opening of the Atlantic from the Jurassic onwards was a comparatively swift and straight-forward event. In contrast rifting in East Africa commenced in the late Carboniferous, but Gondwana only successfully broke-up at the end of Lias, with the drift of Madagascar with Seychelles, India and Australia to the south. Further rifting episodes occurred within Eastern Gondwana fragment again leading to further distinct source facies and subsequent oil types.

The dominant source in West Africa developed in marginal marine conditions in the Late Cretaceous, whilst the dominant source in East Africa are the Lower Mesozoic lacustrine to restricted marine to fully enclosed marine shales. Lacustrine source rocks of Triassic age are attributed to East Africa’s largest oil accumulation, that of Bemolanga and Tsimiroro, Madagascar. Similar aged lacustrine shales (Majiya Chumvi) may be found in Kenya and certain oils from both Mozambique and Tanzania have lacustrine affinities as may a new sample from Kenya.

As the early rift drift source rock accommodation areas of the East African margin grew in size in the Early Jurassic a series periodically inter-connect inland seas and lakes developed leading to the deposition of rich organic sometimes saline to hyper-saline deposits seen at outcrop in Tanzania and evidenced through oil seep and show biomarker assemblages seen throughout out the Western Indian Ocean margin. Beyond the mid Jurassic fully marine conditions persisted and no further marine source rock development to place.

Evidence for the East African early Mesozoic source system can be traced south as far as Rovuma basin in Northern Mozambique. Due to the lack of sample material there is currently a data gap in central and southern coastal Mozambique; further South there is a curious development of Upper Jurassic source rocks in southern South Africa seen as far north at the Durban basin.

On the west coast Hauterivian aged lacustrine syn rift source rocks have been encountered in the Orange basin. Further north the source rocks are dominated by the classic upper Cretaceous marginal marine shales.

Perhaps the only time equivalent similarities that exist between East and West Africa may be seen through Tertiary deltac of the massive Rovuma delta than of the Niger delta, that is unless there is a link from the Upper Palaeozoic Salt Pond oil through the Central Rift system to the earliest oils of East Africa…
Structure and thermal history of the obliquely divergent Equatorial Guinea-NE Brazil margins

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Two end member kinematic models dominate descriptions of so-called passive margins – transform margins and (orthogonally) rifted margins. However, many margins like those of the South Atlantic are highly segmented with adjacent segments oriented variously with respect to the regional divergence vector. In the first part of this contribution, we show how the structure of obliquely divergent settings is complicated by their non-coaxial kinematics (i.e. rotational strains about vertical axes). Deep-imaging reflection seismic profiles offshore Gulf of Guinea, West Africa are used to constrain the structure and composition of the ocean-continent transition. Gravity modelling of the seismic data reveals a c.70km-wide zone of fractured ‘proto-oceanic’ crust interpreted as a leaky transform (Ascension transform and fracture zone). Continuous overprinting of faulting within this mega-shear zone led to later faults dissecting, and translating in their hanging walls, a mixed assemblage of crust and serpentinized mantle peridotite.

In the second part, our structural model is augmented by apatite fission track (AFT) and vitrinite reflectance (VR) data from both margins of the conjugate Equatorial Guinea-NE Brazil system. All the AFT and VR samples are interpreted to have experienced higher temperatures in the geological past due to i) their exhumation from formerly greater burial depths (thickness of section eroded in the Middle Cretaceous: 1400m, Late Cretaceous: 1650m, Palaeogene: 800m, Neogene: 1850m), and ii) elevated basal heatflow (in well Rio Muni-1 decaying from 58°C/km in the Middle Cretaceous to 21.5°C/km in the Neogene). All but the Palaeogene cooling episodes correlate with major unconformities observed at both margins. They are interpreted as a record of the superimposition of local and regional effects related to i) the transition from breakup to drift conditions along the evolving Ascension Fracture Zone, ii) movement of the South American and African plates over the St Helena and Ascension plumes during the Late Aptian-Albian, iii) plate reorganization c.84Ma., and iv) far-field stress originating from the early stages of the Africa-Eurasia collision during the Santonian.
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Ground Floor Plan of the Geological Society, Burlington House, Piccadilly