Rifts III: Catching the Wave
Just when you thought it was safe to go back in the water...

22-24 March 2016

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15 March 2016

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Dear Rifts III Contributor,

Petroleum Geoscience Thematic Set Invitation

I am writing on behalf of the Convenors of the Rifts III conference to invite you to contribute a manuscript to a special thematic set provisionally entitled:

Rifts III: Catching the Wave

The thematic set will capture and publish results from the papers presented during Geological Society Petroleum Group conference entitled Rifts III: Catching the Wave, held in March 2016. As you may know, Petroleum Geoscience seeks to publish inter-disciplinary papers covering one or more of the rock-related disciplines and engineering, in an applied setting. Following discussions with the convenors, the co-editorial team believes that the topic of the thematic set is very well suited to the journal's aims and we have agreed to target the issue of August 2017 for publishing the set. The journal presently enjoys its highest ever five-year impact factor and its individual and institutional subscriptions are over 8,000. Content can also be accessed on-line through GeoScience World, the GSL Lyell Collection and the EAGE EarthDoc, thereby providing global coverage including American and Asia-Pacific readers.

Time line

To publish in August 2017, we need reviewed, revised, copy-ready papers by early March 2017. A printed thematic set is as fast as the slowest paper (but see below), so allowing for reviews and revisions, we advise a first submission date no later than **1 June 2016**.

Online First

GSL is pleased to offer early publication through Online First to those papers which have been accepted and are ready to print. Early submission and acceptance can then be rewarded with a publication date, prior to appearance in print, with a citable digital object identifier (doi) reference.

Editors

The lead convenors (Scot Fraser, Mike Lentini & Al Fraser) will act as guest editors for the set, with responsibility for arranging reviews. I will act as supervisory co-editor to advise and assure consistency in quality. Dr Sally Oberst (sally.oberst@geolsoc.org.uk) is production editor.

Next Steps

If you are willing to participate in the thematic set, we would be grateful for an early expression of interest by responding to myself at pafc1@slb.com and to Scot Fraser at Scot.Fraser@shell.com Some further information regarding the publication follows below.

EAGE

Published by the Geological Society Publishing House for the European Association of Geoscientists & Engineers, and the Geological Society of London.

Manuscript Preparation

If you decide to contribute to the set, we would be glad if you would prepare manuscripts in accordance with the guidelines in Information for Authors on the GSL website (http://www.geolsoc.org.uk/pg_authorinfo). We suggest a maximum length of 5-7 journal pages for a paper, and there is guidance on estimating the final size of a manuscript in the Information for Authors. If 7 pages is insufficient there is also an option to place supporting material on-line in Supplementary Publications.

Electronic Submission

We request that submissions be made via the Editorial Manager online manuscript tracking system (http://www.editorialmanager.com/petgeo/default.aspx). Further details can be found in the Information for Authors and both Sally and I are ready to assist with queries.

Colour Charges

Petroleum Geoscience does charge for printed colour figures but not for greyscale figures. A budgetary guideline is £500 for a printed paper which requires colour plus £50 per colour figure. Since this is a thematic set, we will finalise the charges for colour when we know how the printed issue is laid out. It may be possible to arrange the organisation of the papers to minimise overall colour charges for the set. If you prefer not to publish in print in colour, it is possible to have a colour pdf at no charge, so long as we can print from the same pdf in greyscale. This requires some careful design and attention to figures.

Reprints

A pdf of the final article, which can be in colour even if the printed pdf is in greyscale, will be available to authors subject to the journal's copyright policy.

On behalf of *Petroleum Geoscience* I would like to thank the convenors for proposing this thematic set which I am certain will make a valuable contribution to the literature. If you have further questions, please do not hesitate to get back in touch with me, Scot or Sally. We look forward to working with you on this exciting project.

Yours sincerely,

PAF Christie

P. A. F. CHRISTIE

PAFC/pafc/

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Tuesday 22 March

Session One

Keynote Speaker: Controls on Structural and Magmatic Variability along Rifted Margins: From Observations to Interpretations

G. Manatschal; J. Tugend, M. Gillard, A. Decarlis, I. Haupert, P. Chenin, M. Nirrengarten, M.E. Epin, *IPGS-CNRS-EOST, Université de Strasbourg, Strasbourg, France*

Recent advances in the development of long offset, high-resolution seismic imaging methods, combined with drill-hole data and direct field observations resulted in a paradigm shift in interpreting the structural and magmatic evolution of rifted margins. In particular, the discovery of hyper-extended domains associated with variable amounts of late magmatic additions results in a fundamental question: what controls the pronounced structural and magmatic variability observed along rifted margins (Figure 1)? In order to identify and understand the processes that may account for this variability, a new approach has been developed that enables the mapping and interpretation of the architectural variations observed along Atlantic type rifted margins. The key is to combine geological and geophysical observations. To first order, the architecture of the crust can be linked with direct constrains on the depositional environments and sedimentary facies, the nature and kinematics of basement structures, subsidence evolution and the volume and timing of magmatic additions observed at different parts of the margin.

The first part of the presentation reviews, using multi channel seismic sections and outcrop observations, key architectural features, such as tilted blocks, necking zones, hyperextended and exhumed mantle domains and various types of magmatic additions observed in Atlantic type rifted margins. The focus will be on first order geometrical relationships between these building blocks as well as on their stacking order as observed in onshore remnants. A key result is that, on a first order, rift systems can be subdivided in mappable rift domains that can be identified using geological and geophysical criteria. The mapping and characterization of these domains highlights the along-strike structural, magmatic and stratigraphic variability of the margin. A first order screening of conjugate margins also confirms the asymmetry of distal parts of margins and their segmentation.

A second part discusses the interaction between extensional structures and magmatic processes at rifted margins. A key observation is that major crustal/lithospheric thinning predates in most margins an excess magmatic event that is commonly related to breakup. This observation suggests that the link between magmatic/asthenospheric and structural/lithospheric processes is more complex and cannot be predicted with a simple depth-dependent rift model. Indeed, the evolution of rift systems reflect the interplay between their inheritance (innate/"genetic code") and the physical processes at play (acquired/external factors) that may explain the observed changes in time and space across a rift system. Understanding when, where and how magma is first produced and how it interacts with the extensional systems is a key to understand final breakup as well as to explain the structural and magmatic variability observed along Atlantic-type systems. Observations suggest that both inheritance and rift-induced processes play a significant role in the development of rift systems. Thus, it is not only important to determine the “genetic code” of a rift system, but also to understand how it interacts and evolves during rifting. The discussion of how these different processes may interact in time and space and how they may control the final architecture of rifted margins is the major subject of the talk.

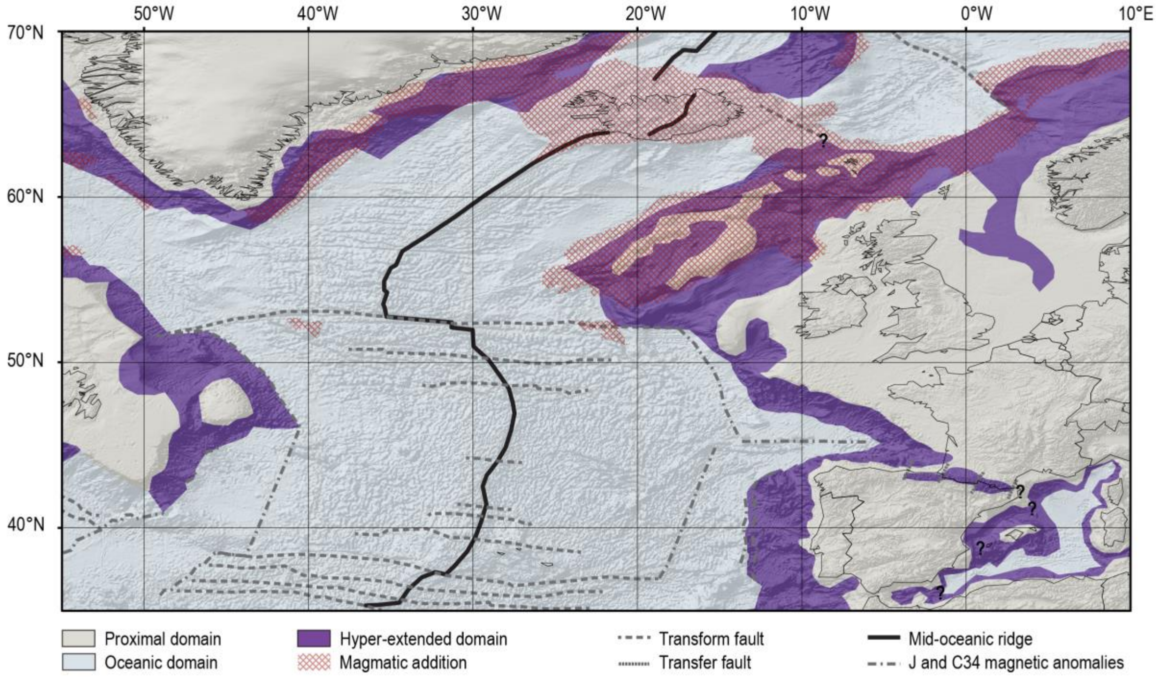

Figure 1: Map of the rift domains and break-up related magmatism along the North Atlantic margins (modified after compilation from Chenin et al., 2015, see references in the paper)

NOTES

Rifted Margins and Extension Rates

Lundin, E.R.[1], Doré, A.G,[2] Redfield, T.F.[3]

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[2]*Statoil (UK) Ltd., One Kingdom Street, London, W2 6BD, UK.*
[3]*Geological Survey of Norway, Leiv Erikssons v. 39, 7040 Trondheim, Norway*

Rifted margins are commonly classified as either magma-rich or magma-poor, although arguably a gradual transition may exist between the two end members. Magma-poor margins may form during ultraslow to slow extension, and conversely magma-rich margins during more rapid extension. Numerical modelling to some extent supports this general notion. Nevertheless, these relationships are based on limited data sets. Rates for magma-poor margins are mainly based on the Iberia margin where the syn-rift development has been addressed by use of a sequence of ODP boreholes that span the margin in the dip direction. However, the boreholes were targeted on the updip end of the half grabens and only partially sampled the synrift successions. Exhumation rates have been based on cooling ages of lower crust in the outer hyperextended margin, weak magnetic anomalies of debated nature within the exhumed mantle, and ages of sediments overlying the exhumed mantle.

We know of no well-constrained extension estimates for magma-rich margins. Probably the NE Atlantic margins represent the best documented case, but there the pre-break-up extension rate is poorly constrained. Subsequent seafloor spreading rates are well-constrained by tightly spaced magnetic isochrons, which reveal a rapid initial spreading (ca 25 mm/yr half rate) that soon diminished. Initial seafloor spreading in the southern South Atlantic was also rapid. These rapid initial seafloor spreading rates along magma-rich margins have possibly led to the general perception that such margins always form during rapid extension. However, the concept needs more rigorous testing with a better worldwide database. Other magma-rich margins, such as the eastern US seaboard (Central Atlantic) formed during the magnetically quiescent period in the Early - Middle Jurassic. Currently favored ages of break-up and the first isochron indicate ultraslow to slow spreading, but notably the age of break-up is poorly constrained.

The assumption that there is a direct proportionality between extension rate and magma production appears to be supported by the limited data set, but the reasons why this is the case is not yet clear. We present some ideas and critical data in an effort to illuminate the underlying processes with emphasis on the following questions:

1) Do available data really support the notion that magma-poor and – rich margins form during slow and fast extension respectively?

2) How might geological elements missing in many models (small-scale convection, lithospheric composition, or structural inheritance) affect numerical models?

3) Is hot, rising asthenosphere required to generate the observed melt?

NOTES

GloRiDa - The Global Rifts Database

Christian Heine, *Upstream New Ventures, Shell International Exploration & Production B.V., Den Haag, The Netherlands Formerly: EarthByte Group, School of Geosciences, The University of Sydney, Australia*

Rift basins and passive margins are an archive of extensional processes affecting the shape and integrity of lithospheric plates. The spatio-temporal occurrence and dynamics of these structures are not only relevant for resource exploration but also contain important information on forces acting on continental lithospheric plates and for a next generation of plate kinematic models with deforming plates. I present the first quantified geospatial database of global rift structures for the Phanerozoic which allows a “big data” approach to the analysis of lithospheric extension patterns over geological time.

I will analyse the geological history of global rift patterns and relate these with tectonic parameters such as magnitude of rifting, duration and time of occurrence, lithospheric and crustal substrate, and proximity to plate boundaries. The analysis shows distinct temporal patterns in the rate of 'failed' versus 'successful' rifts over geological time as well as in the lifespan of active rifting, related to plate tectonic environment. In addition, I will utilise a new global sediment thickness compliation to extract kinematic information from those rift basins and present how this information is used for plate tectonic models with deforming plates.

NOTES

Crustal Reheating and Mantle Upwelling During Continental Break-Up Triggered By Lithospheric Instabilities

Luc L. Lavier[1,2], Andrew J. Smye[1*], Daniel F. Stockli[1] and Thomas Zack[3]

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[3]*Department of Earth Sciences, University of Gothenburg, Box460, 40530, Göteborg, SWE*
[*]*Present address: Department of Earth Sciences, University of Oxford, South Parks Road, Oxford, OX1 3AN, U.K.*

Oceanic basins are formed where continents are broken apart. At magma-poor continental margins, this has long been explained by uniform thinning of the lithosphere accompanied by passive upwelling of hot asthenosphere. Non-uniform, depth-dependent thinning has been proposed as an alternative to explain the anomalously shallow environment of deposition along many continental margins. Depth-dependent thinning models predict that the lower crust and sub-continental lithospheric mantle undergo a phase of increased heat flow during thinning of the lithospheric mantle. However, this early syn-rift heating is yet to be clearly documented at magma-poor continental margins and the physical mechanism responsible for initiation of depth-dependent thinning remains enigmatic. Here, we show that the lower crust of the Alpine Tethyan margin experienced reheating during the break-up phase of continental rifting, consistent with the depth-dependent thinning hypothesis. Diffusion modeling of U-Pb ages and trace elements in rutile from the Ivrea Zone, Southern Alps, shows that conductive heating of the lower crust occurred during the transition from plate stretching to thinning and was followed by advective heating associated with emplacement of asthenospheric melts. Combined with dynamic models of the rifting process, we use these data to show that a mechanical instability forms in the lithosphere during coupling of deformation in the crust and lithospheric mantle. Growth of the instability drives depth-dependent thinning. Our results demonstrate that active mantle upwelling during formation of magma-poor rifted margins can be initiated by lithospheric processes alone and does not require anomalously hot asthenosphere.

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Tectono-Magmatic Evolution at Distal Magma-Poor Rifted Margins: From Crustal Breakup to Lithospheric Breakup

M. Gillard, J. Autin, G. Manatschal, *IPGS-CNRS-EOST, Université de Strasbourg, Strasbourg, France*

The discovery of large domains of hyper-extended continental crust and exhumed mantle along many present-day magma-poor rifted margins questions the processes leading to lithospheric breakup and onset of seafloor spreading. In particular, the evolution of faults, the amount of magma and its relation to tectonic structures are yet little understood. Trying to find answers to these questions asks to work at the most distal parts of rifted margins where the transition from rifting to steady state seafloor spreading is recorded.

The deformation recorded in the sedimentary units along several magma-poor rifted margins, such as along the Australia-Antarctica and the Iberia-Newfoundland Ocean Continent Transitions (OCT's), highlights a migration of the deformation toward the future ocean. In particular, the observation that each tectono-sedimentary unit downlaps oceanwards onto the basement suggests that final rifting is associated with the creation of "new real estate" by a process that is not yet steady state seafloor spreading. These observations lead to a new model for the evolution of exhumed mantle domains implying the development of multiple, polyphase extensional detachment faults organizing out-of-sequence, i.e. stepping backwards into the previously exhumed footwall. This spatial and temporal organization of faults may explain the final symmetry of exhumed mantle domains generally observed at several magma-poor OCT. Indeed, it appears that the current models implying in-sequence detachment faults to explain the presence of exhumed serpentinized mantle cannot account for the observations made at OCT's.

We propose that this fault evolution observed in exhumed mantle domains at magma-poor rifted margins is linked to cycles of delocalisation/re-localisation of the deformation. These cycles of deformation appear to be strongly influenced by the magmatic budget, but also by the thermal state and hydrothermalism during mantle exhumation, resulting in alternations between pure shear and simple shear modes. This evolution implies the presence of a decoupling interface between an upper brittle layer made of serpentinized mantle and a yet poorly-defined underlying level. The complex interaction between out-of-sequence detachment systems and the successive rise of the asthenosphere may explain the observed transition from a fault- to a magma-controlled strain accommodation and the transition to more symmetric and localized accretion associated with the formation of a stable and localized spreading centre.

However this model of evolution for exhumed mantle domains raises the question of the nature and dating of magnetic anomalies in such OCT's and their value for the interpretation of the kinematic evolution of conjugates rifted margins.

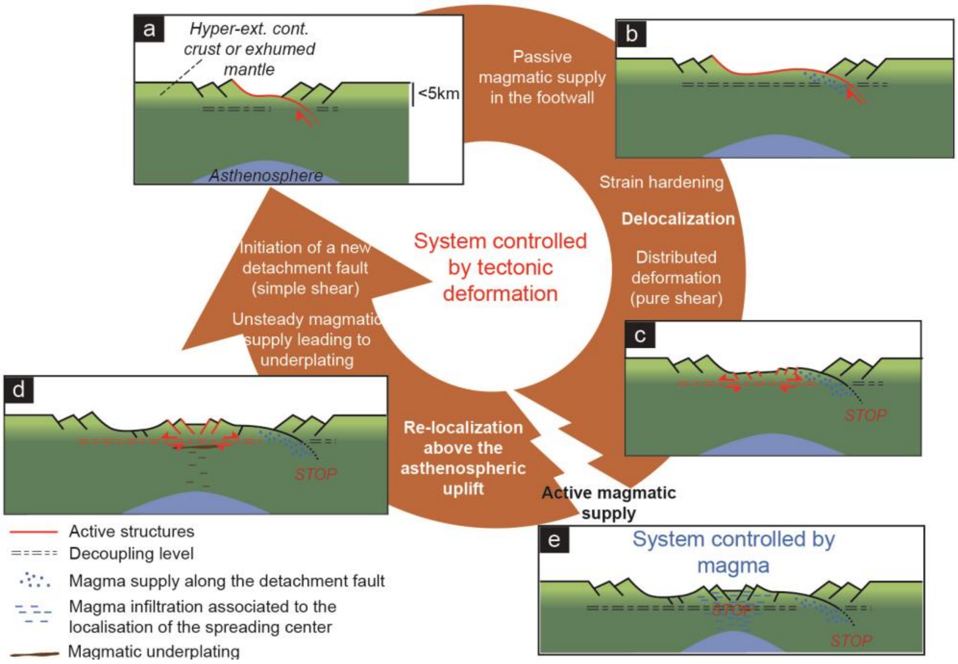

Figure showing the model of cyclic evolution of the exhumed mantle domain. From *Gillard et al. in press*.

NOTES

Construction of Magmatic Rifted Margins

David G. Quirk and **Alaister Shakerley**, *Maersk Oil, Copenhagen, Denmark*

Oceanic basins are the ultimate product of rifting. While significant advances have been made in understanding the attenuation of continental lithosphere prior to final break-up, less attention has been paid to the role magma and volcanism plays in the transition from break-up to the formation of new oceanic crust. Using deep seismic images along the Atlantic margins, we show that seaward-dipping reflectors (SDRs) provide evidence for the processes involved.

A key premise is that landward-dipping nonral faults are an integral part of the ascent o fmagma during plate separation, allowing crust both to be stretched and accreted concurrently. We have developed a generic model where buoyant transitional crust is rolled out on either side of an axial horst cored by a domed pluton or magma chamber comprising gabbroic melt fed from upwelling asthenosphere. The axial horst was formed at the point of break-up of the upper crust but its continental origin becomes disguised by multiple intrusions and footwall collapse. The landward-dipping faults defining the horst are a type of low angle detachment which accommodates the construction of new crust by propagating away from the continent as the plates diverge. Melt flows to the inherent low pressure zone beneath the footwalls where space is created for magma to collect as the faults move, a generic process we term “magma-assisted extensional growth”. Below where the faults detach, new gabbroic crust is accreted along the flanks of the magma chamber in dilational shear zones in the mid crust, transferring and deforming gabbro from the footwall to the hanging wall as the shear zones move. Dykes are intermittently sourced from the top of the magma chamber and traverse the horst, leading to periodic eruptions of basalt which collect as sub-aerial lava flows in the hanging walls on either side of it. The lavas become seaward-dipping due to roll-over onto an igneous weld at around 4 km depth where the faults meet the upper edge ofthe magma chamber.

While upper and mid crust is accreted and deforms by simple shear, the underlying lower lithosphere is inherited from the continent and progressively thins by pure shear, making the transitional plate relatively buoyant. The width of the transition depends on the degree of necking and the amount of thickening by intrusions in the lower lithosphere. Eventually, when the mantle lithosphere has thinned to a critical point, the axial horst splits to form an embryonic mid-ocean ridge where normal oceanic crust is formed by seafloor spreading. Heat and extension becomes focussed at the plate boundary and the oceanic crust on either side subsides to oceanic depths as cooling mantle accrets to its base.

Reference: Quirk, D.G., Shakerley, A. & Howe, M.J., 2014. *A mechanism for construction of volcanic rifted margins during continental breakup*. Geology, 42, 1079-1082

NOTES

Møre Volcanic Rifted Margin, Sea-Floor Spreading and Microcontinent: Insights from New High-Resolution Aeromagnetic Surveys

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The Continental Shelf Geophysics team at NGU has acquired and processed more than 88.000 km of new aeromagnetic data over the entire oceanic Norway Basin (NB) located between the Møre volcanic rifted margin (MVRM) and the Jan Mayen microcontinent (JMMC). The new compilation allows us to revisit the crustal structure of the conjugate rifted system and its spreading evolution from the Early Eocene breakup time (at Chron C24) to the Late Oligocene when the Aegir Ridge became extinct. Seismic data and potential field modelling suggest that the size and thickness of the continental blocks/rafts preserved beneath the Cretaceous Basin of the MVRM are larger and thicker compared to the allochthonous blocks often described in distal "hyper-extended" domains. The continental crust preserved on top of the outer lower crustal bodies in the outer part of the MVRM remains relatively thick (> 5-8 km) to favour a broad zone of exhumed and denudated serpentinized mantle adjacent to the oceanic domain. Modelled Vp velocities of 7.2-7.3 km/s for the underlying lower crustal bodies would possibly require an increased process of serpentinization that usually is symptomatic of more drastic crustal thinning (ßcrustal >> 4) and/or complete mantle denudation. Such a crustal configuration is not so obvious in the outer part of the MVRM where a marginal plateau is suggested nearby the lava flows. To explain the magnetic anomalies observed in the central part of the MVRM, our potential field modelling suggests also the preservation of middle crustal material with high magnetic susceptibilities associated with the crustal rafts observed on seismic data. We favour a "super-extended" tectonic scenario where a large part of the crust observed underneath the sedimentary basin represents both preserved upper continental basement and mid to lower crustal lenses of inherited and intruded, high-grade metamorphic rocks also controlling the inner necking zone. We interpret the nature of the crust closer to the SDRs as a similar mixture of residual continental crust later affected by breakup-related intrusions. No zone of exhumed and serpentinized continental mantle has been clearly identified from magnetic chron C24n3n towards the continent. The long period of rifting (and intra-thinning cooling event ?), the large amount of pre-breakup sedimentation and the significant amount of breakup magmatism (SDRs) make the MVRM to appear quite different from (Iberian type) magma-poor margins. The spreading system is now fully covered by reliable data and reveals a more complex system of asymmetric oceanic segments locally affected by episodic ridge jumps. The new aeromagnetic compilation confirms that a controversial fan-shaped spreading evolution of the NB was clearly active before the cessation of seafloor spreading and extinction of the Aegir Ridge. An important Mid Eocene kinematic event at around magnetic chron C21r can be recognized in the NB. This event coincides with the onset of dyking and the increase of rift activity (and possible oceanic accretion?) between the proto-JMMC and the East Greenland margin. It led to a complete and second phase of breakup and microcontinent formation in the Norwegian-Greenland Sea ~26 Myrs later in the Oligocene.

NOTES

The Along-Strike Pattern of Magmatism during Breakup in the Southern South Atlantic: The Relative Roles of Deep Mantle Plume and Lithospheric Segmentation

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Whilst our understanding of rift formation and evolution has matured in recent years there remains a fundamental debate on the relative roles of deep processes, and in particular mantle plumes, compared to shallower processes in the lithosphere or uppermost asthenosphere. Current interest in this topic is partly driven by the increased exploration for hydrocarbons in deep- and ultra-deep-water. Mitigating the high risks associated with exploring in these settings requires an improved understanding of the geodynamics of passive margin formation.

Here we investigate the pattern of magmatism in the South Atlantic between the Florianopolis and Falkland-Agulhas Fracture Zones. This region is recognized as a prime example of conjugate volcanic margins, with extensive seaward dipping reflector sequences (SDRs) and high velocity lower crust (HVLC), but it remains relatively under-studied and has a somewhat chequered exploration history. Recently, based on closely spaced, but shallow recording academic reflection data, it has been suggested that rather than a systematic increase in the volumes of the SDRs towards the ancestral Tristan da Cunha hot-spot there is an alternating pattern correlating with first order, ~500-km long segments bounded by transfer zones which link to onshore continental structures that may have controlled the Cretaceous rifting. Here, we test this observation, which would imply a lithospheric rather than deep plume influence on melting, by adding observations from 18,000 km of long-offset commercial seismic reflection data that images to 40 km depth to the analysis.

To explore the along-strike variations in magmatism we have also compiled observations of initial ocean crustal thickness as a measure of the melt production immediately post-breakup. We show that along both conjugate sides there is a systematic decrease in oceanic crust production with distance away from an assumed ancestral Tristan hotspot impact point, averaging 1.4 km/1000 km. We explore the implications of these observations of melt volumes by comparing against results from a 2D numerical simulation of continental breakup. In these models we include independent estimates of initial lithospheric thicknesses and extension rates to isolate mantle temperature influence. The observed pattern can be matched with numerical models with a 200 km thick hot later beneath the lithosphere, where the excess temperature reduces from 2000C to 500C over a distance of 1500 km, southwards away from the plume centre. These results suggest that a simple plume concept is appropriate for these margins to a first order, albeit with modification from plate thickness.

NOTES

Tuesday 22 March
Session Two

Keynote Speaker: Strain Accommodation by Faulting and Magmatism during Rift Initiation

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Rift initiation in thick, strong continental lithosphere challenges current models of continental lithospheric deformation, in part owing to gaps in our knowledge of strain patterns in the lower crust. New geophysical, geochemical, and structural data sets from youthful magmatic (Magadi-Natron, Kivu), weakly magmatic (Malawi, Manyara), and amagmatic (Tanganyika) sectors of the cratonic East African rift system provide new insights into the distribution of brittle strain, magma intrusion and storage, and time-averaged deformation. We compare and contrast time-space relations, seismogenic layer thickness variations, and fault kinematics using earthquakes recorded on local arrays and teleseisms in sectors of the Western and Eastern rifts, including the Natron-Manyara basins that developed in Archaean lithosphere. Lower crustal seismicity occurs in both the Western and Eastern rifts, including sectors on and off craton, and those with and without central rift volcanoes. In amagmatic sectors, lower crustal strain is accommodated by slip along relatively steep border faults, with oblique-slip faults linking opposing border faults that penetrate to different crustal levels. In magmatic sectors, seismicity spans surface to lower crust beneath both border faults and eruptive centers, with earthquake swarms around magma bodies. Our focal mechanisms and Global CMTs from a 2007 fault-dike episode show a local rotation from ~E-W extension to NE-SE extension in this linkage zone, consistent with time-averaged strain recorded in vent and eruptive chain alignments. These patterns suggest that strain localization via widespread magma intrusion can occur during the first 5 My of rifting in originally thick lithosphere. Lower crustal seismicity in magmatic sectors may be caused by high gas pressures and volatile migration from active metasomatism and magma degassing, consistent with high CO_2 flux along fault zones, and widespread metasomatism of xenoliths. Volatile release and migration may be critical to strength reduction of initially cold, strong cratonic lithosphere. Our comparisons suggest that large offset border faults that develop very early in rift history create fluid pathways that maintain the initial along-axis segmentation until magma (if available), reaches mid-crustal levels.

NOTES

The Influence of the Nature of Brittle Failure in Numerical Models of Extension

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[2]*School of Earth Sciences Melbourne University, Melbourne, VIC, AUS*
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Differing styles of extension, such as horst-and-graben, half-graben, metamorphic core complexes and areas of distributed crustal thinning, are observed in rift basins on Earth. The morphology of the rift basin may be asymmetric or symmetric, with the large majority of rifts being classified as asymmetric. Faulting zones can range from either being distributed, where individual faults are characterized by a relatively steep angle and small offset, to highly localized, where individual faults exhibit a low angle and very large displacement. Observations indicate that rheological properties exert control over the extensional deformation style, symmetry, and fault spacing in extension zones. We present time-dependent numerical models of extension that focus on the influence of the nature of brittle failure, specifically differences between (a) a Mohr-Coulomb yield criterion implemented through a transition to a non-linear, transversely isotropic viscous flow rule, and (b) a Drucker-Prager yield criterion implemented as an non-linear, isotropic, viscous flow rule. Unlike the classical implementation of the Mohr Coloumb plasticity law, which limits both the shear and normal stresses along a plane of failure, our transversely isotropic plasticity law limits the shear stress only and the normal stress remains unchanged. The use of a transversely isotropic rheology in the extension models produces an upper crust strength profile that is a closer match to predicted upper crust strength profiles from laboratory experiments, slightly smaller fault spacing, increased asymmetry and increased fault interaction in comparison to the models using an isotropic yielding mechanism. These outcomes can be attributed to the larger portion of normal stress being transferred across the faults. In addition these models are more likely to have three dimensional deformation patterns, due to increased interaction between faults, The results imply that employment of a transversely isotropic rheology to generate rift zones produce more Earth-like results, as stresses and forces are transmitted across simulated faults in the same manner as stresses and forces are transmitted across faults on Earth. An accurate stress field is essential to understanding rifting phenomena such as rift initiation, interaction between normal faults, and the role of stress transfer in earthquake occurrence.

NOTES

Oblique Rifts: Structure, Kinematics and Infill. The Example of the Main Ethiopian Rift

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The Main Ethiopian Rift (MER) is an oblique continental rift separating Nubia from Somalia. Since decades, it is a natural laboratory for geologists and geophysicists who study continental rifting processes, tectono-magmatic interactions within an extending continental crust, incipient crustal break-up and seafloor spreading. In oblique rifts, such as the MER, the deformation pattern is characterized by two sets of anachronously formed faults: (i) border faults defining the outer boundaries of the rift and trending obliquely to plate displacement which are controlled by pre existing weaknesses and (ii) internal faults affecting the rift floor that trending orthogonally to the plate displacement and formed in response to the regional stress field. The amount of obliquity controls the strain migration from border faults to inner faults, increasing strain localization, enhancing both faster and higher thinning and triggering the emplacement of larger magmatic bodies.

In such oblique rifts, it is commonly expected that structures striking orthogonal to the extension direction show dip-slip kinematics whereas those being oblique display strike-slip kinematics. However, natural oblique rifts, among which the MER, show earthquake focal mechanisms and fault slip data contradicting this statement. With the aid of analog models, we investigate faults kinematics of oblique rifts. We show that there is a re-orientation of the extension direction, giving rise to pure dip-slip

NOTES

What Lies Beneath - Do We Really Know What Type of Crust SDRs Sit Upon and does it Matter?

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[3]*Tectonic Analysis*
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The Argentinian Passive Margin provides an exceptional example of a volcanic passive margin that has been a focus, along with much of the South Atlantic, for hydrocarbon exploration. Understanding the crustal architecture and the processes that led its present configuration is essential for exploration success. Recently acquired, well imaged, seismic reflection data are used to constrain the margin architecture. These new data provide significant improvements in imaging throughout the oceanic and continental lithosphere that enables us to interpret lower and mid crustal reflectivity, the continental and oceanic moho, seaward dipping reflections and oceanic crust domains.

Despite this high quality imaging uncertainty still remains in both the interpretation of the data as well as the geophysical properties of the margin, including the extent of lower crustal magmatic bodies, the geometry of break-up volcanics and Seaward Dipping Reflection emplacement. Constraining these interpretations have a fundamental control in our understanding of the processes involved in continental rifting and break up.

Interpretation of previous data, as well as existing models of the margin, do not account for such uncertainty in the interpretations. In this study we present multiple seismic-structural interpretations for data that are geometrically valid. We then use a number of techniques, including kinematic restorations, gravity modelling, backstripping and subsidence analysis to test the validity of each of the models.

By addressing the uncertainty inherent in any sub-surface data we can better constrain the suite of likely scenarios. This enables us not only to understand the evolution of, hence process involved in lithospheric stretching, it also allows us to discuss how these uncertainty will influence the risking of future exploration in such frontier areas.

NOTES

Continent-Ocean Transitions, How Do They Form? An Example from Sergipe Alagoas, Brazil.

Ian Clark, Scot Fraser, *Shell International Exploration and Production.*

Traditional views of the boundary between ocean and continent tend towards relatively simple models, partly due to the lack of geophysical data that image these areas. We present an example of an ocean-continent transition spanning an area of over 22000km2 from the Sergipe Alagoas Basin, a volcanic rifted margin offshore central Brazil. Using recently acquired, high resolution 2D seismic data it is possible to define the 'building blocks' of the ocean continent transition in this area, consisting primarily of seaward dipping reflectors and large areas of volcanic deposits. The geometries recorded in seaward dipping reflectors are interpreted to represent a steady increase in accommodation due to extension. The large volcanic areas are interpreted to represent areas of lesser extension and a relatively fixed magma source. These new observations based on geophysical data from these settings could have important implications for our view on the early processes of continental break up.

NOTES

Insights into the Evolution of the Volcanic Margin of Western India and Associated Intracratonic Rifts

Mark T. Ireland, R.W. Wilson and S. Shoulders, *BP Exploration*

The Western continental margin of India (which includes the offshore Kutch, Saurashtra, Bombay and Kerla Konkan basins) and the intracratonic rifts of NW India (Cambay, Narmarda and Barmer basins), formed as a result of series of rifting events associated with the break-up of Gondwanaland during the Mesozoic and Early Cenozoic. Rifting initiated along inherited Proterozoic trends, and influenced the resultant basin geometries. All of these rifted basins have an associated volcanism, evident from the Deccan flood basalts, resulting from the Indian plate passing over the Reunion Plume during the Cretaceous–Paleocene. As a result much of the rifting of the western margin of India has been described as magmatic, however this is an over simplification.

We use observations from seismic reflection and potential field's data, simple isometric modelling, and subsidence studies to understand the basin/ crustal structure and geodynamics in both the onshore and offshore domains. In the offshore basins, features common to volcanic margins (including seaward dipping reflectors, volcanic intrusions, and eruptive centres) can be seen. Accompanying these volcanic features are major along strike variations crustal structure. These variations are coincident with changes in basement terrane onshore (indicative of tectonic inheritance), though may also relate to the varying influence of the Reunion Plume. In the offshore Deccan age volcanism post-dates much of the initial rifting, and generation of accommodation. In contrast, initiation of the intracratonic rifting appears to be approximately contemporaneous with the Deccan volcanic event, and as a result, there is significant post-volcanic accommodation spaced created.

Understanding the relative timing of extension (and creation of accommodation space) and volcanism is key to the sedimentary fill history of the basins. In the intracratonic basins, rift initiation is interpreted as contemporaneous with the Deccan volcanism, whereas on the continental margin the volcanism post-dates the main period of rifting. This has implications for hydrocarbon prospectivity, in particular for defining the extent of stretched continental crust and syn-rift sedimentary section, and the thermal history of the region.

NOTES

Passive Continental Margins Formation in the Scotia Sea Basins, Antarctica

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The Scotia Sea is a complex geological area located in the Southern Ocean, to the east of Drake Passage (Fig. 1). Its onset occurred during the last steps of Gondwana breakup when the continental bridge between South-America and the Antarctic Peninsula fragmented. The structural highs of continental nature generated during this fragmentation are at present surrounding the abyssal plains of the south Scotia Sea and restricting small isolated and deep sedimentary basins (Fig. 1). The onset and stratigraphic evolution of these basins is approached in the present study through seismo-stratigraphic and morpho-structural analysis of the available multichannel seismic profiles.

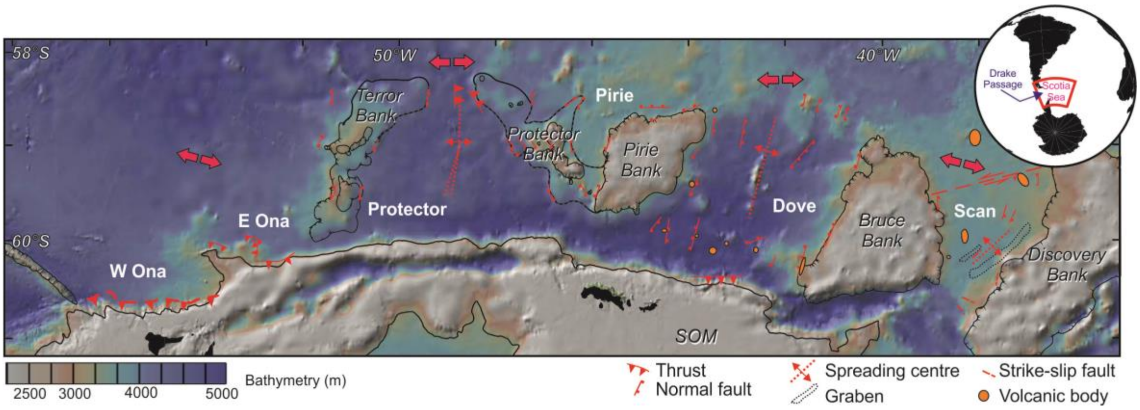

Figure 1.- Simplified structural map of the southern Scotia Sea basins. Bathymetry from GMRT database. The red bold arrows represent the extensional field direction during the basins opening.

The southern Scotia Sea basins opened in a back-arc context, although the structural margins of the five small basins and their intrinsic features are different and allow to divided them into two groups: one formed by the two end basins, Ona and Scan; and other formed by the two central basins, Dove and Protector, together with the slightly north Pirie Basin (Fig. 1). The margins of Ona and Scan basins do not resemble the classical continental blocks of typical rifting, as do the well-known margins of the North Atlantic Ocean. Otherwise, Protector, Dove and Pirie, present asymmetric margins comprising several tilted blocks that diminish in height oceanwards and rotate on a progressively rising detachment fault as are typically seen in passive margins. Such margins structure, together with other structural differences, highlight two different types of fragmentation along the south Scotia Sea.

The two basins located in the Scotia Sea extremes (Ona and Scan) present fragmentation processes typical of passive volcanic rifted margins and the onset of their formation would have entailed crustal thinning and diffuse spreading, with abundant volcanic intrusions. Otherwise, the central basins of south Scotia Sea (Dove, Protector and Pirie) reflect the architectural evolution of magma-poor margins and the rift of previously thinned continental crust could be reconstructed since the entire crust broke up before exhumation of the mantle.

The resulting evolutionary model of the Scotia Sea entails three major stages, divided by two main events, which have deeply conditioned the sedimentary stacking pattern. During Paleogene the onset of the Scotia Sea started through WNW-ESE extension. Ona and Scan basins formed during this extension (Fig. 1). But the extensional direction changed during early Miocene due to the end of the Weddell Sea subduction and the subsequent regional change in the extensional field stress. Dove, Protector and Pirie basins started their formation after this change, during the eastwards progression of the Scotia Arc (Fig. 1). The next tectonic readjustment during middle Miocene allowed the opening of major gateways around the Scotia Sea and the instauration of a new palaeoceanographic setting is reflected in the onset of the sedimentary homogenization along the southern Scotia Sea.

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NOTES

Spatial and Temporal Evolution of Rift Systems: Some Implications at the Scale of a Plate Boundary

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Unravelling the mechanisms of continental lithosphere extension that control the formation and evolution of rift systems leading to continental breakup and creation of plate boundaries remains one of the main challenges in tectonics. Combined studies conducted in present-day rifted margins and their onshore fossil analogues reveal contrasted crustal architectures and the complex spatial and temporal development of rift systems.

The Bay of Biscay and Pyrenees are part of a Late Jurassic to Mid Cretaceous rift system located at the transition between the Iberian and European plates. The transition from preserved oceanic and rift domains to the west to their complete inversion in the east provides access to seismically imaged, drilled and exposed parts of a rift system. The originality of this natural laboratory enabled the development and application of an innovative offshore-onshore approach. We combine observations from seismic reflection data, gravity inversion results and field mapping to characterize, identify and map former rift domains from offshore to onshore, i.e. from a present-day margin to remnants of former margins preserved in the Pyrenean orogen.

This new mapping approach highlights the complex architecture of the paleo Iberian-European plate boundary that is characterized by the existence of strongly segmented rift systems spatially disconnected by weakly thinned continental ribbons (Figure 1). Rift system segmentation seems to be partially inherited from the pre-rift structuration and controls the formation of the rift systems as well as lateral variations of the architecture.

Based on the restoration, subsidence and deformation history of the rift systems, we illustrate the evolution of strain partitioning between them and present the implications at the scale of the Iberian-European plate boundary. Our results show that the deformation history is more complex and polyphase than previously assumed. We suggest that the onset of the Late Jurassic to Early Cretaceous rifting was partitioned between a set of distinct left-lateral transtensional rift systems. A plate kinematic reorganization at Aptian-Albian time resulted in the onset of seafloor spreading in the Western Bay of Biscay and extreme crustal and lithosphere thinning in intra-continental rift basins to the east.

Eventually, this work may provide insights on the partitioning of the deformation at transform to transtensional plate boundaries and may represent an analogue to unravel the initiation of segmented or strongly oblique shear margins observed worldwide. In spite of its transient nature, the Iberian-European plate boundary may provide new insights on (1) processes preceding lithosphere break-up, and (2) the complex partitioning of extensional deformation in propagating rift systems observed at nascent plate boundaries.

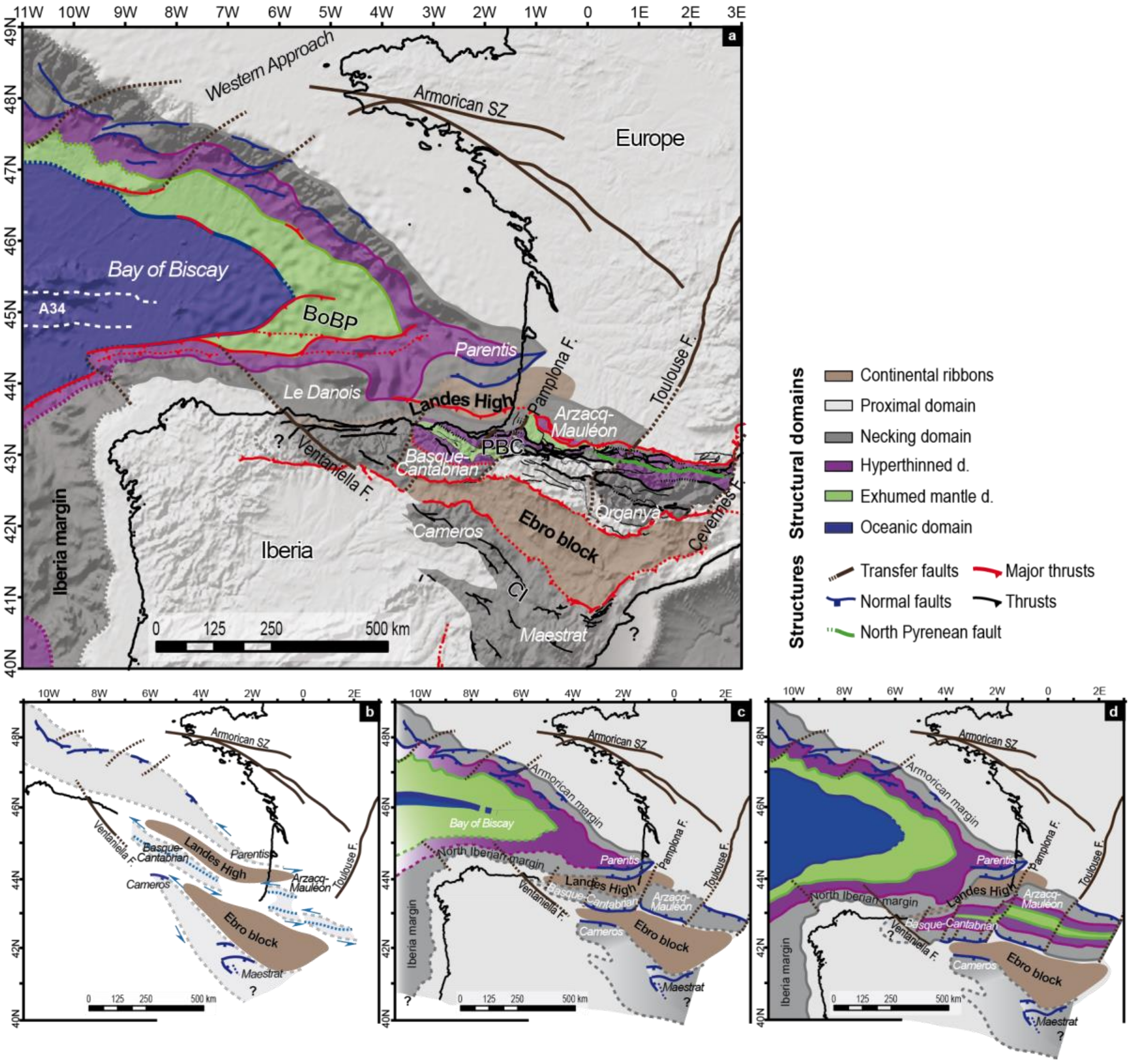

Figure 1: (a) Map of the rift systems preserved at the transition between Iberia and Europe (after Tugend et al., 2014). Spatial and temporal evolution of Iberian-European plate boundary (after Tugend et al., 2015) (b) Transtensional rifting stage (Late Jurassic) (c) Sea-floor spreading initiation and northeast-southwest extension (Aptian–Albian) (d) Failed tentative localization of plate boundary (before Santonian).

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NOTES

Insights into the Mechanism of Rift and Transform Zones for Resource Exploration

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Whether at a hotspot or not, any extensional plate boundary consists of rift segments, transform faults connecting these segments, and transcurrent faults, i.e., the extension of the transform faults beyond rift segments. Rift and transform zones act together during the lifetime of a basin. While the features of the rift-parallel normal faults are well known, those of the transform zones have received less attention, partly because few outcrops exist for detailed studies, and partly because their fracture sets are more subtle and thus often undetected on seismic, gravimetry, and magnetic data. For these reasons, the role of transform faulting is currently undervalued in rift models. Equally under-investigated is the instability and re-location of the rift systems (rift jumps) in time. Selective field-based results from Iceland, backed up by other rifts worldwide, illustrate the importance and complexity of the rift-transform combination.

Iceland lacks major sedimentary basins due its high position above sea level, but its tectono-magmatic processes, crustal structures and seismicity are a basis for modelling the rift and transform mechanisms. Two active rift and two transform segments exist at various stages of evolution, ranging in age from 4-6 Ma to present. Due to successive rift-jumps over the last 24 Ma., a series of extinct rift and transform segments also stretch from central Iceland, with an increasing age, towards West-Northwest.

The island is on the Iceland-Faroe-Greenland Ridge where NW dykes dominate. However, under a WNW spreading direction, Iceland undergoes rifting along NNE and NS normal faults and eruptive fissures. The associated central volcanoes are loci of high temperature geothermal fields, severe alteration, and earthquakes related to magma intrusions. The fracture pattern of the transform zones consists of Riedel shears (strike- and/or oblique-slips), and periodical earthquakes occur along individual faults that increase the fracture permeability but also cause landslides. Rift-parallel fractures represent 1/3 of young fracture populations where rift and transform segments are superimposed or at oblique-rifts. Initially, the fracture density is high, with some major and a great number of broken zones of fine short fractures, which coalesce in time. While eruptions occur along eruptive rift fissures and dykes, sills are frequent, and magma injects into both the rift normal faults and the strike- and oblique-slips of the transform zones. Fracture reactivation is also seen in their cumulative displacements, or when the young fractures of the active plate boundaries extend into rift shoulders or into the micro-plates where they connect to older faults and dykes.

Where rift and transform zones are combined, Riedel shears control the gravimetry, aeromagnetic response, and resistivity. The highly deformed crust is buried and the fracture reactivates upwards in the younger crust. When the rift system re-locates, the new spreading site undergoes the same fracturing, compartmentalisation and processes.

Rift-transform interactions are critical in controlling oceanic break-up and widening, rift propagation, basin configuration and, hence, petroleum systems. Observations in Iceland, where such interactions can be studied in detail onshore, can elucidate these processes and be applied to petroleum resource exploration in basins with lower data density.

NOTES

Deciphering the Rheological, Stratigraphic and Thermal Evolution of Magma-Poor Rifted Margins: Coupling Thermo-Mechanical Models With Observations and Interpretations from Seismic Reflection Data.

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Interpretations derived from crustal-scale seismic reflection datasets across the Newfoundland and Angola-Brazil margins are used as input for thermo-mechanical models. Numerical models that replicate the first-order crustal geometries highlight possible geodynamic processes that may have occurred to create the rifted margin structures and accommodation space observed today. Numerical experiments are used to quantify and display, in a coherent way, the temporal and spatial evolution of rift-related processes (e.g., mechanical, thermal, magmatic, sedimentary) for the whole rift evolution.

Observations suggest that basement heat-flow evolves in relation to the dynamic rift process and sedimentary loading. Rifting can fail, but it appears that the process of successful coupling between the brittle upper crust and mantle is the point at which rifting processes rapidly localize. This coupling of the upper crust and mantle may enable hot mantle-derived fluids to circulate, overprinting the already elevated “background” conductive heatflow that results from the process of crustal thinning.

Our models highlight the importance of crust and mantle rheology in defining the thinning processes leading to hyperextension and depth-dependent extension. Necking occurs in both the crust and the mantle. Once strain has localized and coupling between the upper crust and the brittle upper mantle occurs we observe significant changes in the evolution of rifting. Coupling of the brittle-ductile layers sets up the H-Block structure, and mecahnically forces localization basinwards in accordance with the observation of the creation of a necking unconformity over the future proximal margin. In addition our models highlight that syn-tectonic sedimentary supply/facies (e.g. salt), and magmatic budgets have an influence upon the evolution of subsidence and heatflow and the onset of seafloor spreading processes across magma poor rifted margins.

NOTES

Wednesday 23 March

Session Three: Rifting Process and Models

Keynote Speaker: Linking Lithosphere Deformation and Sedimentary Basin Formation over Multiple Scales

Ritske Huismans, *Department of Earth Science, University of Bergen, Allégaten 41, N-5007 Bergen, Norway*

Here we focus on the relationships between tectonic deformation and sedimentary basin formation. Resolving the interaction and feedback between tectonic crust-lithosphere scale deformation and surface processes through erosion of elevated areas and formation of sedimentary basins over multiple scales has been a long-standing challenge. While forward process based models have been successful at showing that a feedback is expected between tectonic deformation and redistribution of mass at the earth's surface by erosion, transport, and deposition, demonstrating this coupling for natural systems has been an even greater challenge and is strongly debated. Observational constraints on crust-lithosphere deformation and surface processes are typically collected at highly varying spatial and temporal scales, while forward process based models are typically run at either very large lithosphere-mantle scale, or at the scale of the sedimentary basin making it difficult to investigate and explore the detailed interaction and feedback between these systems. Here I will report on recent advances in forward modelling linking crust-lithosphere deformation with surface processes over a large range of scales resolving tectonic plate scale deformation and sedimentary basin formation at stratigraphic scales. The forward numerical models indicate a linkage and interaction between the structural style of thick-skinned large-scale mountain belt and rift-passive margin formation, erosion-transport-deposition processes operating at the surface, and the thin-skinned deformation occurring in the associated sedimentary basins.

NOTES

Upper Mantle Temperatures during Extension and Breakup

John Armitage, *Institute de Physique du Globe de Paris, France*

It has become widely, but not completely, accepted that mantle temperature is the primary control on the quantity of volcanism during extension and break-up. It is most likely that this hot mantle is a consequence of a convecting mantle heated from below, where large instabilities will inevitably form. Yet we cannot measure the temperature of the mantle. Instead indirect estimates of the temperature of the mantle below rift zones must be made. For example below the active rift zone in Afar, at the northern end of the East African Rift, estimates of the temperature of the mantle vary from 1350 to 1450 °C from geochemical and geophysical observations. This active rift is demonstrably volcanic, yet if the lower estimate is true then the mantle below the volcanic massif of Erta Ale is no hotter than anywhere else. This begs the question: does upper mantle temperature really control breakup volcansim?

Building upon examples from breakup in the North Atlantic, Northwest Indian margins and Afar, I will show that by using a combination of geophysical and geochemical observations, the role of the thermal structure of the upper mantle in defining breakup magmatism can be better understood. During the formation of the North Atlantic a large volume of melt was generated, associated with the extensive on-shore flood basalts. Breakup of the continent occurred after a series of extensional events spanning the Carboniferous up until the Late Cretaceous. This extension of the lithosphere, combined with increased mantle temperatures, led to the volcanism that accompanied breakup. Off-shore of the Deccan Traps in western India the story is different, with magama-poor break-up occurring after the trap volcanism and the formation of a series of failed volcanic rifts. In these two locations, mantle temperature is key, but the degree of volcanism is modified by the degree of extension that the lithosphere experiences prior to the interaction with thermal plumes.

The stories I wrote above can be tested using forward numerical models of the deformation of the upper mantle and crust. Predictions of melt volume and composition can be tested against observations of the volume and seismic velocity of intrusions, the composition of erupted lavas and present day seismic wave speeds through the upper mantle. Using an idealised 2D model of the upper mantle I will first demonstrate how rift history has impacted melt production in both the North Atlantic and Northwest Indian margins. I will then focus on the only present day volcanic and active rift zone, Afar. Here there is a history of multiple phases of extension and a complex distribution of crustal strength along strike. These factors can influence breakup, yet by combining multiple geophysical and geochemical constraints, and comparing these with model predictions, we can demonstrate that mantle potential temperature is the primary driver of volcanism and below Afar the mantle is hot (1450 °C). While crustal and lithosphere structure can heavily modify break-up volcanism, ultimately, mantle temperature controls the evolution of continental breakup.

NOTES

OCT Structure, COB Location and Crustal Type at Rifted Margins from Integrated Quantitative Analysis: Maximizing the Value of Deep Long-offset Seismic Reflection Data

Nick Kusznir[1], Leanne Cowie[1] & Alan Roberts[1] , Paul Bellingham[2] and Brian Horn[3]

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The composition and thickness of crustal basement are critical to frontier hydrocarbon exploration in deep-water rifted continental margin settings. We apply a set a quantitative geodynamic analysis techniques based on interpretations of ION BasinSPAN seismic reflection data to investigate the structure and tectonics of deepwater rifted margins. These quantitative analytical techniques consist of:

(i) Gravity inversion, incorporating a lithosphere thermal gravity anomaly correction, to give Moho depth, crustal basement thickness, continental lithosphere thinning and remaining continental radiogenic crustal thickness

(ii) RDA (residual depth anomaly) analysis, to give departures from oceanic bathymetry corrected for sediment loading using flexural backstripping.

(iii) Subsidence analysis using 2D and 3D flexural backstripping to give the distribution of continental lithosphere thinning.

(iv) Joint inversion of PSTM deep seismic reflection and gravity data to give lateral variations in basement density and seismic velocity.

The combined interpretation of these independent quantitative measurements are used together to determine OCT structure, COB location and crustal type. This integrated approach has been validated on the Iberian margin where ODP drilling provides ground-truth of ocean-continent-transition crustal structure, continent-ocean-boundary location and crustal type. Superposition of the 3D Moho surface determined from gravity inversion onto PSDM and PSTM seismic sections provides assistance to, and validation of, deep seismic reflection interpretation.

Examples of the application of the quantitative analysis of ION BasinSPAN deep long-offset seismic data are presented for the Black Sea Basin, NW shelf of Australia and offshore Uruguay & northern Argentina.

Continental lithosphere thinning determined from gravity inversion is used to predict the preservation of continental crustal radiogenic heat productivity, and the transient lithosphere heat-flow contribution within thermally equilibrating rifted continental margin and oceanic lithosphere. These, together with base lithosphere background heat-flow, are used to produce maps of top-basement heat-flow history. Grids of lithosphere β factor, the residual radiogenic continental basement thickness and heat-flow history produced by quantitative analysis provide valuable input to petroleum system modelling. We believe that the integrated quantitative analysis of deep long-offset seismic data assists new ventures exploration strategy and maximises the value of ION deep seismic reflection data

NOTES

Modes of Extension and Oceanization at Magma-Poor Margins: An Example from the Brazilian-African Margins

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It is well known that the amount of magmatism and occurrence of serpentinised mantle at rifted margins and oceanic ridges fundamentally depends on spreading rate and mantle potential temperature. Here we show that during continental extension the rheology of the continental lower crust also plays a key factor in determining the onset and amount of melting and serpentinisation. Furthermore, using numerical modeling constrained by multi-channel seismic reflection and wide-angle data from the magma-poor margins of Brazil and Africa, we explore whether it is possible to associate margin architectural styles to types of ocean-continent transitions.

Observed margin architectural styles can be explained by a combination of extensional modes: core-complex, wide and narrow (Buck, 1991), with a fourth mode, sequential faulting, that accounts for conjugate margin asymmetry (Ranero & Perez-Gussinye, 2010, Brune et al., 2014). The prevalence of any of these modes during extension depends on lower crustal rheology, which controls the coupling between crust and mantle deformation, and hence mantle uplift velocity and type of oceanization. For a given extension velocity, a weak lower crust leads to small degree of coupling between crust and mantle, to ultra-wide hyper-extended margins and also to slower mantle uplift, inhibiting melt production and serpentinisation. Hence, ultra-wide hyper-extended margins (North Santos-South Kwanza conjugates, or the Campos-Kwanza conjugates) will tend to present an abrupt transition to thin oceanic and magmatic crust. On the other hand, if lower crust is stronger, mantle uplift velocity and crustal thinning will be fast and effective, leading to the formation of narrow conjugates and a continent-ocean transition that may consist of exhumed and serpentinised mantle, if horizontal extension velocity is slow enough (e.g. as in the Camamu-Gabon margins).

NOTES

Tectono-Stratigraphic Evolution and Variability of the Offshore Central South Atlantic Basins – Implications for Margin Evolution Models

Simon Higgins, Grégoire Messager, Ian Sharp, Mark Scott, Ulrike Freitag, Heike Gröger, *Statoil ASA*

Significant differences exist between current models addressing the mechanism of lithospheric thinning on rifted continental margins. Our understanding of these systems has traditionally been data-limited due to a number of factors, including the deep-water setting and geophysical imaging challenges. Recent acquisition of high-quality 3D seismic over super-regional swathes of distal rifted margins, along with frontier deep-water drilling campaigns, provide new observations that can help constrain established models. In particular, the increased density and resolution of seismic and grav-mag data has allowed continuous interpretation over large areas and has highlighted the dramatic down-dip and along strike variability in rift-to-drift structural style and evolution. Consequently, recent observations blur much of the distinction between established conceptual end-member models of passive margin formation.

In this contribution we present a conjugate margin lithospheric-scale case study from the Central South Atlantic, and address the structural evolution from the proximal rift shoulder to the oceanic crust. Striking first-order similarities in the spatial and temporal progression of extensional deformation allows the definition of mega-regional structural domains, which can be mapped along both margins. Down-dip, domains show a similar progression to those documented in published schemes (e.g. Peron-Pinvidic et al. 2013); from proximal areas with limited crustal thinning, to lithospheric necking zones, to the distal margin where structural style and crustal geometries change dramatically. The Namibe rifted margin, Angola, is used to demonstrate domain development and definition, as well-exposed Cretaceous outcrops provide detailed tectono-stratigraphic observations (Sharp et al., 2016, this conference) that can be linked to the offshore.

The down-dip progression through distinctive domains observed in the Namibe Basin is also present in the neighbouring Benguela, Kwanza and Congo Basins to the north, as well as in the conjugate Santos, Campos and Espirito Santo Basins offshore Brazil. There are, however, important differences. At the basin scale we see variations in factors such as margin width, symmetry and orientation, subsidence history and accommodation space. Whilst within individual domains, characteristics such as fault style, depositional facies, distal margin geometry, timing of deformation and degree of volcanic addition can vary rapidly along strike. Some changes are gradual, such as sediment thickness and “sag” distribution, whilst others are abrupt, such as differences in pre-salt structural style across transfer zones. In the Distal Margin such dramatic variability along strike mean elements of both classic “magma-poor” and “magma-dominated” margins can be observed within tens of kilometers in the same basin.

Although the presented tectonic scheme is primarily based on South Atlantic basins, initial observations from the North Atlantic, and comparision to examples from published literature clearly indicate that rapid strike variability in structural style is a theme common to many rifted margins. Our understanding of rift-to-drift margin formation is evolving quickly as more data becomes available, and these new data and observations will require a revision of existing “end-member” models. The significance of model revision is manifold; from the fundamental mechanism of lithospheric thinning, to understanding palaeo-geographic evolution, to improved facies prediction, to better heat flow predictions through time.

NOTES

Seismic and Stratigraphic Expression of Heterogeneous Crustal Deformation during South Atlantic Rifting, Campos Basin, Brazil

David Sanford Lewis[1], Scott Pearse[1], Alaister Shakerley[2], Kristan Reimann[2]

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Understanding the processes controlling the evolution of rift architecture is a critical step towards petroleum exploration success, especially in basins where the source rocks and/or reservoirs were deposited in syn-rift stratigraphy. Rifted margin extensional geometry, timing, and subsidence history are crucial inputs into the models of heat flow and burial history that constrain the evolution of petroleum systems. Recent work in rifted margins reported in the literature has suggested that extensional processes vary significantly in character, spatial distribution, and timing from margin to margin, or even along a contiguous margin.

Lewis et al. (2014) presented a study of extension timing in the Campos Basin, Brazil, based on detailed well correlations and seismic interpretation. This work proposed that the brittle rift deformation recorded in tilted fault blocks below the "sag" deposits was post-dated by a phase of deep-seated, ductile extension, indicating that active extension continued throughout the deposition of the sag. The end of brittle extension is marked by an isopachous interval of shallow-water carbonates ("coquinas") present in wells across the Campos Basin hinge, indicating that water depths were consistently shallow at this time. Subsequent short-wavelength changes in basin depth of up to 2 km across the hinge, as well as erosion of the pre-salt stratigraphy, however, indicate that some active extensional process was still operational at the end of salt deposition. Lewis et al. (2014) attributed this late stage extension to deep-seated ductile deformation of the lower crust, linked to abrupt crustal thinning evidenced by Moho reflections visible in long-offset seismic data.

This presentation discusses the kinematic and isostatic constraints on the proposed crustal thinning model, and shares recent well results that add insight to the nature of the pre-salt stratigraphy in the southern Campos and support the proposed model.

Brittle faults visible in the pre-salt section were restored to top basement in order to determine the amount of extension recorded in the brittle upper crust. Further restoration work generated an estimate of the total amount of extension necessary to account for the thinning of the crust from pre-extension crustal thickness to the observed and estimated thickness in the final margin configuration.

In order to further constrain the amount, distribution, and nature of extension, the overall subsidence history of the Campos Basin was examined. Post-salt stratigraphy was backstripped and isostatically restored to determine the extent of post-rift subsidence due both to loading by sediments and to the thermal effects of crustal thinning. The subsidence implications of multiple model controls were estimated; e.g., varying the effective elastic thickness of the plate, considering alternative paleo-water depth estimates, altering density estimations, and varying syn-rift to post-rift transition timing.

The remaining subsidence recorded in the stratigraphy after backstripping is the tectonic component attributable to active extension. Comparison of the total expected tectonic subsidence to the subsidence evident in imaged brittle structures in the region of the Campos Basin Hinge allows a determination of the role of heterogeneous crustal deformation and the applicability of the deep-seated ductile extension model.

Lewis, D.S., Ensley, R., and Leander, M., 2014. New insights into timing and distribution of late synrift subsidence from detailed well ties and seismic mapping, Campos Basin, Brazil. In: Pindell, J., Horn, B., Rosen, N., Weimer, P., Dinkleman, M., Lowrie, A., Fillon, J., Granath, J., and Kennan, L., (eds.), Sedimentary Basins: Origin, Depositional Histories, and Petroleum Systems: 33rd Annual GCSSEPM Foundation Bob F. Perkins Research Conference, 33, 98-115.

NOTES

The Palaeo-bathymetry of Base Aptian Salt Deposition on the Northern Angolan Rifted Margin and the Composition of Underlying Basement

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The bathymetric datum with respect to global sea level for Aptian salt deposition on the deep-water Angolan rifted margin and the composition of underlying basement are hotly debated. Hyper-extended continental crust, oceanic crust and exhumed serpentinised mantle have been proposed to underlie the Aptian salt. Some models propose that the salt was deposited in an isolated ocean basin in which local sea level was between 2km and 3km below global level. Quantitative analysis of deep seismic reflection and gravity anomaly data together with reverse post-breakup subsidence modelling has been used to investigate ocean-continent transition structure, continent-ocean boundary location, crustal type and the palaeo-bathymetry of Aptian salt deposition. The analysis has been applied to the ION-GXT CS1-2400 deep long-offset seismic reflection profile and the P3 and P7+11 seismic cross sections of Moulin (2005) and Contrucci et al. (2004) offshore northern Angola.

The palaeo-bathymetry of base Aptian salt deposition has been examined using 2D reverse post-breakup subsidence modelling consisting of the sequential flexural isostatic backstripping of the post-breakup sedimentary sequences, decompaction of remaining sedimentary units and reverse modelling of post-breakup lithosphere thermal subsidence. The reverse modelling of post-breakup lithosphere thermal subsidence requires knowledge of the continental lithosphere stretching factor (β), which is determined from gravity anomaly inversion.

Our analysis predicts that Aptian salt was deposited between approximately 0.2 and 0.6km below global sea level, and that the inner proximal salt subsided by post-rift (post-tectonic) thermal subsidence alone. In contrast, the predicted water-loaded bathymetries of the more distal base salt at breakup time are much greater (ranging between 1km and 3km) implying that the base outer distal salt was deposited pre-breakup and underwent additional syn-tectonic crustal-thinning subsidence. The predicted bathymetries of the first unequivocal oceanic crust at breakup are approximately 2.5km, as expected for newly formed oceanic crust of ‘normal’ thickness.

Gravity inversion to give Moho depth and crustal thickness, RDA (residual depth anomaly) analysis to identify departures from oceanic bathymetry and subsidence analysis shows that the distal Aptian salt is underlain by hyper-extended continental crust rather than exhumed mantle or oceanic crust. Our analysis argues against Aptian salt deposition on the Angolan margin in a 2-3 km deep isolated ocean basin, and supports salt deposition on hyper-extended continental crust formed by diachronous rifting migrating from east to west, culminating in late Aptian breakup.

NOTES

Rifting, Subsidence and Evolution of Benguela Basin, Angola

Alex Bump, Bryan Gill, Chris Pearse, Teresa Sabato-Ceraldi and Nicki Adams, *BP Exploration*

The Benguela basin lies on the rifted Atlantic margin of southern Angola, between the narrow Namibe basin and the broader Kwanza basin. Discovery of hydrocarbons in the conjugate Brazilian Santos and Campos basins has focused exploration on the pre-salt sections of Benguela and Kwanza and led to the acquisition of modern, high quality seismic surveys. In Benguela, these data show a crustal structure characterized by a narrow proximal margin and necking zone and very broad region of hyper-extended crust, averaging 2-3km in thickness with apparent local windows where tilted growth strata appear to rest directly on mantle. These data also show evidence of at least 2 generations of faulting, with early, detached faults rotated to low angle and cross-cut by younger, high-angle faults that cut much or all of the crust. Close to the margin, these faults tip out well below salt, while farther outboard they reach and even offset base salt. The resulting tilted fault blocks are covered by variable thicknesses of pre-salt sediments, interpreted as Hauterivian extrusive volcanics, Barremian and Aptian clastics and Aptian lacustrine carbonates. The pre-salt sedimentary section is thickest close to the margin and thins toward paleo outer highs where salt rests directly on basement. Fossil and geochemical evidence indicates a progression in depositional environment from sub-aerial to increasingly saline waters, culminating in the deposition of a thick evaporate section before the establishment of normal marine conditions.

Integration of these observations with subsidence modelling and regional tectonic interpretations yields a model for the rifting and deposition of the prospective section: Rifting began with the peneplaned remnants of the Pan-African thrust belt and a topographic surface above sea level. The onset of extension is marked by the outpouring of Parana-Entendeka flood basalts at 132Ma. Extension initiated over a relatively wide and progressively focussed toward the line of eventual break-up. Initial deposits were sub-aerial and shallow-water clastics, deposited above sea level in an externally-drained lake. As rifting progressed and the crust subsided, lake level sank and drainage degraded, resulting brackish conditions and local deposition of coquinas. The volcanic Walvis Ridge separated the lake from marine waters to the south while continued rifting and subsidence caused lake level to sink below global sea level. Development of internal drainage resulted in increasingly saline waters and a mass-off, marked by an unconformity and condensed section. Establishment of hyper-saline microbes then led to deposition of carbonates within the photic zone, even as lake level subsided further. By the late Aptian, when marine waters began to overtop the Walvis Ridge, subsidence modelling suggests that lake level was perhaps 400-600m below global sea level. Repeated marine incursions and evaporation led to the rapid deposition of 1-2km of evaporates.

This model links observations of rift history and interpretations of subsidence to water chemistry and stratigraphic observations, creating a framework within which to understand exploration results and perhaps the development of other rifted margins.

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Insights on the Opening of the South Atlantic from the Evolution of the Pre-Salt Lacustrine Carbonates

T. Sabato Ceraldi, D. Green and A. Bump, *BP Exploration*

The discovery of the Lula field in the Santos Basin in Brazil has uncovered a pre-salt play in lacustrine carbonate reservoirs, and since then many significant discoveries in both Brazil and Angola have been made in the same play. Little was known of the lacustrine systems and how the systems were aligned to the evolution of the opening of the South Atlantic. Moreover, the understanding of the tectono-stratigraphic systems that lie beneath a thick layer of salt could provide insights into the formation and history of the early South Atlantic opening.

The observations coming from a conjugate pair of regional seismic lines between Kwanza and South Campos basins, help define the key megasequences: pre-rift, rift, sag, salt basin, post-rift carbonates, post-rift clastic. The subsidence and stratigraphy of the pre-salt deposits can be further described by 3 critical events:

1) Syn-rift lakes (Valanginian – Hauterivian to Early Barremian): Onset of continental break and syn-rift grabens with formation of several deep fresh-water basins (overfilled) lakes above the sea level. with clastic-rich fluvial-lacustrine deposits.

2) Sag 1 (Barremian to Early Aptian): Syn-kinematic stretching of the continental crust and/or continuous rifting with continuous subsidence. In this phase the lacustrine sediments still maintain a high biodiversity, stable isotope analysis suggests the system is evolving into wide, potentially interconnected lakes with fresh-brackish water in balanced filled conditions

3) Sag 2 (Early - Late Aptian): Continuous subsidence the basin: the lake becomes hydrologically isolated (underfilled lake) thus provoking a dramatic change in the lake chemistry. The lake becomes very alkaline as demonstrated by the limited diversity of fauna, widespread occurrence of microbialite in most well penetrations, and prevalence of authigenic Stevensite. Stable isotope analysis supports the concept of a large closed hyper-saline alkaline lake connected from Angola to Brazil.

Carbonate reservoir intervals developed in both steps 2 and 3 above. Coarse-coquina grainstones, deposited as shoreface deposits along the lake margin and paleo-highs constitute the best reservoir in Step 2. Microbial deposits predominate in Step 3, and occur along the basin margin but are most prolific near basement-rooted paleo-highs away from the basin margin (outboard highs). Authigenic stevensite with calcite spherulites, are commonly associated with the microbialite textures, likely representing the deeper/lower energy areas of the lake.

The transition from Sag 1 to Sag 2 stage is the most critical stage in the evolution of the pre-salt salt tectono-stratigraphy. This could possibly represent the time when the lake level falls below the sea level forcing the lake to become hydrologically isolated and underfilled.

In this talk we describe an holistic approach based on the integration of seismic data, well data, stable isotopes analysis with lake hydrology and subsidence modelling that results in a regional predictive model for reservoir presence for both types of reservoir and offer insights on the opening of the South Atlantic.

NOTES

Laptev Sea: A Natural Laboratory for Studying Breakup of Continents

S. S. Drachev, *ExxonMobil International Ltd, ExxonMobil House, MP44, Ermyn Way, Leatherhead, Surrey KT22 8UX, UK*

Laptev Sea continental margin in the Siberian Arctic is one of a few places worldwide where a spreading ridge (the Gakkel Ridge) abuts upon a continental margin shaping its structural style, which is unusual for a typical continental passive margin. This mega-structural T-junction has been evolving since at least Late Cretaceous resulting in a continental lithosphere breakup along a Timanian edge of Baltica in Barents-Kara region, and in formation of a wide continental rift zone within Laptev Sea underlain by a younger crust dominated by Mesozoic fold belts. The present day divergent plate tectonic boundary between NA and EUR plates crosses the Laptev Sea, and associated extension represents a most recent attempt of breaking up the Eurasia continent – a reminder of the Pangaea Supercontinent. Two earlier successful attempts were realized in the Newfoundland-Iberia and Labrador-British Isles segments of the North Atlantic in Jurassic and Cretaceous times. All three cases are characterized by:

i) Similar T-like conjugation of a spreading ridge with a large transcurrent fault (fracture zone) shaping a continent-ocean transition: the Azores–Gibraltar, Charlie Gibbs, and Khatanga-Lomonosov faults;

ii) Development of wide continental rift zones on an apparent projection of oceanic spreading axis;

iii) Broad strain partitioning from low-magnitude half-grabens to hyperextended rift basins underlain by exhumed mantle;

In the Laptev Sea, the first failed attempt of a spreading axis breakthrough has probably taken place in Late Cretaceous to Early Eocene in its western part. And resulted in formation of a hyperextended Ust' Lena Rift. Its failure has probably been caused by a pre-existing Khatanga-Lomonosov Fracture Zone, which started to defer extension strain eastward soon after the breakup event in the Eurasia Basin at c. 56 Ma. The Laptev Sea rifting has probably ceased between c. 56 and 33 Ma during the main spreading phase along the Gakkel Ridge, and resumed around Mid Miocene. The recent extension is focused in the eastern Laptev Shelf along another zone of weakness in the basement - offshore extent of the Early Cretaceous South Anyui Suture.

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Laptev Sea – Amount and Style of Continental Rifting Based On Gravity Modelling

S. Mazur[1,2], S. Campbell[1], C. Green[1,2] and R. Bouatmani[1]

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An outstanding question concerning continental rifting is the relative contributions of extensional plate boundary forces on the plate and thermal effects, such as from a mantle plume. Magma-rich continental margins and rifts generally represent some combination of these two effects, with large and complex thermal anomalies further complicating the situation. The magma-poor Laptev Sea continental rifts, however, provide an excellent opportunity to study the contribution of rifting dominated by extensional forces.

The Laptev Shelf offshore eastern Siberia represents an interesting tectonic setting, where an active oceanic spreading centre, the Gakkel Ridge, approaches the continental margin. The North America – Eurasia plate boundary, corresponding to the Gakkel spreading axis, continues farther south, passing into the continental area. From the latest Cretaceous to the Pliocene, a continental rift system developed in that area comprising several deep subsiding grabens and high-standing basement blocks identified on seismic sections.

We used 2D gravity modelling and 3D gravity inversion, constrained by published seismic reflection profiles, to assess the amount of crustal stretching across the North America – Eurasia plate boundary in the Laptev Shelf and to understand extension partitioning within the continental crust. Performing our extension calculations separately for top pre-rift sediments and top crystalline crust, we were able to discriminate the effects of the Cenozoic North America-Eurasia interaction from the pre-existing extension that also contributed to the finite crustal thinning.

The joint interpretation of Moho and basement depths from gravity inversion and public domain seismic data suggests that this part of the Siberian margin was already significantly stretched, in a fairly uniform manner, by the Late Cretaceous. The latest Cretaceous–Cenozoic extension in that area was partitioned between two rift zones, the Laptev Rift System and the New Siberian Rift. The models reveal a rapidly increasing extension towards the shelf edge in the Laptev Rift System explained by its connection to the active spreading axis of the Eurasia Basin - the Gakkel Ridge. In contrast, the New Siberian Rift terminates at the continent-ocean boundary and is characterised by a uniform stretching along strike.

The Laptev Rift System represents a mature continental rift zone, the architecture of which provides new insight into the development of magma-poor passive margins. Our study suggests that an estimate of ~500 km of total extension is sufficient to entirely eliminate crystalline continental crust. The continental mantle is already exhumed at the base of the late Mesozoic sediments before the break-up of lower lithosphere and the upwelling of the asthenospheric mantle. This situation appears to be a prerequisite for the exhumation of continental mantle after initiation of spreading. The example of the Laptev Rift System shows that extension driven by divergent movement of continental plates is a sufficient factor to produce almost complete continental break-up without substantial heat input from upwelling asthenospheric mantle.

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Wednesday 23 March

Session Four: Illuminating Rifts – New Data and Observations

Keynote Speaker: Numerical Modelling of Rift Dynamics: Linking Observations on Fault, Basin and Global Scale

Sascha Brune, *GFZ German Research Centre for Geosciences, Potsdam, Germany*

Dynamic processes in rift systems operate on a variety of spatial scales: Plate tectonics and mantle convection involves global dimensions, while typical rift zones feature a width of few 100 kilometres width, where brittle faults and ductile shear zones dissect the crust. Using recently developed numerical forward modelling techniques, I link observations on fault, basin and global scale addressing two major topics concerning rift evolution and the formation of rifted continental margins: (i) thermo-mechanical rift evolution during crustal hyper-extension and (ii) the dynamic interplay between rift strength and large-scale plate velocities.

Hyper-extended domains at magma-poor continental margins are one of the most promising frontier exploration provinces. Despite the discovery of significant hydrocarbon reservoirs in frontier deep-water basins, their tectono-thermal evolution and the underlying geodynamic processes remain elusive. However, recent advances in computational geodynamics allow to reproduce crustal hyper-extension using a joint elasto-visco-plastic formulation of rheology. These models presented here suggest that rift migration is a key process during hyper-extended margin formation, which is accompanied by sequential faulting in the brittle crust and controlled by lower crustal flow. The resulting syn-rift subsidence evolution severely depends on the location and shows a complex history of thinning-related subsidence, depth-dependent stretching, lithospheric flexure and long-term thermal sag. Due to lateral migration of the rift system, the timing of rapid syn-rift motion and initiation of the post-rift sag phase differs significantly for different points along the margin. Moreover, the model implies that during rift migration large amounts of material are transferred from one side of the rift zone to the other. This concept can be applied to many hyper-extended margins worldwide, such as the Central South Atlantic, Iberia/Newfoundland, the Australia-Antarctica conjugates, the Australian North West Shelf, and the Alpine Tethys margins that are now exposed in the European Alps.

Extension velocity is a key parameter during continental rifting, controlling not only surface heat flow and the amount of partial melting but also the depth of the brittle-ductile transition and fault evolution. Investigating rift kinematics globally by applying a new geotectonic analysis technique to revised global plate reconstructions, I show that rifted margins feature an initial, slow rift phase (< 10 mm/yr, full rate) and that abrupt acceleration introduces a second, fast rift phase. The transition from slow to fast extension takes place long before crustal break-up so that significant margin area is created during each period. The two-phase behaviour and the rapid plate speed-up can be explained through numerical forward models with constant-force boundary conditions. The extension models suggest that this characteristic velocity evolution is caused by a rift-intrinsic strength-velocity feedback, which can be robustly inferred for diverse crustal and mantle rheologies. While motions of Earth's plates are thought to be driven by slab pull, basal drag, and ridge push, this finding reveals that plate motions during continental break-up are decisively controlled by the non-linear decay of a resistive force: rift strength.

NOTES

Gulf of Mexico Crustal Structure and Plate Kinematics from Gravity Inversion

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An understanding of crustal thickness, ocean-continent-transition structure, the distribution of oceanic lithosphere and kinematic evolution is a critical component of petroleum systems evaluation in the Gulf of Mexico (GoM) and elsewhere. Using public-domain data and OCTek 3D gravity inversion, we have produced regional grids and maps of Moho depth, crustal-basement thickness, continental-lithosphere thinning-factor and residual continental-crustal-thickness for the GoM. Crustal-basement thickness and lithosphere thinning from the 3D gravity inversion show the distribution of oceanic crust within the GoM and constrain continent-ocean-boundary location.

Superposition of shaded-relief satellite free-air gravity anomaly onto maps of crustal-basement thickness and lithosphere thinning from gravity inversion show clearly the pattern and location of the extinct ocean-ridge and transform segments within the western and central GoM. These in turn reveal sea-floor spreading trajectory and provide important indications of pre-breakup rifted-margin conjugacy. By aligning small-circles with the transform faults visible in the free-air gravity data, the poles of rotation for the opening of the GoM can be refined. As a result of doing this we find that the opening of the GoM occurred in two stages. Initial rifting and breakup occurred along a N-S trajectory with the Yucatan block still linked to South America and to which the West Florida margin acted as a transform boundary. In the second stage, subsequent propagation of sea-floor-spreading between Yucatan and South America caused the Yucatan block to rotate anti-clockwise, resulting in sea-floor spreading within the GoM occurring about a pole locally-situated off the SW coast of Florida. In this second stage of GoM formation, the West Florida margin becomes an extensional feature. By refining the plate-reconstruction models in this way, we also gain a better insight into the linked development of the GoM in the context of the formation of the early Central Atlantic.

Crustal cross-sections using Moho depths from the 3D gravity inversion show the form of the ocean-continent transition, the distribution of crustal type (continental crust, oceanic crust, exhumed mantle) and help constrain models for petroleum-system development in the overlying stratigraphy. Building on this new understanding of kinematics in the GoM, flexural-backstripping and subsidence modelling, driven by lithosphere thinning/beta-factors from gravity inversion, have been used to predict the evolution of palaeobathymetry through the post-breakup history of the eastern GoM.

NOTES

A New 3D Seismic Academic Dataset across the West Galicia Margin

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The west Galicia margin (western Spain) represents an ideal location to study the processes of continental extension and break-up. The margin is characterised by hyper-extended continental crust, thinning to less than 3 km, well defined rotated faults blocks with associated syn-kinematic sedimentary wedges, and exhumed serpentinized continental mantle. Faulted blocks are located above a strong reflector, the S reflector, generally interpreted as both a detachment and the crust-mantle boundary. In addition, the structures of the margin are well observed from seismic data due to limited post-rift sedimentary cover and poor volcanic activity.

During summer 2013, a new 3D high-resolution multi-channel seismic dataset has been acquired over the Galicia margin. It consists in 800 inlines (12.5m in spacing) and 5000 crosslines distributed on a ~680 km2 areal extent across the edge of the continental crust. This new 3D dataset is thus the largest academic one of its kind. These data capture the 3D nature of extension and break-up of the northern Atlantic continental margins, structured from the middle Jurassic to Early-Cretaceous.

Here we present some results from our interpretations of the 3D volume, focussing on the mapping of specific horizons: the seafloor, the base of the post-rift sedimentary cover, the top basement and the S reflector. Mapping these horizons provide 3D views of the margin structure, and the tight network of the data, as well as the quality of the seismic profiles reveal the texture of each horizon in 3D. The main crustal structures are roughly N-S oriented, in agreement with the direction of extension during the rifting. However the structures vary both along strike and cross strike, revealing the complex three-dimensional architecture of the margin. There is also a surprising NW-SE trend, observable at the scale of the margin in the organization of the crustal structures, but also at a smaller scale by corrugations at the top of the S reflector and on the top basement. This trend suggests more complex directions of extension and thinning mechanisms than expected. Furthermore, we focus on the internal structure of some of the faulted blocks through detailed interpretation of the crustal normal faults (see results in the poster session). We then show that the main faults are generally connected downward on the S reflector, revealing interactions between crustal thinning and the S. This demonstrates the important role of the S during the extension and the complex nature of the rifting processes.

Further works will lead to time-to-depth conversion of the seismic data, from our interpretations of the main horizons. It will allow for avoid local pull-up or velocity effects. This will enable to better define rifting processes and break-up mechanisms that led to the present-day architecture of the margin.

NOTES

The Deliberate Search for the Subtle Fault at Magma-Poor Rifted Margins

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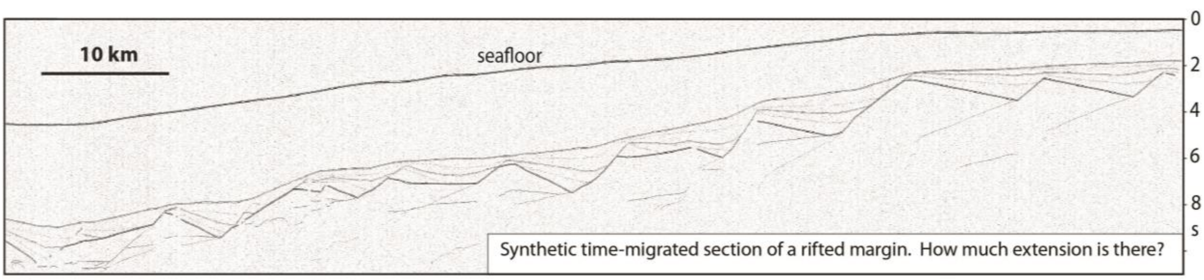
Magma -poor rifted margins form by the breakup of continents and the opening of the ocean basins in the absence of voluminous magmatism. As a result they are characterized by thinning of the crust to nothing, unusual paleogeographies associated with the formation of a deep rift within a continent, and the eventual onset of seafloor spreading. We investigate the process of rifting to breakup at these margins through a combination of seismic interpretation of both industry and bespoke seismic reflection data, including a large academic 3D survey collected in 2013 across the Galicia margin, analysis of the distribution of crustal thinning from wide-angle seismic profiles, and through seismic modeling of the sort of structures that might be expected to form during progressive extension.

Even magma-poor margins, where extension should be close to constant volume and not obscured by lavas, exhibit a pronounced extension discrepancy: the amount of extension that can be measured from the geometry of faults on seismic images is far too little to explain the observed crustal thinning and subsidence. Either the crust has been thinned in some other way or the amount of extension has been severely underestimated. Examination of the crustal structure of all margins well constrained by wide-angle data reveals no evidence for depth-dependent thinning on the scale required to explain the extension discrepancy: within error, stretching appears close to depth uniform. We conclude that the extension discrepancy must be caused by the failure to recognise all the faulting. Although sub-seismic faulting and distributed deformation contribute, much of the remaining extension that should be recognized is not. To investigate this, we created a model structural section across a rifted margin by focusing extension in the center of a rift, producing successive phases of crosscutting faults. From one side of this section, a synthetic seismic image is generated (see below) and interpreted as if it were a real profile. Just as for real margins, apparent listric faults and eroded fault block crests are seen, but these are not present in the model and instead represent intersecting fault surfaces, and are thus diagnostic of polyphase faulting. Just as for real margins, the amount of extension measured from the seismic is only a fraction of the true extension. Just as for real margins, this extension discrepancy increases markedly oceanward. Demonstrably for the synthetic margin, and by implication for real margins, the extension discrepancy is the failure of the seismic method to image unambiguously the polyphase faulting required to accommodate increasing extension, combined with a general lack of awareness of the features, diagnostic of such faulting. We conclude by showing some of these diagnostic features from the Galicia margin, showing that this margin formed by multiple phases of cross-cutting faults.



Synthetic time-migrated section of a rifted margin. How much extension is there?

NOTES

Deep Structure of the Porcupine Basin Using Seismic Refraction

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The Porcupine Basin is a narrow V-shaped failed rift basin of Permo-Triassic to Cenozoic age, with the main rifting phase in the Late Jurassic to Early Cretaceous. It is located offshore SW Ireland. A previous study shows increasing stretching factors from less than 1.5 to the north to more than 6 to the south using basin subsidence analysis. A ridge feature, the Porcupine Median Ridge (PMR), has been identified in the middle of the southernmost part of the basin. During the last three decades, this ridge has been successively interpreted as a volcanic structure, a diapir of partially serpentinised mantle, or a block of continental crust. Its nature still remains debated today. In this study we use a seismic refraction profiles acquired across the northern and southern Porcupine Basin to derive P-wave velocity models using tomography modelling, following a layer-stripping strategy. We use the data from two 300 km long shot lines recorded by 25 and 30 seismic receivers, for the northern and southern lines, respectively. The profiles are approximately 90 km apart, oriented west-east and cross the entire basin from the Porcupine Bank to the Irish Continental Shelf. This two seismic refraction lines are coincident with seismic reflection profiles, which are used to help seismic velocities interpretation. Thus, we image the deep structure of the basin, the geometry of the continental thinning from margin to margin, and the PMR. Our main results are (1) an asymmetric crustal thinning, especially along the southernmost profile, implying some simple shear during the extension, (2) a wider zone of ultra-thinned crust along the southern profile (~ 90 km) than the northern one (~ 30 km), with thinning factors up to 6 along the northern profile and up to 10 along the southern profile, (3) a low velocity mantle, with velocities < 7.5 km/s, together with ultra-thinned crust, implying up to 20% upper-mantle serpentinisation, and (4) velocities of 5-5.7 km/s in the PMR, associated with a high velocity zone in the sedimentary sequence. This observation argues in favour of an igneous nature of this ridge and associated features. The project is funded by Petroleum Infrastructure Programme (PIP).

NOTES

The Morocco-Canaries Atlantic Margin – A Classic Rifted Margin or A More Complex Failed-Breakup Basin?

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The continent-ocean-boundary offshore southern Morocco is traditionally thought to lie between the Moroccan coast and the Canary Islands. OCTek gravity inversion, however, shows a ribbon of thick crust extending NE from the Canaries, one interpretation of which is that the Canaries are located on a rifted continental block or "micro-continent", rather than on oceanic crust. We have tested this hypothesis via:

- Further analysis of the gravity inversion results
- Geodynamic analysis of four regional seismic transects between the Moroccan coast and the Canaries, focussed on backstripping, with supportive structural forward-modelling
- A new plate-reconstruction model for the N.Africa-N.America Atlantic margins

Best-case crustal-thickness and thinning-factor maps for the central and southern Atlantic have been produced from the gravity inversion. These incorporate corrections for regional dynamic topography and volcanic addition during rifting and breakup. From these maps profiles of integrated extension across the conjugate N.Africa-N.America margins have been calculated in order to constrain the magnitude of the pre-breakup rifting phase within the new plate-reconstructions.

Backstripping analysis of basement-subsidence suggests that, in the area between Morocco and the Canaries, oceanic crust is only likely to be present in the far north. Thinning-factors decrease southwards within this area, suggesting that Morocco and the Canaries are primarily separated by highly-thinned continental crust rather than oceanic crust. This result is compatible with the "V-shaped" basin and thinning-factor distribution identified by gravity inversion.

Further backstripping analysis of the Jurassic-Tertiary stratigraphy along the Moroccan coast suggests that the whole area is currently supported by ~500m of dynamic uplift, possibly initiating during the Late Cretaceous. This result is compatible with the assumptions used in the gravity inversion. A likely origin for the dynamic uplift is the proximity of the Canaries magmatic province. Incorporating dynamic uplift into the backstripping model allows us to make predictions of palaeobathymetry and depositional environments back from the Tertiary into the Jurassic.

Finally, all of the preceding work has been incorporated into a new plate-reconstruction model, which highlights:

(i) the "plate overlap" resulting from pre-breakup rifting along the conjugate margins

(ii) initial propagation of Atlantic seafloor-spreading southwards into the Morocco-Canaries "V-shaped" basin

(iii) abandonment of this initial plate-boundary as a "failed-breakup basin", leading to

(iv) final separation of Africa from America to the west of the Canaries.

The hypothesis that Morocco and the Canaries are separated by thinned continental crust, rather than oceanic crust, has implications for petroleum-systems analysis in the area. As a consequence we have modelled the temperature/heat-flow history at a number of key-locations constrained by continental stretching-factors from the gravity inversion and backstripping analyses, together with temperature constraints from nearby wells.

Failed-breakup basins with a “V-shaped” geometry are not uncommon at rifted continental margins, other examples on the eastern Atlantic margin are the Faeroes-Shetland Basin and the Galicia Interior Basin. We believe they are diagnostic of the segmented manner in which offset zones of continental stretching ultimately link together into an ocean margin as continental rifting proceeds to continental separation.

NOTES

Continental Breakup, the Final Stretch: Seismic Reflection and Borehole Evidence from the Danakil Depression, Ethiopia

Ian Bastow, Adam Booth, Derek Keir, Giacomo Corti, Craig Magee, John Warren, Jason Wilkinson, Jason Wilkinson, *Imperial College London*

During continental breakup, the locus of strain shifts from a broad zone of border faulting and ductile plate stretching to a narrow zone of magma intrusion in a young ocean basin: a mid-ocean ridge. Recent studies of rifts and margins worldwide suggest that the shift to magmatic extension occurs sub-aerially, prior to the onset of seafloor spreading, We explore this hypothesis using recently-acquired seismic reflection data and accompanying borehole geological constraints from the Dallal basin of the Danakil Depression, northernmost Ethiopia: a unique region of incipient transition from continental rifting to incipient oceanic spreading, Our data reveal thick sequences of evaporites deposited in an asymmetric basin, whose subsidence has been controlled primarily by a major, east dipping normal fault Surprisingly, no significant magmatism is observed in the upper ~1000 km. Age constraints on the potash-bearing sequence being mined in the basin demonstrate that Dallol's thick evaporate sequences have been deposited in the last several tens-to-hundreds of thousands of years. Basin formation cannot be easily attributed to the effects of magmata intrusion. Instead, an abrupt, localized, late-stage plate-stretching phase marks the final stages of breakup, prior to the onset of seafloor spreading. It is unclear whether the localized stretching is due to heating and weakening of the plate by protracted dyke intrusion, or whether strong, flanking lithosphere of the Nubian plateau and the Danakil micro-plate control the focusing. Regardless, the magmatic locus of strain, developed during the final stages of breakup, may not necessarily represent the final break-up boundary and ultimate spreading center location.

NOTES

Genesis and Evolution of the Punta Del Este Basin, Offshore Uruguay: The Relationship between Crustal Structure and Normal-To-Oblique Rifting During the Formation of the South Atlantic

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The crustal structure along the Uruguayan margin is highly complex and does not fit into conventional rifting models. This complexity has major implications for hydrocarbon exploration in that the relict rift architecture influenced basin evolution and sedimentation until the Late Cretaceous – well into the post-rift (drift) phase – controlling sedimentation along the margin.

Regional 3D and long-offset 2D seismic data from offshore Uruguay show how initial South Atlantic rifting developed normal to the margin but became more margin-oblique over time resulting in the creation of a major oceanic depression that runs up to the Florianopolis High in Brazil. At the southern end, directly offshore Uruguay, a sigmoidal pull-apart basin was created (the Punta del Este Basin) covering over 20,000km2. Limited age data along the margin suggest the depression and the Punta del Este Basin formed over a period of approximately 15my (Hauterivian to mid-Aptian).

The Punta del Este Basin is fault-bounded to the north and south against packages of seaward dipping reflectors (SDRs) and oceanic crust; to the east the basin margin is marked by a faulted contact with oceanic crust. The western margin is marked by the Polonio High, a granitic body interpreted to be part of the Neoproterozoic Dom Feliciano Belt. To the south of this high the basin connects into the La Plata rift, which extended from offshore Uruguay south-west into Northern Argentina.

Underneath the Punta del Este Basin the crust comprises a mix of proto-oceanic crust (i.e. highly stretched/fragmented continental crust), intrusive volcanics and a spectacularly imaged failed spreading centre flanked by SDRs. Regional data shows a significantly elevated Moho under the basin with the highest point directly beneath the spreading centre, with a crustal thickness of 3km locally. Seabed heat flow measurements show a correlation with the underlying crustal structure, with local maxima immediately above the failed spreading centre.

The syn-tectonic fill of the Punta del Este Basin records the transition, both spatially and stratigraphically, from continental to marine conditions. Internally, the fill is dominated by alluvial fans, lacustrine and deltaic deposits along with fault-controlled channel systems. In addition to subaerial and subaqueous sedimentation the basin shows evidence of subaerial and subaqueous (hyaloclastites) volcanism; the latter is particularly prevalent along the south/ eastern basin-bounding faults. The final basin fill is marked by an Aptian-age flooding event which marks the progressive development of fully marine conditions along the margin and the start of sedimentation within the Pelotas Basin.

Following the creation of the Punta del Este Basin South Atlantic rifting continued, resulting in the creation of various oceanic fracture zones. Whilst the Punta del Este Basin and the Meteor fracture zone share a common structural orientation they are not directly linked: the area between the basin and the tip of the fracture zone shows an area of apparent strike-slip faulting, imaged by opposingly dipping fractures within the oceanic crust.

NOTES

Thursday 24 March

Session Five: Rift Petroleum Systems

Keynote Speaker: Deep-Water Margins, Dynamic Topography and Sequence Stratigraphy

Nicky White, *Bullard Laboratories, Madingley Rise, Madingley Road, Cambridge, CB3 0EZ*

An evolving pattern of convective circulation within the Earth's mantle generates and maintains dynamic topography, which is some fraction of observed topography. Spatial variations of dynamic topography are easy to measure within the oceanic realm since the subsidence history of oceanic lithosphere as a function of age is well understood. A group of us have used substantial inventories of seismic reflection and wide-angle profiles to determine dynamic topography of the oldest oceanic lithosphere which abuts passive rifted continental margins. Our results show that this old oceanic lithosphere has dynamic topographic anomalies of +/- 1 km with wavelengths of 500-1000 km. These significant anomalies often intersect coastal shelves and so we expect that the development of these anomalies has affected the evolution of deep-water rifted margins and their sequence stratigraphic architecture in important ways. A series of examples will be used to illustrate how the configuration of rifted margins can be profoundly influenced by changing patterns of dynamic topography. First, along the West African and Brazilian margins sets of dynamic topographic domes intersect the adjacent shelves. Onshore, Neogene growth of these domes is recorded by emergent marine terraces and by radial drainage patterns. Offshore, switches from aggradation to progradation together with a series of younger disconformities have modified stratigraphic architectures of these shelves. Secondly, along the Northwest Shelf of Australia there is excellent evidence for about 700 metres of dynamic drawdown of the oldest oceanic floor which abuts this shelf. Regional mapping and backstripping of clinoformal geometries within a Miocene carbonate reef complex shows that there is a dramatic switch from progradation to aggradation which cannot be attributed to glacio-eustatic sea-level variations. Instead, this switch appears to reflect growth of dynamic drawdown within the mantle. Finally, the Icelandic plume is a large convective upwelling which has controlled vertical motions along fringing North Atlantic continental margins over the last 60 million years. There is independent evidence that the temperature of this plume fluctuates as a function of time over the last 60 million years. These fluctuations are indirectly recorded within the sequence stratigraphic architecture of fringing margins where a series of ephemeral terrestrial landscapes have been mapped on three-dimensional seismic volumes. In this way, transient activity of the Earth's convecting mantle is stratigraphically recorded. Thus the sequence stratigraphic architecture of many, if not all, rifted continental margins appears to be an important repository of details about convective circulation which are otherwise difficult to obtain.

NOTES

Invited Speaker: Post-Rift Development of Passive Continental Margins: Source Areas That Act As Sinks and Sinks That Act As Sources

Peter Japsen[1], Paul F. Green[2], Johan M. Bonow[3,4] & James A. Chalmers[1]

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It is a common assumption that landscapes along elevated, passive continental margins (EPCMs) are directly related to the processes of rifting and crustal separation. The elevated plateaux along such margins are widely believed to have remained high since continental separation and remained flat by continuous erosion to a perched base level (no surface uplift) or alternatively represent a breakup surface (no rock uplift), despite continental-stretching theory predicting deposition of a thick post-rift sequence overlying both the rift and its margins. The absence of a post-rift section from many EPCMs is taken as evidence that none was ever deposited, consistent with these margins being permanently elevated since rifting.

However, our recent studies in Greenland and Brazil show that typical EPCM landscapes formed many tens of millions of years after break-up along these margins, and that the present-day high-level plateaus are the remnants of post-breakup erosion surfaces (peneplains) that were uplifted in the Neogene. Similar characteristics of EPCMs around the world, with elevated plateaux cut by deeply incised valleys terminated by areas of rapid decline in elevation to a coastal plain, suggest that similar processes controlled their development. We thus infer that EPCM landscapes in general are unrelated to the processes of rifting and continental separation.

We present geological, geomorphological and thermochronological evidence from EPCMs around the world in support of this hypothesis, and we argue that the absence of a post-rift section at many EPCMs does not mean that none was deposited. Instead, the post-rift section along many EPCMs was removed by erosion during post-breakup uplift events that are unrelated to formation of the margin but relate in some way to the presence of the margin. Since EPCMs develop through episodes of burial and exhumation, sources and sinks along the margin vary through time and in space. Erosion of basins along uplifted margins may thus transform basins into source areas whereas presently uplifted margins may have acted as sinks during previous burial episodes, both prior to, during and after break-up (Fig. 1). Consequently, for the source-to-sink concept to work, it is important to compare erosion events with the ultimate sink from that event.

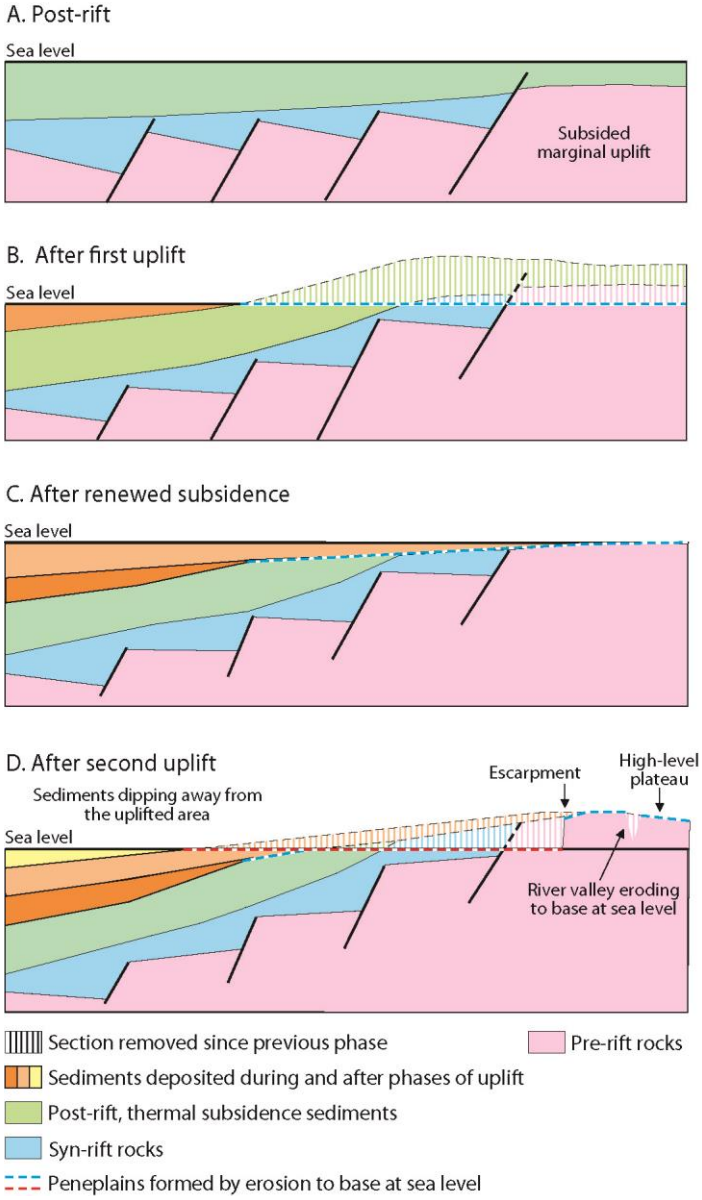

Figure 1. Cartoon to illustrate the post-rift development of an EPCM based on observations in Greenland and Brazil. (**A**) A rift margin in continental crust approximately 30–50 Myr after cessation of rifting: Accumulation of syn-rift sediments (blue) and post-rift sediments (green), due to cooling of the rift and its margins. (**B**) After one phase of uplift of the rift and its margin: Erosion has formed a peneplain, governed by the base level. The surface of the peneplain is uniform regardless of the resistance of the underlying rocks. Subsidence continued offshore and the accommodation space filled with sediment (orange). (**C**) After renewed subsidence: Sediments (beige) cover the erosion surface forming an erosional unconformity in the basin and burying the peneplain across basement rocks to some extent. (**D**) After a second phase of uplift: The peneplain that formed after the first phase of uplift is now an uplifted high-level surface. Sediments that were deposited horizontally in the post-rift section now dip seaward and are truncated by the new erosion surface. Subsidence still continued offshore and the accommodation space filled with sediment (yellow). From Japsen et al. (2012a).

NOTES

Meso-Cenozoic Source-To-Sink Analysis of the African Margin of the Equatorial Atlantic

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The objective of the Transform Source to Sink Project (TS2P) is to link the stratigraphic architecture of the offshore sedimentary basins of the African margin of the Equatorial Atlantic to the evolution of their source areas on the West African Craton. Alternating transform and oblique segments from Guinea to Nigeria produced a variability along the margin in terms of necking style (i.e. margin width), onshore geology and relief, subsidence/accumulation patterns that we analyzed from subsurface data, geology and geomorphology. It is a low-elevation margin characterized by a dissected marginal upward that is preserved only in the 1200-1900 m high Guinea Rise. This upwarp separated a continental interior (Man-Léo basement domain, southern Taoudeni and Iullemmeden intracratonic basins) from the passive margin domain (Liberia, Ivory coast, Ghana and Benin passive margin basins).

For the Cretaceous, we compared the long-term stratigraphic trends of each of the margin segment. We produced new paleo-geographic maps since the rifting, delineating domains on the craton and along the margin, which accumulated material resulting from the erosion of the craton and the marginal upwarp. We estimated onshore denudation from thermal histories determined by low temperature thermochronology along 3 transects across the upwarp in Guinea, Ivory Coast and Benin. We are estimating sediment accumulation history in the different margin basins to compare them to the denudation history.

For the Cenozoic, we have reconstructed onshore denudation distribution and drainage history from dated and regionally correlated geomorphic markers. We identified contributing areas for each margin segments, over that period, and quantified the volume of sediments produced by denudation. We compared the associated stratigraphic signature of these fluxes along the margin. We show that, 60 Myrs after the rifting, the preservation of the Cenozoic wedge is strongly influenced by the necking style of the margin's segments. Nonetheless, specific stratigraphic events, such as the major unconformity in the Oligocene, are preserved along the whole margin, regardless of the necking style.

NOTES

Sediment Starved or Accommodation-Nourished Basins during North Atlantic Continental Rifting?

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Late Jurassic-Cretaceous rifting and continental break-up of the North Atlantic Ocean was markedly complex, and present-day paleogeographic reconstructions do not address the position of micro-plates such as Iberia's. As an alternative method to predict source and reservoir potential on North Atlantic rift basins, the focus has changed in recent years towards understanding the topography of paleo-rift axes, continental slopes, marginal highs and shelves, through the analysis of seismic and stratigraphic data from multiple sources.

This presentation will focus on the Late Jurassic-Early Cretaceous depositional record of West Iberia, extrapolating the results to conjugate margins off Newfoundland, Ireland and the UK and Norwegian North Sea. Well-dated unconformities in West Iberia accurately mark the main rift-related tectonic events that precede continental breakup. In such a setting, West Iberia differs from the North Sea, proximal Newfoundland basins and Ireland by presenting excess accommodation space for sediment sourced from hinterland areas very early in its evolution. In effect, the Lusitanian Basin was a very marginal depocentre through which a substantial volume of sediment was transported on its way to deep continental slope basins. This character marked important by-pass of sediment towards the North Atlantic rift axis, with excess accommodation space resulting in enhanced conditions for the generation of 'black shales' in these regions.

This talk will focus on: a) the recognition of Late Jurassic-Early Cretaceous migration of slope facies towards the west and southwest in West Iberia, b) the predominance of a slope-fed depositional system through the latter stages of rifting and continental break-up, c) the near-permanence of topographically sheltered, 'sediment starved' conditions in the future region of continental break-up during the Late Jurassic and Early Cretaceous. This setting was maintained until continental break-up was achieved throughout the West Iberian margin, from which point slope progradation ceased, subsidence increased dramatically in offshore basins and bypass of sediment predominated on the continental slope through major submarine canyons. The locus of sediment starvation shifted at this stage from the future Abyssal Plain region to the newly-formed continental slope.

Hydrocarbon potential in distal rift axes, or troughs, will vary depending on multiple factors. Of importance to the (relatively) accessible continental-slope basins is the correct assessment of paleodepths during the phases of slope progradation, and post-breakup erosion on the proximal margin. Exhumation and recycling of sediment in 'continental breakup' conditions is particularly noted in ODP and DSDP data, together with the establishment of strong oceanic currents during the later Early Cretaceous. Point-sources for sediment derived from the hinterland are crucial in terms of assessing source and reservoir potential in deep offshore basins. Also important is the correct assessment of magmatic events on what is a 'non-volcanic margin' with abundant evidence for Late Jurassic to Late Cretaceous volcanism.

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The Promises and Pitfalls of Integrating Geodynamic with Petroleum System Modeling

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Petroleum system modeling is a key component of the exploration workflow. A wide range of plausible maturation histories, migration scenarios, and structural evolutions are routinely investigated before exploration decisions are made. Petroleum system models (PSM) are designed to simulate multi-phase porous flow as well as the details of petroleum generation and expulsion. They are, however, not well suited for investigating the structural and thermal evolution of rift systems. In fact, PSM usually only resolve the sedimentary basin itself – all larger scale geodynamic processes need to be parameterized in terms of a basement heat flow boundary condition.

Recent advances in 2-D and 3-D lithospheric rift modeling have significantly increased our understanding of how strain is partitioned and temperature evolves during rift formation. It seems a natural way forward to integrate these new insights into the petroleum system analysis workflow by instructing PSM with information on basement heat flow extracted from lithosphere-scale models. For such a multi-model approach to work, progress has to be made in the understanding of feedbacks between shallow sedimentary and deep lithospheric processes. Here we present results of a Norwegian margin case study that illustrates how strongly the time-varying rate of sedimentation deposition affects strain partitioning, temperature, and mantle serpentinization during margin formation.

We then take these ideas further and investigate how predictions of geodynamic models can be integrated into petroleum system models. For this purpose, we have performed case studies for the Norwegian and North Sea. We find significant differences in the timing of hydrocarbon maturation and in the GORs of hydrocarbon accumulations predicted by models that do and do not resolve the interrelations between sedimentation, crustal thinning, and basement heat flow. To investigate the underlying mechanisms, we have analyzed the predictions of thermotectonostratigraphic forward models on the evolution of basement heat flow in terms of the relative contributions from tectonic and sedimentary processes. We find that sediment blanketing effects and the diminishing importance of crustal radiogenic heating during extension often dominate over the tectonic heat flow component. This implies that in terms of basement heat flow, resolving a basin's sedimentation history is at least as important as the details of the employed rifting model. A consequence is that predictions from geodynamic models that do not resolve the sedimentation history cannot be easily transferred into basin-scale petroleum system models. We here show how such integration can be successful, which benefits are to be expected, and what kind of pitfalls should be avoided.

In conclusion, we find that strong feedbacks exist between shallow sedimentary and deep lithosphere processes. These should be considered in geodynamic and in petroleum system models. Multi-model approaches that combine both types of models are promising and have the potential for significant improvements in the quality of the thermal and structural solutions used in PSM but care must be taken that model consistency is ensured and sediment blanketing effects are accounted for.

NOTES

The Relationship between Rifting History and Petroleum Systems in the North Atlantic

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Oil-source correlation studies along the north-east Atlantic Ocean margin west of Britain and Ireland indicate source intervals ranging in age from Middle to Late Jurassic and in facies from lacustrine/fluvio-deltaic to marginal marine form the dominant regional Jurassic petroleum system of the NE Atlantic. This contrasts with the common assumption of a ubiquitous marine Late Jurassic rich, oil-prone source rock as seen, for example, in the syn-rift North Viking Graben and Haltenbanken sections.

The distribution of Jurassic source rocks along the Atlantic Ocean margin is strongly related to the development of rift basins associated with the break-up of Pangaea. Marine flooding of the Permo-Triassic rifts in the earliest Jurassic resulted in the widespread deposition of source rocks through much of the basin system. The earliest source rocks of Hettangian – Sinemurian age occur in the more southern parts of the basin system with a Tethyan fauna. Younger source rocks with a boreal provinciality occur in the Sinemurian – Pliensbachian and in the Toarcian, the Toarcian marking the maximum extent of the transgression with widespread deposition of rich, marine source rocks through much of the basin system.

Regional uplift in the Middle Jurassic led to a major marine regression and the end of widespread marine source rock deposition. Non-marine lacustrine and fluvio-deltaic source rocks were deposited during both the Aalenian and in the Bathonian – Callovian of the Hebrides and Slyne Basins and continued into the Oxfordian and Kimmeridgian with increasing marine influences becoming more apparent. These source rocks are very widespread through the basin system including the Porcupine and Faroe-Shetland Basins, the Jeanne d'Arc and Flemish Pass Basins on the Canadian conjugate margin and the Lusitania Basin of Iberia.

Late Jurassic tectonics had a strong influence on source rock deposition with thick, marine oil-prone shales being deposited in rifting basins such as the North Viking Graben, Haltenbanken and Barents Sea (Kimmeridge Clay / Draupne / Mandal / Spekk Formations). Again marine flooding of these actively rifting basins appears to have been critical in the development of these source rocks. However, the Atlantic Margin basins do not show an equivalent thick Late Jurassic source rock development with just a relatively thin transgressive "skim" of rich source rock overlying the thick Middle – Late Jurassic section, seen in the Porcupine and Faroe-Shetland Basins. Elsewhere marginal marine or non-marine deposition took place, with equivalent aged lacustrine source rocks deposited in the North Celtic Sea Basin.

Widespread regional uplift at the end of the Jurassic ended source rock deposition throughout western Britain and Ireland basin systems, heralding the onset of major plate-break up between Canada, Iberia and Ireland as well as the Bay of Biscay in the early Cretaceous. A major new rift basin system developed and open marine conditions in these often hyper-extending basins unified the marine systems of the proto NE Atlantic, flooding the former restricted basin systems which promoted the formation of Jurassic source rocks. Occasional phases of oceanic anoxia in the Hauterivian – Barremian and later in the Aptian and Turonian-Cenomanian deposited thin but widespread rich marine black shales with source potential, primarily gas-prone. To date, these represent the only documented non-Jurassic source rocks along the margin, with the exception of a local Carboniferous source for gas off western Ireland.

NOTES

How Do Normal Faults Grow?

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Normal faulting accommodates stretching of the Earth's crust, and it is arguably the most fundamental tectonic process leading to continent rupture and oceanic crust emplacement. Furthermore, the incremental and finite geometries associated with normal faulting dictate landscape evolution, sediment dispersal and hydrocarbon systems development in rifts. Displacement-length scaling relationships compiled from global datasets suggest nornal faults grow via a sympathetic increase in these two parameters (the 'isolated fault model'). This model has dominated the structural geology literature for >20 years and underpins the structural and tectono-stratigraphic models developed for active rifts. However, relatively recent analysis of high-quality 3D seismic reflection data suggests faults may grow by rapid establishment of their near-final length prior to significant displacement accumulation (the 'coherent fault model'). The isolated and coherent fault models make very different predictions regarding the tectono-stratigraphic evolution of rift basin, thus assessing their applicability is important. To-date, however, very few studies have explicitly set out to critically test the coherent fault model thus, it may be argued, it has yet to be widely accepted in the structural geology community. Displacement backstripping is a simple graphical technique typically used to determine how faults lengthen and accumulate displacement; this technique should therefore allow us to test the competing fault models. However, in this talk we use several subsurface case studies to show that the most commonly used backstripping methods (the 'original' and 'modified' methods) are, however, of limited value, because application of one over the other requires an a priori assumption of the model most applicable to any given fault; we argue this is illogical given that the style of growth is exactly what the analysis is attempting to determine. We then revisit our case studies and demonstrate that, in the case of seismic-scale growth faults, growth strata thickness patterns and relay zone kinematics, rather than displacement backstripping, should be assessed to directly constrain fault length and thus tip behaviour through time. We conclude that rapid length establishment prior to displacement accumulation may be more common than is typically assumed, thus challenging the well-established, widely cited and perhaps overused, isolated fault model.

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Tectono-Stratigraphic Evolution of Multi-Phase Rifts

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Continental rifts typically develop from an early rift initiation stage, characterised by the growth of multiple, small, geometrically and kinematically isolated fault segments, through a fault interaction and linkage stage, when co-linear fault segments link to form longer faults with larger throw and other fault segments begin to die, to a rift climax stage, when extension is focused on a small number of large, half-graben bounding normal faults. This three-stage evolution of structural style also explains many of the first-order stratigraphic and sedimentological characteristics of syn-rift sequences. However, many continental rifts have formed in response to multiple phases of extension, thus parameters such as pre-existing basement and cover structures, rheological heterogeneity, and lithosphere thermal structure may modify the three-stage evolutionary model outlined above, and the overall geometry and tectono-sedimentary evolution of rifts. We use results from regional studies of the Northern North Sea and other parts of the Norwegian Continental Shelf to investigate the structural style o f multiphase rifts and their tectono-sedimentary evolution.

Where basement/upper crustal structure is relatively well imaged on seismic data, for example on the Horda Platform and in the Stord Basin, narrow (single- or double-wavelet) reflections and several kilometre-wide zones of reflectivity, some of which extend down into a strongly reflective lower-crust, characterise the intra-crystalline basement structure. Some of these zones form the offshore continuation of major shear zones exposed on the Norwegian mainland. These pre-existing basement structures seem to have played a significant role in controlling the first-order geometry and segmentation of the North Sea rift system by controlling rift segmentation, and the location and strike of major rift-related normal faults. However, in detail, the relationships between basement structures and cover normal faults are more complex. For example, some of the basement structures have been truncated and offset by Permo-Triassic and Late Jurassic-Early Cretaceous normal faults whereas others are reactivated. The degree of physical linkage between basement faults and shear zones and cover faults can vary locally along strike. Similar complexity exists between Permo-Triassic and Late Jurassic-Early Cretaceous normal faults. For example, in some areas, such as the East Shetland Basin, pre-existing normal faults appear not to control the Late Jurassic-Early Cretaceous fault geometry and basin development, with limited fault reactivation and most pre-Triassic faults being cross cut by new faults. In other areas, such as the Horda Platform, some Permo-Triassic faults are reactivated, but others are not, and new, Late Jurassic normal faults also develop that are unrelated to Permo-Triassic faults. The regional scale of this study also highlights the diachronous development of the fault network, thus bringing into question the validity of using rift-related megasequence terms (i.e. pre- syn- and post-rift) at the basin-scale, even in this low-strain setting that became extinct long before breakup.

The results of our study indicate that bespoke tectono-stratigraphic models are required for multi- phase rifts; existing models, based on 'pristine' crust and analogue models for multi-phase rifting, fail to capture the full complexity present in natural multi-phase rifts. To be relevant, physical and numerical models, which provide critical insights into the controls on structural style and evolution in rifts, need to account for this complexity.

NOTES

The Spectrum of Types of Passive Margins and their Differentiated Petroleum Potential

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Passive Margins can nowadays be classified as Magma-Poor or Sedimentary, Volcanic and Transitional, once crustal structure, phased evolution and compositional filling of the associated rifts are taken into account. The three comprise a spectrum of passive margins resulting from different modes of thermo-tectonic evolution during the rupture and breakup of mega-continents. The evolution of Magma-Poor Margins take longer and involve stretching and thinning mechanisms of the continental crust practically devoid of magma. This allows for the continental crust to breakup and for the lithospheric mantle to exhume. The final lithospheric breakup, however, is carried out by asthenospheric magma. Volcanic Margins are impinged directly by mantle plumes that carry a lot of heat, and, thus, magma. Magmatic activities are abundant before, during and slightly after rifting. This allows for extreme ductility and hyper-extension of the continental crust and a very quick evolution from the inception of rupture to the final concurrent crustal and lithospheric breakup. Grabens are filled mostly by volcanic material (SDRs). Transitional Passive Margins start as Magma-Poor Margins but, towards the end, evolve into Volcanic Passive Margins in the vicinities of the imminent breakup. No mantle exhumation occurs in these two types.

The different modes described also result in a differentiated petroleum potential. Magma-Poor Margins present wide and thick rift sequences developed during the stretching, thinning and exhumation modes. Large packages of lacustrine organic-rich shales are present in the grabens, as well as different types of reservoirs such as microbialites, coquinas, sandstones and fractured volcanics/basement. Eventually there may be so much oil generated in the rifts that a large amount may migrate upwards and be stored in post-rift reservoirs (turbidite sandstones, shallow marine carbonates). Petroleum systems associated to both the Rift and Drift Stages may be extremely rich, such as in the Santos, Campos, Espírito Santo Basins in Brazil and in the Kwanza and Congo Basins in Angola and Congo.

On the other hand, Volcanic Margins barely contain any sedimentary deposits inside their grabens, if any. Volcanic and volcanic-derived rocks fill the underlying rift entirely. So, the chances for source rocks in the Rift Stage are close to nil. At first glance, Volcanic Margins are devoid of petroleum potential in the Rift Stage. However, as the rifting takes place in intense volcanic mode, the thermal subsidence that follows creates a large amount of depositional space. The Drift Mega-Sequences of Volcanic Margins are much thicker and well developed than in Magma-Poor Margins. The Pelotas Basin in Brazil presents a Drift Stage with thicknesses of up to 9 km. This allows for the extensive maturation of marine anoxic organic-rich shales deposited in the lower parts of this stage and the generation of large quantities of hydrocarbons. Slope and basin plain turbidites constitute the major reservoirs, mostly in stratigraphic traps. The Pelotas Basin, the Volcanic Margin of Uruguay and Argentina and the marginal basins of Namibia and South Africa may present significantly rich petroleum systems in their Drift Stage.

The Transitional Passive Margins possess the same petroleum potential of Magma-Poor Margins in the proximal domains (onshore, shallow to deep waters) and that of Volcanic Margins in the more distal domains (ultra-deep waters). Such is the case of the Sergipe-Alagoas, Potiguar and Ceará Basins in Brazil.

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Thursday 24 March

Session Six: Plays to Production (case studies)

Keynote Speaker: Exploration of Mature Areas on the Norwegian Continental Shelf Since 2000

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The reactivation of the exploration of the Norwegian Continental Shelf since 2000 has been successful. This is the result of conceptual renewal by a diversity of organic growth companies. The process was initiated by the authorities and companies that believed in an unreleased resource potential. The preceding decade was characterized by acquisition and mergers that lead to more equal asset based companies. Such a focus resulted in exploration drilling around producing fields and underinvestment in drilling of breakthrough concepts. The result was a majority opinion that the time of large discoveries had come to an end. Between 2000 -2006 1 billion boe was found and from 2007 6 billion boe. The behaviour reference curve for the discovery process in any area is nonlinear and demonstrates that the main growth phases are related breakthroughs created more by actions than predictions

Uncertainties that are accepted create a room of possibilities with the right philosophy, teams, data, tools and methods. Possibilities are created by seeing new relations between maximum diversity of differently scaled geological parameters at highest possible entropy level. Reliable subsurface models are based on basic geological principles formulated by Hutton, Walter and Wheeler. Models must be formulated deterministically and realize that the same data can support several equal likely scenarios. Modelling will always be tautological.

The tools and methods must adapt to reality not the opposite. Facts can never be substituted by indirect methods. The subsurface knowledging should focus on what the situation is and then why it can be such. This reflect Gödel's incompleteness theorem; "The truth cannot be described in a finite net" and David Bohm's implicit order; "Reality is unfolded by interactions" and holistic principle; "The details in the whole and the whole in the details"..

The first new important discoveries after 2000 were the Kneler and Boa oil discoveries that together with the earlier Kameleon gas and oil discovery triggered the development of the 300 million bbl Alvheim oil field. These structures were prior to the drilling considered as gas satellites to the Heimdal Gas Field. The Kneler under saturated oil discovery demonstrated that new concepts of reality are created outside the 2-3 standard deviations. Expected value decisions repeat the past and do not create the future. Perceptions of the tacit domain are essential in the exploration decision.

The southern Utsira High had been unsuccessful explored by all the major companies from 1967 to 2007. The successful discovery of the significant Edvard Grieg by well 16/1-8 in 2007 triggered a wave of new discoveries culminating with the discovery of the supergiant Johan Sverdrup by well 16/2-6 in 2010.

The basic hypothesis for the renewed exploration in 2004 was based on all earlier wells and 3D seismic. The new model was that the Utsira High was an inverted high that could be one saturated oil system linked to a veneer of Volgian and older Jurassic sands above an OWC 1940-60 m MSL. The hypothesis was supported by a model for late and ongoing petroleum migration. This was based on the fact the Johan Sverdrup structure got its current position at base Pleistocene time and clear seismic indications of vertical and lateral hydrocarbon migration.

During the drilling operations coring was essential. The Edvard Grieg reservoir is feldspar rich and could easily have been interpreted as a non-hydrocarbon bearing reservoir with only wireline. Coring through hiatuses and testing have improved the understanding of the reservoirs and fluid connectivity between sequences around the Base Mid Jurassic, Base Volgian and Base Cretaceous unconformities in all the discoveries.

The kinematic of the southern Utsira High is influenced by wrenching along the Sorgenfri Tornquist lineament from Palaeozoic to Pleistocene. In addition the early Mid Jurassic thermal inversion and the Pleistocene glaciations have influenced the petroleum habitat of the area.

The Loppa High in the western Barents Sea was explored from 1985 in relation to Jurassic, Cretaceous sandstone and Late Palaeozoic carbonate plays. The Loppa High was inverted in two phases; Base Triassic and Base Jurassic. The breakthrough of oil discoveries in relation to the Jurassic play concepts were made in 2011 and the Palaeozoic plays in 2013 and 2014. The ruling theories from earlier exploration failures were that oil had leaked out during the glaciations in Pleistocene or late uplift phases. Late and ongoing efficient oil migration could compensate for such leakage and active gas flares at seafloor indicate such processes.

The Johan Castberg field discoveries at the Base Cretaceous west flank of Loppa High are saturated oil discoveries sourced from the Upper Jurassic Hekkingen Formation. The Gohta and Alta late Palaeozoic carbonate discoveries in the Loppa High core are saturated non biodegraded oil discoveries sourced from Permian and Triassic. Coring and testing was essential in discovering the carbonate play.

All the new discoveries on the NCS are made in already explored areas and are made very close to drilled wells. In hindsight the discoveries could have been found earlier through a more fact based knowledging during operations. The best online adaptions to reality are always done by the people that formulated the exploration concepts.

Piet Hein's saying; "To know what thou knowest not is in essence omniscience", is the basis for all generative learning. The tools at hand will continuously improve without ever reaching the panacea status.

NOTES

The Role of Rift Transection and Punctuated Subsidence in the SW Atlantic Margin

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A new interpretation of an extensive offshore data set of seismic and well data revealed the existence of two superimposed buried rift systems north of the Falkland Islands. Although refered to as the North Falkland Basin, the area in fact contains two sub-basins, a Late Jurassic NW-SE striking horst and graben system and superimposed an Early Cretaceous N-S striking one. Both sub-basins are tilted and partially eroded due to several post-rift phases of uplift, therefore seismic and well data were not able to detect both rift systems everywhere and it rather required a comprehensive study that analyses the basin as a whole.

We have carefully mapped both rift systems, something that has led to the recognition of their component mega-sequences, and identified pronounced periodes of uplift and inversion. Regional and detailed seismic interpretation has been undertaken in order to better understand the age relationships and kinematic interaction between differently oriented basins and intersecting fault systems, the role of inherited structures, the amount and timing of uplift and inversion and the extent and age of unconformities.

Both extensional basins comprise asymmetric half grabens containing a preserved sedimentary thickness of at least 10 km at its deepest part. The Cretaceous rift system initially developed in a fluvial and later lacustrine environment before becoming predominantely marine in the Tertiary. Rapid extension led to the development of arcute shaped fault segments with hanging wall sub-basins into which sediments where deposited as fans. A prograding delta system filled the main Cretaceous rift basin from the north during the early post-rift phase. Contemporaneously, sediment was shed off the segmented basin-bounding fault via long-established feeder drainage systems through breached relay ramps into the depocentre. The resultant sediment dispersion led to deposition of numerous lacustrine turbidites that created the Sea Lion fans and its affiliates, the location of which is probably controlled by the underlying syn-rift sub-basins.

At least three major phases of uplift affected the North Falkland Basin: the oldest detectable is the exhumation of the Jurassic rift during commencement of the Early Cretaseous rift, followed by the uplift during the Aptian in the post-rift phase of the Cretaceous rift, and the Cenozoic exhumation of the Falkland Islands that imparted a tilt both Jurassic and Cretaceous rifts northwards. The Aptian phase was short-lived and created a long and gentle north-south striking anticline that runs along the central basin axis punctuating post-rift subsidence without inhibiting petroleum prospectivity.

NOTES

Tectono-Stratigraphic Evolution of the Onshore Namibe-Benguela-Kwanza Basins, Angola – Implications for Margin Evolution Models

Ian Sharp[1], S. Higgins, G. Messanger, R. Swart, J. Marsh, L. Gindre, C. Puigdefabregas, K. Verwer, H. Ferreira, M. Snidero, V. Machado, E. Holtar, M. Dongala, D. Jerram, E. Blanc, H. Groger, M. Scott, U. Freitag, F. Lapponi, J. Verges, D. Hunt, M. Zeller, J-D Martin, M. Moragas, I. Cruz, V. Baques, E. Casciello, O-P Wennberg, J. Warren

[1]*Statoil ASA*

Onshore Angolan outcrops have been studied as part of a Brazil-West African conjugate margin project. Focus has been on rift margin to break-up axis tectono-stratigraphic evolution and associated strike variability of oblique and orthogonal rifted segments (Higgins et al., this conference). In this contribution we highlight key observations from Pre- and Post-Salt outcrops that occur as an elongate coastal strip extending from Namibe in the south to Kwanza in the north.

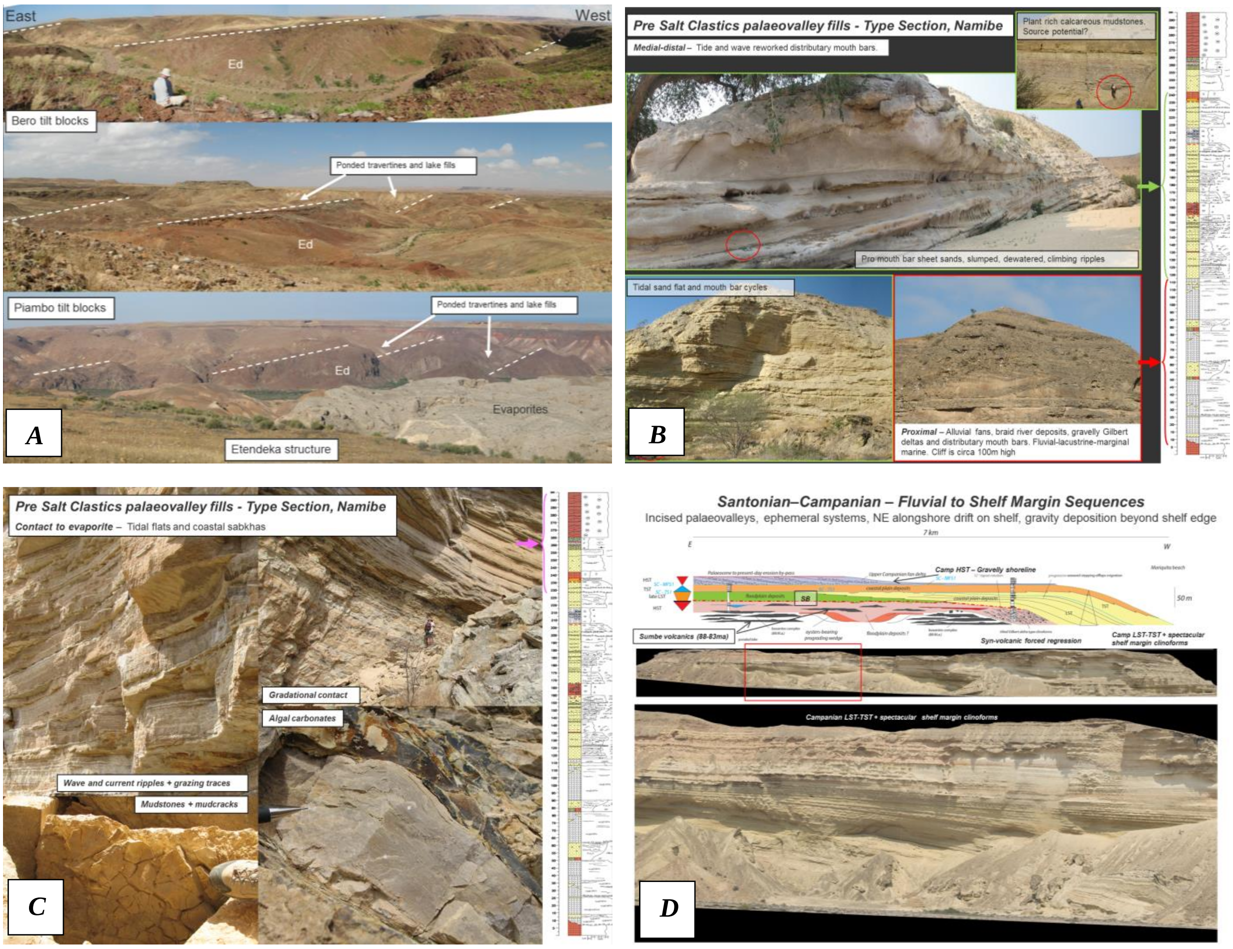
Rift initiation deposits include interbedded basalts, rhyolites and aeolian-alluvial clastics that sit with low angle discordance on Pre-Cambrian basement. Volcanics (dated 132Ma) have geochemical affinity to the Parana-Etendeka LIP. Pre-rift fluvial-lacustrine deposits are locally evident beneath the volcanics, preserved as incised antecedent valleys.

Rift climax and early sag sediments are absent onshore, with deposition focused outboard of the hinge line (present day offshore), whilst areas inboard of the hinge underwent uplift, erosion and sediment by-pass. By Early Aptian times a progressively onlapping-overstepping fluvial to marine Pre-Salt succession was deposited along the entire West African margin, cumulating in deposition of Loeme Fm evaporites. This succession includes spectacular fluvial-tidal incised palaeovalleys overlain by algal laminate-sabkha facies with halite pseudomorphs that pass transitionally into the overlying evaporite. Importantly for geodynamic models, this latest sag megasequence transgresses the subaerial rift margin, and effectively “seals” rift-related faults. The presence of evaporites within all studied palaeovalleys indicates extreme aridity and rift margin drainage shut-off. Sag outcrops also include lacustrine and “dam and cascade” carbonates (travertines, Sharp et al., 2013). Secondary diagenesis is complex (karstification, dolomitisation, silicification). The onshore observation of rift-initiation clastics/volcanics overlain by latest sag transgressive sediments, separated by a significant unconformity, can be linked to offshore seismic stratigraphic megasequences and distal margin evolution.

Original onshore depositional thickness of evaporite, and percentage halite, is hard to estimate - 200-500m is postulated based on halokinetic structures within the overlying Pinda Gp, the basal part of which is pre-halokinetic (Binga Mbr), whilst the overlying mixed carbonate-clastic succession (Dondo-Catumbela) is syn-halokinetic, with spectacular growth geometries. Significant hinge line rotation is also recorded by the Albian succession. In all 3 basins Pinda Gp clastics show a close spatial relationship to Pre-Salt Aptian and modern valleys, indicating W. African drainage is antecedent in nature.

Late Albian platform collapse follows, associated with extensional faulting, establishment of U. Albian slope successions and widespread emplacement of shallow sub-volcanic intrusives, subaerial to subaqeous lava flows and major volcanic centres (Sumbe Volcanics). Volcanism is diachronous along strike (Kwanza - 100-97Ma, Benguela - 91-86Ma, Namibe - 88-79Ma). In the Namibe Basin volcanism is proceeded by thick (>1500m) Albian-Cenomanian alluvial clastics with divergent hinge line growth geometries. Clastics are point sourced, associated with palaeovalley and palaeofan morphologies. Disconformably overstepping the Albian and older units is a Cenomanian-Coniacian transgressive sequence (Salinas Fm), itself intruded and overlain by Sumbe Volcanics. Volcanism in Namibe was locally associated with a return to subareal to lacustrine conditions (including travertines).

Finally, flat lying successive transgressive-regressive passive margin wedges of Santonian-Campanian, Maastrichtian, Eocene, Miocene, Plio-Pleistocene and Holocene age were deposited, locally associated with spectacular seismic scale clinoforms.



Selected outcrop images from the Namibe Basin, SW Angola
A – Dip sections of 132Ma Parana-Etendeka equivalent volcanics exposed within steeply rotated fault blocks passively onlapped and overstepped by late sag, evaporite and post salt successions, Bero and Piambo area, Namibe Basin. **B + C** – Type section Namibe Basin of Late Sag palaeovalley fills and transitional contact to Loeme Fm evaporites. **D** – Spectacular depositional dip section of drift phase Late Cretaceous shelf margin clinoforms, Maraquita area, Namibe Basin.

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Structural and Stratigraphic Controls on Diagenesis within Carbonate Platforms in Rift Basins

Cathy Hollis[1], Eivind Bastesen, Hilary Corlett, Robert Gawthorpe, Irina Korneva, Hamish Robertson, Atle Rotevatn and Fiona Whitaker

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The depositional architecture of carbonate platforms on the crest of rotated footwall fault blocks has been well studied, but with little attention to the controls on the structural and diagenetic processes that affect these platforms. This is critical, since porosity and permeability can be modified significantly by diagenesis from marine, meteoric fluids and hydrothermal fluids circulating within interparticle pore systems and along faults throughout platform growth, burial and uplift.

In the Suez rift, an aborted arm of the Late Oligocene to Miocene Red Sea Rift, pre- and syn-rift carbonate platforms are exposed within tilted and rotated fault blocks. Dolomitized areas are focused along major block-bounding faults, particularly in areas of significant structural complexity, such as rift-scale accommodation zones. Detailed characterisation of one of these platforms, the Hammam Fauran Fault (HFF) Block, western Sinai, shows that dolomitisation of the pre-rift Eocene Thebes Formation occurs in two principal forms:

stratabound dolomite, that preferentially replace remobilised facies (debris flows and grainstone turbidites) and extend discontinuously away from the HFF for up to 2km. These bodies are offset by the Gebel Fault that formed during the earliest syn-rift, implying dolomitisation at rift initiation. 87Sr/86Sr isotope data support this, with a late Oligocene age.

massive, non-facies-selective dolomitised pods, up to 500m wide, confined to the fault damage zone and interpreted to have formed at the rift climax. This is supported 87Sr/86Sr isotope dates equivalent to Miocene seawater.

Stable isotope and trace element data indicate dolomitisation from contemporaneous seawater at temperatures up to 120oC. Fluid flow models show that the proto-HFF and early-rift intra-block faults could have provided up-fault conduits for fluids convecting within the Nubian Sandstone aquifer at rift initiation. Since the HFF tipped out within the sediment pile, the permeability architecture favoured discharge of fluids via the Thebes Formation to form stratabound dolomite bodies. At rift climax, the HFF breached the surface, and seawater convection along the fault plane and within the damage zone formed the massive dolomite pods.

The results of this study indicate dolomitisation can occur on carbonate platforms in rift basins at zones of structural complexity. In particular, the massive dolomite bodies are located within the linkage zone of two segments of the HFF against the Zaafarana regional transfer zone, which enhances structural complexity and permits vertical fluid flow. The shape, size and distribution of the geobodies were therefore strongly influenced by the timing of fluid flux in relation to faulting along basement-connected lineaments. The dolomite and limestone underwent further diagenetic modification by marine and meteoric processes during uplift and footwall rotation. The result is complex, multi-scale, fracture-connected pore networks, influenced by the extent of dolomitisation.

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Rift Dynamic Based On a Stratigraphic Architecture and Paleogeographic Basin-Scale Study: Example of the Gulf of Suez (Egypt)

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Rift basin geology is a major issue because of its economic importance for petroleum industry as well as its related scientific challenges such as the relationship between deep and surface processes. A major limitation to go further is the calibration of theoretical concepts to real data observations at basin-scale and with high resolution time lines.

We propose a high resolution basin-scale (~300 x 100km) study of the pre-salt to salt sedimentary fill from the Gulf of Suez (Egypt) based on outcrop and subsurface data (279 wells, 31 sedimentological sections). The stratigraphic architecture has recorded five main stages of rift evolution, from rift initiation to finally tectonic quiescence recorded by salt deposits.

Rift initiation (ca. 1-4Myr duration): the Suez rift was initiated at the end of the Oligocene along the NNW-SSE trend of the Red Sea with evidences of active volcanism. Continental to lacustrine deposits are only preserved in isolated depocenters.

Rift widening (ca. 3Myr duration): the rift was propagated from south to north (Aquitanian), with first marine incursions from the Mediterranean Sea. The rift was subdivided into numerous depocenters controlled by active faults. Sedimentation was characterized by small carbonate platform and associated sebkhra deposits to the south and shallow open marine condition to the north with mixed sedimentation organized into an overall transgressive trend.

Rift climax (ca. 5Myr duration): the rift was then flooded during Burdigalian times. The faults were gradually connected and reliefs on the rift shoulders were high as evidenced by a strong increase of the uplift/subsidence rates and sediment supply. Sedimentation was characterized by very large Gilbert-type deltas along the eastern margin and associated submarine fan and turbidite along the basin axis. Isolated carbonate platforms and reefs mainly occurred in the Southern Basin and along tilted block crests.

Flexuration to rift narrowing (ca. 4Myr duration): during the Langhian times, the basin recorded several falls of relative sea level and bathymetry in the rift axis was progressively reduced. The former reliefs induced during the rift climax were quickly destroyed. During Serravalian times, the rift basin recorded several disconnections with the Mediterranean and Red seas as evidenced by massive evaporites in major fault controlled depocenters.

Tectonic quiescence to flexuration (ca. 7Myr duration): the Tortonian is then characterized by the deposition of very thick salt series (>1000m) which has recorded a period of maximum restriction for the Suez rift. The basin was still subdivided into several sub-basins bounded by major faults. The basin was totally and permanently disconnected from the Mediterranean Sea, and possibly connected to open marine condition via the Red Sea. The Messinian is also characterized by a thick salt series, but the evaporite typology and sedimentary systems distribution suggest a more humid climate than during Tortonian times.

Rates and fluxes derived from this basin-scale study can be used to implement and test numerical models, as well as better understand other rift systems.

NOTES

Similarities of Rifting To Seafloor Spreading Between the Red Sea and South Atlantic

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Interpretation of Saudi Aramco proprietary gravity and magnetic data has shown many similarities of the Red Sea rifting framework compared to published work on the South Atlantic. These similarities include the extent of volcanics, salt tectonics, sediment grabens, hotspot deeps and seafloor spreading.

An analysis of the Red Sea gravity and magnetic data has revealed the following observations:

1. Rift structural elements:
    - A defined crustal oceanic boundary only along the spreading axis and deeps.
    - Salt flow affected by location of deeps.

2. Volcanism:
    - Magnetics defined location of volcanic activity.
    - Complex onshore volcanic dike orientation and density.
    - Deeps are volcanic hotspots.

3. The spreading axis:
    - A Red Sea propagator spreading model.

4. Seafloor spreading:
    - Gravity expression of volcanic fill.
    - Magnetic polarity reversal of seafloor spreading.
    - Magnetic indication of transform faults.

A discussion of these observations in relation to published data on the Red Sea and South Atlantic will show that a single model for the rift structural elements can potentially be used for these and other rifted systems.

NOTES

Cretaceous Deformation of the Demerara and Guinea Plateaus during South Atlantic Opening

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The Demerara and Guinea Plateaus were part of the residual eastern part of the Gondwana land when they have rifted apart from the North America in Middle Jurassic. Now the Demerara Plateau is located in the northwest corner of the equatorial segment of the Atlantic Ocean. It has rifted from the Guinea Plateau on the African margin during the Early Cretaceous opening of the Central Atlantic. The episode of Early Cretaceous compression predated the passive subsidence of the conjugate plateaus during the drift phase of the African and South American separation. Early Cretaceous compression produced a significant deformation of the southern edge of Guinea Plateau and north–northeast edge of the Demerara Plateau. Our earlier plate tectonic modeling used rigid African and South America plates and have estimated at least 20–50 km of shortening on Demerara Plateau during Early Cretaceous. It is topped by Albian unconformity, which according to our modeling has removed up to 6 km of sediments from the Demerara Plateau.

In our previous work we focused on Equatorial Transform Margin and Demerara during Cretaceous Atlantic opening and questions on the nature of the deformation observed on the Demerara Plateau. Our most recent seismic interpretation of the pre-Albian deformation on the conjugate Guinea Plateau and the contemporary deformation observed in the Amazon Solimoes Basin allowed us to revise our rigid Plate model of 2014 further to account for a full shortening during Early Cretaceous compression between Demerara and Guinea Plateaus. In this paper we present interpretation of seismic and potential fields data on the Guinea Plateau complimentary to our earlier interpretation of Demerara Plateau and incorporate published interpretation from the Solimoes Basin into the plate model of South Atlantic opening.

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Crustal Architecture and Nature of Continental Breakup along A Transform Margin: A Case Study from East Africa Transform Margin (Tanzania-North Mozambique)

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The Tanzania-North Mozambique continental margin is one of the most conspicuous transform margins in the world. The most distinguishing feature associated with this margin is offshore Davie Fracture Zone (DFZ). So far, the DFZ has been generally described as a very long linear oceanic fracture zone, commonly linked with rifting and breakup between Eastern and Western Gondwana.

We carried out a combined study of gravity, magnetic and seismic data to determine the crustal architecture, geometry and the kinematic nature of continental breakup along a transform margin. The nature of DFZ and its role and kinematic linkage with overall continental breakup processes were also investigated. Our datasets include ION GXT's deep reflection seismic data together with magnetic and gravimetric investigations and public domain dataset (Lamont-Doherty laboratory, USA). This study is primarily focused on the transform margin segment along Tanzania-North Mozambique corridor.

The entire margin, from Somalia to the South Africa, is highly segmented into both rifted and transform segments. The Somalia-Majunga (Madagascar) and North Mozambique-Antarctica conjugate margins were developed as a result of normal fault controlled extension. These two extensional margins were connected through dextral Davie Strike-Slip System (DSS) forming a transform margin along the Tanzania-North Mozambique segment. The transform margin along the Tanzania is mostly transtensional. Classical synrift signatures, as observed in the extensional margins, are not as prominent in this transform margin segment. However, smaller scale rift signatures are observed in deep water, which roughly resembles hyper-extended distal margin architecture. We interpret a possible fossilized incipient spreading center within a very large pull-apart system with some remnant fossil asthenospheric diapir. These features also suggest that the extension was reached at quite advanced stages of rifting, which was mostly controlled by magmatic and thermal weakening. It appears that the incipient spreading were initiated with large pull-apart systems, but eventually failed as the hard-linkage were established between northern and southern extensional margins through DSS as Madagascar started to move from North to South. Along north Mozambique, the transform margin becomes almost a pure strike-slip system from its transtensional Tanzanian counterpart. Here, the total extension is highly localized within a narrow zone. Therefore, post breakup kinematic linkage between northern and southern extensional margin and dextral movement along the Davie Strike-Slip fault controls the complex nature of continental breakup along the transform margin.

The oceanic-continental boundary suggests a narrow zone of continental crust in the transform margin of Tanzania-North Mozambique corridor in comparison to the wide zone of extended continental crust seen in the Somalia region and Southern Mozambique region in the north and south respectively. Our forward gravity modelling carried out along select ION lines and magnetic anomaly patterns have led to underpinning the newly interpreted ocean-continent boundary.

NOTES

A Methodology for Exploration in Mature Rift Basins - Why Play Mapping Integrated with Well Failure Analysis Matters - An Example from the Rift Systems of the North Carnarvon Basin, North West Shelf, Australia.

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Many sedimentary rift basins have been intensively explored, typically over many decades in a competitive environment where the full application of the technological armory available to explorers today (e.g. 3D seismic imaging and depth conversion, AVO, etc) has been extensively refined and deployed. Typically in these basins all of the potential source kitchen areas have been tested and in the proven charge areas all of the significant simple structural traps such as anticlines and highside fault blocks/horsts have been drilled. In these areas exploration is consequently now be focussed on the remaining smaller sub-economic simple traps and on larger more complicated trap types. Many of these more complex trap types involve base seals, fault seals and/or pinch outs making them inherently more risky and harder to define than the simpler highside traps which are generally well defined by modern seismic methods.

The challenge for explorers in these basins is how to collate what is typically a voluminous dataset of wells and seismic data in such a way that the most prospective areas for subtle and or complex traps can be efficiently determined together with a calibrated understanding of the relative historical success rates and discovery sizes for these different trap types. An effective methodology is the application of well-established play fairway mapping such that areas of proven reservoir, seal and charge are mapped out spatially on a play by play basis. There are many approaches for doing this but the best method, particularly in areas of complex and laterally variable geology, is the construction of "split risk" common risk segment (CRS) maps where the shared and independent risk elements are separated for each risk element. The key additional element in the proven fairway areas is the proven areas is systematic classification and analysis of well failures, discoveries and prospect inventories by specified trap types Exploration failures associated with any complex traps that are beyond the proven play fairway are consequently excluded in this analysis, such that the explorer can then determine both a spatial focus and extract the real exploration record for these subtle/complex tests and thus ultimately quickly determine and high grade the best remaining focus areas for detailed mapping and prospect generation efforts. An example is presented of low side fault block traps in the Upper Jurassic plays of the Barrow- Dampier-Exmouth portion of the North Carnarvon Basin, along with a review of the exploration record for this trap type, the methodology used, and the remaining potential identified.

The methodology presented is repeatable and applicable to any mature basin type but is particularly applicable in mature rift basins where the trap target and failure analysis data is publically available for collation. Large complex trap discoveries are not common and are frequently non-amplitude supported and solitary (e.g. the Buzzard discovery in the Inner Moray Firth in the North Sea), but when they occur they do have a transformational impact on both exploration companies and government treasuries and always re-invigorate the exploration efforts in what was previously considered a relatively inactive or fallow basin.

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Poster Presentation Abstracts

Sedimentology and Architecture of Early Post-Rift Submarine Lobe Deposits; the Los Molles Formation, Neuquén Basin, Argentina

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The sedimentary architecture of submarine lobe-dominated successions in early post-rift settings are poorly understood despite commonly being proven hydrocarbon reservoir systems, in part because these types of systems are rarely exposed. Exhumed early post-rift deposits in the Neuquén Basin, Argentina, have been investigated in the Jurassic Los Molles Formation, to help understand and predict the subseismic distribution of facies around inherited syn-rift structures. Two distinct depocenters, La Jardinera and Come Yeguas, are located between NW-SE trending extensional syn-rift footwall highs.

The well exposed submarine lobe-dominated successions have allowed sedimentological and architectural changes in the Los Molles Formation to be constrained by use of correlation panels constructed along a 12 km strike section in La Jardinera and a 2.5 km cross strike section towards syn-rift faults in Come Yeguas. The early post-rift deep-water stratigraphy is characterized by the onlap and pinchout of sandbodies, which in combination with hardground development on footwall highs indicates that deposition occurred across fault-block highs.

The basin physiography during deep-water deposition was, therefore, demonstrable conditioned by inherited syn-rift structures that influenced the timing and location of bypass, erosion and deposition of sand-rich sediment gravity flows. The infill architecture of the two depocenters record different stratigraphic architectures and stratal patterns of sand-rich strata, inferred to be the result of the contrasting responses of marine clastic sedimentation to the inherited syn-rift topography, differential subsidence, sea-level variations and sediment supply. This study provides criteria to decipher relationships between the organization of lobe deposits and inherited syn-rift structures that can be integrated to improve the prediction of reservoir bodies in underexplored early post-rift successions.

Seismic Structure of the Crust and Upper Mantle of Porcupine Basin from Wide-Angle Data

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The evolution of continental rifted margins plays an important role in understanding the geological process of continental extension. As a key rifted basin located to the southwest of Ireland, the Porcupine Basin is a large V-shaped sedimentary basin of Late Palaeozoic to Cenozoic age. It formed during the opening of Atlantic Ocean, around Mid-Late Jurassic time. A geological feature named Porcupine Median Ridge (PMR) is identified at the southernmost part of the basin. However, the origin of PMR has remained debated, with serpentinization, volcanic activity and crustal faulting being suggested. Previous studies, mainly using seismic reflection and gravity data, show an increasing stretching factor from north to the south (from less than 1.5 to greater than 6). Wide-angle seismic data acquired along a ca. 100 km long profile across the basin axis yield new insights into the crustal and upper mantle structure. During this study, both refractions and reflections recorded by the OBS are used to perform a joint travel-time inversion, and a 2D P-wave velocity model has been obtained which contains information about the sedimentary, crustal and upper mantle structure. Multi-channel seismic data have been used to constrain the accuracy of all the seismic phases. The tomographic model is consistent with the forward modelling result. Analysis of the velocity features from both models reveals the crustal thickness at the south Porcupine Basin is up to 12 km in the middle of the basin, and then gradually decreases to 10 km under the PMR. Thus, the stretching factor is significantly lower than that inferred from former studies. Based on the results, we discuss the rifting process and the geological nature of the PMR. This project is part-funded by the Irish Shelf Petroleum Studies Group (ISPSG) of the Irish Petroleum Infrastructure Programme Group 4.

The Use of Velocity Analysis of Long-Offset Seismic Data to Interpret the Seaward-Dipping Reflectors Imaged Along the Argentinian And Uruguayan Rifted Margins

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Seaward-dipping reflectors are packages of syn-rift volcanic effusive material and are a key characteristic of volcanic margins. These packages are composed of sub-aerial tholeiitic lavas, thin tuffs and are commonly interbedded with thin layers of terrestrial sediment. This complex structure presents difficulties with conventional seismic imaging of the volcanic packages themselves and underlying structures. Here, we present a detailed view of the internal geometry and surrounding structure of the seaward-dipping reflectors offshore the southern segment of South America based on high-quality multichannel industry seismic data. We demonstrate that the interpretation of the internal and sub-basalt seismic reflections can be enhanced by detailed velocity analysis of pre-stack seismic gathers.

The seismic data were acquired by ION-GXT between 2009 and 2012 offshore Argentina, Uruguay and southern Brazil using 10200 m long-offset streamers, with a 12.5 m CDP interval and towed at a water depth of 10 m. As a result of recording long-offsets and low-frequencies, down to 3 Hz, this data is capable of imaging the internal and sub-basalt features along the continental margin. In the analysis we prepared the data by picking mutes, band-pass filtering (3-40 Hz), attenuating random noise, and making supergathers from 10 CDPs. The velocity analysis was completed every 250 m to ensure the resulting model was not too fine. The analysis shows that the seaward-dipping reflectors are commonly defined by a steep velocity increase at their top, a variable internal velocity structure and a prominent velocity inversion at their base. Internally, the velocity structure of these packages varies by up to 1 km/s, where the highest velocities are observed at the centre of the thickest packages. In some regions, the basal velocity inversion is as much as 0.5-1 km/s. The data were then re-migrated using the refined velocity model. The resulting images showed a more geologically reasonable geometric relationship with potential underlying tilted fault blocks.

The seismic velocity and imaging results are interpreted in terms of a change between heterogeneous basaltic flows (hyaloclastites) and more homogeneous continuous flows, a change in the ratio of sediment-basalt, or perhaps, a transition from tholeiitic basalt to crystalline crust. This study has increased our understanding of the internal structure of the volcanic sequences, provided a distinction between the volcanic material and potential sub-basalt structures and produced a better image of the sub-basalt structure.

Continental Hyper-Extension and Mantle Exhumation at the Ocean-Continent Transition, West Iberia: New Insights from Wide Angle Seismic.

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Rifting and the subsequent breakup of continental lithosphere has given rise to the magma-poor Deep Galicia rifted margin in the North Atlantic Ocean. Here, hyperextension of continental crust and has been accommodated by the rotation of continental fault blocks, which are underlain by the S-reflector, an interpreted detachment fault, which has exhumed serpentinised mantle peridotite. West of these features is the enigmatic Peridotite Ridge (PR) which has been suggested to delimit the western extent of the ocean-continent transition. An outstanding question at this margin is where unequivocal oceanic crust begins, with little existing data to constrain this boundary and a lack of magnetic seafloor spreading anomalies.

We present results from a 160-km-long wide-angle seismic profile, which encompasses the S-reflector to the east, the PR, and the unidentified basement west of the PR. This profile consists of 32 OBS/H recording wide angle seismic data from coincident multichannel seismic surveying. Forward and inverse travel time tomography models of the crustal velocity structure were produced using a range of algorithms, with the best fit model having a RMS travel time misfit of 47 ms, a $\chi 2$ of 0.98 and strong correlation with the structure observed in seismic reflection images. East of the PR, highly thinned and rotated crustal blocks overlie the S-reflector, which generally correlates with the 6.0-6.5 kms-1 velocity contours, giving a crustal thickness of 1.0-1.5 km and an average velocity gradient of 0.75 s-1. Similarly, west of the PR we observe a basement layer which is 3.0-4.0 km thick and has an average velocity gradient of 0.95 s-1. High velocity gradients, and an absence of velocities typical of oceanic layer 3 and of clear mantle reflections suggest the presence of exhumed, serpentinised mantle peridotite west of the PR, which could be analogous to the large expanses of mantle peridotite exposed at the seafloor on the flanks of the ultra-slow Southwest Indian ridge.

Additionally, we present the initial results of full waveform inversion performed on this wide angle seismic dataset, showing an increased resolution in the seismic velocity structure associated with the S-reflector and the patterns of mantle serpentinisation beneath the detachment fault.

Untangling the Faults: Using 3D Data at the Galicia Margin to Determine Faulting History

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The western Iberian margin, due to its limited post-rift sedimentary cover and limited volcanic activity, has provided significant data to aid the formulation of models of continental extension and breakup. Structural elements characteristic of highly extended post-breakup continental margins include: rotated faults blocks and associated syn-kinematic sedimentary wedges, low angle detachment faults, exhumed and serpentinised continental mantle and allochthonous blocks. In addition, the extension as measured by heave on faults that have been imaged in seismic data is not enough to account for the stretching or subsidence associated with this extension: there is an extension discrepancy.

The mechanisms postulated to account for these characteristic structures and the extension discrepancy include: depth-dependent thinning, sequential ocean-ward faulting and polyphase faulting. These mechanisms have resulted in a range of, often complex, evolutionary models that are 2D representations of an inherently three dimensional process.

A new, ~680 km2 3D seismic survey (the largest academic one of its kind) consisting of 800 inline (12.5m bin spacing) and 5000 crosslines has provided high resolution images of the edge of the continental crust. This data captures the 3D nature of extension and breakup as the northern Atlantic continental margins ‘unzipped’ northwards from the middle Jurassic to early Cretaceous.

Detailed interpretation of the deformation seen within the rotated fault blocks and their corresponding syn-kinematic sediments are presented and reveal a complex structural history. Changes in the style and relative ages of the dominant faulting imaged within the rotated fault blocks vary along the strike, revealing spatial and temporal variations in the accommodation of strain. More recent (steeper faults) are seen to dissect large blocks and cut earlier faulting. Steep antithetic faults seem to suggest structural collapse within discrete segments of some blocks. Fault linkage and the reactivation of earlier phases of faulting are essential characteristics of the progressive deformation. Furthermore the interaction between intra-block faults and a low angle detachment (the S reflector) demonstrates the complex patterns generated by the rifting process. This interaction is investigated using maps of the S reflector amplitudes showing the major fault intersections.

Further work is introduced including: untangling the fault movements both spatially and temporally, 2D restoration of the internal deformation of the individual blocks and restoration of blocks on the intra-block faults and the detachment fault. This will enable various breakup mechanisms to be tested and new ones developed. Such mechanisms are essential in the development of accurate heat and fluid flow models. Of particular interest from this work are the possible conduits for fluid flow in the heavily interconnected fault network.

New Insight into a Dynamic Early Rift System and Associated Break-Up Volcanics; 3-Dimensional Geometry of Seaward Dipping Reflections (SDRs) In Offshore Uruguay

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Seaward Dipping Reflections (SDRs) are a commonly occurring feature of volcanic margins worldwide, representing extrusive volcanics recognised by wedges of arcuate reflections with a predominantly seaward dip. Despite their widespread occurrence their 3D geometry is poorly understood. We investigate for the first time, the three-dimensional geometry of an SDR wedge, offshore Uruguay, and consider implications for the volcanic-structure interaction at the time of continental break up. Found along the continent-ocean boundary, SDRs are associated with the opening of the South Atlantic in the early Cretaceous (~134 Ma).

A newly acquired regional 3D seismic dataset covering over 13000km2 is used in conjunction with long-offset 2D data to provide insights into the complexity of SDRs and the early rift morphology. 3D data allows the delineation of a detailed volcanic architecture through restorations, seismic facies mapping, and the identification of stratal relationships with overlying and infilling sediments. An approach of seismic facies characterisation has been adopted with terminology analogous to sequence stratigraphy. Reconstruction of the early rift palaeo-environment may be achieved by the flattening of prominent top package reflections to a pre-rotational architecture at the time of extrusion.

Early rift topography was complex and laterally variable because fault controlled subsidence was synchronous with laterally variable pulses of volcanic extrusion. These created both positive relief features and local topographic lows within the newly forming rift basin. The seismic character of basinal low fill, suggests a variety of lithologies including extrusive volcanics and hyaloclastic deposits, where subaqueous conditions have occurred, as well as lacustrine, sediment dominated sequences.

Extrusive sub-aerial highs show an erosional top, with the overlying reflections of SDR wedges also representing an erosional unconformity into which underlying reflections truncate. Volcanic extrusion was poly-phase as well as spatially variable, a result of the migrating location of both the central vent and off-axis magmatism as rifting progressed. The volcanic infill of topographic lows and isolated magmatic lenses represents off-axis magmatism, bound by transtensional faulting and laterally synchronous with SDR formation. These volcanics, though likely to be synchronous, are deemed to be distinct from SDRs on the basis of differing geometry, seismic facies and the nature of their emplacement.

Faulting within the SDRs shows evidence of minor steep faults with small displacements confined to individual packages. Local incision can be seen along the top of several individual segments of the southern wedge, where distinct periods of sub-aerial exposure are recognised between volcanic pulses. These are shown in down-lapping reflections creating incised 'valleys' and in low reflectivity, discontinuous reflections towards the top of

packages. This suggests that the magmatic system is episodic with active erosion etching into the sub-aerially exposed flow surface, during periods of low volcanism. The interplay between rift faulting and volcanics results in a range of features which influence the palaeo-morphology of the early rift basin and subsequently determine depocentre distribution.

Structural Styles associated with Fault-Propagation Folds in Salt-Influenced Rift Basins: Halten Terrace, Offshore Norway

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Normal fault growth is typically associated with the development of fault-propagation folds; especially in evolving salt-influenced rift basins, whereby the presence of a ductile, evaporite-rich unit in a brittle succession may decouple folded supra-salt (cover) and faulted sub-salt (basement) strata. Cover structures and the underlying fault blocks may form hydrocarbon traps, although imaging can be poor. This study examines the along-strike variability and controls on structural styles associated with a salt-influenced fault-related fold underlain and controlled by a series of down-stepping fault blocks.

A 2000 km2, high quality, 3D seismic reflection survey of Halten Terrace, offshore Norway, has been used to understand how normal fault growth in the presence of salt controls fault-linkage, fold development, basin physiography and syn-rift stratigraphic response. Moreover, we relate fold geometry, and cover-restricted fault strike variations to salt thickness, sub-salt fault throw and polarity. Halten Terrace forms an ideal setting as the pre-rift Triassic salt lacks the effects of extensive diapirism and is well imaged. This permits detailed mapping of salt thickness variations and deconvolution of the spatial relationship between supra- and sub-salt faults and folds.

Quantitative analysis and 3D mapping of fault geometry shows salt strongly influences fault-linkage i.e. the propagation of sub-salt faults to higher stratigraphic levels and development of fold amplitude along-strike. We have identified a series of <15 km long, <400 ms throw, N-S- to NE-SW-striking basement-restricted faults below an 18 km long, >15 km wide, NW-facing, S-plunging monocline. At the southern extent of the fault-fold system, cover-restricted faults show similar strikes and polarity to their W-dipping, NE-SW striking sub-salt counterparts and are soft-linked. In the centre, throw is focused along W-dipping, N-S hard-linked faults to the east, and fold amplitude increases with greater salt thicknesses atop steeper sub-salt topography. Northwards, total throw decreases and greater fault polarity and strike disparity occurs between sub- and supra-salt faults associated with cover gravity-gliding and folding over increasingly flat, wider spaced, lesser-throw fault blocks.

We illustrate how basement-involved deformation can influence the fold structural style at different stratigraphic levels producing an extensive range of structural geometries and trapping styles. These are controlled by sub- and supra-salt fault coupling, salt thickness and fault throw.

Active Rifting at an Incipient Oceanic Spreading Centre: A Study of Local Earthquake Data in Northern Afar

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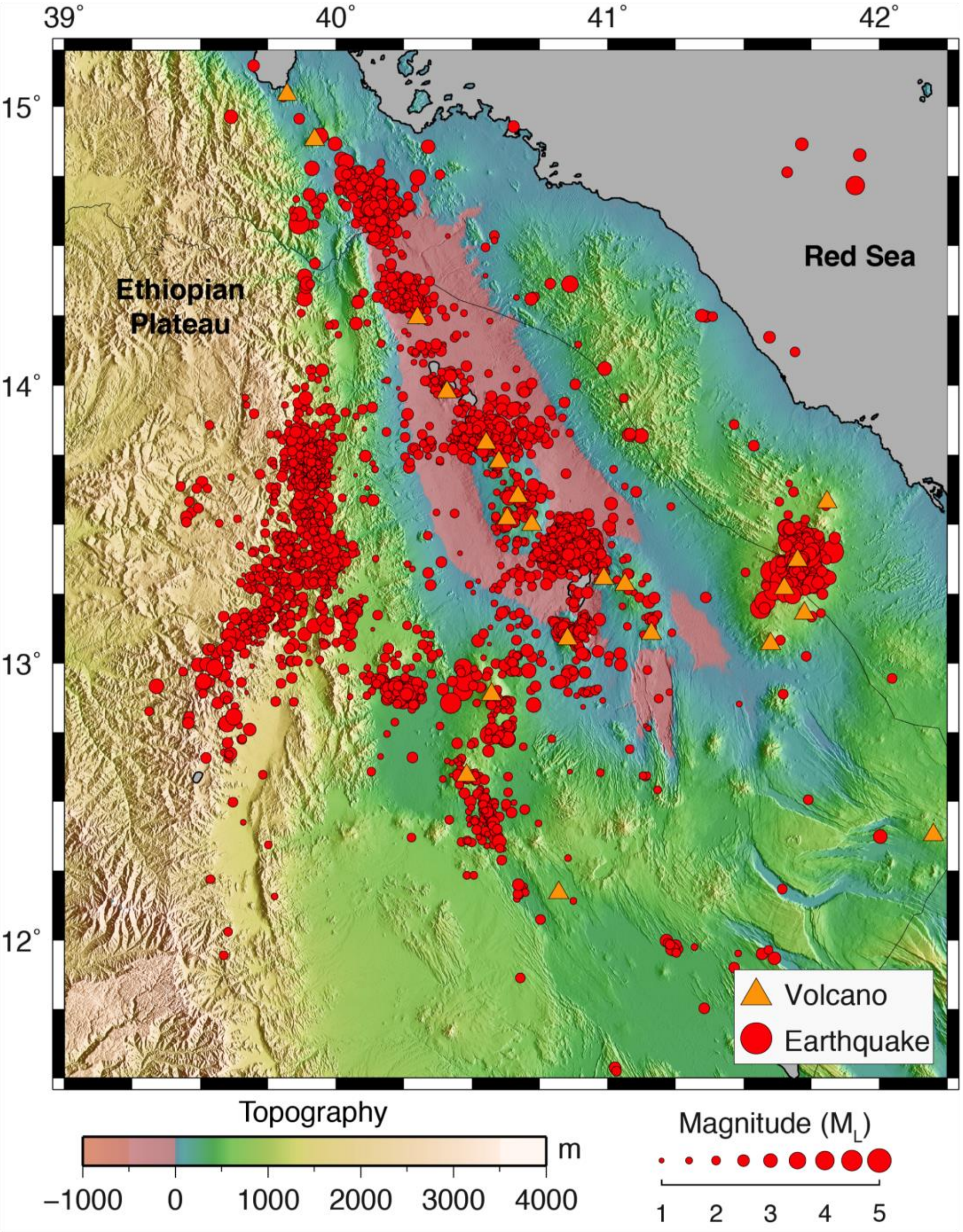
The end stages of continental breakup is characterised by both lithospheric thinning and magmatic intrusions. How these rifts transition from continental rifting to seafloor spreading is not well understood. It is difficult to answer such questions by studying previously rifted continental margins, as the area of transition is buried deep beneath volcanic and sedimentary sequences. Northern Afar presents a unique opportunity to resolve this problem, as it exposes subaerially the magma-rich transition from continental rifting to an oceanic spreading centre. The region therefore acts as a laboratory in which the geological signatures of continental breakup can be investigated unambiguously. For two years, between 2011 and 2013, a seismic network of 20 seismic stations was deployed in the area. I present here the hypocentral locations and local magnitudes of over 4500 earthquakes. Seismicity is focused along the western border fault and at active volcanic centres. The seismic activity is characterised by a b-value of 1.09, suggesting that extension is mainly accommodated by swarms of small magnitude earthquakes. Magma pathways beneath active volcanoes are clearly defined by seismicity spanning the entire crust. Seismic moment release is calculated and used to examine how extension is accommodated in the region. I discuss the implications that these results have on our understanding of the distribution of extension, melt storage and migration and upper mantle processes during the final stages of continental rifting.


39°
40°
41°
42°
15°
14°
13°
12°
Ethiopian Plateau
Red Sea
Volcano
Earthquake
Topography
m
−1000
0
1000
2000
3000
4000
Magnitude (M_L)
1
2
3
4
5

The Geology of the Namibe Basin, Angola

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The onshore Namibe Basin provides a unique insight into the development of South Atlantic rift systems. It is the southernmost of the Angolan Atlantic margin basins, bordered to the south by the Walvis Ridge and to the north by the transform faulted Benguela Basin. The Namibe Basin is an oblique rifted margin – essentially the conjugate margin to the Santos Basin and Sao Paulo Plateau province of Brazil. The outcrop belt is a narrow 3-20 km wide and 220 km long coastal strip. Mapping of the basin was undertaken from 2009-2011 and a revised stratigraphy and map for the basin have been compiled.

The oldest rift related deposits are a sequence of basalts, acid volcanics/volcaniclastics and intrusives with aeolian-fluvial sediments (Bero Volcanic Complex). The complex is an extension of the 132 Ma Paraná-Etendeka province, confined to the southern half of the area and resting with an angular discordance on the Precambrian basement.

After eruption erosion resulted in a topography that was later infilled by clastics (Tumbalunda Fm), carbonates and travertines (Cangulo Fm). Age constraints are poor, but these units are overlain by Aptian-aged evaporites (Bambata Fm), an equivalent of the Loeme Fm further north. The evaporites comprise a 40-70m thick package of gypsum-anhydrite. In large parts of the basin this unit has been completely removed by later dissolution.

Relatively thin (10-50m) carbonates with marine and non-marine clastics (Gaio Fm) overlie the evaporites. These are age equivalent of the Pinda Group carbonates and post-salt carbonate systems of the Brazilian margin.

The Gaio Fm is overlain by a thick (locally >1500m) Albian to Early Cenomanian succession of clastics (Giraul Fm). Alluvial fans and braided rivers were shed over large areas at this time. In the northern part, west of Lucira, there are carbonates and marine sandstones, time equivalent to the Giraul Fm, which represent the transition to a marine environment (Santa Marta Fm). Near the Inamagando River, a progradational mixed carbonate-clastic succession is exposed (Inamagando Mbr). This has an upper contact with alluvial-aeolian clastics.

Onlapping and overstepping the tilted Albian and older units is a succession of fossiliferous marine to non-marine conglomerates, sandstones and carbonates of Latest Cenomanian to Turonian/Early Coniacian age (Salinas Fm). The sediments of the Salinas Fm are intruded and overlain by basanite rocks (Bentiaba Fm), dated as 88Ma in age (Coniacian). Locally subaerial to lacustrine carbonates include travertines, spring mounds, fissure ridges and silicified trees which grade laterally into lacustrine carbonates and mudstones (Mariquita Member).

The Bentiaba Fm is onlapped and overstepped by a transgressive wedge of fossiliferous Santonian to Campanian age sandstones (Piambo Fm). This unit forms an unfaulted, transgressive to regressive sequence of shelf margin, shoreface to lower delta plain sediments. A younger Maastrichtian transgression has a greater landward extent and consists of a simple transgressive-regressive cycle. At Chapéu Armado there is an undated nephelinite complex, which appears slightly younger than the Bentiaba Fm (Chapéu Armado Volcanic Complex).

The post Cretaceous stratigraphic record is represented by Eocene and younger shoreface to shelfal wedges and both marine and river terrace deposits.

Uplift Histories and Sedimentary Flux at Passive Margins: Examples from Africa

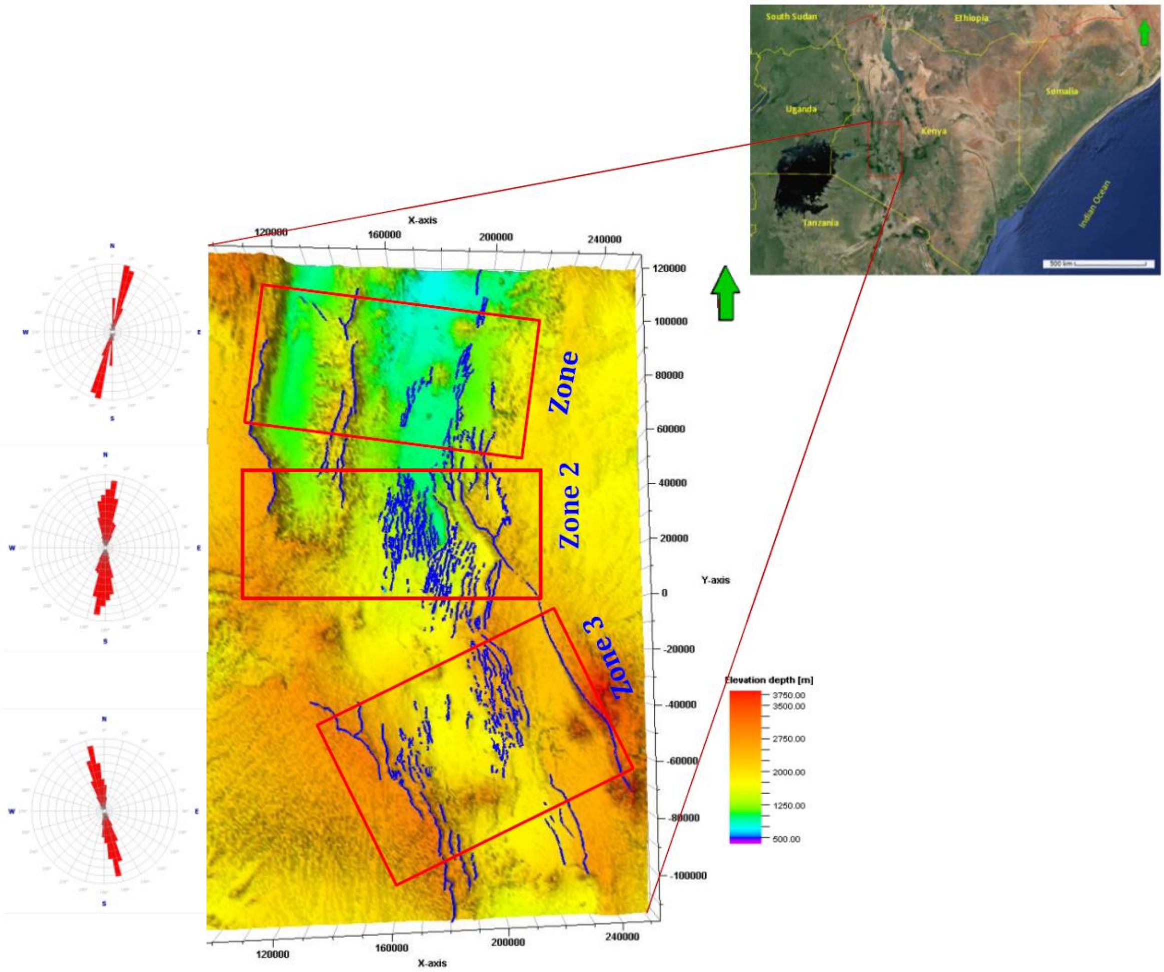
Bhavik Lodhia, Gareth G. Roberts, Al Fraser, *Department of Earth Science and Engineering, Imperial College London*

It is generally accepted that topographic swells in Africa have grown in response to changing patterns of sub-crust support. Drainage patterns, magmatism, uplifted terraces and sediment efflux at its margins indicate that sub-crust and probably sub-plate support has varied during the last 30 million years. We measure the Cenozoic sedimentary flux to the northwest African passive margin using a dense grid of 2D and 3D reflection data and 43 wells. Isopachs of six Eocene-Recent horizons have been mapped and tied to well data. Depth converted and decompacted isopachs indicate that solid sedimentary flux has varied during Cenozoic times. We compare our measurements to flux predicted by inverting a dense onshore drainage network centered on the Senegal River. Calculated Neogene uplift is consistent with removal of deltaic top-sets observed in the reflection data on West Africa's continental shelf. We tentatively suggest that Cenozoic dynamic support has controlled the delivery of sediment to the western seaboard of North Africa.

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 scaling properties of 502 faults within the central Kenya rift are examined for fault populations defined from ASTER DEM data. 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. Three fault populations with varying trends have been defined as zone1 (NNE), zone2 (NNE to NNW) and Zone3 (NNW). Fault size populations (maximum displacement, length and geometric moment) exhibit well-defined power-law distributions in the three zones. Knowledge of the power-law exponent (fractal dimension) allows assessment to be made about the mount of deformation in a given geological setting. Slight differences in the fractal dimension (slop) of displacement population reflect strain variations across the study area. A decrease in the slop of fault population with increasing strain indicates fault evolution, which is reflected by a northward increase in the rift growth. Variations in strain localization and fault orientation in the three zones with respect to extension direction can be attributed to the influence of pre-existing structures. This influence is marked by the well correspondence of the three defined fault population zones with the pre-existing structures that were defined as heterogeneous substratum and foliations in the Precambrian basement.



Three zones defined within the study area showing fault populations with distinct orientations.

Depositional Systems and Palaeothermal History in an Active Rift-Graben Setting and Its Effect on Hydrocarbon Systems, Upper Rhine Graben, Germany

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The Upper Rhine Graben (URG) in SW Germany, known as a classical hydrocarbon province in Germany and France, is part of the European Cenozoic Rift System. Active rift graben development has developed a complex sedimentary sequence of terrestrial and marine deposits. It is dominated by a thick clastic succession with several fine-grained, organic-rich units in between, providing several potential reservoir units and source rocks.

The study covers the almost the entire rift-basin fill, Upper Eocene to Lower Miocene, based on 4 wells in the northwestern URG. It aims to analyse the interaction between the active rifting and the sediment facies and paleoenvironment development and its effect on the development and quality of potential source rock units. Organic maturation is studied in addition to understand the complex palaeothermal history of this rift system and its effect on the development of active hydrocarbon plays.

Palynofacies analysis suggests rapidly changing sediment facies and paleoenvironements within the sediments through time due to rapid sea level changes and a complex tectonic setting during graben formation. Based on the results of petrographic, organofacies and geochemical analysis different types of source rocks are defined. The different types of source rock are characterized regarding their depositional history and hydrocarbon prospectivity, showing the influence of the rift-controlled depositional system of the northern URG on the generation and productivity of hydrocarbon source rocks. Detailed vitrinite reflectance analysis was done in all four wells. The high-resolution maturation trends help to understand the local to regional maturation pattern and mechanisms, controlling the palaeothermal history within the complex tectonic setting of the rift-system. Long-lasting, high-temperature hydrothermal fluid systems seem to have a significant effect on organic maturation in this tectonically active setting. The combination of the results of facies and maturation analysis provides new insights into the complex interaction between development, activation and prospectivity of hydrocarbon systems and the rift-graben development in the northern URG.

Lateral Magma Flow in Sill-Complexes: Towards A Paradigm Shift in Volcanology

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The structure of magma plumbing systems controls the distribution of volcanism, thereby influencing continental break-up and passive margin evolution. However, delimiting the structure of entire plumbing systems is difficult because: (1) intrusion networks cannot be directly accessed at active volcanoes; (2) field outcrops are limited by exposure; and (3) the resolution of geophysical data imaging the sub-surface is restricted. As a result, models involving the vertical transfer of magma in dikes, which extend from a melt source to overlying reservoirs and eruption sites, dominate the volcanic literature. Whilst there is evidence supporting the existence of vertically stacked plumbing systems, we compile a series of field- and seismic reflection-based case studies documenting the importance of extensive lateral magma transport (up to 4100 km) within sill-complexes. Most of these sill-complexes are emplaced into sediment-filled rift basins (e.g., Rockall Basin, NE Atlantic; Ceduna Sub-basin, offshore southern Australia; Karoo Basin, South Africa). There is also evidence that some sill-complexes occur within crystalline, continental crust (e.g., in the Yilgarn Craton, Australia). The case studies presented demonstrate that sill-complex emplacement is largely controlled by host rock lithology and structure, particularly in sedimentary basins. Mechanisms of sill emplacement have important implications for host rock deformation. For example, sill intrusion may be accommodated through roof uplift or, alternatively, via non-brittle processes (e.g., porosity reduction induced by host rock fluidization) that may not deform the overburden. We show that plumbing systems need not be vertically stacked. Magma can instead be transported within laterally extensive (up to 3 × 106 km2) sill-complexes, compartmentalising sedimentary basins and promoting the development of volcanoes that do not overlie the melt source.

Thermal Reconstruction in Extension Tectonics: Coupling Geodynamic Modelling With Petroleum System Modelling, the South Atlantic Conjugate Margins As a Case Study

Beniest, A., Burov, E., Cloetingh, S., Sassi, W., Guichet, X.,

Deep offshore oil exploration deals with petroleum systems situated in basins with a syn-rift and sag-basin history. The hydrocarbon potential of such a setting is still very uncertain, due to risks concerning too early maturation and subsequent hydrocarbon leakage. Progress in the field of geodynamics can be used to better predict the maturation history and petroleum system development. The thermal evolution of the South-Atlantic sedimentary basins has been studied with the use of a thermo-mechanical model that covers a time span of 100 Ma. The basins formed under pulsed extension during the Early Cretaceous. Absolute extensional velocities are determined from plate reconstruction software. Moho-temperature evolution over time, retrieved from the thermo-mechanical model, are implemented in a petroleum system modelling software. The Orange basin (offshore Namibia) and its conjugate the Colorado basin (offshore Argentina) are used as reference basins to investigate the effect of lithosphere scale processes on the source rock maturation of conjugate basins. Coupled phenomena between large-scale asthenospheric ascent, lateral flow of ductile materials in the lower crust and brittle structure of the upper crust are at the base of the thermal evolution. The thermal evolution of the basins resulting from crustal stretching, syn-rifting and continental break-up happen very fast in only few ten millions of years. With this study we suggest that fast, large-scale thermal processes have a yet to be quantified influence on the thermal evolution of sedimentary basins in the South Atlantic.

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

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