Rifts Renaissance: Stretching the Crust and Extending Exploration Frontiers

19-21 August 2008

The Petroleum Group and the Society for Sedimentary Geology would like to thank Apache Corporation, BHPBilliton, BP, Cobalt International Energy, ExxonMobil, ION GX Technology, Shell, and StatoilHydro for their support of this event:

Tuesday 19 August **Continents to Oceans**	
07:00	Registration + coffee
09:00	Welcome and opening
Session 1 *Sponsored by BHPBilliton* bhpbilliton	
09:25	Fraser, Scot, Mike Lentini and H. Scott Sumner Lithospheric stretching – Apparent paradoxes, contradictions and complexities
09:50	Manatschal, G. et al KEYNOTE: Field analogues to understand the evolution of hyper-extended ultra-deep water passive rifted margins: the examples of the Alpine Tethys and the Western Pyrenees/Bay of Biscay
10:15	Tea / Coffee
10:55	Sawyer, Dale S. and Stephen A. Clark West and South-directed mass wasting from the Galicia Bank: How these may affect interpretations of rifting processes during Atlantic breakup?
11:20	Crosby, Alistair et al Evolution of the Newfoundland-Iberia Conjugate Margins
11:45	Srivastava, Shiri and Jean-Claude Sibuet The Transition from Continental to Oceanic crust as recorded by magnetic anomalies along Passive Margins
12:10	Lunch

Session 2

Sponsored by Cobalt International Energy

13:30	Ian Norton, Lawrence Lawver, Lisa Gahagan Plate motion of Iberia relative to Europe in the Cretaceous: problems with the fit at MO time
13:55	Peron-Pinvidic, Gwenn and Gianreto Manatschal KEYNOTE: Constraints on magma-poor rifting evolution and continental breakup from the Iberia-Newfoundland conjugate margins
14:20	Harry, Dennis L. Shifts in extension centers and the transition from amagmatic rifting to sea-floor extension
14:45	Shillington, Donna J. et al An abrupt transition from magma-starved to magma-rich rifting in the eastern Black Sea
15:20	Tea / Coffee
15:45	Corfield, Richard et al Break-up history of a volcanic margin: Western India and Pakistan
16:10	Dickson, William G. et al Broad versus Deep: Viewing the Steershead from the Stratosphere
16:35	Bird, Dale and Kevin Burke Geodynamic evolution of extended rift terrains
17:00	Manik Talwani, Dale Sawyer, John Hopper, Brian Tucholke, Greg Mountain, Brandon Dugan, David Feary, Jerry Dickens, Mike Arthur, Brad Sageman Exploration-Focused Rifted Margin Drilling Using the D/V JOIDES Resolution
17:30	Wine Reception

Wednesday 20 August
Models to Margins

07:30	Registration + coffee
	Session 3 *Sponsored by BP and Shell*
08:15	Introductory Remarks
08:35	Ranero, Cesar R. and Marta Perez-Gussinye KEYNOTE: A Tectonic Model of Faulting during Rifting and the Development of the Asymmetry of Conjugate Non-volcanic Margins
09:00	Kusznir, N.J. and R.J. Fletcher KEYNOTE: Sag Basin Development and Rifted Continental Margin Asymmetry
09:25	Reston, Tim The extension discrepancy at rifted margins: unrecognised faulting or depth-dependent stretching (DDS)
09:50	Ritske Huismans KEYNOTE: Dynamical Models of Depth-Dependent Lithospheric Extension at Rifted Continental Margins: Effects of Strong and Weak Lower Crust
10:15	Tea / Coffee
10:55	Lavier, Luc and Gianreto Manatschal Modeling the Tectonic and Thermal Evolution of Rifted Margins
11:20	Heine, Christian et al A global review of intraplate basin evolution in a mantle dynamic and plate kinematic framework
11:45	White, Nicky et al The Vertical Expression of a Horizontal Flow: Stratigraphic Manifestations of Transient Mantle Convection
12:10	Lunch

Session 4

Sponsored by ExxonMobil and StatoilHydro

ExxonMobil StatoilHydro

13:30	**Rupke, L.H. et al** Automated Thermotectonostratigraphic Reconstruction of Sedimentary Basins in Frontier Areas
13:55	**Roberts, Alan et al** Mapping crustal thickness and the ocean-continent-transition in the Santos and Campos Basins, Brazilian South Atlantic
14:20	**Heyn, Teunis et al** Modern Analogue for Interlayered Evaporites and Seaward Dipping Volcanic Reflectors: Danakil Depression, Northern Afar, East Africa
14 :45	**Hooper, Robert et al** Testing experimental concepts for oblique rifting with outcrop data from the Western U.S.A. and subsurface data from European Basins
15:20	Tea / Coffee
15 :45	**Hunsdale, Rob, Jon Blickwede and Terje Veum** Identifying and understanding the role of thick skinned crustal elements in basins and margins dominated by thin-skinned deformation: examples from the Gulf of Mexico and South Atlantic
16 :10	**Dinkelman, Menno G. et al** Transition between Oceanic and Continental Rift Systems as exemplified by short-lived, small ocean basins
16 :35	**Lentini, Michael and Scot Fraser** Observations from the South Atlantic - How Conjugate is the Conjugate Margin?
17 :00	**Mohriak, Webster et al** Geological and geophysical interpretation of the Rio Grande Rise, Southeastern Brazilian margin: extensional tectonics and rifting of continental and oceanic crusts
19 :00	Conference Dinner

Thursday 21 August Basins to Barrels	
07:30	Registration + coffee
Session 5 *Sponsored by Apache Corporation*	
08:15	Introductory Remarks
08:35	Larry L Garmezy & Robin F M Hamilton HC exploration in rift basins - past, present, future
09:00	Stern, Robert J. et al <u>KEYNOTE</u>: Towards Understanding the Formation of the Gulf of Mexico: Evidence for a Late Triassic Precursory Domal /Rift Flank Uplift and a Volcanic Rifted Margin for the Texas-Louisiana sector of the Gulf of Mexico
09:25	Fillon, Richard H. et al Shallow computed depth to "magnetic basement" relative to correlated Mesozoic well and seismic stratigraphic events in the Gulf of Mexico: Evidence for the nature of Yucatan block rotation?
09:50	Scholz, Christopher A. and Robert P. Lyons <u>KEYNOTE</u>: Precessional Forcing of Lacustrine Source Rock Facies: Recent Results from Scientific Drilling in Lake Malawi
10:15	Tea / Coffee
10:55	López-Gamundí, Oscar Sedimentation styles and variability of organic matter types in the Triassic, nonmarine half-grabens of west Argentina: implications for petroleum systems in rift basins
11:20	Reynolds, Dave Structural and climatic controls on evolving drainage systems in extensional basins
11:45	Underhill, John The role of release faulting in controlling the development and hydrocarbon prospectivity of rift basins
12:10	Lunch

Session 6 *Sponsored by ION GX Technology* GX TECHNOLOGY	
13:30	Teasdale, J. P., and L. Jensen A new structural model for the pre-salt Santos Basin, Brazil, based on 'bottom-up' basin analysis
13:55	Wilson, R. W. et al Structure and evolution of the Santos Basin, SE Brazil – oblique extension, strain partitioning and implications for South Atlantic Rift evolution
14:20	Moy, D.J. et al The tectono-stratigraphic evolution of the NW Vøring Basin, offshore Norway: the role of transfer zones in rift and passive margin segmentation
14:45	Sumner, H. Scott Tectono-Stratigraphic Framework and Petroleum Systems of Transtensional Tertiary Rift Basins in Southeast Asia
15:20	Tea / Coffee
15:45	Cullen, Andrew B., Paul Reemst, Catalina Acuna Working Towards Intra-plate Models for SE Asia Rift Basins
16:10	Sinclair, I.K. et al A detailed view of rift structure and tectonostratigraphy within the Jeanne d'Arc Basin with regional implications for the Grand Banks region, Newfoundland
16:35	Baum, Mark S. et al Oblique inversion of the Fundy rift basin on the passive margin of southeastern Canada
17 :00	Henry, Steve, Al Danforth and Sujata Venktraman Indian Continental Margin: Diachronous Rifting, Ridge Jumps and Continental Fragments
17 :25	Wrap-up and concluding remarks
17 :35	End of Conference

Tuesday 19 August

Continents to Oceans

Session 1
Sponsored by BHPBilliton

Lithospheric Stretching – Apparent Paradoxes, Contradictions and Complexities

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The lithospheric mantle and whole crust response to extensional stresses results in the development of rift basins. Whether the origin of the extensional stresses is manifest at the plate margin or in an intra-plate continental setting, a definitive model that predicts the syn-rift and post-rift thermo-mechanical response of the lithospheric mantle and whole crust to rift-related processes remains equivocal. Established rift theory proposes two end-member deformation models that describe extension of the brittle upper crust and ductile lower crust in terms of pure and simple shear strain mechanisms. Both models only consider the instantaneous transition to organized oceanic spreading without any implication for complex episodic or poly-phase extension history. This assumption whilst elegant in its clarity appears contradictory to observed tectono-stratigraphic relationships recorded by continued movement on extensional border faults over several millions of years in known rift basins. Indeed where slow rates of extension are inferred distributed extension develops broad regions of lithospheric deformation and wide rifts evolve. Additionally, these rift paradigms predict the development of symmetric planar fault-controlled extensional basins or alternatively asymmetric basins dominated by crustal–scale low angle detachment faults that potentially span the entire lithosphere. Implicit within each model is a distinctive symmetric and asymmetric lithospheric cross-section. The resultant structural configuration is critical to understanding how modeled thermal stress is accommodated by the extended crust and transferred to the rift-related sedimentary sequence during basin development. The geometry of the low angle detachment surface consequent of simple shear deformation determines the relative lateral displacement of crust and lithospheric mantle thinning. The two rift models describe contrasting thermo-mechanical geometry's with respect to the rift axis. The consequence of elevated heat flux from the perturbed lithosphere to the base of the rift requires careful consideration when trying to quantify or predict the spatial distribution of post-extensional, thermal subsidence patterns. The magnitude and extent is dependant on the assumed stretching mechanism and or rift model. Indeed, anomalously thick late syn-rift thermal "sag" sequences have been explained by invoking differential stretching of the brittle crust and lithospheric mantle. The depth dependent stretching model seeks to reconcile the discrepancy between the paucity of syn-tectonic extension in relation to apparent thermal subsidence. Whilst the thermal and structural simplicity of these end-member models seems appealing, new empirical data from the South Atlantic basins suggests that the inferred mutual exclusivity of the models is somewhat challenged. Theoretically, the along-strike co-existence of apparently end-member simple and pure shear extensional characteristics seems paradoxical. However, a series of thermo-structural boundaries are interpreted to partition along-strike crustal behavior in the South Atlantic Margin basins whilst convergent evidence from recent geophysical datasets implies crustal thickening processes appears to be an important mechanism that accompanies South Atlantic rift basin formation. The nature and transition to oceanic crust from highly attenuated continental crust demonstrates significant along-strike variability. We contend that this is further evidence for a complex rift margin evolution and that the simple theoretical models now require to be challenged based on these new integrated relationships. The basins of the South Atlantic Margin provide an exceptional laboratory in which to do so and new datasets are providing further insight into the anomalies that require reconciliation.

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Field analogues to understand the evolution of hyper-extended ultra-deep water passive rifted margins: the examples of the Alpine Tethys and the Western Pyrenees/Bay of Biscay

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The study of rifted margins is incontestably undergoing a paradigm shift. The discovery of exhumed continental mantle and hyper-extended crust devoid of significant normal faulting directly overlain by shallow marine sediments, as observed in the Iberia-Newfoundland and S Atlantic margins, is proving fundamental in defining the controls and processes that thin continental lithosphere. However, the development of these new concepts and their application in the hydrocarbon industry critically depends on the access to pertinent geological and geophysical data sets, which remains a key problem. At present, little is known about the depositional environments, sedimentary facies, the kinematics, age of structures, or the subsidence and thermal history of pre-to syn-rift sediments of many distal margins. Having access to these data is necessary in order to test in a rigorous way the new conceptual and numerical models proposed for the evolution of hyper-extended ultra-deep water rifted margins.

The aim of our presentation is to describe the rift structures and related crustal and mantle rocks and depositional systems associated with extreme crustal thinning observed in the Western Pyrenees-Bay of Biscay and ancient Alpine Tethys margins. In both examples top-basement detachment faults occur and can be traced from relatively unextended continental crust towards exhumed mantle and in the Alps, into the first embryonic oceanic crust. These structures are overlain by extensional allochthons, tectono-sedimentary breccias and syn- and post-rift sediments and, further oceanwards, by MOR-basalts. In detail, these structures are complex and can not be described as one simple low-angle detachment fault as commonly shown in the classical simple shear model. Our investigations suggest that extension at these rifted margins developed through a sequence of rift phases. In the case of the Alps, rifting initiated with distributed normal faulting that was followed by localization of the deformation in a conjugate system of upper crustal and lower crustal/mantle detachment faults. In the case of the Western Pyrenees/Bay of Biscay, rifting initiated with a strong transtensional component that prestructured the area of later extension resulting in more segmented and asymmetric rift basins. In both cases, the detachment faults that were responsible for the thinning of the crust interacted and were decoupled along mylonitic shear zones in a quartz-rich middle crust. During this stage, the future distal margins remained at shallow water conditions. Only when the crust became brittle, i.e. when it was attenuated to less than 10 km, detachment faults were able to cut through the entire crust and to exhume mantle. This process is associated with a fast subsidence of the distal margins. Although in both examples there is a lack of syn-rift volcanic activity, in the Alps, magmatic infiltration has occurred in the underlying mantle while the crust was thinning, whereas in the Western Pyrenees/Bay of Biscay extensive magmatic activity post-date mantle exhumation. These crucial observations have major implications for the thermal evolution and consequently for the rheology and isostasy of the extending lithosphere and the survivability of syn-to post-rift petroleum systems in hyper-extended margins.

NOTES

West and South-directed mass wasting from the Galicia Bank: How these may affect interpretations of rifting processes during Atlantic breakup?

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We interpret seismic profiles ISE-1 and ISE-9, crossing the west and south sides of the Galicia Bank, west of Spain in the Atlantic Ocean, to show evidence of very large mass wasting events presumed to have occurred late in or shortly after the process of continental breakup and the initiation of seafloor spreading. The events were presumably driven by large topographic relief created at the boundary between the half-thickness, extended, continental crust of the Galicia Bank (0 to 1.25 km water depth) and crust composed of mantle rocks exhumed to the seafloor (Zone of exhumed continental mantle; ZECM; 4 to 7 km water depth) after the continental crust had separated and before normal seafloor spreading was established. The landslide material is interpreted to consist of blocks of Galicia Bank extended continental crust and pre-sliding sediment. A portion of this slide material was likely emplaced over the ZECM and this relationship could easily be confused with detachment faulting tectonics. To the west of the Galicia Bank, the proposed west-directed landsliding would be in the same direction as the rift extension direction and therefore difficult to unambiguously separate. However, the proposed south-directed landsliding is normal to the rift extension direction and therefore more clearly distinct.

We examine possible consequences of this controversial hypothesis for the well-known and widely interpreted ODP Legs 149 and 173 drilling in the Iberia Abyssal Plain and nearby seismic profiles Lusigal 12 and IAM-9. We interpret that profile Lusigal 12 crosses the foot of the proposed south-directed landslide. We argue that the several low-angle faults (including H, HD, and HDD) observed in profile Lusigal 12 were formed within and at the base of the foot of the slide covering ZECM. We interpret that profile IAM-9 crosses the region of ZECM just to the south of the toe of the landslide. However, because the landslide moved continental crustal blocks to the south of their original position, we interpret that the pre-slide boundary between extended crust of the Galicia Bank and ZECM lies tens of km north of its presently mapped position. Specifically, we map this boundary north of both profile Lusigal 12 and the ODP 149/173 drilling transect. This suggests that the eastern part of the drilling transect overlies mantle rocks that were exhumed at the seafloor and existed at the seafloor for some time before the continental rocks and pre-rift sediments were placed on top by southward sliding off the Galicia Bank. If true, this contrasts with the now commonly accepted model in which the eastern part of the drilling transect lies over mantle that was continuously covered by continental crust and pre-rift sediment, and where all movements of continental crust were to the west in detachment-bounded slivers.

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Evolution of the Newfoundland-Iberia Conjugate Margins

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It is accepted that mildly extended sedimentary basins form by largely uniform thinning of continental lithosphere. No such consensus exists for the formation of highly extended conjugate rifted continental margins. Instead, a wide range of models which invoke differing degrees of depth-dependent thinning has been proposed. Much of this debate has focussed on the well-studied Newfoundland-Iberia conjugate margins. We have tackled the problem of depth-dependency at this pair of margins in three steps. First, we have reconstructed water-loaded subsidence histories by making simple assumptions about changes in water depth through time. Secondly, we have used these reconstructed subsidence histories to determine the spatial and temporal variation of lithospheric strain rate. An inversion algorithm minimizes the misfit between observed and predicted subsidence histories and crustal thicknesses by varying strain rate as a smooth function of distance across the margin, depth through the lithosphere, and geologic time.

Depth-dependent thinning is permitted but, crucially, our algorithm does not prescribe its existence or form. Given the absence of significant volumes of syn-rift magmatism, we have also applied a minimal melting constraint. Inverse modeling has yielded excellent fits to both reconstructed subsidence and crustal observations, which suggest that rifting occurred from c.150-135 Ma and at rates of up to 0.3/Ma. Strain rate distributions are depth-dependent, suggesting that lithospheric mantle thins over a wider region than the crust. Beneath highly extended parts of the margin, crustal strain rates greatly exceed lithospheric mantle strain rates. Thirdly, we have tested our strain rate histories by comparing the total horizontal extension with the amount of extension inferred from normal faulting patterns. Both values agree within error.

We freely acknowledge that there are important uncertainties in reconstructing the subsidence histories of deep-water margins.

Nevertheless, stratigraphic records remain the only, albeit imperfect, means of determining how crust and lithospheric mantle thin through time and space.

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The Transition from Continental to Oceanic crust as recorded by magnetic anomalies along Passive Margins

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Detailed geological and geophysical measurements and deep sea drilling across the Iberia and Newfoundland margins have shown that a large part of these margins are underlain by exhumed mantle rocks forming transition zones. Yet across these transitional zones we observe the presence of magnetic anomalies, which can be modeled using geomagnetic reversal time scale during Mesozoic as if they were formed by seafloor spreading. The question then one asks is: what causes these anomalies as there does not seem to be presence of any basalt in these regions? In a recent paper, Sibuet et al. (2007) have proposed that mantle during its exhumation to crustal levels get serpentinized and magnetized in the same way as the basalt does during its cooling cycle thus creating magnetic anomalies similar to those produced by seafloor spreading. On the basis of paleomagnetic and geological data of the drilled samples from Iberia-Newfoundland margins and a comparison with fossil ocean-continent transition in the Alps, they proposed that during the exhumation of sub-continental mantle i) a first episode of mantle serpentinization takes place, during which a strong component of magnetization is acquired ii) a second episode when it outcrops at the seafloor and enters into contact with the cold sea water. Serpentinized peridotites are altered in the upper tens of meters without acquiring new magnetization. Therefore, the serpentinization of exhumed mantle during the first episode of exhumation is able to produce magnetic lineations formed in a way similar to those formed by seafloor spreading with the exception that the degree of magnetization can vary somewhat along it unlike in the basalts formed by seafloor spreading. This then gives rise to magnetic anomalies, which can vary in amplitudes unlike those formed by seafloor spreading. The implications of this finding are enormous as it makes magnetic anomalies over exhumed mantle rocks as informative in our studies as those created by seafloor spreading.

Within the transition zones, sequences of magnetic lineations can thus provide information concerning the timing of emplacement of crust but not its nature (oceanic versus exhumed mantle). For example, we find ages of exhumed mantle rocks at Ocean Drilling Program Sites 1068 and 1070 in the Iberia Abyssal Plain and Site 1277 in the Newfoundland Basin comparable with those obtained from the overlying magnetic anomalies at these sites. It then raises the question concerning the reasons of sub-mantle exhumation. The answer probably lies in the lack of melt available within the upper part of the mantle due to i) slow to ultra-slow extension in such regions as suggested by the modeling of magnetic anomalies and ii) the rifting processes, which involves the mantle to flow from beneath the thinned continental crust in order to afford for the depth dependent extension during the last phase of continental rifting. The paper discusses this type of ideas with examples from different parts of the world to illustrate the variability of the transition zones across passive margins.

Sibuet J.-C., Srivastava S. and Manatschal G., 2007. Exhumed mantle-forming transitional crust in the Newfoundland-Iberia rift and associated magnetic anomalies, J. Geophys. Res., 112, B06105, doi:10.1029/2005JB003856.

NOTES

Session 2
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Plate motion of Iberia relative to Europe in the Cretaceous: problems with the fit at MO time.

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Conjugate sets of sea floor magnetic chron M0 (120 Ma, Early Aptian) that have been mapped between Iberia and Newfoundland provide an apparently well-constrained plate reconstruction of Iberia relative to North America. Other North Atlantic-bounding plate positions are less well constrained in the Early Cretaceous because these reconstructions require estimates of total extension vectors in basins bordering the North Atlantic. Published estimates of extension can, however, be used to build a satisfactory plate fit of Europe to North America in the Early Aptian. The resulting plate reconstruction shows a large, eastward-widening gap between eastern Iberia and Europe in the space now occupied by the Pyrenees. With M0 being at the beginning of the Cretaceous Superchron, the next youngest available plate reconstruction constrained by sea floor magnetic data is chron 34 (83 Ma, Campanian). The position of Iberia relative to Europe in this reconstruction suggests that the gap that existed between Iberia and Europe in the Aptian (at least in the M0 reconstruction) was closed by Campanian time. This implies several hundred kilometers of convergence between Iberia and Europe in the mid Cretaceous. Although feasible, such a large convergence amount should be recorded as a foldbelt and/or subduction system. Available data from the area suggest, however, that the mid Cretaceous was a time of tectonic quiescence, with the Pyrenean orogeny only initiating in the Eocene. One possible implication of these observations is that the fit of M0 is incorrect and that the magnetic lineation mapped as M0 is in fact not a sea floor spreading lineation. M0 occurs at the boundary between normal oceanic crust and the wide zones of exhumed mantle material found on both the Iberian and Newfoundland margins. We suggest that the M0 lineation is caused by a boundary effect between these different domains. An additional implication is that the boundary itself is not an isochron and is diachronous, with the transition from exhumation to sea floor spreading getting progressively younger to the north along both margins.

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Constraints on magma-poor rifting evolution and continental breakup from the Iberia-Newfoundland conjugate margins

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First models of magma-poor rifted margins proposed uniform continental crust formed by tilted blocks juxtaposed, along a sharp boundary, against a three layered oceanic crust. It was generally considered that rifting is monophase and breakup instantaneous. The discovery of exhumed mantle rocks along the Galicia margin began to severely scrutinize the validity of this pure shear model and resulted in the development of other models as the simple shear one. During the last 20 years, the increasing number of high quality seismic surveys enabled, together with magnetic and gravimetric investigations, to constrain the geophysical characteristics of the deep rifted margins. However, the more detailed description resulted in unexpected results. The simple juxtaposition of continental and oceanic crusts with a well defined boundary has been replaced by a zone of exhumed continental mantle, often also referred to as an ocean-continent transition. This zone exhibits specific characteristics that are neither continental nor oceanic like weak and nonlinear magnetic anomalies, pronounced basement topography, a particular seismic velocity structure with strong gradients and a lack of a clear Moho reflection.

All these observations fundamentally question the concepts and initial models used to explain rifted margins and ask to propose new models. Questions such as: what and where is the first oceanic crust, what is syn-rift, what processes thin the continental crust, altogether considered as being answered, return back in the domain of research. The change in paradigm that is currently taking place ask to reevaluate more carefully the available data sets in order to scrutinize the existing generic models that are shown to be inapplicable to deep margins.

Our work aims to examine the morphotectonic evolution of the distal domains of the Iberia-Newfoundland margins in order to constrain their final rifting and continental break-up history. The architecture of basement structures and dated sedimentary units has been mapped and drilling results from ODP legs have been reviewed. We established a composite section across the conjugate system and inverted it in order to describe the evolution of rifting and continental breakup. The results show evidence for a complex overall migration and localization of deformation into the area of final breakup that is linked with a change in the mode of deformation. These observations strongly underline that classical indicators used to determining location and age of breakup can not be used as stand alone criteria. Recurrence of distributed tectonic extension and magmatic activity even after onset of localized seafloor spreading suggests that continental breakup is a polyphase, transitional and complex process that can occur, in magma-poor environments, over 10s of millions of years and result in hundreds of kilometers of crust that is neither oceanic nor continental. Although our study is limited to the Iberia-Newfoundland rift system, comparisons with other margins suggest that the described evolution is probably more common and applicable for a large number of rifted margins. These new results have major implications for plate kinematic reconstructions and ask to rethink the terminology, the processes, and the concepts that were used to describe continental breakup.

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Shifts in extension centers and the transition from amagmatic rifting to sea-floor extension

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The pre-rift thickness of the crust and thermal state of the lithosphere exert primary control on the mode of continental rifting. High heat flow and thick crust promote a core complex mode of rifting, characterized by formation of a low angle detachment and structural exhumation of the middle and lower crust. Low heat flow and thin crust promote a narrow mode of rifting, characterized by high-angle normal faulting and rift flank uplift. A wide rift mode may occupy an intermediate state at relatively low extension rates. This mode of rifting is characterized by extension distributed over ca. 1000 km and may involve both high- and low-angle faulting.

Local strength heterogeneities modulate the mode of rifting and are responsible for shifts in intra-rift depocenters. These can be separated into two classes. 1) Intrinsic heterogeneities, which result from minor variations in rock properties (e.g., cementation, grain size, composition, and structural fabric) over scales of meters to kilometers. Geodynamic models parameterize intrinsic heterogeneities in a stochastic fashion, and have shown that they can lead to periodicity between intra-rift basins and uplifts on wavelengths of the order of 10’s of km, depending on the thickness and temperature of the crust. 2) Inherited heterogeneities, which are produced by major prior tectonic events. In many rifts these are associated with previous orogenic episodes. In such instances, faulting and/or foreland basin formation create weaknesses in the crust that control early syn-rift subsidence and basin formation. The thickened crust in the orogen hinterland creates a weakness in the mantle that controls the location of lithospheric necking and, ultimately, continental breakup. The interaction of these inherited heterogeneities cause shifts in depocenters during rifting over scales of 100’s of kilometers and 10’s of million years, resulting in the formation and later abandonment of interior rift basins.

The location and relative magnitudes of the crust and mantle weaknesses may also determine the magmatic behavior of the rift. If the crustal weakness is comparable in magnitude to the mantle weakness and the two weaknesses are not co-located, lithospheric thinning is initially distributed over a broad region that includes both the crust and mantle weaknesses. This results in a prolonged period of magmatic rifting. Once lithospheric necking becomes focused, extension shifts away from the crustal weakness, where the early rift interior basins form, and into the region where the mantle weakness is located. This results in formation of deep offshore basins adjacent to the ocean-continent boundary. If the magnitude of the crustal weakness is small in comparison to the mantle weakness, only minor off-axis extension occurs and lithospheric thinning is restricted to the region encompassing the mantle weakness. In such instances, prolonged amagmatic rifting may occur before lithospheric necking becomes pronounced. Once necking becomes focused, it progresses rapidly to seafloor spreading. In such circumstances, magmatism may not begin until as little as 2 m.y. before breakup, and is restricted to a ca. 20 km of the ocean-continent boundary.

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An abrupt transition from magma-starved to magma-rich rifting in the eastern Black Sea

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The amount of magmatism that accompanies the extension and rupture of the continental lithosphere varies dramatically at rifts and margins around the world. Quantifying the volume and distribution of synrift magmatism is important for hydrocarbon exploration in frontier basins because it is an indication of the thermal history and can modify the crust and the oldest sediments. Some margins preserve a transition from magmatically-robust to magmatically-starved rifting along strike (e.g., offshore Nova Scotia, Gulf of California, etc). A gradual transition from magma-poor to magma-rich rifting is expected to result from along-strike changes in mantle temperature or composition, strain rate or other factors that influence synrift melt production. We present data and results that provide the first images of such a transition and show that it is abrupt.

In February-March 2005 we conducted a major seismic experiment using ocean bottom seismometers across the eastern Black Sea Basin, a deep rift basin of uncertain age and crustal affinities and a frontier basin for hydrocarbon exploration. We acquired four long wide-angle seismic profiles across different parts of the basin, including a ~450-km along-strike profile, using a 9-gun, 3140 cu. in. airgun array, tuned to provide a seismic source rich in low frequencies. On each profile, between 14 and 34 four-component ocean bottom seismometers were deployed, and the airguns were fired at 60 or 90 s intervals. Shots were also recorded on three-component land stations up to 50 km from the coast. The lines were approximately coincident with existing industry deep seismic reflection profiles. The experiment resulted in a very high-quality dataset, with reflected and refracted phases recorded from a series of sediment layers, from the crystalline crust, and from the uppermost mantle. Wide-angle seismic data were modeled using both first-arrival tomography and joint reflection-refraction tomography.

Analysis of crustal arrivals revealed substantial along-strike changes in crustal thickness and type in the basin. In the western part of the basin, continental crust thins abruptly from ~32 km to ~8 km over ~30 km distance across the northeastern margin of Archangelsky Ridge, and thinned continental crust appears to be present across the center of the basin, with no evidence for magmatic addition to the crust during rifting. In contrast, the eastern part of the basin is underlain by 11-13 km crust with a velocity structure typical of thickened oceanic crust, indicating robust magmatism. The transition between these two crustal types takes place over only 20-30 km along-strike and appears to coincide with an inferred NE-SW-trending transform fault. These results indicate that 3D mantle flow and melt focusing, which are observed in modern rifts and mid-ocean ridges, can produce sharp along-strike changes in magmatism in the presence of gradual changes in mantle properties.

NOTES

Break-up history of a volcanic margin: Western India and Pakistan

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Volcanic passive margins are widely understood to form where continental break-up is associated with anomalously high mantle potential temperatures resulting in voluminous extrusive and intrusive volcanism. Due to challenges in imaging beneath the basaltic extrusives understanding of the underlying rift geometry associated with the passive margin formation is typically difficult in this setting. We present a case study which provides new data and interpretation of the three-dimensional structure of a volcanic margin.

In this case study we examine the complex break-up history of the west-Indian margin. Initial separation of Africa occurred between the Indian and Madagascan continent in the late Jurassic following a prolonged period of rifting during the Jurassic. Remnants of this phase of passive margin formation are preserved in the onshore Indus Basin in Pakistan and potentially in the offshore Indus basin. There was no significant volcanism associated with this break-up event.
In the Cenomanian-Turonian Madagascar separated from India resulting in the formation of a new passive margin along the western Indian margin south of the Indus basin. Once again there was no significant volcanism associated with this break-up event.

The final phase of passive margin formation in western India occurred at the Cretaceous-Tertiary boundary when the Seychelles very rapidly broke away from the Indian margin associated with massive volcanism and the extrusion of the Deccan Traps. There was significant along strike variability in the style of break-up. Offshore Mumbai break-up took place between India and a fragment of continental crust preserved in the Laxmi ridge with a subsequent jump to spreading between the Laxmi ridge and the Seychelles. To the south of Mumbai in the Konkan-Kerala basin the end Cretaceous break-up may have occupied a position close to the pre-existing continent-ocean boundary.
The northern limit of the break-up event is evident beneath the Indus Fan with interpreted transform faulting accommodating the northern termination. The transform faulting appears to have formed the locus for a chain of NE-SW trending volcanic seamounts beneath the Indus Fan sediments. These formed topographic highs for the development of shallow water carbonates flanked by basins with deeper water facies during the Paleocene-Eocene post rift phase.

The presented structural evolution provides important insights into the interaction of a mantle plume with an evolving passive margin and the degree to which the break-up is controlled by the presence of a region of elevated mantle potential temperatures.

NOTES

Broad versus Deep: Viewing the Steershead from the Stratosphere

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Our efforts since 1998 have generated multi-disciplinary, regional overviews on both coasts of the Atlantic and across East and Southeast Asia. The foundation of synthesized potential field and related data have demonstrated generational improvements in coverage and resolution but local features smaller than 5 – 10 km in x and y are seldom imaged. Given the scope and typical resolution of these projects, the resulting interpretations are necessarily broad and based on plan view.

The regional gravity isostatic anomaly (GI) normally follows basement architecture and its first vertical derivative (GI-1VD) is an excellent proxy for basement structure in most of the study areas. Exceptions are few but noteworthy: deep detachment basins of SE Asia (the Malay Basin and Red River Basin, both relatively young pull-apart rifts), and the Congo and Amazon Fans where recent sediments are so thick as to mask basement signature. Combinations of other gravity attributes with magnetic and other data still reveal the tectonic framework of these basins with just a little extra effort.

Anomalies that are clearly geological but not necessarily well-explained by standard plate tectonic theory are common in both Atlantic and Asian regions. The sheer number of anomalies means that few are investigated in profile view using model inversions constrained by deep penetration multi-channel seismic and wells.

Recurrent observations of a band of anomalous crust ('the broad') around the Atlantic margins may evidence transitional basement flooded with early basaltic intrusives, basaltic plateaux characteristic of the initiation of spreading, or hyper-extended continental crust; we call this "proto-oceanic crust". Long-standing experience in the Atlantic suggested a similar presence in the South China Sea, along truly passive components of its margin. One area in the NE South China Sea shows comparable characteristics, but seems to be older simatic crust.

Other than ridge-normal fracture zones, various features dot Atlantic oceanic crust along trends that match up with zones of weakness in adjacent continental crust. Some of these correlations are striking on paleo-reconstructions from 99 to 168 Ma, raising questions about propagation of continental trends as ocean basins are formed. It is probably causal that oil families and basins are separated by at least two of these trends.

We invite discussion or further work ('the deep') that might extend our understanding onto a more predictive basis.

NOTES

Geodynamic evolution of extended rift terrains

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Back-arc extension occurs along convergent plate boundaries by rifting in the overriding plate that is commonly attributable to slab rollback. Within oceans, rifting of island arcs leads to the formation of small oceanic back-arc basins. Where ocean floor is subducted beneath a continent, extension typically produces arc-crestal rift basins that are 100 to 200 km wide, although in some cases those rifts may also develop into small ocean basins. We concentrate on broad regions of extended continental rifting in the Great Basin, the Aegean Sea and Western Anatolia province, the sub-West Siberian Basin, and the combined Lord Howe Rise and Norfolk Ridges rift systems. These regions are here called Extended Rift Terranes (ERT). An ERT is a broad continental region, greater than 500 to 600 km wide, characterized by basin and range type geomorphology that may include metamorphic core complexes and major detachments. The tectonic conditions that lead to ERT development appear to be relatively rare because less than 1% of over 550 rift basins identified globally lie within ERTs.

The proposed model suggests that ERTs form where low strain rates are produced as a result of high angles of relative motion between subducting and overriding plates in relation to the intervening trench. The ERTs studied here formed as back-arc basins, but typical rollback induced extension was accompanied by lateral motion of the overriding plate relative to the subducting slab. Lateral motion in the Great Basin and in the Aegean Sea / Western Anatolia province are related to the San Andreas and North Anatolian Fault systems. Similar strike-slip motion has been suggested to have been a component of motion as the sub-West Siberian Basin and Lord Howe Rise / Norfolk Ridges rift systems formed. The effect of this motion was to reduce the strain rate in the overriding plates and in that way to generate regions of strain softening over an extensive area.

NOTES

Exploration-Focused Rifted Margin Drilling Using the D/V JOIDES Resolution

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We are proposing to use the D/V JOIDES Resolution, the vessel ordinarily used for the Integrated Ocean Drilling Program (IODP), for 16 months of drilling between 2010 and 2013. Our work will be a collaborative program focused on science objectives of high value to the academic and commercial communities and has been developed with three themes in mind: an improved understanding of rifting and early seafloor spreading, the distribution and properties of deep water sands, and the development of petroleum source rocks associated with oceanic anoxic events. Areas of operation extend from the Norwegian-Greenland Sea to the S. Atlantic.

The first theme is designed to investigate the genesis and evolution of extensional margins and basin architecture Rifted continental margins show great diversity and the processes that govern continental breakup remain among the least understood aspects of plate tectonics. These processes control the deformation history, the thermal history, and the uplift and subsidence history of the world's rifted margins and have important implications for understanding prospective petroleum systems in frontier exploration areas. The proposed drilling will explore three key regions where essential information regarding the geologic and tectonic history is currently lacking and where fundamental new knowledge regarding the mechanics of extension can be gained. We will obtain stratigraphic data from the continental margin off NE Greenland, and on the Jan Mayen micro-continent north of Iceland. We will drill through basalt on the Moere margin in the Norwegian Sea and sample the sub-basalt sediments. We will test the top basement detachment hypothesis at the Flemish Cap off Newfoundland. We will sample deep stratigraphy and basement seaward of the salt in the Pernambuco Basin off NE Brazil.

The second theme will test fundamental models of shelf, slope, and basin floor sedimentation. All drilling in this component will be in areas with 3D or high-density, high-resolution 2D seismic data that provide an advanced level of baseline information. The JOIDES Resolution will drill transects of densely-spaced holes and employ Logging-While-Drilling and Advanced Piston Coring to determine mechanisms, timing, and rates of transfer of sediment from shelf-margins to slope basins at spatial and temporal precision previously unavailable. Two areas are proposed: a series of linked mini-basins of the Brazos-Trinity system in the central northern Gulf of Mexico, and the shelf-margin Fuji-Einstein delta and adjacent channel-levee complexes in the northeastern Gulf.

The third theme is a study of the distribution of Cenomanian-Turonian source rocks in the South Atlantic Ocean. The Cenomanian-Turonian Boundary (CTB), which occurred in the middle Cretaceous about 93.5 million years ago, marks a brief interval of widespread deposition of marine organic carbon. Thick intervals of CTB black shale serve as a source rock in many locations. We will drill a series of holes targeting the CTB on the margins of both South America and Africa.

NOTES

Wednesday 20 August

Models to Margins

Session 3
Sponsored by BP and Shell

A Tectonic Model of Faulting during Rifting and the Development of the Asymmetry of Conjugate Non-volcanic Margins

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The tectonic processes that create the architecture of rifted continental margins are still debated. When continental lithosphere is initially extended it thins and subsides forming rifted sedimentary basins like the North Sea basin. This type of relatively shallow water basins has been extensively investigated by industry and academics for decades. However, if lithospheric extension continues to final break up, eventually giving birth to a new oceanic plate, the greatly thinned continental plates subside well below sea level forming a conjugate pair of rifted margins. Those deep-water segments of the rifted margins have been less methodically studied and only in the last decade have become the locus of intense exploration. When intense lithospheric extension occurs with little associated magmatism, it forms the so-called ‘non-volcanic rifted margin’ (NVRM). Conjugate sets of NVRMs are found worldwide, including examples like West Iberia-Newfoundland, South Labrador Sea-Greenland, Armorican-Flemish Cap, South Australia-Antarctica, and Nova Scotia-Morocco. Previous work in those deep margins has recognized two apparent paradoxes: A widely recognized apparent first paradox is that one margin displays gradual crustal thinning and pervasive large-scale faulting, whereas the conjugate displays far abrupter crustal thinning but little large-scale faulting. Attempts to explain this structural asymmetry have invoked simple shear extension during much of the rifting along crustal- or lithospheric- scale detachment faults. However, seismic data have only convincingly imaged potential detachment faults near the continent-ocean transition, where the crust is extremely thinned to less than ~6 km. Thus, those potential detachments could not explain the large-scale asymmetry of conjugate margins. A second often-cited apparent paradox, for both conjugate margins, is the discrepancy between a seemingly small extension created by faulting (measured as horizontal tectonic stretching) compared to a greater crustal thinning (measured thinning factor). Invoked explanations range from rheologically-controlled depth dependent stretching to superposition in the same location of multiple phases of faulting (i.e. extension). We present depth seismic images of conjugate margins that show the structure created by faulting and crustal thinning as extension progressed from both rift flanks to the area of continental break-up. These images permit the accurate calculation of fault extension that can be compared to independently measured crustal thinning. The observations support a new model of the temporal evolution of fault activity during rifting that resolves both apparent paradoxes described above. The model proposes that as extension progresses, fault activity becomes increasingly sequential in time, leading to a mode of fault-controlled crustal thinning that reconciles extension factors estimated on faults with those measured from crustal thinning (second apparent paradox). Moreover, sequential fault activity naturally leads to the asymmetric structure observed at non-volcanic rifted margins (first apparent paradox), without the need for large-scale detachment faults.

NOTES

Sag Basin Development and Rifted Continental Margin Asymetry

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Continental breakup and sea-floor spreading initiation requires the thinning and rupture of continental lithosphere. Both non-volcanic and volcanic rifted continental margins, including conjugate margin pairs, show depth-dependent lithosphere thinning and stretching. Several different models of continental lithosphere thinning leading to continental breakup prior to sea-floor spreading initiation have been proposed. Depth-uniform (pure-shear) models of continental lithosphere thinning leading to breakup fail to explain observed depth-dependent lithosphere stretching and the exhumation of continental lithosphere mantle. Decoupled pure-shear models of lithosphere thinning leading to continental breakup, while able to predict depth-dependent lithosphere stretching, require significantly larger amounts of upper crustal extension and faulting than is observed. A new model has been developed in which continental lithosphere thinning is achieved by a simultaneous combination of pure-shear and upwelling divergent flow within continental lithosphere and asthenosphere. The upwelling divergent flow is assumed to be driven by thermal and melt buoyancy initiated by pure-shear lithosphere stretching. While horizontal tensile plate forces provide the driving force for the pure-shear deformation, the induced upwelling divergent flow provides the main contribution to continental lithosphere thinning. The induced upwelling divergent flow model of continental lithosphere thinning successfully predicts depth-dependent stretching of continental margin lithosphere for both non-volcanic and volcanic margins and mantle exhumation at non-volcanic margins. The model predicts a simple transition from pre-breakup lithosphere thinning to sea-floor spreading, and provides an explanation for the paucity of pre-breakup brittle deformation in the upper crust as observed at rifted margins. The observed diversity of rifted continental margin structure and width of the ocean–continent transition can be explained by variability in the form of the upwelling divergent flow field. The induced upwelling divergent flow model provides an explanation for the formation of asymmetric rifted margins and pre-breakup sag basins. Crustal thinning and lithosphere temperature predicted by the new margin formation model are used to determine rifted margin bathymetry and gravity anomaly. Observed bathymetry and gravity anomalies predicted by the new margin formation model have been used to invert for kinematic parameters describing breakup lithosphere deformation and to predict rifted margin lithosphere structure, OCT location, subsidence and heat-flow history. The induced upwelling divergent flow model of continental lithosphere thinning and rifted margin formation has been successfully applied to rifted margins including conjugate pairs. For the N. Iberian - N. Newfoundland margins, pure-shear breakup lithosphere thinning model predicts that the onset of melt generation occurs prior to breakup rupture of the continental crust for normal mantle temperature and chemical composition. In contrast the upwelling divergent flow model predicts the onset of melt generation after continental crust rupture leading to ~ 100 km mantle exhumation on each margin.

NOTES

The extension discrepancy at rifted margins: unrecognised faulting or depth-dependent stretching (DDS)

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Across rifted margins, the prerift continental crust thins from ~ 30 km, reaching zero at the continent-ocean transition (COT) beyond which either oceanic crust or unroofed mantle forms top basement. However at most margins, the amount of extension measured from fault geometries (β_f typically < 1.2) is far less than that required to explain whole crustal and lithospheric thinning, deduced from crustal thickness (whole crustal β_c tending to ∞) and subsidence. This is the extension discrepancy.

If the observed faulting records all the upper crustal extension ($\beta_f \sim \beta_{uc}$), the implication is that crustal extension is strongly depth-dependent, with the upper 20% of the crust being far less extended at rifted margins than the underlying 80% ($\beta_{uc} << \beta_c$). Depth-dependent stretching (DDS) is an attractive explanation for the extension discrepancy as it appears to explain the observations without implying that any of these are incorrect, as there is independent evidence for lithospheric DDS during the formation of rift basins (e.g. postrift onlap) and of rifted margins (e.g. unroofing of lithospheric mantle in the COT), and as it predicts a continuous prerift succession even at deep-water rifted margins. However, there are several problems in explaining the extension discrepancy through crustal DDS. First, excess thinning of the lower 80% of the crust should somewhere be balanced by thickening of the same or by excess thinning of the upper 20%. Neither is observed. Second, the seismic velocity structure of the 14 conjugate margins where crustal structure is best constrained provides no evidence for significant crustal DDS. Finally, ODP Legs 149 and 173 of the deep west Iberian margin found lower crustal rocks are present and not removed by DDS.

An alternative explanation for the extension discrepancy is that not all the faulting that has extended and thinned rifted margins has been recognized ($\beta_f << \beta_{uc} \sim \beta_c$), perhaps related to the far greater extension undergone at margins than at rifts. As extension increases, it is expected that the original faults should rotate to lower angles and eventually lock-up to be replaced and in places cut by a second generation of faulting. This should occur when approaches 2, and has been observed in highly extended terranes on land. Modelling shows that the complexity of the resulting geometries, particularly if mass-wasting accompanies faulting, hinders recognition of such polyphase faulting on seismic sections, although it can be inferred at the west Iberia margin. A complementary explanation is that some faults do not lock-up, but remain active, developing into large-offset normal faults, sometimes termed top basement faults as their footwall forms top basement for many km. Failure to identify top basement as the exhumed footwall of such a fault would again result in a major underestimation of the amount of brittle extension and hence in the extension discrepancy. Both cases of unrecognized faulting predict that prerift and early synrift units are dismembered and scattered across deep water margins.

NOTES

Dynamical Models of Depth-Dependent Lithospheric Extension at Rifted Continental Margins: Effects of Strong and Weak Lower Crust

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Contrasting end members of volcanic and non-volcanic passive margin formation show a large variability in structural style and associated subsidence history that imply strong variability in the underlying thermo-mechanical conditions at the time of rifting. For instance the Iberia-Newfoundland non-volcanic conjugate margin system has evolved from initial wide to late stage narrow, most probably asymmetric rift, leading to exhumation of mantle lithosphere and sub-lithospheric mantle in a wide ocean-continent transition zone under essentially cold conditions. In contrast rifting in the non-volcanic Central South Atlantic conjugate passive margins resulted in very wide (> 250 km) strongly thinned crustal conjugates which remained close to sea level until break-up providing conditions for the late syn-rift shallow water salt basin, implying high thermal gradients at the time of rifting. Volcanic rifted margins such as in the North and South Atlantic show excess magmatic activity and shallow water conditions at the rift-drift transition implying even higher geothermal gradients.

We use thermo-mechanical finite element model experiments to investigate factors that are potentially important controls during volcanic and non-volcanic passive margin formation which may explain these characteristic differences including processes that create shear zones, on the rheological stratification of the lithosphere, and on processes that lead to differential thinning of upper and lower lithosphere during rifting. Dynamic modeling cases are compared where the crust is strong, weak, or very weak, and the mantle lithosphere is either strong or weak. Strain softening takes the form of a reduction in the internal angle of friction with increasing strain. Predicted rift modes belong to three fundamental types: 1) narrow, asymmetric rifting in which the geometry of both the upper and lower lithosphere is approximately asymmetric; 2) narrow, asymmetric, upper lithosphere rifting concomitant with narrow, symmetric, lower lithosphere extension; 3) wide, symmetric, crustal rifting concomitant with narrow, mantle lithosphere extension.

NOTES

Modeling the Tectonic and Thermal Evolution of Rifted Margins.

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We present numerical experiments of lithospheric extension using a parameterization for failure in the both the brittle and ductile media. We use a semibrittle fracture criterion based on critical plastic work done to deform the material. This allows us to simulate numerically the formation of a semi-brittle media in the continental crust that is both temperature and strain dependent. Mohr-Coulomb yield and flow is used to simulate brittle deformation and viscoelastic Maxwell flow approximates ductile flow. We show that the formation of sub-horizontal ductile shear zones in the middle to lower crust allows for the development of mixed pure and simple shear modes of deformation. A small fraction of crustal attenuation (formation of low viscosity layer) leads to coaxial necking of the lithosphere and the formation of low-angle normal faults.

We test this rheological parameterization for lithospheric extension by comparing the model results to structural observations in different rift settings. For initial conditions similar to that of magma poor margins, we model three consecutive phases of deformation consistent with geological and geophysical observations. 1- A diffuse stretching mode in which deformation is distributed over several half-grabens. 2- A localized thinning mode that leads to the formation of detachment faults exhuming middle to lower crust. 3- A localized to diffuse exhumation mode during which lithospheric mantle is exhumed at the seafloor. We show that by only varying the initial geotherm in the lithosphere we are able to isolate two of these characteristic modes of extension. A hot localized thinning mode where core complexes structures develop. These structures are similar to those observed in the Basin and Range Province. A cold localized thinning mode leading to the formation of a narrow rift. Eventually extreme crustal thinning and detachment faulting occurs. For each one of these modes the formation of a semi-brittle layer in the crust progressively weakens and decouples the upper crust form the lower crust. This weakening leads to the formation of zones of exhumed middle to lower crust similar to core complexes. We conclude that thinning of the continental crust must be accompanied by the formation of detachment faults in a wide range of environments with a thermal evolution specific to crustal and mantle exhumation.

NOTES

A global review of intraplate basin evolution in a mantle dynamic and plate kinematic framework

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Subsidence of continental crust and the formation of sedimentary basins is most commonly caused by plate boundary processes, such as continental extension and rifting, or flexural loading in compressional regimes. However, many large intracontinental basins subside slowly over long time intervals, showing a ``saucer-shaped'' geometry in cross section, even though they are located far away from recently active plate boundaries. These basins subside long after the initial thermal disturbance and lack signs of extensive brittle deformation. Conventional basin models fail to explain the additional accumulation of sediments in those basins.

We review the crustal structure data of a global set of more than 200 intracontinental sedimentary basins and integrate it with plate kinematic and mantle convection models. We demonstrate that large-scale crustal structure data from global and regional datasets allows the computation of a robust anomalous total tectonic subsidence estimate, based on sediment thickness versus crustal thinning observed underneath a given basin. Comparing sediment- and crustal-derived extension, we are able to identify basins where depth-dependant stretching has resulted in differential thinning between the crust and the mantle lithosphere.

The anomalous tectonic subsidence data are then compared to uplift and subsidence history inferred from plate kinematics and mantle dynamics of the basins, linking deep earth processes with basin evolution. We show that the anomalous tectonic subsidence stored in intracontinental basins is partly due to the creation of additional accomodation space due to dynamic subsidence, resulting from the motion of plates relative to large scale patterns of mantle convection during supercontinent dispersal.

NOTES

The Vertical Expression of a Horizontal Flow: Stratigraphic Manifestations of Transient Mantle Convection

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Convection in the Earth's mantle appears to be strongly time-dependent on geological time scales. However, we lack direct observations which would help constrain the temporal variation of convection on timescales of 1-10 Myrs. Recently, it has been demonstrated that transient uplift events punctuated the otherwise uniform thermal subsidence of sedimentary basins which fringe the Icelandic plume. In the Faroe-Shetland basin, three-dimensional seismic reflection surveys calibrated by well logs have been used to reconstruct a 55 million year old transient event. The minimal amount of uplift is 490 m, which grew and decayed within 2 Myrs. This event has also been mapped 400 km further east in the North Sea basin, where peak uplift with an amplitude of 300 m occurred 0.2-1.6 Myrs later. Neither observation can be explained by glacio-eustatic sea-level changes or by crustal shortening. We describe a simple fluid dynamical model which accounts for these transient and diachronous observations. In this model, we assume that the Icelandic plume was already in existence and that it had an axisymmetric geometry in which hot (e.g. 1400 degrees Centigrade) asthenospheric material flows away from a central conduit within a horizontal layer. A transient temperature anomaly introduced at the plume center flows outward as an expanding annulus. Its geometry is calculated using radial flow between two parallel plates with a Poiseuille cross-stream velocity profile. The expanding annulus of hot asthenosphere generates transient isostatic uplift at the Earth's surface. Stratigraphic observations from both basins can be accounted for using a plume flux of 1.3 X 108 km3 Myr-1 for a layer thickness of 100 km. Plume flux is broadly consistent with that required to account for Neogene (0-20 Myr) V-shaped ridges south of Iceland, although our transient temperature anomalies are larger. We suspect that the stratigraphic expression of transient convective behavior may be common and that a careful examination of appropriate records could yield important insights.

NOTES

Session 4

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Automated Thermotectonostratigraphic Reconstruction of Sedimentary Basins in Frontier Areas

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The self consistent reconstruction of the thermal, tectonic, and stratigraphic evolution of sedimentary basins is a challenging task. Good results have been obtained based on McKenzie's pioneering work (1978). However, with the current petroleum prospects moving further and further into frontier areas, characterized by deep water and extreme stretching of the lithosphere, the McKenzie approach does not suffice any longer. Required additional physics include depth dependent stretching, formation of new oceanic crust, and mineral phase transitions. We have implemented all standard as well as these frontier area relevant mechanisms into a novel basin modelling framework called TECMOD2D (Rüpke et al. 2008). This framework automates the basin reconstruction process and allows quantifying the geological processes active in frontier areas. Key to this is the coupling of a forward model to an inverse scheme for automated parameter update. The forward model resolves simultaneously for lithosphere processes (e.g. thinning, flexure, temperature, mineral phase transitions, breakup) and sedimentary basin processes (e.g. sedimentation, compaction, maturation). The inverse algorithm automatically updates crustal and mantel thinning factors as well as paleo-water depth until the input stratigraphy is fitted to a desired accuracy. The potential of this new basin modeling framework is demonstrated through a series of case studies that illustrate how breakup and mineral phase transitions can influence basin evolution.

Basins in frontier areas often show three enigmatic characteristics: late synrift uplift, little synrift infill compared to postrift, and seismic inferred stretching factors that are systematically lower than what models predict. Increased stretching with depth explains part of these observations, however, not the magnitude of the effect. In addition, recent studies (Kaus et al. 2005) have shown that for moderate to large stretching (mantle) rocks do not only undergo thermal expansion but phase changes occur that strongly influence subsidence. Our models with mantle phase transitions activated demonstrate that phase transitions can have an effect on isostasy that is comparable to the thermal one, effectively doubling the effect of stretching on vertical motion. Furthermore, models with phase transitions are characterized by reduced synrift subsidence and late synrift uplift. Since phase transitions amplify the effect of lithospheric thinning less stretching is required for the same response when phase transitions are activated, leading to a reduced thermal input into the sedimentary basins and preventing hydrocarbons from overcooking.

We show that automated basin reconstructions are possible, easily fit into exploration workflow, and can be applied to standard as well as frontier areas. In the case of areas with large stretching we are able to demonstrate that phase transitions have a first order influence on the sedimentary basin formation. Real rock experiments show that the phase transitions we include in our models take place and are not inhibited by kinetics. Models with these additional physics lead to a better understanding of some of the remaining puzzles in basin formation in frontier areas.

NOTES

Mapping crustal thickness and the ocean-continent-transition in the Santos and Campos Basins, Brazilian South Atlantic

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

The modelling techniques used include the isostatic consequences of:

- lithosphere thermal perturbation during Cretaceous rifting and continental breakup
- volcanic addition to the crust during the breakup process

Both are critically important to the geodynamic analysis of any extended continental margin.

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

A key sensitivity issue in predicting the crustal structure of the Santos/Campos margin is the amount of volcanic addition assumed to have occurred during stretching and breakup. For both the gravity inversion and the flexural backstripping we have tested sensitivity to:

- no volcanic addition, a "rift basin" model
- a maximum 7km of volcanic addition, a so-called "non-volcanic margin"
- a maximum 10km of volcanic addition, a so-called "volcanic margin"

We believe the Campos margin is best considered to be a "non-volcanic margin", while the Santos margin is almost certainly a "volcanic margin". This has considerable implications for heat-flow history.

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

Subsequent to work in Brazil these techniques have been successfully applied to the analysis of several other rifted continental margins worldwide.

NOTES

Modern Analogue for Interlayered Evaporites and Seaward Dipping Volcanic Reflectors: Danakil Depression, Northern Afar, East Africa

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Seaward Dipping Reflectors (SDR's) are observed on seismic data of passive margins, but their relationship to salt is difficult to observe. In Northern Afar a series of shield volcanoes have formed from extension between the Danakil Horst (microplate) and the Ethiopian Plateau (20 mm/yr). This region, known as the Danakil depression, lies below sea level and is characterized by Quaternary shield volcanoes fed by lava from deeper magma chambers and dykes. Volcanic crests along the centre of the Depression rise above sea level leaving the surrounding low lying valleys to accumulate evaporates; 1.6 Km of halite was deposited near Dallol along the north flank of the northern shield volcano located closest to the Red Sea. Thin gypsum deposits are observed on Landsat images further south along the depression. Basaltic flows from the shield volcanoes will develop into SDR's if continued extension and subsidence of the surrounding valleys occurs. Old lava flows will rotate beneath the loads of progressively younger eruptions. Accommodation space for the rotated flanks of the volcanoes must be provided by plastic deformation in the asthenosphere. The depression is expected to widen as the crust is progressively thinned by episodes of dike injection and faulting and will continue to be infilled with evaporates and lava flows. Eventually, extension and subsidence will outpace salt deposition when the Danakil microplate breaks away. Marine incursion will occurs and submarine pillow basalts will begin to form instead. In this process, the mantle must rise below the subsiding Danakil Depression as continental crust is progressively attenuated. The Danakil Depression is experiencing the transition from rift to drift and represents a modern analogue for understanding evaporites and SDR's.

NOTES

Testing experimental concepts for oblique rifting with outcrop data from the Western U.S.A. and subsurface data from European Basins

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Conceptual models derived from fieldwork and scaled physical-model experiments combined with modern high-resolution seismic data have significantly enhanced our understanding of the geometry of rift-systems particularly when rifting is oblique to pre-existing zones of crustal weakness or when offsets occur in the rift-system. In this talk, we review recent experimental data then compare those results to outcrop examples from the western U.S.A. and subsurface data from the Polish Trough and basins in the UK and Norway.

Orthogonal and oblique rifts are characterized by the orientation of the rift axis with respect to the extension direction. In an orthogonal rift, the rift axis is broadly orthogonal to the extension direction; in an oblique rift, however, the rift axis is inclined to the extension direction. Orthogonal and oblique rifts have many basic features in common. In both rift-systems the component faults and fault-systems are soft-linked. Major cross-strike faults do not develop in either rift type. Changes in the polarity of basins along the trend of the rift are accomplished via transfer zones that are oblique to the trend of the rift.

Despite the similarities, there are several key differences between the geometry of orthogonal and oblique rifts. Orthogonal rifts tend to have long, straight border-faults that have grown via segment linkage of initially separate fault strands. The border faults typically have low fault-curvature (i.e. they are relatively straight) with relatively small fault-fault overlaps between the component faults. Intra-rift faults are broadly parallel to the border fault-systems. In contrast, in oblique rift settings the border faults tend to be shorter and arranged in an en échelon manner. Fault-fault overlaps are significantly larger than in orthogonal rifts. The amount of overlap is related to the degree of obliquity; in general terms, the higher the degree of obliquity, the larger the fault-fault overlaps. Faults in oblique rift settings are often strongly curved with both concave and convex fault segments developed. Intra-rift faults tend to curve onto parallelism with the border rift faults. This is because in the center of the rift, where deformation is relatively unconstrained, the component faults align broadly normal to the extension direction. Towards the rift borders, however, the component faults become progressively forced into alignment with the border-faults and hence curve into the orientation of the rift border.

Scaled physical-models for rift-systems can also be constructed with offsets in the rifts. Within an individual rift compartment, the models show the characteristics typical of oblique rifts. In the regions of the offsets, however, faults within each basin compartment rotate into alignment with the offset direction creating oblique shear zones that separate extending ‘basinal areas’ from the relatively stable ‘platform’ areas.

The location and orientation of rifting in a physical model can be controlled by a rubber sheet within the base-plate of the modeling rig. Obliquity is introduced simply by changing the orientation of the rubber sheet with respect to the base plate – when the rubber sheet is orthogonal to the base plate, and thus the extension direction, an ‘orthogonal rift’ develops; when the rubber sheet is inclined to the base plate, an ‘oblique rift’ will develop. In the natural world, obliquity and offsets in rift-systems can be caused in several ways including preexisting zones of weakness, or facies changes that are inclined to the subsequent extension direction, and prolonged or multiple rift events where the relative direction of rifting changes.

Obliquity can occur during a single rift-event where the location of the rift border-fault system is controlled by pre-existing structures that are oblique to the extension direction (e.g. on the Volcanic Tablelands near Bishop, CA, where a buried basement-horst, that is oblique to the recent extension direction, controlled the location of deformation in the overlying cover-rocks, or on the UK-Ireland Atlantic Margin where the trend of older Caledonian basement fabrics, and early Paleozoic to Mesozoic basin fault-systems are oblique to the early opening direction of the North Atlantic). Preexisting zones of weakness can also localize offsets within rift-systems (e.g. across the Judd Platform at the southern-end of the Faeroe-Shetland basin-system where there is a pronounced step in the margin as the basin-system steps-off and links to northern Rockall).

Obliquity can also occur in a multi-rift setting where a younger-rift is oblique to an older-rift or where the direction of rifting changes markedly through time (e.g. as in the North Viking Graben or in mid-Norway). The resultant rift-architecture will combine elements from both rift events with transfer zones in the old rift-system often becoming focal points for offsets in the younger rift-system.

Obliquity in a rift-system can also be introduced when marked changes in stratal facies or thickness, particularly in weak layers such as salt or shale, are oblique to subsequent deformation (e.g. on the western margin of the Polish Trough where facies variations within the Zechstein Fm. force the distribution of structures with the overburden) or where weak interbedded layers can cause deformation partitioning (e.g. on the western margin of the Polish Trough where halites in the Middle and Upper Triassic cause deformation partitioning between within the section).

NOTES

Identifying and understanding the role of thick skinned crustal elements in basins and margins dominated by thin-skinned deformation: examples from the Gulf of Mexico and South Atlantic.

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In sedimentary basins and oceanic margin settings where thin-skinned deformation processes dominate, identifying and characterizing the nature of deep-seated crustal structure can be challenging and is often overlooked, especially where exploited petroleum systems relate mainly to the thin-skinned architecture. As a result the distribution of early extension and the nature of the deep crust are often overlooked, even though their understanding is fundamental to heat flow, subsidence and palinspastic reconstruction studies that are used to constrain petroleum systems modeling. In the case of the Jurassic and Cretaceous salt basins of the Gulf of Mexico and the South Atlantic the relationship to the pre-existing rift topography and the late syn-rift to post-rift salt successions can have a profound effect on the style and distribution of subsequent thin-skinned deformation.

Indeed, for the two regions mentioned above it can be argued that the deposition of salt in a post-rift phase followed by very rapid subsidence to deep marine depositional conditions marks the transition from late rift to drift in the development of the basin/oceanic margin. In the central South Atlantic, for example, deepwater well data shows that Aptian salt deposits are followed almost instantaneously (geologically speaking) by the deposition of deep marine sediments. This indicates that the continental margins adjacent to what is considered unequivocal oceanic crust subsided at approximately that time, rather than being coeval with oceanic crust that was forming much earlier to the south of the Florianopolis Transfer Zone and the Santos Basin. This interpretation suggests that the opening history of the South Atlantic was more complicated than the Bullard rigid plate model suggests and exemplifies the importance of incorporating deepwater well data to evolving geological models. Similarly, in the Gulf of Mexico, it appears that Callovian salt deposition was immediately followed by deep marine conditions, at least in the present day deepwater areas. Data here is more ambiguous and there are a wide range of models that attempt to explain the deep seated structure and crustal nature of the gulf.

Using potential fields data, structural modeling, plate reconstruction and seismic mapping a number of observations can be made concerning the pre-Palaeogene evolution of the Gulf of Mexico. With reference to the oceanic margins of the South Atlantic and the defined techniques a range of interpretations for the deep crustal structure of the Gulf of Mexico are presented for discussion.

NOTES

Transition between Oceanic and Continental Rift Systems as exemplified by short-lived, small ocean basins

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The most familiar examples of the intersection of ocean spreading centers with continental margins are the transformations of the East Pacific Rise into the San Andreas in the Gulf of California and the Indian Ocean Ridge into the AFAR system. They showcase the importance of en-echelon spreading centers with offsetting short transform faults in one case as a transition in margin type, and the other as a stable triple junction. Some short-lived small ocean basins around the world capture complications in the early stages of the process, each of which occurs in a different plate situation. They typically involve continental crust at unstable triple junctions that rapidly break down to a stable plate arrangement.

Recent 40-km record, long-offset PSDM seismic data from two examples, supported by potential fields modeling, illustrate the transition. The southern sector of the Canada Basin and the Mackenzie Delta shows a presumed fossil Canada Basin spreading center as it encounters the continental margin. Despite a possible modern analog in the intersection of the Gakkel Ridge (Arctic Eurasian Basin) with continental Eastern Siberia, this is one of the least understood oceanic-continental transitions. An almost 15-km thick wedge of sediments obscures details of the transition. Proterozoic and Paleozoic units overlie the continental crust. Hauterivian and slightly older synrift sediments are the oldest sediments overlying oceanic crust. “Drift” sediments overlie the 130-my unconformity. Mackenzie River delta sequences occur in pulses younger than 80 Ma that extend from the coast line into water depths of almost 2 km. They are affected by a complex of Early Tertiary through Early Miocene crustally-driven and gravity-induced structures. The basal detachment for the thrusts is interpreted to be at almost 15 km depth, and was folded in a late phase of inversion affecting oceanic crust. A region of anomalous crustal thickness, thicker than normal oceanic crust, lies to the west of the fossil spreading center. Its origin is problematical. But it is overlain by sediments that overlap the normal oceanic crust, suggesting its origin may be related to the propagation of the spreading tip onto the continent. Recently acquired long-offset 2-D seismic data is expected to provide structural clarification of the Mackenzie River Delta area and its relationship to the Canada Basin fossil spreading center.

Oceanic crust and its transition to continental crust is clearer in two surveys in the late Jurassic and early Cretaceous parts of the western Indian Ocean basin, offshore Kenya-Tanzania and north and west Madagascar. These data may provide some insight into the Canada Basin: despite a thick drift section the geological matchup between the conjugate margins, imaging of the oceanic crust, and comparison of modeled and seismically-observed Moho are all good. Volcanic addition to the crust is large and focused on the continental margin and fracture zones within the oceanic crust. In this system the early rift history involved the onshore Anza graben as one arm of the triple junction, which was abandoned early. The 3-plate system rapidly was replaced with a 2-plate Ridge-Transform system.

NOTES

Observations from the South Atlantic - How Conjugate is the Conjugate Margin?

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Continental crust extension is the pre-cursor to passive margin formation. Rift basin evolution is the response of the continental plate-margin to whole crust and lithospheric mantle extensional stresses. The consequence of the duration, extent and magnitude of lateral (extension) versus vertical (thermal) subsidence patterns along the South Atlantic margin shows significant along-strike complexity. The variation in deformation style and whole crust subsidence patterns reflects pre-existing crust-mantle heterogeneity and differential responses to plate-scale lithospheric extension. To challenge the “conjugate” relationships that resulted from the rifting of Africa from South America we should address the important perceptions around rifted margin evolution. What are the implications of the unique arrangement of margin-opposed rift basin architectures and can we reconcile the along-strike character of, and transition to an organized oceanic spreading axis? Plate-margin reconstructions are able to constrain the evolution of oceanic basins however reconstruction of the extensional phase prior to oceanic spreading is more problematic. What determines the position of the rift and why does the rift form asymmetrically along certain segments? We have restored the mapped conjugate attenuated continental crust to derive a consistent model for extension relationships prior to oceanic spreading. Moreover, the assumption that the lithospheric stresses that determined rift-basin formation are not necessarily in a continuum to those that operate during the early drifting phase evolution of passive margins is demonstrable. The early phases of rifting may be dominated by far-field plate tectonic stresses that are different than those during the oceanic drift phase. The rift-related lacustrine basins of the South Atlantic margin provide an empirical laboratory to challenge conventional paradigms for the fundamental processes that determine the character of “conjugate” rather than “mirror-image–symmetric” rifted margins. North of the Walvis Ridge/Rio-Grande Rise volcanic trend, rift-basin architecture documents a strong asymmetry with oblique extension dominating brittle crust response of the Santos and Kwanza Basin basement. Rhombo-chasmic sub-basins are common with strongly over-lapping basement fault segments and listric faults geometry’s. In contrast the Campos and Lower Congo Basins are more consistent with orthogonal stretching with a well organized simple half-graben developed, characterized by steeply dipping planar fault arrays. In addition the landward expression of the transition from oceanic crust to continental crust systematically differs along the length of the “conjugate” basins. The presence of a conspicuous coast parallel linear gravity anomaly referred to as the “terminal horst” defines the basinward extent of attenuated continental crust in the Campos and northern Lower Congo Basins. The topographic expression of this structure appears to define the depositional edge of the early post-rift salt depo-centres and is believed to document the most basinward brittle crust response to “orthogonal” lithospheric extension. Primary salt basin thicknesses are greater than those developed to the south with the terminal horst providing a more dramatic silled-basin profile. Indeed in the southern Lower Congo Basin in excess of 3km of seismo-straigraphically defined “sag-basin facies” are coincident with the thickest autochthonous halite. Paradoxically, in the Santos and Kwanza Basins, the ocean-continent transition becomes equivocal and less easily recognized on gravity maps. As a consequence the relationship of deposition of primary salt thicknesses to the final stages of rifting and the formation of oceanic crust appears more spatially complex. A zone of small transitional sub-basins and apparent complex crust is particular to the most distal attenuated “continental” crust belonging to the Kwanza Basin. Several alternative rifting hypotheses have been presented to explain these differences and more importantly the apparent paradox of thick late-syn rift basin sequences dominated by thermal subsidence with little associated fault related extension. These observations challenge the convention of pure shear, uniform stretching models. We speculate that the transition from continental extension to oceanic crust formation is segmented across major vertical lithospheric discontinuities and that the segmentation is temporal in the dip dimension. Pre-existing crustal and presumably lithospheric mantle scale heterogeneities are believed to impart a first order control on the along-strike brittle deformation mechanisms and the thermal expression of this contrasting behavior is recorded in the late syn-rift and post-rift whole lithosphere subsidence response and palaeo-heat flow distribution. Fundamental structural boundaries are recognized to be present and are important along the entire length of the South Atlantic Margin. They are recognized as major offsets at the coast and are present on regional gravity derivative maps as conspicuous linear anomalies. These structurally determined heterogeneities are believed to partition crustal strain and juxtapose end-member mechanisms of pure-shear and simple shear deformation styles as recorded by the complex distribution of syn-rift thermal subsidence patterns.

NOTES

Geological and geophysical interpretation of the Rio Grande Rise, Southeastern Brazilian margin: extensional tectonics and rifting of continental and oceanic crusts

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This paper discusses the geological and geophysical interpretation of rift structures in the region extending from the Rio Grande Rise, in the Southeastern Brazilian margin, towards the Cabo Frio High, which separates the Campos and Santos basins.

We have analyzed potential field (gravity and magnetic) data over the Campos, Santos and Pelotas basin, which show a relatively negative Bouguer anomaly in an area that corresponds to a positive bathymetric structure marked by volcanic activity as recent as Eocene. This elevated region is also marked by rift structures aligned along a NW-SE direction, forming a NW-SE trending shear zone (Cruzeiro do Sul lineament) that extends from the Cabo Frio High towards the Rio Grande Rise, thus involving both continental and oceanic crust.

The Rio Grande Rise is also associated with the E-W trending Rio Grande Fracture Zone, which is marked by a several aligned magnetic anomalies. This fracture zone continues landward as the São Paulo Ridge, and extends towards the Santos Basin platform as the Florianópolis High. Oceanic propagators are identified from Argentina towards the Pelotas and Santos basins, and locally we observe rupturing of the salt layer. The fracture zone is marked by an abrupt topographic offset separating the Pelotas Basin from the southern Santos Basin, which also limits the southernmost occurrence of the late Aptian evaporite sequence. The evaporate sequence shows remarkable layering of halite, anhydrite and carnalite in this segment of the continental margin. The Walvis Ridge, offshore Namibia, is a positive topographic high that is conjugate to the Rio Grande Rise. However, the rift structures observed in the Brazilian side are apparently unique in the South Atlantic.

Alternative interpretations for the origin of these structures include: a volcanic edifice or plateau with deep root in the mantle; an intraplate shear zone affecting both continental and oceanic crust; an area of great igneous productivity in an oceanic area caused by a hotspot; a paleo-spreading center in the Cretaceous Atlantic Ocean; an area of volcanic activity from mantle differentiation due to adiabatic decompression; and less probably, an isolated remnant of continental crust left outboard of the Brazilian continental margin during the drifting process.

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Thursday 21 August

Basins to Barrels

Session 5
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HC Exploration History of Rift Basins

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HC Exploration in “Rift” basins, here defined in the continuum of “Rift”, “Rift + Sag” through “Cratonic” basins, initiated in the early 1900’s and these basins have delivered at least a third of the approximately 3 TBoe of conventional discovery volume to date. The most significant phase in the discovery record was 1960-1980, which saw the opening of the major provinces of West Siberia, North Sea and major North African basins such as the Sirte.

Global creaming curves indicate maturity in the Cratonic basins but less so for the Rift and Rift + Sag basin categories. Field Size distributions for the discoveries have also remained reasonably consistent over the last 25 years. This continued pace in the material discoveries reflects mainly the development and testing of new play concepts and extensions in proven petroleum systems e.g. Norwegian Offshore, Barents Sea in the 80’s, N.W. Shelf of Australia in the 90’s, and SE Brasil margin in the last few years.

Review of the Petroleum System context for the major Provinces shows that significant HC source rocks may be developed in each of the Pre-Rift, Syn-Rift and Post-Rift megasequences. Most volumetrically prolific Petroleum Systems have associated SRs that have been developed in the late Syn-Rift or early Post-Rift megasequences (e.g. West Siberia Bazhenov, North Sea Kimmeridge, SE Brasil Lagoa Feia Petroleum Systems). Similarly, key reservoir-seal pairs in Rift basin petroleum systems are found in all three megasequences but have been most important where developed in the Syn-Rift and basal Post-Rift.

Current exploration focus in Rift basins includes; the deep pre-cursor rift basin phase below passive margin basins, deeper conventional plays in existing provinces inspired by new technology or understanding and unconventional tight gas plays.

NOTES

Towards Understanding the Formation of the Gulf of Mexico: Evidence for a Late Triassic Precursory Domal /Rift Flank Uplift and a Volcanic Rifted Margin for the Texas-Louisiana sector of the Gulf of Mexico

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The Gulf of Mexico passive margin began to develop in early Mesozoic times, when Pangea ruptured Mesoproterozoic lithosphere along the trend of the Late Paleozoic Ouachita Orogeny. Because the NW Gulf of Mexico (GoM) passive margin has been subsiding and receiving a large clastic sediment flux from major rivers of North America, evidence for rifting-related tectonic events in the region is deeply buried and poorly understood. Here we present evidence that rifting was associated with a significant domal uplift and/or rift-flank uplift (D/RFU) associated with the development of a volcanic rifted margin (VRM), similar to the Vøring margin of Norway. D/RFU with relief of up to 2km are often but not always associated with early stages of rifting. The related questions of whether or not significant D/RFU was precursory to GoM rifting and seafloor spreading, as well as the nature of transitional lithosphere around the GoM are important for understanding the paleogeography and sedimentary history of southern Laurentia during the early Mesozoic, subsidence history of the NW Gulf of Mexico passive margin, and for paleogeopgraphic reconstructions. Two lines of evidence are discussed. 1) U AZ geochronological studies of detrital zircons from Triassic sandstones across the SW USA indicate that a flood of clastic sediments flowed WNW-ward from central Texas during late Triassic time. These studies indicate that the sediment source was like the crust of Texas and Oklahoma and that this source evolved rapidly, as expected for drainage integration on an evolving uplift. Detrital zircons in basal Santa Rosa (lower Carnian; ~225 Ma) are dominated by Cambrian grains (peak at 516 Ma), inferred to be from the Amarillo-Wichita uplift. In middle Carnian time (~220 Ma), a major sediment source from Ouachita-Marathon fold-and-thrust belt or from reactivated associated foreland basins developed, overwhelming sediments derived from the Amarillo-Wichita uplift. There are also abundant Mesoproterozic zircons in Santa Rosa and higher Chinle-Dockum formations, which likely come from uplifted TX basement. A still younger source appears in zircon age spectra for Trujillo and Cooper Canyon formations. These Norian (~217 - 204 Ma) sediments contain abundant middle Triassic zircons (main peaks at ~240 Ma), inferred to reflect the headwater migration or drainage integration of the Late Triassic river southwards towards a Triassic "Las Delicias/Nazas" arc in eastern Mexico. 2) A major magnetic high along the Texas-Louisiana coast is best explained as manifesting the presence of a thick zone highly magnetized crust that is now deeply buried. This magnetic high disappears beneath coastal Mexico, which is thought to have evolved as a sheared margin. We infer from these relationships that a significant uplift developed in the TX-OK region during Late Triassic time, which evolved as extension continued into a VRM beneath the present TX-LA coasts during the Early Jurassic. These lines of evidence indicate a protracted evolution for rifting to form the Texas passive margin, beginning with first evidences of uplift ~225 Ma ago, continuing until true seafloor spreading began ~170 Ma ago.

NOTES

Shallow computed depth to "magnetic basement" relative to correlated Mesozoic well and seismic stratigraphic events in the Gulf of Mexico: Evidence for the nature of Yucatan block rotation?

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Geohistory (age vs. depth) data from wells with regionally consistent biostratigraphic control and from well tied, depth converted, seismic stratigraphic interpretations, provide synoptic views of depth to Jurassic through Recent chronostratigraphic surfaces (chrons) across most of the Gulf of Mexico Basin. "Magnetic basement" in the region is considered to consist of rocks that are "strongly magnetic" and probably of basaltic composition. Throughout much of the Gulf of Mexico Basin, depths to "magnetic basement" calculated from aeromagnetic data are typically ca. 3,500 meters deeper than the oldest recognized Mesozoic chrons. Our magnetic basement depth estimates are therefore well within the range expected. Across a large portion of the deep western Gulf Basin, however, depths calculated to the upper limit of strongly magnetic rocks are unexpectedly shallower by up to 3,500 meters than the oldest Mesozoic chrons, i.e., latest Early Cretaceous, correlated across that part of the Basin. This large calculated regional anomaly can be explained by various combinations of the following: (1) vigorous basaltic magma intrusion into strata as young as Late Cretaceous; and, (2) unanticipated variations in the magnetic susceptibility of deeper basaltic rocks, i.e., in their magnetic petrology. The location of the defined anomalous region outboard of salt, its prominent northeast-southwest elongation, and the strong possibility of both "shallow" basaltic rocks and petrologically anomalous crust suggest a strong link to basin opening. While the actual causes and geodynamic implications of the striking magnetic basement anomaly in the deep Gulf deserve further careful study, we tentatively compare the computed feature with two published kinematic basin opening models one of which invokes back arc spreading (Fillon, 2007). If back arc spreading is indeed involved in opening the western Gulf, the origin of the observed anomaly might be related to the higher than expected magnetic susceptibility of low titanium titanomagnetite characteristic of back arc basalts. We believe at the very least that the configuration of the magnetic basement vs. chron depth anomaly provides a unique basis for differentiating among the contrasting initial orientations and kinematic trajectories proposed for Yucatan block rotation.

NOTES

Precessional Forcing of Lacustrine Source Rock Facies: Recent Results from Scientific Drilling in Lake Malawi

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Recent exploration successes in Lake Albert (Uganda & Democratic Republic of the Congo) demonstrate the prospectivity of the late Cenozoic active extensional basins of the East African Rift System. Lake Malawi is situated ~1400 km to the south of the Lake Albert discovery wells, along the western branch of the Great Rift Valley, and contains syn-rift, dominantly lacustrine sequences of comparable age and thickness. Much deeper than Lake Albert, with a maximum depth of 700 m, Lake Malawi is one of the world's largest and oldest extant lakes.

In 2005 a scientific drilling program recovered a 380-m core from the upper sedimentary section of a deep-water site in Lake Malawi, representing more than a half-million years of continuous lacustrine sediment accumulation. Sediment types vary from organic-rich, finely-laminated muds, deposited during intervals of high-productivity in a deep, stratified lake, to dense, massive, carbonate-rich, and TOC-poor intervals deposited during periods of very low lake levels. Down-core lithologic and geochemical data, correlated to nested seismic reflection site survey data sets, suggest that marked variations in total organic carbon, d13C, C/N, and Rock-Eval data are linked to high amplitude, climatically-forced lake level shifts. TOC values vary from near zero to ~5%, with high values correlated to high lake-level conditions, and low TOC intervals to periods when the lake level was reduced 550 m or more (lake volume reductions of at least ~98%). The dramatic climate shifts included periods of megadrought, and were controlled by orbital precession during periods of high orbital eccentricity, prior to about 70 kyr BP. During intervals of high orbital eccentricity the cycles of organic-rich versus carbonate-rich are marked and predictable; during periods of low-eccentricity the consistent stratigraphic pattern breaks down, and lake levels and the accumulation of organic matter in the lake basin may be influenced by high-latitude climate forcing. Similar eccentricity-modulated source-rock facies variability is anticipated deeper in the stratigraphic section in Lake Malawi, as well as in other tropical lacustrine-rift basins.

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Sedimentation styles and variability of organic matter types in the Triassic, nonmarine half-grabens of west Argentina: implications for petroleum systems in rift basins

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In west Argentina and Chile, extensional relaxation after the collapse of Late Paleozoic–Early Triassic terranes led to rapidly subsiding, fault-bounded, narrow troughs or half-grabens. The Cuyo rift basin was the largest of these fault-bounded troughs; cumulative production from this basin exceeds a billion barrels. Two linked asymmetric half-grabens have been identified in the Cuyo basin: Cacheuta in the south and Las Peñas-Tamberías in the north. These sub-basins are linked through a cross-over offset or accommodation zone. Their stratigraphy exhibits a classic tripartite internal organization with an intermediate lacustrine interval. The basin fill in both half-grabens shows significant lateral thickness variations that reflect the contrasting subsidence rates on the fault and flexural margins.

The lacustrine shales in the Cacheuta half-graben have an average TOC of 4%, locally reaching 20%, dominated by type I, amorphous, algal organic matter and high HI values. The shales are associated with parasequences interpreted as mouth bar deposits in river-dominated deltas. Oils derived from these source rocks are waxy. This interval in the Cacheuta half-graben can be assigned to a slightly overfilled to balanced-fill lake type (cf. Carroll and Bohacs, 1999).

In the Las Peñas-Tamberías the dominant source rock facies in the lacustrine section is made up of calcareous shales with oil prone, type I(II) kerogen and TOC values up to 13% and high HI values. The presence of gammacerane and b-carotane, common in saline conditions, is conspicuous. The presence of oolitic and bioclastic grainstones and microstromatolitic limestones on the ramp margin and clastic facies on the border fault suggests a slightly underbalanced to balanced lake type.

The Cuyo rift basin branches to the northeast into the Ischigualasto half-graben. Lacustrine, organic-rich shales along the fault margin of this half-graben are dominated by type II, gas-prone organic matter with TOC values up to 4% and low HI values. These shales are associated with carbonaceous shales, coals and sandstones stacked in coarsening-up parasequences with steep front slopes interpreted as mouth bars in a Gilbert-type delta. These characteristics are consistent with an overfilled lake basin type where sedimentation rate exceeds subsidence rate.

Lake basin types exert a strong influence on hydrocarbon generation, and indirectly on the petroleum systems of rift basins. The Triassic rift system of west Argentina shows the gamut of lacustrine source rocks that, combined with the analysis of diagnostic associated facies, allow the discrimination of lake basin types and their influence in the resulting hydrocarbon phase.

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Structural and climatic controls on evolving drainage systems in extensional basins

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A key issue facing explorationists working in rift basins is the quality and distribution of play element. Understanding the controls on sand deposition in these basins is central to addressing this problem. Reservoir quality, in particular, and its relationship to seal facies are controlled to a large amount by the distribution of accommodation produced by climatic and tectonic processes. In rift basins, extensional processes produce the topography which controls regional drainage systems. The geometry and location of border faults therefore, exert a strong control over where fluvial systems enter rift basins and, ultimately, where potential reservoir facies may be located. Changing water levels control the location of shorelines and the lateral extent of seal facies. This talk will examine examples where both transverse and axial drainage systems have been modified by tectonic and climatic variation.

Deformation associated with a propagating fault tip changes topography (and/or bathymetry) in such a way as to produce predictable changes in drainage systems and, therefore, facies distribution through time. Progressive footwall uplift creates backshed drainage away from the basin. However, these drainage systems frequently coalesce and enter the basin near fault tips. As the fault tip propagates laterally, the drainage system's entry point into the basin migrates as well. In the case of alternating half-grabens, capture of the backshed drainage from one half-graben is enhanced by subsidence produced at the flexural margin of the adjoining half-graben. These concepts are illustrated from a variety of rift basins including the Salt Flat Graben and Lake Tanganyika. In both, drainage systems have migrated in advance of a propagating fault tip. Abandoned channels are observed in the "wake" of this propagation. This model illustrates how knowledge of fault evolution can improve the prediction of facies distribution and reservoir connectivity.

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A new structural model for the pre-salt Santos Basin, Brazil, based on 'bottom-up' basin analysis

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The pre-salt geology of the South Atlantic margin basins is challenging to decipher using conventional 'top-down', seismic-based interpretation, largely due to poor seismic imaging beneath the salt. We present an alternative, 'bottom-up' workflow, where:
(i) Analysis of the basement terranes beneath and adjacent to the South Atlantic margins is used to predict pre-salt structural style, and
(ii) Innovative, integrated use of gravity, magnetic and PSDM seismic data are used to map top-basement topography and structure.

Jurassic-Early Cretaceous, south-to-north rifting and breakup in the South Atlantic exploited pre-existing basement structures; principally a series of Neoproterozoic-Early Paleozoic mobile belts that formed during the amalgamation of Gondwana. The contrasting crustal-scale structural framework of each mobile belt is reflected in the related geometry of each overlying basin compartment. The asymmetry, width and structural style of each basin can be predicted by understanding basement geology and the extensional rifting kinematics.

The Santos-Namibe Basin Compartment overlies the Cabo Frio Terrane, an early Paleozoic accretionary complex with a pervasive, shallowly-east-dipping structural grain. Both model and actual analogs show that when extended, shallowly-dipping, pre-existing basement structures are often reactivated via simple shear to form highly asymmetric conjugate margins; often termed 'upper' plate (narrow) and 'lower' plate (wide) margins. In the wide, lower-plate Santos margin which, analogs predict high levels of upper crustal extension with sub-horizontal detachments and highly rotated fault blocks, at odds with the conventional notion that the Santos pre-salt is dominated by an upright 'horst-and-graben' rift geometry.

Integrated imaging, modeling and interpretation of gravity, magnetic and PSDM seismic data verifies this view of the pre-salt basin geometry in the Santos Basin. Firstly a set of 2D crustal cross sections were constructed to understand the pre- and syn-rift structure of the basin. These cross sections were improved using structural restoration and gravity modeling. Enhancement processing and imaging of magnetic and gravity data were undertaken to reveal map-view basement structures and igneous feature, which were combined with the 2D cross sections to interpret the map-view structural geometry of the basin. Shell's proprietary Bathogram technology was used to model depth to basement from magnetics. Finally a top-basement surface was sculpted by integrating all of these outputs.

This new 'bottom-up' view of the Santos Basin can be used to understand and predict pre-salt paleogeography and petroleum systems distribution, then generate 'sweet spots' for hydrocarbon exploration. It shows that:

- Early syn-rift sediments are likely to be irregularly distributed and structurally rotated (with implications for source distribution and maturity).
- A significant proportion of the basin is floored by low-angle detachment fault planes.
- The steepest basement topography is likely to occur at the top of fault blocks.
- Fault block tips may be eroded, with implications for syn-rift clastic reservoir distribution.
- Base-salt structural highs (i.e. main hydrocarbon traps) form above basement and/or igneous highs due to differential compaction.
- Post-salt reactivation of key rift structures caused counter-regional tilting that formed the largest hydrocarbon traps.

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Structure and evolution of the Santos Basin, SE Brazil – oblique extension, strain partitioning and implications for South Atlantic Rift evolution

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Much of the structural complexity found in rifted passive margins can be related to the influence and reactivation of pre-existing basement structures, many of which lie significantly oblique to the regional extension vector. The passive margins of Brazil and Angola display complex variations in margin trend, width and structure along strike which appear to correlate well (both spatially and geometrically) with changes in existing fabrics of the Neoproterozoic Brasiliano-Pan-African Orogeny. In recent years the Santos Basin of SE Brazil has seen a sudden increase in exploration interest, with particular focus on early syn-rift facies and structures, culminating in a number of significant hydrocarbon discoveries. Here we present a structural and evolutionary model for the early development (i.e. pre-break-up) of the Santos Basin, based on interpretations of 2D seismic and regional geophysical data. This model has then been combined with regional plate reconstruction models (inc. onshore basement correlations) to restore rifts from the Brazil and Angola conjugate margins and build an early Cretaceous rift model for the South Atlantic.

The rift architecture of the Santos basin is characterised by N-S to NNE-SSW trending faults. These intra-basin faults can be segmented into distinct dip domains separated by ESE-WNW and ENE-WSW (margin parallel) transfer zones. The latter margin-parallel set are only apparent in the NW of the basin and are coincident with similar trending gravity and magnetic anomalies. Localised basement inheritance appears significant in near-shore and onshore areas, but not in deep water, therefore leading us to define zones of rifting where basement control is strong at the margin edge and extension-dominated rifting in deepwater areas where basement control is absent. At least two phases of rifting can be identified, with the oldest faults in the NW of the basin and youngest (syn-/ post-salt deposition) in the SE, thus defining a basinward migration with time. These also define an early pre-salt depocenter, and a younger syn-salt depocenter in the deepest part of the basin.

An extensive Aptian salt basin extends across the basins of the Central South Atlantic forming a well defined time marker horizon. This salt basin is believed to be almost coincident with the onset of sea-floor spreading in the Campos and Kwanza basins. However, in deepwater Santos, the late phase of rifting appears to continue at this time, offsetting the base salt strata. We suggest that this rifting is coincident with the onset of sea floor spreading in the Campos basin, and therefore that the transition from rift to drift occurs later in oblique margin segments. This may also explain why the ocean-continent boundary is so difficult to place in the deep water Santos.

Pre-existing basement effects appear to have played an important role in the development of the Santos/Angola margins. Basement fabrics appear to have partitioned the margin into proximal highly basement-influenced zones and distal extension dominated zones and also helps to explain the asymmetric break-up along the Santos margin.

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The tectono-stratigraphic evolution of the NW Vøring Basin, offshore Norway: the role of transfer zones in rift and passive margin segmentation

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The NE Atlantic margin initiated during continental break-up between Norway and Greenland, which followed a protracted phase of crustal stretching that culminated during Late Cretaceous-Early Tertiary rifting. The rifts have a mainly NE-SW orientation, but regional gravity and magnetic datasets highlight a series of NW-SE trending lineaments – or “transfer zones” – along the length of the margin. Previous authors have suggested that some transfer zones may have originated due to reactivation of basement structures as old as 2.5 Ga, but the origin and structural significance of these lineaments is generally unclear. An improved understanding of the nature and tectonic significance of these transfer zones is of practical interest to the hydrocarbon industry, given their likely role in controlling the structural segmentation of basinal depocentres at a variety of scales. The aim of this study is to constrain the impact of two NW-SE trending transfer zones on the structural and stratigraphic evolution of a segmented rift system in the NW Vøring Basin, prior to continental breakup ca. 54 Ma. In particular, the relative timings of movements on the NE-SW and NW-SE structures will be constrained and their impact on sediment provenance and the stratigraphical evolution of the basin will be discussed.

The NW Vøring Basin is characterised by two NE-SW trending structural highs - the Gjallar Ridge and Nyk High – that formed during Late Cretaceous-Palaeocene rifting. The Gjallar Ridge and Nyk High are offset in an apparent dextral sense across the NW-SE trending Surt Lineament, although previous authors have postulated left-lateral strike-slip along the Surt Lineament synchronous with Late Maastrichtian-Paleocene rifting. The preservation of breakup lavas at the northern end of the Surt Lineament implies focused flow along a tectonically inactive topographic low associated with this structure at around the time of continental break-up. However, the relationship between the Surt Lineament and NE-SW trending rift-related depocentres is unclear due to the complexity of the fault patterns observed at the intersections between the transfer zone and the Gjallar Ridge / Nyk High. A second NW-SE trending feature – here termed the Gleipne Lineament – appears to intersect the Gjallar Ridge. This feature has a much less distinct structural expression than the Surt Lineament, but nevertheless appears to have had an important impact on syn-rift sedimentation within the NW Vøring Basin. These results suggest that although the two lineaments are likely to have contrasting structural – and possibly geophysical – expressions, each structure impacted on the pre- to syn-breakup accommodation space within the basin.

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Tectono-Stratigraphic Framework and Petroleum Systems of Tertiary Rift Basins in Southeast Asia

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The Tertiary rift basins of Southeast Asia are situated on a stable Pre-Late Cretaceous tectonic core, “Sundaland”, which underlies much of present-day Indochina, Thailand, and western Indonesia. During the Cenozoic Sundaland was surrounded by subduction zones and was wedged between the Eocene-age India/Asia collisional domain in the northwest and the Miocene to Recent-age Australia/Asia collisional domain in the southeast. The polygenetic character of the Tertiary rift basins superimposed upon Sundaland is largely a product of the interaction of these two collisional domains.

The resultant tectonic evolution of the basins can broadly be divided into three stages: 1) Early Eocene-Oligocene intra-plate transtensional, backarc, and “slab-pull” related rifting caused either directly or indirectly by far-field stresses associated with the India/Asia collision; 2)Late Oligocene-Early Miocene early postrift thermal subsidence; 3)Middle Miocene-Recent late postrift compression caused by the collision of Australia with the southeast margin of Sundaland and the Reed Bank Block with northwest Borneo. During this stage many basins in the south experienced inversion, superimposed forelands, and hinterland uplift. Coeval orogenic collapse of some of the uplifted hinterlands (e.g. Tibet and possibly Borneo) resulted in local rifting that continues to the present-day.

Each of the three stages of regional basin development described above has a predictable association of stratigraphic megasequences and related petroleum systems. The petroleum systems can be profoundly affected locally within rift basins by variations in heat flow/ temperature, fluid pressure regimes, and seal/ reservoir/ source rock distribution and character. The rift stage is generally associated with fluvial-lacustrine megasequences and oil-prone petroleum systems overlain by transgressive deltaic megasequences and oil/gas-prone petroleum systems. The early postrift thermal subsidence stage is associated with transgressive non-marine to marine megasequences and gas-prone petroleum systems. The compressional late postrift stage is associated with regressive deltaic megasequences and gas/oil-prone petroleum systems. Statistical analysis of hydrocarbon production data demonstrates the strong impact basin development and paleogeographic position have on stratigraphic megasequences, petroleum systems, and hydrocarbon volumes and mix.

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Working Towards Intra-plate Models for SE Asia Rift Basins

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Southeast Asia has a complex tectonic history with multiple episodes of extension and rifting overprinted by periods of orogeny and inversion. Disagreement exists over driving mechanisms, the relative importance of extrusion tectonics, the interpretation of paleomagnetic data, as well as the extent and nature of regional shear zones. There are 3 main periods of extension:

1) Eocene extension is probably the most widespread, but has multiple origins that include strike slip, post-orogenic collapse, and possibly slab role back mechanisms.
2) Oligocene to Early Miocene extension culminated with sea floor spreading in the South China Sea, and includes a large area of attenuated continental crust in Vietnam, Malaysia, and the Natuna region of Indonesia.
3) Middle Miocene extension in the Sulu Sea extends to the onshore of SE Sabah. Recent work on the NW margin of Borneo, indicates this is event is more widespread than previously recognized.

This talk addresses the nature of these extensional events, highlights their areal extent as fundamental aspect of the region's structural evolution, and discusses their impact on the region's petroleum systems. Lastly, the need for improving intra-plate kinematic models is discussed in terms of placing under-explored basins in a better paleogeographic context to address critical success factors related to reservoir, source rock, and burial history.

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A detailed view of rift structure and tectonostratigraphy within the Jeanne d'Arc Basin with regional implications for the Grand Banks region, Newfoundland

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The Grand Banks, Newfoundland, is a shallow promontory of continental crust bordered on three sides by successively younger oceanic crust moving from south to north. These passive margins represent the culmination of rifting episodes during Late Triassic through Cretaceous time. We use high-quality 3D seismic and well data, mainly from the Terra Nova oilfield located within the oil-rich Jeanne d'Arc Basin, to provide a detailed view of multi-episode rifting and a better understanding of the regional tectonic events that were fundamental to the creation of the Grand Banks region and related North Atlantic borderlands.

Regional uplift occurred in the Terra Nova region during Late Jurassic (Tithonian) time. Simultaneously, the Jurassic strata above the Upper Triassic/Lower Jurassic salt experienced E-W extension. This extension was accommodated by numerous N-striking, suprasalt normal faults with local subsidence. Stratal thickness variations across these faults, observed in closely spaced wells, show that extension rates varied during this tectonic event. Widespread normal faulting continued with uplift in the south and sediment infilling to the north until at least the mid-Valanginian, followed by a brief re-establishment of broad patterns of subsidence with limited faulting. Additional regional uplift and progressive erosion occurred in the south during late Hauterivian through Barremian (to possibly Early Aptian) time. The Late Aptian through Albian marked a new tectonic episode, this time characterized by N-S to NE-SW extension accommodated by W- to NW-striking, suprasalt normal faulting. These faults interacted with the pre-existing N-striking normal faults in several ways (i.e., intersection and offset of older faults, termination at older faults, and continuity above the upper tip line of older faults). Locally, older faults or fault segments reactivated with oblique-slip during the later episode of faulting. Scaled experimental (analog) models with two phases of non-coaxial extension recreate and aid in interpreting these complex fault patterns.

What do these documented patterns of uplift, subsidence, and normal faulting reveal about the tectonics of the Jeanne d'Arc Basin during Late Jurassic to Early Cretaceous time? Specifically, are the two observed episodes of extension related to gravity-driven processes or plate-tectonic processes? The observed scales and patterns of uplift and erosion versus subsidence and sediment accumulation in the Jeanne d'Arc Basin are inconsistent with purely gravity-driven processes. Instead, the observed patterns of faulting and folding resemble those in rift basins with basement-involved normal faulting and salt (e.g., the Haltenbanken area of offshore Norway) with large fault-propagation folds above basement-involved normal faults and numerous detached normal faults in the sedimentary cover above the salt. Thus, we believe that both episodes of detached normal faulting in the Jeanne d'Arc Basin reflect crustal extension.

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Oblique inversion of the Fundy rift basin on the passive margin of southeastern Canada

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Rift-basin inversion involves a reversal in deformational style, specifically an extensional phase followed by a shortening phase. Orthogonal inversion occurs when the directions of the extension and shortening are coaxial, whereas oblique inversion occurs when the directions of the extension and shortening are non-coaxial. Our goal is to better understand the structural characteristics of oblique inversion by studying a natural example, the inverted Fundy rift basin of southeastern Canada. We have defined the 3D geometry and kinematics of inversion structures in the Fundy rift basin using seismic (offshore and onshore), field, aeromagnetic and DEM data. Of critical importance are the contrasting structural styles associated with differently oriented segments of the border-fault system. NE-striking border faults are gently dipping, whereas ENE-striking border faults are steeply dipping at the surface but gently dipping at depth. All segments were active during Late Triassic – Early Jurassic sedimentation.

The hinges of most post-depositional, shortening-related folds parallel the major border faults. The tightest and narrowest folds occur adjacent to the most steeply dipping upper fault segments, whereas broader folds occur adjacent to the more gently dipping upper fault segments. Some of the folds are traditional anticlinal buttress folds. Others, however, consist of trains of hanging-wall anticlines and synclines and are a combination of buttress and detachment (buckle) folds, with the low-angle fault surface or evaporites acting as the detachment surface. In outcrop, the folds are bounded and/or cut by high-angle faults with mostly left-lateral strike-slip. The inversion-related deformation is, at least partially, partitioned into pure-shear and simple-shear components. The fault-parallel buttress/detachment folds accommodate the pure-shear component, whereas the left-lateral strike-slip or gently raking oblique-slip faults accommodate the simple-shear component. Thus, the buttress/detachment folds do not necessarily indicate the regional shortening direction but rather reflect the variable local shortening direction associated with the pure-shear component of the deformation. Based on kinematically compatible slip vectors on differently oriented border-fault segments and the results of experimental models of oblique inversion, the regional shortening direction during inversion of the Fundy rift basin was NNE-SSW to ENE-WSW, which is moderately oblique to sub-parallel to the passive margin. In contrast, the likely shortening direction for inverted rift basins in the southeastern United States was sub-perpendicular to the margin.

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Indian Continental Margin: Diachronous Rifting, Ridge Jumps and Continental Fragments

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About 18,000 km of 2D, deep imaging, long offset, large source, pre-stack depth migrated seismic data (IndiaSPAN), has been acquired around the continental margins of India. This type of reflection seismic data is providing an unprecedented view of continental margins, imaging the deep crustal reflectors and providing insights into how the overlying basins (sag and drift) have formed. This new type of data is providing images of the continental transition zone that required refining previous estimates on continental plate boundaries, and is currently leading to a new generation of more accurate plate margins and better models on the crustal mechanics of rifting.

The new data has imaged deep (15-25 km) reflectors on both the east and west coasts that has required the re-interpretation of how India separated from Gondwana. In this presentation we will present a model of diachronous rifting, beginning in the Karoo (Rift1), with a second phase of rifting in the Jurassic (Rift2) over which a thick (5-15 km) sag basin developed. On the east coast oceanic crust was generated by the successful Valanginian (Rift3) rift, and on the west coast oceanic crust was generated by the strike-slip separation of Madagascar (Rift3) at the end of the Cretaceous.

The successful Rift3 on the east coast appears to have abandoned partially attached and fully detached (85E Ridge) continental fragments, likely the result of a ridge jump and subsequent change in the direction of separation with Antarctica. Southwest of the 85E Ridge, the oldest drift sediments observed on oceanic crust are Aptian, and northeast of the ridge the oldest drift sediments are Turonian. This suggests that the Elan Bank (continental fragment) separated from India before the Kerguelen Plateau, with both segments later detaching from Antarctica.

On the west coast, the Rift3 separation with Madagascar created large (100 km) compressional anticlines indicating a strong component of strike slip. These deep through going crustal faults provided conduits for large volumes of volcanics and the generation of well imaged seaward dipping reflectors (SDRs). The Laxmi ridge and the Seychelles have both been previously recognized continental fragments. The Laxmi ridge is now well imaged and appears to overlie several segments of 20-25 km thicker continental crust with SDRs on both the east and west flanks.

The IndiaSPAN data has identified a much broader (>100 km) continental margin than used previously in plate tectonic reconstructions. Using these newly interpreted boundaries, a new plate fit will be presented that will include the continental fragments observed along the Indian margins, and published outlines for the Seychelles, Madagascar, Elan Bank, Kerguelen Plateau, the African and Antarctic continents.

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