Petroleum Systems of Divergent Continental Margin Basins

25th Annual GCSSEPM Foundation - Bob F. Perkins Research Conference

Program and Abstracts

Petroleum Systems of Divergent Continental Margin Basins

25th Annual Gulf Coast Section SEPM Foundation Bob F. Perkins Research Conference

2005

Program and Abstracts

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Edited by

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Foreword

Let's start with the facts. I had a really nice, normal (for me) foreword written for the GCSSEPM 25th Annual Bob F. Perkins Research Conference, Petroleum Systems of Divergent Continental Margin Basins CD. I was going to e-mail it to Norm the last week of August and beat all the deadlines: so much for the best of intentions. As you may know, I work for Minerals Management Service in New Orleans, although we are actually in Jefferson Parish, which is a piece of bureaucratic slight-of-hand.

When I left work Thursday, Katrina was forecast to make landfall around Tallahassee, Florida. Papers like Roberto Fainstein's final on CD were on my worktable at MMS ready to courier to Norm when I received a few more; others, like Gabor Tari's second submission on the proto-Pannonian basin, I planned to edit the next week. Something about best intentions and plans seems to stick in my mind. Hurricane Katrina made landfall the following Monday, August 29. Katrina was one of the strongest storms to impact the coast of the United States during the last 100 years. With sustained winds during landfall of 140 mph (a strong category 4 hurricane on the Saffir-Simpson scale) and minimum central pressure the third lowest on record at landfall (920 mb), Katrina caused widespread devastation along the central Gulf Coast states of the US. Cities such as New Orleans, LA; Mobile, AL; Waveland, Biloxi, Gulfport, and Pascagoula MS bore the brunt of Katrina's force. It did serious damage to the 10-story building where MMS has nine floors. Of course, you would have had to be living in a cave to not know or have seen pictures of the devastation. We lost electricity, at 5:20 AM that morning, and telephone connections after 8:00 PM.

We live just over 35 miles north of New Orleans; north of I-12 and any flood danger amidst pine trees with diameters of 1.5-2' and more than 50' high. The western eyewall of Katrina passed nearly over us. We had sustained winds in excess of 100 mph for more than 4 hours and gusts greater than 140. Rather than go into the effects on us, the living in a cave comment was appropriate. We had no power for nine days, occasional telephone service, could not drink the water, showered in the dog runs; we won't go into the servicing of other bodily functions. For those of us who did not evacuate it was a kind of like living like a caveman: air-conditioning *GOOOOD*: Internet *NIIIICE*.

Many of my friends and colleagues lost their homes and most of their possessions. They scattered like leaves in, yes, a hurricane. When we got phone service back, for the first time the Thursday after Katrina, my first call was to my mother, my second was to Norm. Of course, the phone was only up for about 5 hours, we then lost it again for about a week. It came back for another 4 hours. Finally, after about 19 days, our telephone service generally stayed up. As Norm said, you have lived through a life-changing event. It was also an event that taught a lot of us what is really important in life and what is just not worth considering.

I did not have access to my files on the MMS network. Had I known that the southeast Louisiana area was suddenly the landfall target, I would have taken my files home on my portable hard drive. Still another technological opportunity missed. Finally, in late September, when our electricity and phones, and those of our ISP were all up, I began trying to contact the authors who contributed papers to this conference. I was able to get in touch with many of them via e-mail. Others, I was able to contact via third parties, such as Jason Carneiro, a colleague of Ricardo Bedergal, who forwarded my e-mails to Renato Darros, Marta Guerra and Webster Mohriak. Without the help of people like Jason, pulling this research conference together would not have been possible.

With the devastation of hurricanes Katrina and Rita as a backdrop, and a feel for what is truly important, I would like to thank the management of MMS Resource Evaluation; Dave Marin, David Cooke, and Abdul Khan for allowing me the time to put this conference together, contact authors, author and co-author papers and edit papers. The quality of this conference is a tribute to the input of many people. However, I want to especially thank Webster Mohriak and Dave Brown. Their guidance regarding authors/researchers to solicit for papers and in Webster's case his direct solicitation of so many quality papers from his Brazilian colleagues was invaluable. I also want to extend my sincerest appreciation to Don Olson, who has the cubicle next to mine, and who with me edited most of the manuscripts. Don has the unique ability to determine if things make sense to someone without the technical expertise in areas often assumed by authors. The clarity and readability of many of the papers in this volume is a tribute to Don. In addition, MMS management allowed my colleagues, Stephen Palmes and Kevin Lyons, time to review and edit papers. Geoff Newton, a former Texaco colleague also edited papers. My co-chairs; Bill Bosworth, Marita Bradshaw, Tony Doré, Garry Karner, Webster

Mohriak, and Mike Roberts; and program advisory committee of Al Danforth, Carl Fiduk, Geoff Newton, Stephen Palmes, and Gábor Tari provided insight and comments that helped shape this research conference, set its tone and program. Mark Rowan is one of the people I trust most to give me advice. He reviewed the abstracts and re-worked the program with the themes and speaker order used in this conference. His knowledge of speakers, their backgrounds and their expertise have been invaluable. The flow of the program is a tribute to his skill. Of course, Norm Rosen, one of my oldest friends deserves a lot of credit for keeping me together during the dark days of trying to solicit papers, get the authors to commit, provide their papers, and be a part of this conference. One thing Norm did not do, was to help me herd cats. That is what this organizing and co-coordinating one of these conferences is really all about.

To those of you who took the time to read this my thanks. I hope you appreciate the science, insight, and quality of the papers in this CD. They are a tribute to their authors, their companies who gave them the permission and support to provide the papers, the partners who granted their permission, and the various data owners who allowed their data to be used. Hopefully, the papers presented address many of the exploration issues we sought to clarify when we conceived this conference.

Paul Post

And now a word from the publisher: This is the first time I have decided to add some words to the editor's comment. May you live in interesting times does not come close to describing the past month. Everyone is aware as to how Katrina and Rita affected Louisiana, an area (believe it or not) that I regard as a second home. My wife and I went to school at LSU (Geaux Tigers!), our daughter was born in N'awlins, and some of our best friends in N'awlins were Cajuns. We lived through Betsy, Hilda, Camille, a glancing blow from Fredrick, Celia, and God knows how many other tropical storms I have forgotten. My first well proposal was in Bayou Penchant North **and it came in for some strange reason!** The second proposal that I helped to write was in Horse Shoe Bayou and I cannot explain why, **it came in also!** These are some of the reasons as to why the region means so much to me. May some Being, Force, or God protect this land from the politicians.

During the trying times Paul has described above, one of his main concerns has been this conference. It is no joke that his second phone call was to me. Paul's main concern was that the conference would not happen because so much material was stuck in the Metairie office. Although I tried to explain to Paul that there really are some things more important than this conference, he really did not pay attention to me. I can honestly say that not even a category 4 hurricane can stop Paul Post from his appointed rounds. For this reason, using whatever influence I have, this conference is dedicated to Paul.

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The cover image that was chosen for this year's conference is a satellite image of Hurricane Katrina, one of the stronger storm systems of modern times, reaching rare Category 5 status according to NOAA. This image is credited to the GOES (Geostationary) 12 Satellite, NASA (National Aeronautics and Space Administration)-GSFC (Goddard Space Flight Center), and data from NOAA (National Oceanic & Atmospheric Administration).

Petroleum Systems of Divergent Continental Margin Basins

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Program

Sunday, December 4, 2005

4:00–6:00 p.m. Registration (Grand Foyer) and Poster Setup (Grand Pavilion)

6:00–8:00 p.m. Welcoming Reception and Poster Preview (Grand Pavilion)

Monday, December 5, 2005

7:00 a.m. **Continuous Registration (Grand Foyer)**

8:00 a.m. **Welcome: Mike Styzen, Chair of the Board of Trustees, GCSSEPM Foundation (Grand Pavilion)**

8:10 a.m. **Introduction: Paul J. Post, Program Chair (Grand Pavilion)**

Session I—Crustal Architecture of Divergent Margins

Co-Chairs: A.G. Doré and G. Karner

Keynote Address:

9:40 a.m. **Refreshment Break and Posters**

Session I—Crustal Architecture of Divergent Margins (continued)

Co-Chairs: D. Brown and M.O. Withjack

Session I—Crustal Architecture of Divergent Margins (continued)

Co-Chairs: W. Bosworth and W.G. Dickson

Session I—Crustal Architecture of Divergent Margins (continued)

Co-Chairs: W.U. Mohriak and M.C. Guerra

Session II—Salt- and Shale-Related Deformation on Divergent Margins

Keynote Address:

4:00 p.m. **Mohriak, Webster Ueipass**
Salt Tectonics in Atlantic-Type Sedimentary Basins: Brazilian and West African Perspectives Applied to the North Atlantic Margin *18*

4:25 p.m. **Ruffo, Paolo**; Campobasso, Silvia; Fragola, Daniele; Massimi, Paolo; Scrofani, Giovanni; and Spadini, Giacomo
2D Computational Salt Tectonics: Passive Margins *19*

4:50 p.m. **Guerra, Marta Cardoso de Melo**; Szatmari, Peter; and Pequena, Monica
Analog Modeling of Salt-Related Structures in the South Atlantic *20*

5:30–8:00 p.m. Hot Buffet and Poster Session (Sessions will end at 5:15)
(The cost of this buffet has been subsidized by a very generous grant from Statoil.)

Tuesday, December 6, 2005

Session II—Salt- and Shale-Related Deformation on Divergent Margins (continued)

Co-Chairs: I. Davison and J.C. Fiduk

8:00 a.m. **Davison, Ian**
Tectonics of the South Atlantic Brazilian Salt Basins *21*

8:25 a.m **Matias, Hugo**; Mohriak, Webster; Menezes, Paulo; Sandnes, Frode; Barbosa, Valéria C. F.; Matias, Luis; and Santos, Fernando
Salt Distribution and Morphology in the Offshore Algarve Basin *22*

8:50 a.m. **Fainstein, Roberto** and Krueger, Ana
Salt Tectonics Comparisons Near Three Continent-Ocean Boundary Escarpments *23*

9:15 a.m. **Dyson, Ian A.**
Evolution of Allochthonous Salt Systems During Development of a Divergent Margin: The Adelaide Geosyncline of South Australia *24*

9:40 a.m. **Refreshment Break and Posters**

Session II—Salt- and Shale-Related Deformation on Divergent Margins (continued)

Co-Chairs: S.L. Palmes and M.G. Rowan

10:05 a.m. **Turner, Joshua Creviere**
Turtle Structures Created by Extension in a Low-Salt or Non-Salt Setting *25*

Session III—Sedimentation on Divergent Margins

10:30 a.m. **Palmes, Stephen L.**
Relay Ramps and Lateral Ramps—Active Sediment Fairways During the Passive Margin Stage of Development of the Gulf of Mexico Basin *26*

5:30–8:00 p.m. Beer, Wine, Snacks and Poster Session (Sessions will end at 5:15)

8:00 p.m. **Authors Remove Posters**
(Contractor will remove display boards at 8:15 p.m.)

Wednesday, December 7, 2005

Session IV—Petroleum Systems of Divergent Margins (continued)

Co-Chairs: M. Bradshaw and D. Ryan

9:40 a.m. **Refreshment Break**

Session IV—Petroleum Systems of Divergent Margins (continued)

Co-Chairs: G. Tari and G. Eisenstadt

Session V—Crustal Architecture of the Gulf of Mexico

Challenges and Controversies in Exploration of the Northeast Atlantic Margin

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Abstract

Despite some setbacks in the exploration of this initially highly prospective frontier province, oil and gas discoveries off mid-Norway, and, recently, on the Faroes and western United Kingdom shelf provide continuing encouragement to exploration. Large parts of the area (including the northeast Greenland shelf, a portion of shelf similar in size to the productive area offshore mid-Norway) remain almost totally unexplored. Therefore, numerous basic questions remain unanswered on the region's geological evolution and petroleum prospectivity. These include provenance and source to sink relationships for the principal reservoir targets (Cretaceous and Paleocene sandstones), and the distribution and relative contribution to the hydrocarbon budget of different source rocks. However, in this paper, we concentrate on the fundamental problems relating to the lithosphere-mantle structure of the margin. Many of these challenges stem from the status of the region as a classic volcanic passive margin.

The Northeast Atlantic (Fig. 1) is commonly considered to be an archetype for volcanic passive margins and the region is classified as a large igneous province (*e.g*. Coffin and Eldholm, 1992), referred to as the North Atlantic Igneous Province (NAIP). Flow basalts (Fig. 2), the main phase of which just postdated the main (Paleocene) reservoirs of the region and just predated northeast Atlantic breakup, create significant problems in seismic imaging of reservoirs and traps. Conversely, attempts to resolve this problem have resulted in significant strides in sub-basalt imaging, while locally intense seismic coverage has enhanced our knowledge of the 3D geometry of sills, dykes, vents, hyaloclastites, and other volcanic phenomena.

In general, the magmatic nature of the NAIP has been attributed to Paleocene–early Eocene rifting and breakup influenced by a mantle plume (White, 1988). However, it is difficult to explain all of the phenomena associated with the volcanic margin using this hypothesis, and there is significant controversy over the timing, size, shape, and even existence of the early Tertiary plume. The Iceland "hotspot", although certainly representing an upper mantle upwelling at the current spreading ridge, has few of the characteristics of a classic deeply rooted plume, with most interpretations showing the low-velocity zone under Iceland being confined to the upper mantle (Foulger and Pearson, 2001). It is by no means clear (and certainly cannot be taken for granted) that there is a direct link between the presumed plume under Iceland and the formation of the early Cenozoic NAIP. The assumed link stems from the classic hotspot model of lithospheric drift (in this case, northwestwards) over a fixed plume emanating from a very deep interface such as the core-mantle boundary. However, the "hotspot trail", from West Greenland, across Greenland to the present position of Iceland on the Atlantic spreading ridge (Lawver and Müller, 1994) that many regional interpretations treat as an *a priori* fact (Figs. 1 and 2) is neither proven nor even supported by the evidence. On the contrary, the apparent symmetry of the Greenland-Faroes Ridge (generally taken to represent the oceanic "hotspot track") in the ocean basins either side of Iceland suggests that the Iceland anomaly has remained fixed on the constructional plate boundary (Lundin and Doré, 2005, and *in press*). The near-simultaneous onset of volcanism in the NAIP at c. 62 Ma, in a line from Baffin Island to southwest Britain (thus crosscutting the line of eventual plate breakup), at a time when the plume should have impinged on the most northwesterly outpost of the province, also creates difficulties for standard plume models. For more on the Iceland issue and on the general debate on mantle plume models, see www.mantleplumes.org.

Given the debate on the mantle and lithospheric controls, there is uncertainty surrounding the changes in basal heat flow associated with breakup that should be assumed in constraining source rock maturation, hydrocarbon generation, and migration. One factor of

key importance in the assessment of temperatures is that of the distribution and nature of the anomalous, high-velocity, lower crustal body (HVLCB). This body is associated with the NAIP, identified on refraction and wide-angle seismic data, and commonly interpreted as magmatic underplating from decompressional melting of a plume-influenced mantle during final rifting and breakup (Fig. 2). The HVLCB is estimated by some workers to constitute as much as 60–80% of the total estimated Paleocene magmatic rock volume in the NAIP (White *et al*., 1987).

A long-standing belief about magmatic underplating is that buoyantly rising asthenospheric melts pond beneath the crust because they reach a level of neutral density, spreading laterally to preferentially infill the pre-existing Moho "topography", and forming thick pillows beneath rifts where the Moho was elevated. However, new ocean-bottom seismometer (OBS) work (Mjelde *et al*., 2005) reveals that the HVLCB is highly variable both in thickness and internal velocity. The HVLCB does not seem to have filled in a pre-existing Moho relief and seems to terminate abruptly against margin-perpendicular lineaments. These features seem to extend onshore into lineaments associated with collapse of the Caledonian Orogen along major detachments oriented at high-angle to the orogenic front (Olesen *et al*., 2004). The detachments limit large, exhumed basement culminations and separate high-grade metamorphic assemblages (including eclogites) from low-grade assemblages. Mjelde *et al*. (2005) suggest that the offshore lineaments separate regions containing magmatic underplating from regions of normal mantle and/or from eclogite bodies. Likewise, non-magmatic portions of the inner-Norwegian margin are underlain by HVLCBs, which are not interpreted as magmatic underplating, but as *in situ* eclogite bodies (Christiansson *et al*, 2000) (Fig. 2). The nature of the HVLCB is highly relevant to hydrocarbon exploration, primarily with respect to heat flow. Where the HVLCB represents remnants from the Caledonian root zone, the inferred degree of crustal thinning (and hence heat flow) would be lower. At the other extreme, an up to 10-km thick layer of underplating would generate a transient but significant heat pulse (Fjeldskaar *et al*., 2003).

Even accepting that the HVLCB can primarily be attributed to underplating, its regional extent and effect can be strongly debated. It is often widely assumed that underplating underlies large portions of northwest Europe, thereby explaining widespread Paleocene uplift and allowing predictions to be made of elevated Paleocene–early Eocene heat flow (Clift, 1999). However, the actual extent of the HVLCB, as proven by refraction, OBS, and wide-angle seismic data is essentially limited to the immediate continental margins (Fig. 2). A key issue may well be the nature of material at the base of the highly thinned crust in the Rockall Trough. This area, generally believed to have undergone lithospheric stretching during the Cretaceous, would have been an ideal accumulation area for Paleocene asthenospheric melts, and recent velocity data suggest that a sub-crustal layer in this region is more likely to correspond with serpentinized upper mantle than with underplating (Morewood *et al*., 2005). Detailed thermal histories for the northeast Atlantic margin, based on apatite fission track and vitrinite relectance data, appear to show no evidence for regionally consistent, anomalously high, early Tertiary basal heat flows (Green *et al*. 1999). This is in contrast to what would be expected from models involving a broad plumehead and widespread underplating.

A further complicating factor in modelling the thermal history of the margin is the apparent mismatch between the limited extension (as manifested in brittle faulting) observed in the upper crust compared to the amount of apparent thermal contraction (*e.g.*, as observed in the subsidence of subaerially extruded lavas) following breakup. This apparent exception to the standard McKenzie model of uniform lithospheric thinning may be a paradigm for passive margins at time of breakup. This has been explained by depth-dependent stretching (Kusznir *et al*., 2005), a process whereby the lower crust and mantle lithosphere undergo more stretching than the upper crust. The viability of this model is clearly critical to basin modelling and thermal maturation, since it implies considerably greater input of heat into the system than would normally be inferred from the observed crustal extension. However, considerable problems remain to be resolved before this concept becomes useful in modelling the northeast Atlantic and other passive margins. First, the phenomenon is always inferred from subsidence modelling rather than being observed directly as lithospheric thinning. Its existence is based on the assumption that the McKenzie thermal relaxation model is correct. Thus, the apparent contradiction between observed extension and subsidence must be resolved at depth, where it cannot be observed. Another, more radical, possibility is that the calculation method itself is inapplicable in this setting. Second, the relationship with the assumed underplate at the continental margin is unclear. In most circumstances, addition of underplate at the base of the crust should cause isostatic uplift. Thus, both the vertical motions and temperature effects of the two proposed phenomena – underplating and depth-dependent stretching – are difficult to disentangle. Third, the mechanism for depth-dependent stretching (and, in particular, "disposal" of excess lower crust and lithosphere mantle) is unclear. Kusznir *et al*. (2005) have recently suggested that depth-dependent stretching occurs at, or immediately after, inception of sea-floor spreading rather than during pre-breakup rifting, and propose that thinning of the lithosphere can be predicted as a function of divergent mantle flow from the mid-ocean ridge. This model still requires substantiation in terms of the fate of lower lithospheric material and remains to be tested in a variety of settings (*e.g*., volcanic versus non-volcanic passive margins).

Major phases of uplift and exhumation of both the adjacent landmasses and some of the bordering basins took place during the Cenozoic. The series of sketch maps from late Paleocene to late Pliocene shown in Fig. 3 (after Lundin *et al*., 2004) illustrate the principal uplift events and the controversies associated with them. Latest Cretaceous–Eocene uplift was critical to the distribution of reservoir rocks in the province, including input of sands into the northern North Sea and Faroe-Shetland basin and from Greenland in the west to underexplored basins in the Faroes, mid-Norway, and the United Kingdom (Fig. 3A). Emergence of landmasses in a region previously dominated by Cretaceous marine shelves has been widely attributed to the "arrival" of the Iceland plume, causing transient (dynamic) uplift and permanent uplift (due to underplating), while sand pulses in the Paleocene have been attributed to variations in plume flux (White and Lovell, 1997). However, a number of factors call into question that this vertical movement can be attributed to the impingement of a single plumehead. These include: the wide variation of the uplift in time and space; the simultaneous juxtaposition of uplift and subsidence along the incipient margin; and the uplift of areas such as mainland Norway (including northern Norway, supposedly outside of the main radius of plume influence) where there is neither evidence of volcanic activity nor geophysical evidence for widespread underplating. Vertical motions taking place after breakup also varied in time and space, albeit with some episodes of greater synchronicity, and are even less amenable to the application of single mechanisms. For example, in the period immediately following breakup (early–middle Eocene) most areas along the newly developed margin underwent subsidence (*e.g*., North Sea, Faroe-Shetland Basin, mid-Norwegian margin) while highs such as the Rockall High and Porcupine Bank underwent uplift, the latter causing delta progradation into the Porcupine Basin.

An important question pertains to the origin of large, gentle, compressional structures distributed along the young sedimentary basins of the margin. These features formed in several episodes within the Cenozoic, with most activity in the early Oligocene–Miocene (Fig. 3A and B). Because they deform prospective successions of Late Cretaceous and Paleocene age, they are critical to the hydrocarbon migration and trapping history of the northeast Atlantic margin. While the current authors (Lundin and Doré, 2002) suspect that the compressive structures can be attributed to plate forces associated with the adjacent seafloor spreading (ridge push/mantle drag), others attribute them to far-field (Alpine) compressive stress. There is also considerable debate as to the contribution of compaction (fold flank loading) to the development of the structures. An association may also exist between the structuring and fault reactivation during the plate reorganization occurring at Chron 13 (earliest Oligocene, 35 Ma), during which plate motion in the northeast Atlantic rotated from a northwest-southeast to a more west-east vector. At this time, the Arctic-Atlantic connection evolved from a shear margin to a more directly linked spreading axis (Fig 3B) and the Labrador Sea-Baffin Bay and Aegir spreading ridges were abandoned (Fig. 3C). Continued compressive deformation probably also led to the development of a marine conduit across the previous land barrier of the Greenland-Faroes Ridge in middle Miocene times. This marine mixing resulted in the development of marine erosion surfaces, the redistribution of material as contourite deposits in the southern northeast Atlantic (Fig. 3C), and may have contributed to the deterioration of northern hemisphere climate (Stoker *et al*., 2005).

A widespread phase of late Neogene denudation affecting Svalbard, the Barents Sea, northern and southern Norway, Scotland, and East and West Greenland caused a major redistribution of mass along the margin (Fig. 3D). The episode appears to have been intimately associated with Northern Hemisphere glaciations and cannot be entirely accounted for by erosion, redeposition, and isostatic readjustment. Numerous lines of evidence (*e.g*., onshore measurements, offshore forced regressions) show that initial uplift predated glaciation and may indeed have been an additional trigger for climate change. The causes of this episode are particularly enigmatic. Amagmatic upper mantle circulation changes may explain both this and, conceivably, earlier Cenozoic motions (Rohrman and van der Beek 1996; Stoker *et al*., 2005). Resolution of the viability of this model versus other available mechanisms is one of the more fundamental questions on the large-scale geology of the area. The late Neogene episode exhumed numerous previous depocentres and had a radical effect on the emplaced hydrocarbon systems (Doré *et al*., 2002). The effects of this phenomenon are frequently underestimated in resource and risk assessments on the northeast Atlantic margin.

Effect of Lithospheric Stratification on Extensional Styles and Rift Basin Geometry

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Abstract

Plane-strain, thermo-mechanical, finite element model experiments of lithospheric extension are used to investigate the effects of strain softening in the frictional-plastic regime and the strength of the lower crust and mantle lithosphere, respectively, on the style of extension. Crust and mantle lithosphere strength are varied independently. A simple scaling of wet quartz and dry-olivine rheologies is used to examine crust and mantle lithosphere strength variations. Cases are compared where the crust is strong ($\eta_{wet\ quartz}$ x 100), weak ($\eta_{wet\ quartz}$), or very weak ($\eta_{wet\ quartz}$ /10), and the mantle lithosphere is either strong ($\eta_{dry\ olivine}$) or weak ($\eta_{dry\ olivine}$/10). 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; and (3) wide, symmetric, crustal rifting concomitant with narrow, mantle lithosphere extension. The different styles depend on the relative control of the system by the frictional-plastic and ductile layers, which promote narrow, localized rifting in the plastic layers and wide modes of extension in the viscous layers, respectively. A weak, ductile crust-mantle coupling tends to suppress narrow rifting in the crustal layer. This is because it reduces the coupling between the frictional-plastic upper crust and localized rifting in the frictional-plastic upper mantle lithosphere. The simple strength variation may be taken to represent end-member thermal and/or compositional conditions in natural systems and the relevance for rifting of old, strong, and cold cratonic lithosphere as compared to young, "standard", and moderately weak Phanerozoic lithosphere is discussed.

Large-Scale Structural Variations Across the Eastern Canadian Continental Margins: Documenting the Rift-to-Drift Transition

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Abstract

The eastern Canadian margins from Nova Scotia to Newfoundland and Labrador formed during several periods of non-volcanic continental rifting from ~180 Ma in the south, to ~60 Ma in the north. This paper documents the large-scale styles of structural variations across the deep-water regions of the rift-to-drift transition on these margins. We present a series of seismic transects combining deep **MCS** reflection and wide-angle refraction profiles producing depth sections having similar scales and resolution. The combined profiles exhibit smaller scale structures defined by the reflectivity and larger scale variations defined by the refraction velocity models. These transects show systematic patterns in which changes in crustal velocities can be clearly correlated with changes in reflectivity. All transects include complex variations across broad transitions where the complete sequence from rifted continental crust to oceanic crust occurs over distances of 200–300-km. Within the transition zone, the presence of highly stretched continental crust can exist up to 200-km seaward of the hinge zone. The boundary between continental and oceanic crust is sometimes, but not always, separated by flat basement ~80-km wide probably consisting of highly serpentinized upper mantle. An underlying region 150–200 km-wide of less serpentinized mantle exists where faults cut through the thin crust. Large variations between upper and lower crustal extension occur both between and along transects controlling the deposition of syn-rift sediment; while the deposition of post-rift sediment follows predictions based on the shape of the total crustal extension.

Evolution and Petroleum Potential of Orphan Basin, Offshore Newfoundland, and its Relation to the Movement and Rotation of Flemish Cap Based on Plate Kinematics of the North Atlantic

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Abstract

The Orphan Basin formed during the Mesozoic intra-continental extension, continental breakup, and North Atlantic Ocean opening. New seismic data collected in the Orphan Basin, and regional potential field data, show a wide non-volcanic rift area with two successive rift zones characterized by greatly stretched continental crust. From both tectono-structural and petroleum potential points of views, the Orphan rifted area can be subdivided into an older East Orphan Basin situated in deep water (1,500-3,000m) and a younger West Orphan Basin situated in shallower water (1000-1,500m). Seismic stratigraphic relationships indicate that the first episode of rifting could be as old as the Late Triassic-Early Jurassic in the East Orphan Basin. A petroleum system including Kimmeridgian, marine source rocks is postulated for this basin. A second rifting stage, from latest Late Jurassic to Early Cretaceous, created the eastern part of the West Orphan Basin and re-mobilized basement blocks and older sedimentary features in the east Orphan Basin. A third extensional stage during mid-Cretaceous, probably coupled with Labrador Sea extension and opening, mostly affected the westernmost parts of the West Orphan Basin. A later extensional stage is postulated to have occurred in the early Tertiary, related to the initiation of a new rift between Greenland and northern Canada. The West Orphan Basin petroleum system should be anchored by Cretaceous or early Tertiary source rocks.

The two main rift basins, east and West Orphan, are separated by a major crustal fault zone, the White Sail fault dipping eastward and affecting the entire upper crust. The N 020° linear, tilted faults blocks identified in the West Orphan Basin are perpendicular to the flow-lines of the herein proposed Flemish Cap motion during the M25-M0 period, giving an independent evidence of the validity of the Flemish Cap/North America reconstruction at chron M25 derived from magnetic and gravity data. On the M0 reconstruction, the east and West Orphan basins are located in front of the Porcupine basin and Rockall trough respectively.

The Flemish Cap behaved as a large, monolithic continental block and rotated clockwise 43°, apparently moving more than 200 km to the southeast, while the upper crust of the east Orphan Basin has a = 2.5 average stretching from Late Triassic to early Tertiary. Regional seismic data suggest that trans-tensional movements, although hard to identify on reflection data, played an important role and continued until the

Paleocene. Beyond the Orphan Knoll-Flemish Cap "outer ridge" lineament lies a true divergent margin basin showing little deformation within the sedimentary sequence and which overlies a relatively wide continent-ocean transition zone.

Correlation of Syn-Rift Structures Between Morocco and Nova Scotia, Canada

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Abstract

Reconstructions of the relative positions of the North American and African continents before the opening of the Central Atlantic Ocean have either been based on morphological fits using coastlines/isobaths or seafloor magnetic/fracture data. Additional constraints for the best fit between these continents may come from pre-rift structural elements if they are sufficiently oblique to the line of rifting. None of the existing reconstructions utilize syn-rift structures, which are expected to be preserved on the conjugate passive margins. We report a direct correlation of syn-rift structures across the Central Atlantic based on new reflection seismic and potential field data.

The prominent basement high of the Tafelney Plateau, offshore Morocco, is interpreted as a high-relief accommodation zone analogous to many well studied examples in the present-day East African rift system. It developed between two regional-scale, normal fault systems with opposing polarities. The actual Early to Middle Jurassic breakup occurred obliquely across the Tafelney accommodation zone leaving most of it on the Moroccan margin.

Structural Development of Southern Morocco: Interaction of Tectonics and Deposition

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Abstract

Interpretation of magnetic, gravity, seismic, and geological data shows that the curvilinear Late Paleozoic orogen affected the location of Central Atlantic syn-rift faults. While northeast-southwest striking thrust faults were perpendicular to extension, prominent curvatures, such as the Pennsylvania salient, introduced structural complexities. East-northeast/west-southwest striking, dextral, transpressional strike-slip faults of this salient became reactivated during Carnian-Toarcian rifting. They formed sinistral, transtensional strike-slip "rails" that prevented the Georges Bank–Tarfaya Central Atlantic segment from orthogonal rifting, causing formation of a pull-apart basin system. Central Atlantic segments to the south and north underwent almost orthogonal rifting. "Rails" lost their function after the continental breakup, except for minor younger reactivations. They were not kinematically linked to younger oceanic fracture zones.

Atlantic segments initiated by normal rifting differ from the segment initiated by the Georges Bank–Tarfaya strike-slip fault zone. They contain Upper Triassic-Lower Jurassic evaporites having salt-detached gravity glides, while the connecting transfer segment does not. Their structural grain is relatively simple, divided mostly by northeast-southwest striking normal faults. Northwest-southeast striking oceanic fracture zones kinematically link with continental faults in a few places, controlling the sediment transport pathways across the uplifted continental margin.

The connecting Georges Bank–Tarfaya Central Atlantic segment, initiated as a sinistral transfer-zone, has a complex structural grain, characterized by numerous small depocenters and culminations. Their boundaries are formed by east-northeast/west-southwest striking, sinistral, strike-slip, north-northeast/south-southwest, striking normal and west-northwest/east-southeast striking, dextral, strike-slip faults. Sediment transport pathways have complex trajectories, weaving through local depocenters.

A Review of Tectonic Events on the Passive Margin of Eastern North America

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Abstract

Field, seismic, and drill-hole data provide a wealth of information about the tectonic processes associated with rifting, breakup, and the early stages of seafloor spreading for the passive margin of eastern North America. The onset of rifting, from Florida to the Canadian Grand Banks, was approximately synchronous, occurring by Late Triassic time. The cessation of rifting (and presumably the onset of drifting) was diachronous, occurring first in the southeastern United States (latest Triassic), then in the northeastern United States and southeastern Canada (Early Jurassic), and finally in the Grand Banks (Early Cretaceous). The Central Atlantic Magmatic Province developed simultaneously (earliest Jurassic, ~200 Ma) throughout eastern North America. This magmatic activity occurred after rifting in the southeastern United States, and during rifting in the northeastern United States and maritime Canada. The passive margin, from Florida to southern Nova Scotia, is volcanic, characterized by seaward-dipping reflectors (**SDRs**) near the continent-ocean boundary. The remainder of the passive margin lacks **SDRs** and is, thus, non-volcanic. In the continental crust, most rift-related structures parallel pre-existing zones of weakness created by Paleozoic and older orogenies. Few transfer zones exist, and these also parallel the pre-existing fabric. In the oceanic crust, fracture zones parallel the direction of relative plate motion. Thus, the trends of the fracture zones in the oceanic crust differ from the trends of the rift-related structures in the continental crust. The deformational regime changed substantially after rifting throughout eastern North America: post-rift shortening (inversion) replaced syn-rift extension. Detached structures associated with salt movement also developed after rifting, especially on the Scotian shelf and Grand Banks.

Crustal Architecture of West African Rift Basins in the Deep-Water Province

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Abstract

We used a reprocessed 2D seismic line across the ultra-deep water area offshore Angola to map a thick pre-salt sequence divided by a prominent angular unconformity into two main packages. The seismic line shows a strong reflector at ca 9 seconds two-way time (twt), possibly the crust-mantle boundary (Moho).

We interpret that the pre-salt strata records major crustal extension, followed by rapid sedimentation. Pre-salt decompacted sedimentation rates were in excess of 200–600 m/My, in contrast to a maximum post-salt deposition rate of 50 m/My. This suggests that the transition from pre-salt to post-salt deposition coincided with a dramatic change in climate and/or drainage pattern. This is also indicated by the change from mainly lacustrine clastics in the pre-salt sequence to mainly carbonates in the immediate post-salt sequence.

The total post-rift subsidence in the study area indicates a crustal extension factor between 2.3 and 3.4, increasing from east to west. An alternative estimate of crustal extension, ranging from 3.6 to 4.9, is obtained by assuming that the 9 seconds twt reflector is the Moho. These differing estimates may be reconciled if it is assumed that the study area is uplifted by ca. 750 m relative to the McKenzie (1978) subsidence model predictions. It is noteworthy that an uplift of this magnitude corresponds to the current uplift of continental southern Africa.

West African and Brazilian Conjugate Margins: Crustal Types, Architecture, and Plate Configurations

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Abstract

A combination of seismic reflection and gravimetric imagery has been used to map four sectors of proto-oceanic crust along conjugate segments of the West African and Brazilian margins. These form corridors isolating oceanic crust, produced about the post-118 Ma pole of rotation, from continental crust. Seaward of the proto-oceanic crust/oceanic crust boundary, relatively uniform, thin oceanic crust (4.2–6.5 km thick) has been generated at the paleo-Mid-Atlantic Ridge. Structural variability is limited largely to fracture zones. Proto-oceanic crust in the northern sectors (*i.e.*, Kribi, Mbini, and Ogooue) is up to 10 km thick, block-faulted, compartmentalized, and seismically layered. These sectors of proto-oceanic crust likely were generated by slow spreading, as the relative plate motions evolved from left-lateral dislocation along the Sergipe-Alagoas transform to full-fledged spreading. Thus, proto-oceanic crust in the north is the product of a leaky transform fault and records the evolution from disorganized to organized spreading under a changing stress regime. Proto-oceanic crust in the southern sector, the Gabon sector, may consist of slivers of lower crustal or upper mantle rocks emplaced along detachments and unroofed as the Gabon upper plate detached from the Brazil lower plate. The ocean-continent boundary marks the transition from deeply-subsided proto-oceanic crust to relatively elevated continental crust.

Merging the mapped oceanic crust/proto-oceanic crust boundaries from the conjugate margins results in a rigid closure model at about 118 Ma for this part of the Atlantic. Merging the mapped ocean-continent boundaries (*i.e.*, removing proto-oceanic crust) produces a Neocomian rigid closure fitting the continental sectors of the African and South American plates. Prior to this stage, and beginning in earliest Neocomian, continental deformation was dominated by sinistral shear along the Sergipe-Alagoas transform, parallel to the West African margin between 3° north–1° south (or parallel to the Brazilian margin between 8°–13° south). Shear along the transform produced a complex swath of transcurrent fault branches, relays, pull-apart basins, and transpressional ridges. Conjugate fits of paired seismic lines from the two margins indicate the South American plate moved more than 100 km southwest relative to the African plate, prior to a 40° change in plate motion direction leading to genesis of proto-oceanic crust. Dislocation along the transform obliquely extended both the Gabon rift zone to the south of the transform, and the Jatobá-Tucano-Recôncavo rift zone marking the western boundary of the Sergipe microplate. Conjugate seismic pairings across the adjoined Brazil and Gabon rift zone margins show that a simple shear mode of extension developed in this area as dislocation along the transform progressed. The low-angle main décollement dips toward the Gabonese side and deepens beneath it, dividing a narrow band of abruptly extended São Francisco cratonic crust (lower plate) from a broad zone of extended Congo fold belt rocks (upper plate). With the 40° change in plate motion

direction and the onset of seafloor spreading, extension of the Gabon rift zone ceased and the Jatobá-Tucano-Recôncavo rift zone became an aulacogen.

The plate closure scenarios presented here have an important bearing on matching rock units and basins from the two margins, particularly in an exploration context. The scenarios also explain why previous attempts to pair apparent conjugate seismic lines from offshore Brazil and West Africa have been unable to consistently match both continental and oceanic crustal sectors.

Rift-to-Drift in the Baja California Central Domain of the Gulf of California, México

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Abstract

Extensional tectonics in the Gulf of California region occurred during middle- to early-late Miocene time. One of the best examples is found at Bahía Concepción, which is the largest fault-bound bay on the peninsular gulf coast of Baja California. The extensional basin confined to Bahía Concepción developed within an accommodation zone related to the late Miocene east-west extension in the broader Gulf of California region. This contribution is focused on the large, central part of the gulf region along the peninsular axis, sometimes referred to as the Baja California Central Domain (**BCCD**).

The mainly volcanic Comondú Group is extensively exposed throughout the **BCCD**, but on a local basis it occurs as huge andesite blocks associated with stratified units that characteristically dip in opposite directions. This is a direct result of a main east-west extensional episode that generated normal faults on the surface and listric detachment faults at depth. Half grabens are the most common result of such extensional episodes in the **BCCD**. This event has produced subsidence, creating depocenters for mostly nearshore marine basins. The oldest marine sedimentary units present in the **BCCD** are the late Miocene–early Pliocene Tirabuzón Formation. Less typically, on Peninsula Concepción and at Punta San Antonio, a late Miocene extensional episode has resulted in up-thrown granodiorite basement along bounding faults. Extension on the Bahía Concepción zone was responsible for development of a half-graben structure first fully flooded in late Pliocene time.

The tectono-sedimentary evolution of the adjacent Santa Rosalía and Bahía Concepción areas is recorded by three stratigraphic stages: (1) pre-rift strata represented by the Comondú Group; (2) a syn-rift stage containing syntectonic siliciclastic deposits; and (3) post-rift strata, represented by the late Miocene to Pliocene flat-lying to low-angle marine sedimentary units. The three stratigraphic stages are interpreted from outcrops in this region.

Evolution of the Red Sea—Gulf of Aden Rift System

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Abstract

The Red Sea—Gulf of Aden rift System provides a superb example of the formation of passive continental margins. Three phases are well represented: (1) continental rifting (Gulf of Suez); (2) rift-to-drift transition (northern Red Sea); and (3) sea-floor spreading (Gulf of Aden and southern Red Sea). Recently published radiometric and biostratigraphic ages, outcrop studies, and reflection seismic profiles more tightly constrain the evolution of this rift system. The principal driving force for separation of Arabia from Africa was slab-pull beneath the approaching Urumieh-Dokhtar volcanic arc on the north side of Neotethys. However, the rifting trigger was impingement of the Afar plume beneath northeast Africa at ~31 Ma. Rifting followed quickly thereafter, initiating in the Gulf of Aden, perhaps in the area between Socotra Island and southern Oman. Extension occurred in the central Gulf of Aden by ~29 Ma. Shortly thereafter, at ~27 Ma, rifting jumped to Eritrea, east of the Danakil region. Rifting then spread from Eritrea to Egypt at ~24 Ma, accompanied by a major dike-emplacement event that covered more than 2,000 km in possibly less than 1 Ma. At ~14 Ma, the Levant transform boundary formed, largely isolating the Gulf of Suez from later extension. Constriction of the Suez-Mediterranean and Red Sea-Aden marine connections resulted in widespread evaporite deposition at this time. Sea-floor spreading began in the eastern Gulf of Aden at ~19 Ma, the western Gulf of Aden at ~10 Ma, and in the south-central Red Sea at ~5 Ma. Propagation of the oceanic ridge has taken much longer than the propagation of its continental rift predecessor. Therefore, the rift-to-drift transition is diachronous and is not marked by a specific "breakup" unconformity. The Red Sea sub-basins are each structurally asymmetric during the syn-rift phase and this is seen in the geometries obtained when its present paired conjugate margins are palinspastically restored. During the Late Miocene and Pliocene, regional-scale, intra-salt detachment faulting, salt flowage, and mass-movement of the post-Miocene salt section toward the basin axis masked the deeper fault block geometry of most of the Red Sea basin. This young halokinesis has enormous consequences for hydrocarbon exploration.

Tectonics of the Western Indian Ocean

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Abstract

The tectonic province of the western Indian Ocean is defined by the East Africa Rift Zone to the west and by the Ninety-East Ridge to the east. The area is bounded to the north by the Arabian Peninsula and to the south by the southern Indian Ocean spreading center. The topography-bathymetry is dominated by the triple-junction Indian Ocean spreading center, the mantle plume extrusions forming the Laccadives-Maldives-Chagos and Mascarene Plateau-Mauritius-Reunion chains of volcanic archipelagos and islands, and the mantle plume extrusion of the Ninety-East Ridge.

Initial breakup of ancestral Gondwana, sea floor spreading, and appearance of oceanic crust was preceded by continental sag and development of the Late Carboniferous–Early Jurassic Karoo basins. The first oceanic crust appeared in the Middle Jurassic as the Africa-Arabia plate moved northward relative to the India-Seychelles-Madagascar-Australia-Antarctica plate. This north-south separation continued through the Neocomian.

A major jump in the spreading center occurred in earliest Barremian with Antarctica-Australia separating from India-Seychelles-Madagascar. Madagascar separated from India-Seychelles via a transform fault along the east coast of Madagascar. The trans-tensional transform evolved into a spreading center during the middle Cretaceous Barremian-Aptian-Albian as oceanic crust appeared. The mantle plume Rajmahal Traps first appeared in eastern India during the Aptian-Albian, and as the Indian plate continued to migrate northward, evolved into the Ninety-East Ridge.

The mantle plume-derived volcanic rocks of the Deccan Traps first appeared in western India near the Cretaceous-Tertiary boundary. The Seychelles began to separate from India in the early Paleocene. By the close of the Paleocene, a broad expanse of oceanic crust separated the Seychelles and western India. The mantle plume formed an extensive oceanic ridge that became the Laccadives-Maldives-Mascarene Plateau. Beginning in the Eocene and continuing through the Oligocene, the ongoing spreading center split the oceanic ridge. North of the spreading center, mantle activity extended the Laccadives-Maldives to include the Oligocene-age Chagos Archipelago, while south of the spreading center, the Mascarene Plateau basalts continued as the Saya de Malha and Nazareth Banks. Mantle plume extrusion continued to the south as the plate moved northward, creating Mauritius Island during the Miocene and Reunion Island during Pliocene-Recent.

To the northwest, Red Sea separation of Egypt from Arabia began during the Oligocene. Extension of the Indian Ocean spreading center into the Gulf of Aden between Somalia and Yemen-Oman did not occur until the Miocene.

To the north in Ethiopia-Eritrea, the East Africa Rift Zone originated during the early Miocene and has extended southward through Uganda-Kenya-Tanzania-Mozambique into the southern Indian Ocean.

Salt Tectonics in Atlantic-Type Sedimentary Basins: Brazilian and West African Perspectives Applied to the North Atlantic Margin

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Abstract

The South American divergent continental margin extends from eastern Brazil towards the continental margin off Argentina. This segment is limited, both to the north and south, by transcurrent movements associated with oceanic fracture zones and by the subduction zone north of Antarctica. Within the extensional margin, the transitional phase salt basins are also controlled by transform faults in the eastern Brazilian and West African margins. The evaporite basin is associated with siliciclastic and carbonate sediments deposited above a regional unconformity (breakup unconformity) that marks the beginning of the continental drift phase. This was followed by Aptian evaporite sedimentation between the Sergipe-Alagoas and Santos basins on the Brazilian side, and from the Rio Muni to Benguela basin in West Africa. The evaporitic conditions seem to extend up to early Albian in some regions, as evidenced by extremely thick layers of stratified evaporites, indicating several depositional cycles. A highly mobile evaporite layer resulted in the development of a characteristic tectonic style marked by salt diapirs, and extensional and compressional structures affecting the post-salt sedimentary successions.

The regional deep-penetration seismic profiles acquired in the South Atlantic provide a unique dataset allowing identification of salt tectonic domains from the platform towards the oceanic crust boundary. These prolific hydrocarbon-bearing salt basins constitute a framework for the interpretation of the less-explored salt basins of the North Atlantic continental margins, particularly along the Iberian and North American continental margins. Examples of analogue autochthonous and allochthonous salt structures, and their geodynamic evolution, have important implications for petroleum exploration in the deep-water frontier regions.

2D Computational Salt Tectonics: Passive Margins

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Abstract

Salt tectonics has attracted considerable attention in the last few decades because of its importance in controlling the location of hydrocarbon reserves. As a consequence of its low density and viscous nature, salt is can be deformed by buoyant flow over geological time, deforming and penetrating overlying sedimentary sequences. Salt can act directly as a hydrocarbon seal, and salt-related deformation may totally change the stratigraphic and structural interpretation through the geohistory of the basin. Timing of the salt tectonic evolution may be crucial for hydrocarbon exploration, not only because the structural traps indicated on present-day seismic data may not have been in-place while hydrocarbons were migrating into the area, but also for the direct effect that salt geometries have on temperature distribution and therefore on hydrocarbon generation and expulsion. The economic consequences of increased understanding of salt movements are thus significant.

A 2D finite element numerical code has been developed to allow study of salt motion impact on the structural evolution of a passive margin. In the numerical code, salt and the other sediments are considered as a continuous media possessing variable properties in space and time. Salt is modeled with viscous Newtonian rheology and the overburden with a pseudo-plastic non-Newtonian rheology. The spatial mesh used in the numerical model is triangular, unstructured, and non-uniform. The interfaces between layers are tracked (during evolution) using a lagrangian approach, and, in order to improve the resolution of the tracked interfaces, refinement and de-refinement techniques have been implemented.

A real case study was developed focusing attention on the impact of: sediment density, rheological parameters, and progradation rate of the pre-/sin-kinematic sequences on the evolution of passive margins. This offered a better understanding of salt behavior in a complex structural context.

Analog Modeling of Salt-Related Structures in the South Atlantic

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Abstract

Analog modeling is an important tool to enhance the understanding of the genesis and evolution of geological processes, as well as of the geometry of the resultant structures, since it provides good three-dimensional views of the different stages of their development, in a time scale compatible with human observation. The evolution of the South Atlantic salt basins, especially those located at the southeastern Brazilian continental margin, has been the subject of a series of analog models carried out in the Geotectonics Laboratory of Petrobras.

A novel technique of analog modeling has been developed by Petrobras to permit simultaneous study of salt-related structures and turbidite distribution in evaporite basins. The natural conditions where the processes of turbidity currents develop are well reproduced, showing realistic models of the shelf and slope systems of the South Atlantic basins.

Previous analog modeling studies of salt tectonic processes using silicone to simulate salt, and dry sand to simulate the overlying sediments has resulted in major advances in our understanding of salt tectonic processes. The control of salt tectonics by normal faulting of the overlying sediments has been clearly demonstrated. Nevertheless, active salt diapirism and the formation of salt canopies are not readily reproduced by such a modeling technique. A new approach, entirely developed at the Petrobras Geotectonics Laboratory, has been to submerge both the silicone and the overlying sand in water. The saturated sand layer has its shear strength reduced by increased pore pressure while total overburden pressure increases. As a result, buoyancy-related structures form promptly and the sand is more liable to produce compressive structures. The resulting structures closely resemble diapirs and canopies well known from deep-water environments. Another great advantage is that subaqueous modeling permits combining sedimentation, including generation of turbidite channels and fans, with simultaneous salt tectonics, revealing their intricate interactions and mutual controls. Exaggeration of the density contrasts thus helps to reproduce otherwise hard to achieve structures that are abundantly seen in nature, even though the intentionally distorted dimensioning should be treated with caution in the detailed physical interpretation of the results.

The models reproduce with great accuracy the salt-related structures observed in South Atlantic continental margin basins and may thus support seismic interpretation and hydrocarbon exploration in these basins.

Tectonics of the South Atlantic Brazilian Salt Basins

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Abstract

This paper compares and contrasts salt tectonics on two different types of continental margins in Brazil.

Narrow margins, such as the Jequitinhonha and Camamu basins, are 50–100 km wide and have a steep, (up to 5°) seaward-dipping base of salt seismic horizon. These margins are sediment starved due to their steepness. Consequently, sediment has bypassed the salt basin and been deposited on the abyssal plain. Pronounced contractional folding of the salt overburden is present on these margins. This commenced at the oceanward pinch-out of the salt and propagated back up the continental slope into areas, which are expected to be in extension due to gravity sliding. This is the opposite sense of fold and thrust propagation compared to 'normal' mountain fold and thrust belts. The bathymetric highs above pre-existing diapirs and fold anticline crests were rapidly eroded on narrow margins, which allowed the folds to grow more easily to large amplitudes (1.5 km) at the top salt seismic horizon. Folds continued to unroof until the salt reached the seabed and produced a duck-head shaped diapir due to downslope flow of a salt glacier. This was followed by collapse of the salt structure producing an unconformity-bounded graben.

Wide margins, such as the Campos and Santos basins, are >100 km and <650 km wide and have a sub-horizontal to landward-dipping base of salt seismic horizon. Salt basins on wide margins are effective sediment traps; *e.g.*, sediment loading in the Santos basin has produced a 2° landward-dipping base salt seismic horizon across the outer portion of the basin. Landward dip at the base salt seismic horizon has promoted development of counter-regional faults and enhanced later folding, which appear to develop approximately simultaneously across the whole basin. The folds are limited in amplitude to a maximum of 1 km, as little or no erosion has taken place over the crests and the thick sediment lid above the salt structures produces more competent rocks, causing a high vertical confining pressure, which inhibits fold growth. This compression is probably due to both downslope gravity sliding, and regional tectonic compression is due to ridge push or Andean collisional events.

Salt Distribution and Morphology in the Offshore Algarve Basin

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Abstract

The Algarve basin developed as an extensional basin during the Mesozoic, associated with northwest-southeast transtension in ending at the Azores-Gibraltar plate boundary. Several main episodes could be identified in the evolution of this plate boundary: Triassic rifting and mid-Atlantic extension until the Early Cretaceous; fracturing and strike-slip movement along the Azores-Gibraltar Fracture Zone, from Early Jurassic to lower Eocene; continental convergence between Europe and Africa, beginning in the Late Cretaceous, reaching its culmination during the Neogene.

The study of the Algarve basin began with the interpretation of 2D **MCS** seismic profiles generating structural and isopach maps. These maps show the geometry of the basin to be asymmetric, associated with a depocenter striking northeast-southwest and located very close to Guadalquivir ridge.

Two salt units are interpreted in the Algarve basin: an older one of Triassic age and another of as Late Jurassic age. The latter salt formation is described initially as an evaporitic layer deposited during one of the Jurassic uplift episodes. However, seismic data character suggests that it might not be autochthonous salt and could be allochthonous salt sourced from the Triassic. Salt is also distributed differently throughout the basin: the Triassic salt extends over nearly the entire basin while the Jurassic evaporites are limited to the central and eastern area.

Jurassic salt structures are associated either with extensional tectonics, such as salt-rollers with associated listric faults, or compressional geometries resulting from the reactivation of listric faults as reverse faults during the compressive episodes of the Tertiary. Morphologically, the Triassic salt is characterized mainly by a number of salt piercement features occurring as circular salt diapirs or elongate salt ridges. Although the time of initiation of salt movement cannot be determined, final movement occurred during Miocene time.

Salt Tectonics Comparisons Near Three Continent-Ocean Boundary Escarpments

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Abstract

Deep-water geophysical data acquisition and drilling technologies have had an impact on every aspect of the offshore petroleum industry in recent years. Massive, non-exclusive, speculative 2D and 3D surveys have been conducted offshore Brazil and West Africa and in the Gulf of Mexico at a record pace in the last few years and are now being followed by diverse deep-water, drilling programs. The last frontier, ultra-deep water, is being tackled, and understanding of salt architecture is fundamental for developing exploration plays. This study makes a comparison of three, salt-constrained, deep-water areas: the Sigsbee Escarpment in the Gulf of Mexico, the Angolan Escarpment along the West Africa Congo Basin, and the São Paulo Plateau Escarpment along the eastern Brazilian margin.

Autochthonous salt tectonics shapes the architecture of the mirror image basins of the South Atlantic, such as the producing Campos basin off eastern Brazil and Congo basin off West Africa. However, at the continent-ocean boundaries, major fault scarps affect these basins with possible allochthonous salt movements around the transition area. Deep-water, oil and gas discoveries have been made in a single oil play, the slope-constrained play. The major questions in both the Campos and Congo basins are oil generation in the thick, syn-rift sections beneath salt, and the conduits for hydrocarbon migration through windows in the overlying salt. In the ultra-deep water realm, additional variables are imposed by overburden thickness. Hence, a clear understanding of salt architecture around fault scarps is fundamental.

Oil generation in the area of the Sigsbee Escarpment in the Gulf of Mexico, occurs in sediments that overlie oceanic crust. Hydrocarbon migration is related to allochthonous salt emplacement. This is a distinct phenomenon when compared with basins of the South Atlantic. Models of the oil plays near the Sigsbee Escarpment, compared with the escarpments of the continent-ocean boundaries in the South Atlantic, improve the understanding of salt behavior and provide exploration possibilities.

Evolution of Allochthonous Salt Systems During Development of a Divergent Margin: The Adelaide Geosyncline of South Australia

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Abstract

This paper details the evolution of allochthonous salt systems in the Adelaide Geosyncline of South Australia, a divergent continental margin that developed after rifting of the Neoproterozoic supercontinent. It differs from previous studies in that it suggests salt-sediment interaction had a great influence on stratigraphic architecture of the late Precambrian to Early Cambrian succession. This stratigraphic architecture reflects the high subsidence and sedimentation rates in halotectonic mini-basins during divergent margin development of the Adelaide Geosyncline. Sedimentation can be tied to specific stages in the evolution of the various allochthonous salt systems. Lacustrine, fluvial, and evaporite facies of the rift phase, assigned to the late Precambrian Callanna and Burra groups, were deposited in salt-canopy mini-basins that were floored by shallow-water sediments. Debris flows indicated a stage in the development of the divergent margin where gravity flow deposits were associated with marine sedimentation. The transition phase heralded a series of marine incursions into mini-basins, climaxing in the extrusion of a very thick salt canopy that served as a basal detachment surface for the breakup unconformity. Overlying marine sediments of the late Precambrian Umberatana Group were deposited adjacent to reactive diapirs during the passive margin phase. As diapirs passed into the active stage, they separated mini-basins having counter-regional geometries. Progradation and aggradation of the passive margin resulted in salt-canopy mini-basins floored by deep-marine sediments of the late Precambrian Lower Wilpena Group that evolved into counter-regional salt systems. Christmas tree diapirs were characteristic of this final counter-regional phase.

Turtle Structures Created by Extension in a Low-Salt or Non-Salt Setting

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Abstract

Turtle structures are generally regarded to be the result of passive or extensional collapse of underlying salt bodies. However, subsurface examples in the Columbus basin (Trinidad), onshore south Texas (U.S.A.), and offshore Golden Lane (Mexico), exhibit four-way inversion structures that look at least superficially like turtle structures that formed with little or no salt at the detachment level. Furthermore, many anticlines in the shelf region of the northern Gulf of Mexico are possibly more kinematically akin to extensional turtles than traditional turtle structures.

I propose the term 'extensional turtle' to denote a class of turtle structures at the opposite end of the spectrum from traditional turtles, where a mock turtle lies between. Unlike mock turtles, extensional turtles are generated purely by extension. Even so, they commonly have some mobile-rock withdrawal, as they are always associated with a very weak detachment. The distinguishing feature of such structures is that they are bound by a kinematically linked set of regional and counter-regional, large-offset, listric normal faults. Local complications may occur where younger regional faults repeatedly cut the counter-regional fault, resulting in the counter-regional fault becoming reset downdip. The counter-regional fault may then remain active, resulting in multiple turtle anticlines. Counter-regional rollover followed by regional rollover on opposing arcuate listric faults produces four-way plunging turtle structures.

Offshore Louisiana has numerous turtle structures, extensional faults, and salt diapirs. I suggest that many of these turtles bear significant similarities to extensional turtles, and it is likely that a continuum of structural styles exist between true turtles, mock turtles and extensional turtles.

Relay Ramps and Lateral Ramps—Active Sediment Fairways During the Passive Margin Stage of Development of the Gulf of Mexico Basin

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Abstract

The passive margin stage of development of the Gulf of Mexico basin contains thick sequences of Miocene and younger siliciclastic sediments deposited in a framework of active listric growth faults. At depth, complex structures occur, characterized by multiple listric faults detaching at multiple structural levels. Between laterally adjacent fault blocks, displacement is transferred from shallower to deeper structural levels along lateral ramps, relay ramps, and transfer faults. These features may serve as sediment fairways, delivering reservoir quality sands to deeper structural levels. Continued displacement along the same or younger listric normal faults contemporaneous with deposition can position depositional thicks on the crest of anticlinal highs by displacing these sediments across antilistric fault bends.

Constructing 3D models and kinematically reverse modeling the hanging wall blocks on laterally adjacent, linked fault systems provides a framework for deposition of reservoir quality sand. Forward modeling serves as a predictive tool for trap location, trap geometry, and the depositional extent of reservoir sands. An understanding of the relative timing of structural development to the timing of fluid maturation and migration can reduce the economic risk of a prospect.

This study utilizes observations of 3D seismic data sets to construct 3D conceptual models which are palinspastically restored to the time of deposition of reservoir sands. Observation of seismic data and resulting 3D models yields criteria useful for the recognition of focused deposition and subsequent deformation resulting in trap emplacement. Applying this model to the structures lying beneath and adjacent to the Corsair and Clemente-Tomas fault systems serves as a predictive tool for locating sands and traps that are poorly imaged on seismic data. This model also provides a mechanism for transporting reservoir quality sands into regions typically devoid of sands along the deeper portion of the Texas shelf.

Does the Frio Really Prograde in South Texas?

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Abstract

McAllen-Pharr field is a mature, high-pressure/high-temperature gas field in the expanded Oligocene (Frio) section south of the Norias delta system, Hidalgo County, Texas. The field has produced 1.1 TCFG from a rollover anticline downthrown to the large-scale McAllen growth fault. Detailed studies of the field reveal stratigraphic and sedimentologic characteristics, which provide a new perspective on the depositional history and distribution of sand within the Frio section.

The Frio Formation in the McAllen-Pharr Field consists of three, thick genetic sequences, locally designated the: (1) Hensley-Reichert, (2) Bond-Marks, and (3) Callavo-Card sequences. Each sequence exhibits a vertical succession from basinal shales through layered sandstones to massive sandstones capped by basinal shales. The three sequences are organized in an overall regressive megasequence.

Within each sequence, shale intervals 200 to 500 ft thick alternate with massive sandstones 100 to 300 ft thick. The transition from shales to sandstones is generally very rapid and sometimes sharp; from sandstones to shales, the transition is generally sharp. Shales represent, in a geological time scale, the background sedimentation in the basin, while sandstones represent rapid deposition of coarser grained material during periods of catastrophic fluvial flooding. Uplift and erosion cycles of the continental interior have provided the necessary sediment input while accommodation space is provided by expansion along the McAllen fault and differential compaction of sandstone versus shale. Erosional features are observed upstream, in Vicksburg fields, upthrown to the major Frio expansion faults, at the boundary between the Vicksburg and Frio formations. These erosional features serve as pathways for sediment transport to the basin. Consequently, the three sequences and the enclosing megasequence at McAllen-Pharr are controlled by tectonic activity. Each of these sequences consists of vertically aggrading, fan-shaped lobes of sandstone that have formed in the downthrown block of the expanding McAllen growth fault. Prograding trends are observed only in parasequences at the top of each sandstone unit and at the top of each genetic sequence.

Cenozoic Evolution of the Northern Gulf of Mexico Continental Margin

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Abstract

Winker (1982; 1984) provided the first summary overview of the depositional evolution of the Gulf of Mexico continental margin, along with a suite of criteria for margin recognition. The subsequent more than 20 years of exploration deep drilling in the Gulf has substantiated both his methodology and synthesis. This paper updates Winker's map and locates the paleo-continental margin at the termination of 17 principal Cenozoic depositional episodes (deposodes). Northern Gulf of Mexico margins are characterized by a family of attributes, including transition from outer shelf to upper slope faunal assemblages, syndepositional extensional growth structures, rapid thickening along margin-parallel depoaxes, change from relatively continuous, progradational delta and shelf to highly discontinuous, aggradational slope facies successions, local development of erosional submarine canyon heads and slump scars, and increased regional dip.

Cenozoic shelf margin types include: (1) stable progradational margins; (2) unstable progradational margins, typically associated with high-rates of sediment supply by extra-basinal fluvial systems to large shelf-margin deltas and their associated shore-zone systems; (3) retrogradational margins created abruptly by rapid sub-regional salt withdrawal, commonly accompanied by submarine mass wasting and erosion or slowly by long-term compactional subsidence; and (4) perched margins formed by progradation onto foundered continental shelves. Rates of shelf edge offlap vary greatly in both time and space along the northern Gulf of Mexico margin. Highest rates exceed 30 km/Ma and are associated with Oligocene, middle Miocene, and Plio-Pleistocene depocenters.

The Tectonics of Tranquitas: A Field Study of Rift through Passive Margin Development and Laramide Deformation in Triassic and Jurassic Strata of the Sierra Madre Oriental, NE Mexico

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Abstract

Exposed near Galeana, Nuevo Leon, are sedimentary deposits and contemporaneous structures that record the rifting and opening of the Gulf of Mexico, passive-margin development, and Laramide compression in the region. A mapping, sedimentologic, and structural study utilizing thin sections, measured sections, aerial photos, and kinematic models has produced a detailed stratigraphic section that records the transition from terrestrial to open-marine deposition and the orientation and timing of deformational events. Triassic to Early Jurassic red beds in the Huizachal Group are composed of fluvial and marine sands. The La Boca and La Joya formations are separated by a polymictic cobble conglomerate. The Callovian Minas Viejas represents the initial stages of marine transgression and the overlying interbedded carbonates and evaporites of the Zuloaga and Olvido Formations were deposited in response to cyclic eustatic sea-level fluctuations. The increase of biodiversity through the upper Jurassic strata reflects a change from restricted to open-marine conditions. Rift-related tectonics and gravity driven brittle extensional features within the carbonates have been overprinted by structures that formed during the Laramide orogeny. The red beds have been folded and faulted into a broad Laramide anticlinorium, in which smaller intrusion cored folds have amplitudes on the order of tens of meters. The decollement for Laramide thin-skinned deformation occurs within an evaporate unit. There is a high degree of structural complexity in the overlying carbonates as indicated by tight folding patterns. By integrating concepts of depositional systems with structural deformation the hypothesis, “There is an exhumed preraft block in the Zuloaga Limestone around San Pablo de Tranquitas.” will be tested.

Formation of Submarine Unconformities in Halotectonic Mini-Basins During Passive Margin Development of the Adelaide Geosyncline, South Australia

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Abstract

Salt-sediment interaction influence the stratigraphic architecture of depositional sequences during the passive margin stage of development of the Adelaide Geosyncline in South Australia. This late Precambrian to Early Cambrian succession outcrops in the Flinders ranges and is punctuated by submarine unconformities. The unconformities are interpreted as deep-water sequence boundaries that have no shallow water equivalent. However, they can be traced laterally into condensed sections or major flooding surfaces. These sequence boundaries are typically overlain by deep-water facies that reflect the high rate of subsidence coupled with high sedimentation rates typically found in halotectonic mini-basins. Large-scale slumping and canyon incision often mark the deep-water sequence boundaries. Canyon incision is associated with salt withdrawal or downbuilding in mini-basins. The architecture of submarine canyons is defined by the nature and correlation of bounding surfaces, sandstone interconnectivity and lithofacies elements. These features are often beyond the limits of seismic resolution in basins where passive margin development was influenced by salt tectonics.

Exploration in Rifted Atlantic Margin Basins: New Challenges and New Ideas—Or Just Business as Usual?

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Abstract

Exploration and play types in rifted Atlantic margin basins occur in passive margin as well as failed rift settings. Offshore Brazil and Angola, the passive margin post-rift succession has been viewed as the most prolific, whereas in failed rift basins such as the North Sea basin, the pre-rift and syn-rift succession has had the highest success rate.

In many passive margin basins, source and reservoir rocks are separated by thick autochthonous or allochthonous salt deposits. A major challenge is to understand source rock deposition, maturation, and migration of hydrocarbons: reservoir units often can be easily imaged on seismic data. Source rock deposition warrants new ideas, because seismic imaging below salt is poor. The understanding of source deposition often relies on low-resolution data such as gravity and magnetic data, or deep seismic data tuned towards identification of major structural lineaments. Thus, new play identification is clearly dependent on improved source rock understanding.

On the contrary, in failed rifts, source rock deposition and migration are relatively well understood. Classic plays such as rotated fault blocks containing pre-rift reservoirs are well known and simple to identify. A future challenge lies in identification of less voluminous reservoirs in the syn-rift and early post-rift succession. Such plays may add significantly to otherwise declining reserves and prolong the life of existing installations.

New Insights from CongoSpan Pre-Stack Depth Migrated Imaging in Angola-Congo-Gabon: Petroleum Systems and Plays

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Abstract

A regional survey, consisting of long lines averaging 350 km in a dip direction and 2,500 km in a strike direction, consisting of nearly 13,000 km of 2D pre-stack depth migrated (**PSDM**) seismic data was acquired by GX Technology over the West African salt basins of Angola, Congo and Gabon in 2004 (CongoSpan). This data provide the first consistent acquisition and processing from shallow water (50 m), past the limit of the salt, and into the ultra-deep water (4,000 m or deeper). These profiles are in depth, providing multiple transects of the continental margin, from rifted continental crust, across the crustal transition zone, and onto the interpreted drift volcanic terrain associated with breakup of the South Atlantic. The CongoSpan regional grid provides adequate coverage for observing changes along both strike and dip of the continental margin, avoiding the pitfalls of single line interpretations, and affords insights into rifting process on both sides of the South Atlantic.

The advantage of the **PSDM** images is that they provide improved reflector geometry by minimizing distortions associated with lateral velocity variations caused by salt and water. These depth images present a new view of the crust beneath the salt and the drift volcanics. These improved images have been used in identifying a consistent set of tectono-stratigraphic units (pre-rift, syn-rift, sag, and drift), which have been correlated over the study area. The sag is an important unit that developed in response to post syn-rift thermal subsidence forming a large basin (1,200 x 200 km, and 2 km thick) containing fluvial, lacustrine and possible marine sediments.

The base of the sag unit in the deeper parts of the basin has been difficult to image prior to the acquisition of this data, which images to a depth of 25 km. Because the sag unit contains rich source rocks currently in the active oil generation window over much of the area, its delineation is an important constraint on models for the rifting of the South Atlantic. The change in the style of salt tectonics, from extension to compression, appears related to sag-unit geometry and the underlying basement structure. The structural and stratigraphic insights provided by the **PSDM** data are generating new ideas on the petroleum systems and will be useful for developing the new plays that will continue driving exploration on both sides of the South Atlantic.

Deformation Induced Pathways for Hydrocarbon Migration Through the Aptian Salt Level in the Angolan Margin

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Abstract

Along the Angolan margin, the post-rift structural framework of which is strongly influenced by salt tectonics, a number of hydrocarbon reservoirs that are located above the Aptian salt have been charged by pre-salt source rocks of lacustrine origin. The paper examines the deformation mechanisms that can lead to windows in the salt layer able to provide pathways for hydrocarbon migration. It is shown that extension, due to gravity driven deformation, leads to cover-basement contacts in the sealed, tilted block sub-domain that occurs in the upper part of the margin. Once created, these contacts represent "permanent windows" in the salt layer. In the neighboring rollover sub-domain, the salt layer is also strongly thinned, but more homogeneously, preventing the formation of cover-basement contacts. The analysis of seismic sections shows that in absence of direct observation (*e.g.,* well data) active faulting can provide extremely useful criteria to detect the presence of salt layers too thin to be seismically imaged. The possibility that basement faults cutting through the salt layer could provide "transient windows" cannot be excluded. In the Angolan margin, the supra-salt hydrocarbon reservoirs charged by pre-salt source rocks are mostly located in the sub-domain of sealed, tilted blocks. As indicated by analog modeling, this domain is the most favorable for the creation of permanent windows in the salt layer. It is therefore suggested that hydrocarbon migration from pre- to post-salt sediments is strongly dependant on the significant salt layer thinning and penetration in the sealed tilted block sub-domain.

Exploration Using a Linked System Approach to the Rift and Drift Sections in Brazil

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Abstract

In the core Brazilian Campos and Espírito Santos Basins the petroleum system is complex with post salt reservoirs and structures linked to the to the pre-salt rift basins through salt welds, basement faults and rift geometries. In addition, basement lineaments have influenced the deepwater sand delivery system.

The primary source rocks are rift and sag sediments in the Lagoa Feia Formation. Numerous giant oil fields such as Roncador and the recent Jubarte discovery occur along the Atlantic Hingeline where there has been Lagoa Feia charge focus. Along the basin margins the evacuation of salt and extensional faulting provides charge access from these underlying rift sediments. Hingeline focusing is accomplished both by basement faulting and by the taper of a sag and rift facies wedge. Salt welds within the outboard diapir provenance are also thought to provide charge access, although there are notable failures such as the deepwater BMC10 block. Paleo-migration geometries or residual sub-seismic salt may have prevented charge of large BMC10 four-way structures. Understanding paleo-migration patterns, differentiating effective salt welds from non-effective welds are critical exploration elements.

Basement lineaments also influence deepwater channel and canyon orientation. Liniment focused channels are recognized as important elements in the development of the recent Espírito Santo Golfino discovery and in the outboard Espírito Santo Rio Doce Canyon system. With the existing 2D grid this relationship provides a framework for seismic facies interpretation. Successful exploration requires an understanding of the relationship between the rift and post-salt section.

Only a petroleum system approach which incorporates an understanding of the underlying rift section and the relationship to the post salt drift section can be seen to result in successful exploration.

The link between the underlying rift section and the drift post-salt section is an important element charge focus and reservoir presence

The petroleum system is further complicated by the overprint of salt tectonics on charge from the rift basins, reservoir distribution, and structuration.

Petroleum Prospectivity of the Camamu-Almada Margin, Brazil: Insights from an Integrated Basin Analysis and Modeling Study

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Abstract

The Camamu-Almada basin (northeastern Brazil), is part of the rift system formed during the Early Cretaceous breakup of South America and Africa. The basin contains some small onshore gas accumulations and two offshore oil fields. A previous study (Mello *et al.*, 1995) characterized the occurrence of a single petroleum system in the Camamu-Almada basin: the Morro do Barro(!) petroleum system.

In 2003, **ANP**, the Brazilian National Agency for Petroleum, Natural Gas, and Biofuels, coordinated a study on the tectono-sedimentary evolution and petroleum potential of the basin, headed by Lab2M – Laboratory of Multidisciplinary Modeling of Sedimentary Basins (**COPPE** / Rio de Janeiro Federal University). A combination of sequence stratigraphy and quantitative basin modeling techniques (Karner *et al.*, 1997; Driscoll and Karner, 1998; Karner and-Driscoll, 1999a) was applied in order to allow a better understanding of the spatial and temporal relationships between the elements and processes of petroleum systems.

The application of sequence stratigraphic principles (Vail, 1987; Christie-Blick and Driscoll, 1995) led to the recognition of five, second-order depositional sequences. More emphasis was given to the rift section, which was subdivided into four, third-order depositional sequences (Vail *et al.*, 1991).

The Morro do Barro Formation comprises thick layers of shales having high total organic carbon (TOC) content (mostly from 2 to 5%) and hydrogen index (HI) values (up to 1,000 mgHC/gTOC), indicating that these rocks are composed mainly of a lipid-rich Type I kerogen. The Rio de Contas Formation, under adequate thermal conditions, may prove itself to be an additional hydrocarbon source.

Known petroleum accumulations in the Camamu-Almada basin are associated with structural or structural-stratigraphic trapping within pre-rift and rift reservoirs. Most of the petroleum has been found in the Morro do Barro Formation reservoirs (almost 75% of original volume of oil-in-place), followed by Sergi Formation (around 25% of original volume) and Rio de Contas Formation reservoirs.

The integration of the results achieved by seismic interpretation and basin modeling allowed identification of potential exploratory targets in the basin. Such structural, stratigraphic and combined plays were grouped as pre-rift, rift, or post-rift.

Camamu-Almada basin potential has yet to be fully confirmed. Investments in upcoming years are needed to identify new hydrocarbon accumulations.

Basin Analysis in Brazilian and West African Conjugates: Combining Disciplines to Deconstruct Petroleum Systems

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Abstract

The authors have developed a technique for defining source rock sub-basins, particularly those with lacustrine source rocks, and the limits of the related petroleum systems, determining the risk of the petroleum system processes and elements, particularly for charge and to some extent for seal and reservoir. The key was learning how to integrate geophysical (especially gravity and magnetic data) and geochemical data with geologic understanding. This paper presents the development of the tools, techniques, and data sets assembled by our team with examples from prolific hydrocarbon provinces of Brazil and West Africa.

The initial work used regional gravity and magnetic data sets (Barritt, 1993, Fairhead *et al.,* 1997, Dickson *et al.,* 2003a,b) to define controlling structural/tectonic features, which influenced basin and source rock development and reservoir emplacement. Sedimentary basins were re-defined from gravity data. Correlations between sediment pathways and gravity signatures indicated redefined depocenters, largely controlled by the coast-parallel, syn-rift fault trend. Transfer faults, trending roughly orthogonally to the coasts of West Africa and Brazil resulted in "piano-key-like" segmentation of the margins. These were seen firston gravity imagery and later, along the Brazil margin, interpreted from magnetic attributes.

Adding geochemical data, we plotted oil families and noticed clear separation of these families across some of the coast-orthogonal transfer faults segmenting and dividing the source rock containing sub-basins. Oils tended strongly to stay within the compartments defined by the transfer faults and the coast-parallel, syn-rift fault trend and other lineations. These compartments were first matched to published interpretations of paleo-lakes. The correlation was then carried along the studied margins. Sub-basins correlated with clear differences in oil geochemistry, defining several petroleum meso-systems (Schiefelbein *et al.*, 2003). More detailed analyses, using additional data (such as piston cores and surface slicks), within each basin revealed probable generative sub-basins, hydrocarbon migration pathways and barriers.

Pass-fail tests were established for various criteria, especially burial depth and adequacy of top seal for hydrocarbon generation and retention, respectively. For example, offshore Brazil, depth of burial for oil generation from each source unit was correlated to sediment thickness mapping. The maps were based on magnetics, using multiple depth constraints including published cross-sections, surface geology, wells, and Euler deconvolution of gravity. Resulting depth accuracies of 500 m were sufficient to determine adequacy of present-day burial for the main lacustrine and marine source rocks.

Top seal was risked by correlating gravity attributes to published salt mapping and interpreted profiles to determine areas of near-surface disruption of top seal. We then compared those attributes to oil gravities, piston core gas anomalies, and sea surface seep locations. Areas of diapir concentrations tended to correlate with the presence of oil slicks (from RadarSat) and seepage anomalies demonstrating leakage.

The outcome was a robust understanding of key prospect risks in this region. In addition, our methodology is transportable with application to other areas, including convergent margin basins in Southeast Asia.

Petroleum Systems Related to the Equatorial Transform Margin: Brazilian and West African Conjugate Basins

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Abstract

The integrated analysis of the South American and African equatorial basins provide important clues regarding the kinematic evolution of transform margins and has important implications for the thermal and tectonostratigraphy history of the African and Brazilian basins. The distribution of petroleum systems, on both sides of the Equatorial Atlantic, was quite affected by the tectonic history of this entire segment of the South Atlantic Ocean. Conventional extensional processes cannot explain the kinematics and rift geometry of the Equatorial South Atlantic basins. Accepted pure-shear or simple-shear rift mechanisms, typical of divergent margins, cannot be promptly used in basins generated as a response to major transform motions along a continental-scale plate boundary. The commonly accepted causal processes for rifting, such as passive/active or diffuse/discrete rifting, cannot accommodate the South Atlantic Equatorial data set. Even though shearing signatures and pull-apart features are easily recognized throughout the margin, their magnitude and basin architecture varies significantly as a function of the distance from the main transform faults. These factors have resulted in significant differences in thermal evolution, tectonic subsidence, facies distribution and uplift history. The tectonic evolution of the sedimentary basins along the Equatorial Atlantic is better understood by considering three stages: pre, syn, and post-transform movements. These are related to kinematic and dynamic controls provided by the emplacement of fractured swells as proto mid ocean ridges, followed by the creation of oceanic crust and the onset of transform shearing between Africa and Brazil.

The fragmentation process started as diffuse magmatic and sedimentary events, which began in late Barremian time because of initiation of lithospheric stretching in the equatorial Atlantic, triggered by the onset of transtensional deformation. This event climaxed during the Aptian, when almost instantaneous extension was responsible for the widespread fracturing of the Equatorial Atlantic, generating relatively wide and shallow precursory basins, but there is no evidence of volcanic margins or widespread development of typical syn-rift basins, as expected in orthogonal extensional regimes. The equatorial splitting evolved during the Albian-Cenomanian interval, through a multi-stage basin development, which is better understood if the kinematic and dynamic controls are considered along with the chronologic activation of transform faults, the emplacement of oceanic crust and the onset of drifting between Africa and South America. The geodynamic evolution on the Equatorial Atlantic is addressed by recognizing tectonic stages that pre-date, are synchronous, or post-date the activation of transform faults in the Equatorial Atlantic. Local tectonics and magmatism played a key role in the "post-break-up" subsidence. The resultant basin architecture, facies distribution, and subsidence history for any particular basin vary significantly according to its paleogeographic position and to its proximity to active transform faults. This has had major impact on the regional distribution and the stratigraphic position of source beds. Tectonic uplifts, varying in space and time, also have had a major impact on reservoir distribution. The dynamic juxtaposition of continental crust against oceanic crust or spreading centers on the opposite side of a transform fault caused diachronous deformations, recorded on the sedimentary record as important unconformities, amplified or not by synchronous eustatic sea level variations. The hydrocarbon shows and maturation history is quite related to the thermal history of each basin. Besides the petroleum systems of deep-water Nigeria, where the oil-prone Aptian, late Cretaceous, and Tertiary aged source rocks have been responsible for charging a quite impressive oil province, the rest of the Equatorial Atlantic is relying mainly on the facies distribution and thermal history of the Aptian aged source rocks to measure failure and success on the equatorial margin.

The African and Brazilian margins share the same source rocks characteristics, either proved or expected (in deep water environments). However major differences arise from the tectonic sedimentary evolution of each margin segment, and it is closely related to the kinematic and thermal consequences of a complex transform margin evolution. Exploratory results from both sides of the Atlantic are still limited to a few basins, and the deep-water potential is still controversial.

Laminated Lime Mudstone of the Early Oxfordian Smackover Formation of the Northern Gulf of Mexico Rim: Significance to Environments of Deposition of Carbonate Source Rocks in Rifted Basins

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Abstract

The Late Jurassic (early Oxfordian) Smackover Formation is a highly variable carbonate source rock for high-sulfur oil. Short-range migration from the source rock (lower Smackover) to adjacent reservoir facies (upper Smackover and Norphlet) was common and vertical migration also occurred via the peripheral fault zone and salt to reservoirs as young as Late Cretaceous. High-sulfur oil in upper Smackover and Norphlet reservoirs was thermally cracked in place to residual methane and non-hydrocarbon gases during deep burial. Study of rock and oil samples from the updip Mississippi Salt Basin provides geochemical insight because of shallow burial depth and mild thermal stress. Paleogeography had a major effect on the source rock. The most effective source rocks are laminated lime mudstones with high total organic carbon (TOC) and 100 percent algal and microbially derived kerogen. Petrographic thin sections of the best source rock show that kerogen is preferentially concentrated in thick, continuous laminations separated by barren carbonate. Interpretation of geochemistry and of thin sections suggests relative source-richness was determined by the environment of deposition. Chemical fossils (aryl isoprenoids) from extremophile bacteria show that that some of the best source rocks were deposited under a stratified water column. Algal blooms occurred in oxygenated top water, and organic matter periodically settled through anoxic, sulfate-rich bottom water to be concentrated in sediment-laminations. Anoxic and hypersaline sediment provided an environment of deposition favoring extremophile bacteria, leading to preservation of hydrogen-rich organic matter during burial. Thermally stable diamondoids formed in the sulfur-rich source rock at low temperatures (<100° C) and were later concentrated by thermal cracking of oil to gas. Study of the Smackover source rock shows rapid change in vertical section as well as laterally on a scale of hundreds of meters. The degree of variation in Smackover source rock appears to be similar to that of Smackover reservoir facies, helping to explain differences between Smackover oils. Other laminated lime mudstones from similar paleogeographic settings may have generated high-sulfur oil in the lower continental slope of the northern Gulf of Mexico, Mexico, and the Middle East. Laminated lime mudstones may represent a specific source rock type prone to early generation of high-sulfur oil in rifted salt-bearing basins. In aggregate, this carbonate source rock type may have generated large volumes of high-sulfur oil.

Analysis of Pore Pressure Compartments in Extensional Basins

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Abstract

Pressure compartments are common in sedimentary basins and are the natural result of the interaction between a number of mechanisms generating overpressures in the subsurface (undercompaction disequilibrium, hydrocarbon generation, and the related processes of oil to gas cracking being the most important ones) and the permeability-related processes that maintain and dissipate those pressures over time. Pressure compartment boundaries within any modelled area are commonly sub-parallel to lithology in a vertical sense. Changes in the permeability of the pressure-sealing sections result in differing rates of pressure bleed-off in the underlying units. In a horizontal direction, faults often act as pressure compartment boundaries. A basin modelling program has been developed, allowing calibration to known pressure and porosity data through an inversion methodology and the linking of multiple 1.5D forward models into a 3D framework that permits the description and analysis of the current pressure conditions within the model. An analysis of the main pressure compartments in the Eugene Island 330 Field area offshore northern Gulf of Mexico and in the Cassia Field area of the offshore Columbus basin, Trinidad, shows the use of the program for identifying the sealing portions of pressure compartment-bounding faults. An exploration strategy is outlined for the systematic identification and evaluation of pressure sealing fault traps.

Divergent Continental Margin Basins—
The Habitat of Australian Petroleum Systems

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Abstract

More than two hundred sedimentary basins have been identified across onshore Australia and its offshore marine jurisdiction (Fig. 1). These basins cover in excess of 10 million square kilometres and host a great variety of petroleum systems ranging in age from Proterozoic to Cenozoic (Bradshaw *et al*., 1994; Longley *et al*., 2001.) However, more than 95 percent of Australia's known reserves of petroleum are located in Mesozoic and younger sediments within divergent margin basins encircling the continent.

The majority of the initial oil reserves (3.8 billion barrels of the 6.2 billion barrels of Australia's initial commercial crude oil reserves) were discovered in just one of these basins, the Gippsland, located offshore, southeastern Australia. Other significant volumes of oil were discovered in the Carnarvon and Bonaparte basins on the North West Shelf; as well as major gas reserves, estimated in 2004 at over 100 trillion cubic feet. Australia ranked 30th and 13th in oil and gas global reserves, and 28th and 17th in oil and gas production at year end 2002 (Petrie *et al*., 2005).

Australia's continental margin basins are the legacy of the breakup of Gondwana. The character and timing of the breakup varied along the margin and is reflected in the petroleum systems. The North West margin has a marine history extending back into the early Paleozoic. Successive continental slivers rifted away during the formation of the various incarnations of Tethys, continuing through to the development of the Indian Ocean in the Late Jurassic and Early Cretaceous. North West Shelf petroleum systems are characterized by marine shales providing oil source rocks and regional seals for fluvio-deltaic to shallow marine sandstone reservoirs. In contrast, the late Mesozoic breakup along the Southern Margin occurred between the two major continental blocks of Australia and Antarctica. Non-marine facies characterize the petroleum systems with coals and carbonaceous shales sourcing the hydrocarbons trapped in siliciclastic reservoirs.

Most of the depocenters containing significant oil accumulations can be described as "failed rifts", whether they are located on the North West Shelf or on the Southern Margin. The major oil fields of the Carnarvon basin are located in the Mesozoic Exmouth, Barrow, and Dampier sub-basins, which lie inboard of the giant gas province of the Exmouth Plateau (Fig. 2). The Exmouth Plateau is a submerged continental platform of earliest Jurassic age and older, surrounded on three sides by oceanic crust – the Argo Abyssal Plain to the northeast, the Gascoyne Abyssal Plain to the northwest, and the Cuvier Abyssal Plain to the southwest. The plateau is bounded to the southeast and east by the oil-prone Exmouth, Barrow, and Dampier sub-basins, which are intracratonic rifts that were initiated in the Pliensbachian.

Several kilometers of marine Jurassic sediments were deposited in these sub-basins that are age-equivalent to sections a few meters thick on the Exmouth Plateau. Breakup on the northern margin of the Exmouth Plateau during the Callovian was associated with the formation of the Argo Abyssal Plain and produced further movement on the faults bounding the sub-basins. Restricted, deep-marine environments were established in the subsiding troughs, and the primary oil source rock facies of the Dingo Claystone was deposited during the Late Jurassic (Bishop, 1999; Bradshaw *et al.*, 1998; Longley *et al*., 2002).

A similar pattern is repeated to the north, in the Bonaparte basin, where the oil-producing Vulcan sub-basin is located inboard of the Ashmore Platform (Fig. 3). In this sub-basin, Late Jurassic marine source rocks deposited in restricted marine troughs are the key to the petroleum system (Edwards *et al*., 2004).

On the southeastern continental margin of Australia, the Gippsland basin is one of Australia's most prolific and mature petroleum provinces. The basin is

an intact rift preserved from the later stages of Gondwana breakup. It was initiated as part of the east-west directed Early Cretaceous breakup rift system between Antarctica and Australia. In the Late Cretaceous, the oil kitchen and main depocenter of the Central Deep was established during renewed extension associated with the opening of the Tasman Sea (Bernecker, *et al* 2001; Norvick *et al* 2001). The first marine incursion occurred in the late Santonian. However, the lower coastal plain and coal swamp facies deposited in the Central Deep during the Late Cretaceous are regarded as the major source rocks for the billion-barrel accumulations of the Gippsland basin (Burns *et al*., 1984; Rahmanian *et al*., 1990).

The vast majority of Australia's discovered oil reserves are located within rift systems in three basins – the Carnarvon, Bonaparte, and Gippsland basins. In all three areas, the deposition of source rocks is controlled by rift-basin architecture. The deep-water, frontier Mentelle basin, located offshore of southwestern Australia, has several key features reminiscent of these proven oil provinces. The Mentelle basin is a thick, Mesozoic, depocenter located inboard of a submerged continental platform, the Naturaliste Plateau (Fig. 4). Its tectonic history has some similarities to the evolution of the Gippsland basin, having been formed near the failed arm of a triple plate junction during rifting of Australia, Antarctica, and Australia-Greater India breakup (Bradshaw *et al*, 2003). Geoscience Australia is currently undertaking number of studies in the Mentelle basin to ascertain whether there is any evidence of a petroleum system to compliment this apparently promising configuration.

Systems of the Otway Basin, Southern Australia: Oil and Gas in a Complex Multi-Phase Rift Basin

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Abstract

The Otway Basin is a large, multi-phase rift basin located on the Australian southern margin. Oil and gas recovered from the Otway Basin belong to the Austral petroleum supersystem and are predominately derived from Mesozoic fluvio-lacustrine source rocks. Based on the results of geohistory modeling and oil and gas family analysis, two main petroleum systems are identified in the basin, the Early Cretaceous Crayfish(!) petroleum system and the Early-Late Cretaceous Eumeralla-Shipwreck(!) petroleum system. Both of these petroleum systems are classified as "known". The symbol (!) represents the level of certainty, in this case "known," meaning that the hydrocarbons in the named source rock and the named primary reservoir unit have been geochemically examined and found to be genetically related.

The Crayfish(!) petroleum system is mostly restricted to a series of syn-rift half grabens in the western Otway Basin. The stratigraphic and areal location of potential source and reservoirs rocks in the Crayfish(!) petroleum system is strongly controlled by growth on major half graben faults. Multiple episodes of hydrocarbon charge characterize the Crayfish(!) petroleum system, with oil and gas emplaced during the Early Cretaceous, and a dry gas charge during the Tertiary.

Hydrocarbons from the Eumeralla-Shipwreck(!) petroleum system are sourced from coaly facies developed during the regionally extensive fluvio-lacustrine sag sequence that followed the first rifting phase. The reservoir is a fluvio-deltaic lowstand sequence that was deposited during initiation of the second rift phase. The major factors influencing the distribution of the Eumeralla-Shipwreck(!) petroleum system are Late Cretaceous deltaic loading and Oligocene-Miocene carbonate deposition. Favorable conditions for a recent expulsion phase occur in the eastern Otway Basin, where a thick Oligocene-Miocene prograding carbonate succession overlies the relatively thin Late Cretaceous succession.

The Divergent Continental Margins of the Jurassic Proto-Pannonian Basin: Implications for the Petroleum Systems of the Vienna Basin and the Moesian Platform

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Abstract

The present-day Pannonian basin and the surrounding Carpathian Mountains occupy the rifted continental margin of the European plate. The Middle Jurassic proto-Pannonian basin formed in the same area as an oceanic basin along the northern margin of the Tethys. Based on the latest results of the deep structure of the European plate in the Bohemian Massif and the Moesian platform segments of the European continental margin, a new model of the structural evolution of these margins is outlined.

The Bohemian Massif projects below the Eastern Alps and the western Carpathians as a basement promontory often referred to as the Bohemian Spur. This salient defines a large concave to the southeast segment of the European margin that is interpreted as a lower plate margin. In contrast, some 800 km to the southeast, the Moesian platform forms a convex to the northwest segment of the Tethyan margin beneath the Southern Carpathian fold belt.

For the first time, the Moesian platform is interpreted as the upper plate, conjugate margin of the Bohemian segment of the European margin, rifted and drifted away during the Middle and Late Jurassic. Both margins are classical petroleum provinces. Therefore, the pre-rift restoration has important implications for the petroleum systems. The hydrocarbons in the Vienna basin are largely sourced from the Malmian Mikulov Marl deposited in a restricted basin shortly following the breakup. Similarly, the Dogger Bals Formation is the main source rock interval in the Moesian platform beneath the Carpathian foredeep basin.

Useful structural and petroleum systems analogs for these continental margins are provided by other conjugate margins; for example, the Majunga segment of Madagascar (lower plate) and the Bur Acaba segment of the Somali margin (upper plate). Another important example with similar, Middle Jurassic age for the rifting and breakup is the northern Gulf of Mexico basin (lower plate) and the Yucatan microplate (upper plate).

Petroleum System and Miocene Sequence Stratigraphy: Central Sumatra Basin, Indonesia

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Abstract

The Central Sumatra basin contains the Pematang-Sihapas(!) petroleum system, the most prolific petroleum system in southeastern Asia. A chronostratigraphic framework based on well logs and cores provides insights concerning the occurrence of seals, reservoirs, and the distribution of hydrocarbons. Oil sourced from lacustrine lithofacies of the Pematang Group (*i.e.*, the Brown Shale) in the underlying rift sequence migrated vertically until reaching a thick paleosol horizon (representing the 25.5 Ma sequence boundary). Thereafter, oil migrated toward the eastern margin of the basin charging the giant Minas and Duri fields. Erosional truncation (incised valley development) of paleosols and faults provided "windows" for migration of oil into overlying Miocene (Sihapas Group) marine, sandstone reservoirs. Well log correlations and core data reveal the common presence of incision along the 25.5, 22, 21, and 17.5 Ma sequence boundaries. Oil accumulated preferentially in basal transgressive sandstones. Approximately 80 percent of the recoverable oil resides in the lower part of the 21 Ma depositional sequence. These well sorted, medium-grained sandstones (Bekasap Formation) record deposition in estuarine (presumably macro-tidal) settings. Marine sandstones within the overlying 16.5 and 15.5 Ma depositional sequences are oil-saturated; however, they are very fine-grained and have inherently low permeability. The regional top seal for Sihapas reservoirs is formed by calcite-cemented, glauconitic shales and siltstones (Telisa Group) that record the maximum Miocene transgression. Relatively small oil accumulations in the underlying alluvial-fluvial and lacustrine sandstones of the Pematang Group are sealed by paleosols. The permeability of the fluvial reservoirs is degraded by poor sorting and pervasive authigenic kaolinite. In distinct contrast, Sihapas sandstones have undergone minimal diagenesis. This newly developed sequence stratigraphic framework has dramatically improved the understanding of the correlation and distribution of Miocene hydrocarbon reservoirs and seals in Central Sumatran oil fields.

Constraints on the Interpretation of the Origin and Early Development of the Gulf of Mexico Basin

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Abstract

Numerous conceptual models (interpretations) exist for the origin and early development of the Gulf of Mexico Basin. Geophysical data (aeromagnetic, gravity, and seismic data), new concepts, and geologic datasets (paleontologic and paleobathymetric) are rarely fully incorporated into these models, and the result is often incomplete or inaccurate models. The size of the basin, a lack of lithologic control on deep stratigraphy (outcrops and well penetrations), and poor seismic imaging at depth because of the thickness of the post-rift sedimentary cover sequence contribute to the diversity of concepts and models.

Constraints can be placed on the timing, architectural development, and control of the sedimentary fill, thereby resulting in a more concise and integrated basin model. For example, it must be recognized that the Gulf of Mexico Basin is part of the Central Atlantic Magmatic Province (**CAMP**). Therefore, the importance of seaward-dipping reflectors (**SDRs**) in the Gulf of Mexico Basin suggests a subaerial origin for extruded "proto-oceanic" crust, thereby implying that revisions to some of the published models are necessary because of the style of breakup represented by seaward-dipping reflectors. Understanding that the edges of salt in the northern Gulf of Mexico and the Campeche (Sigsbee) salt basins do not lend themselves to a "jigsaw" restoration for a variety of reasons, significantly affects the interpretation and timing of continental breakup. In addition, interpreting the presence of what may be two "breakup" events, each separating syn-rift from post-rift strata (inferred from seismic interpretations) in the deep-water, northern Gulf of Mexico, suggests a polyphase basin evolution prior to deposition of the thick sequence of late Mesozoic and Cenozoic post-rift sediments. Correct identification of the Mid-Cretaceous Sequence Boundary on seismic datasets (*aka* the Mid-Cretaceous Unconformity), rather than the previously misinterpreted seismic event (recently established by paleontologic data to represent the Cretaceous-Tertiary Boundary), is critical to constraining the architecture and timing of structural and stratigraphic events. Incorporating the existence of Cretaceous through Eocene "Oceanic Red Beds" in the deep-water Gulf of Mexico constrains the paleobathymetric evolution of the basin during this time, resulting in a more coherent model. Publicly released paleontologic data from key, deep-water wells penetrating older strata in the area of the U.S. offshore Gulf of Mexico, using benthonic foraminifera as paleobathymetric indicators, show that generally, this area deepens over time, such that the basin in the area represented by these wells is deeper than, or as deep today as, it has ever been. The polyphase evolution of the Gulf of Mexico Basin, the effects of the loading of the Mexican Cordilleran complex, and the occurrence of igneous dikes, sills, and flows in the northern Gulf of Mexico, often in association with salt structures, should be considered. The change in provenance direction estimated to occur between the Paleocene and the Oligocene from northwest to south has implications for many models of the basin.

This paper points out a few constraints and issues to address in evaluating models of the Gulf of Mexico Basin and is not intended as still another model for basin evolution. Integrating these constraints into interpretations of the origin and development of the early Gulf of Mexico is extremely important since, paraphrasing Dr. Raymond Price, a model that incorporates all the data and observations may not be right, but one that does not is always wrong.

Passive Margin Development in the Atlantic and Gulf of Mexico with a Special Emphasis on Proto-Oceanic Crust

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Abstract

Some new developments in geodynamics and plate tectonics related to the development of continental margins have occurred in the past few years that are important in exploring for hydrocarbons. Development of passive margins appears to proceed in five initial stages. First there is an initial fracturing of the crust that is either propagation of a rift or development of the rift during mantle upwelling and elevation. Second, rifting develops a zone of extended continental crust having large, more periodic half-graben basins. Third, faster rifting develops a zone of highly extended continental crust having less well developed and less periodic half-graben basins. The fourth stage is the formation of “proto-oceanic” crust. The fifth and final stage is the development of “true” oceanic crust.

The development and location of basins during initial breakup of continental plates is controlled by the location of zones of weakness that exist in the continental crust before rifting begins. The initial direction of rifting and spreading appears to depend upon the direction of the controlling zones of weakness. Zones of weakness may not align exactly with the preferred direction of spreading. During rifting and for some period of time thereafter, the interaction of the various continental plates may not be well defined. These two factors, and others, may contribute to development of a forth stage after rifting and prior to the drift phase where the direction of spreading may be somewhat chaotic. During this phase parts of the continental crust may be fragmented and intermingled with volcanic material produced from the embryonic ridge system. Possibly other types of volcanism than mid-ocean ridge basalts may occur. These factors are the basis for the formation of the “proto-oceanic” crust described by Dickson and Odegard (2000) and Odegard (2002) and represent the fourth phase of margin development. This crust undergoes further modification as it descends from its formation at or near sea level to deeper ocean depths. Finally, in the fifth phase, true oceanic crust begins to develop.

This paper describes in greater detail the observation and characteristics of the processes described above, particularly proto-oceanic crust. Observations and interpretation methods are shown for various areas of the Atlantic. Finally these methods are applied to the Gulf of Mexico. Using gravity data enhancements the early location of the Yucatan Peninsula relative to North America is derived from the location of the boundaries between extended continental and proto-oceanic crust. This then gives insight into the rotation of the Yucatan block and the formation of proto-oceanic crust during the opening of the Gulf of Mexico.

An Interpretation of the Crustal Framework and Continent-Oceanic Boundary in U.S. OCS of the Gulf of Mexico, Based on Gravity and Refraction Data Analysis

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Introduction

Geophysical evidence suggests the existence of oceanic crust in the deep-water Gulf of Mexico. However, there is no consensus on the location of the continent-ocean boundary in this important geologic province. This boundary is an important constraint for modeling petroleum systems because thermal histories are partially dependent on both crustal lithology and thickness.

A number of distinct kinematic models have been published for the crustal framework and early tectonic history of the Gulf of Mexico. All these models were constrained by similar seismic refraction data, tectonic subsidence analyses, global plate motions, and/or potential fields data and draw different conclusions on the aerial extent of true oceanic crust. In support of our sub-regional petroleum systems models for the United States Outer Continental Shelf (OCS), we analyzed regional gravity and refraction data and constructed a number of 2D and 3D crustal models. Our models suggest that most of the U.S. OCS is underlain by attenuated continental crust, and that the extent of true oceanic crust in the Gulf of Mexico may be significantly less than many other published models.

Oceanic crust, which is newly formed crust created at a mid-ocean ridge during the drift, or sea-floor spreading phase, has distinct petrologic and geophysical characteristics. In this study, we focus on geophysical properties. Global studies of the earth's crust (Mooney *et al*. 1998) show that oceanic crust is fairly consistent in thickness, velocity, and density. Crystalline oceanic crust is approximately 6 to 7 km thick. Below a relatively thin sedimentary layer, oceanic layer 2 is primarily pillow basalts and sheeted dikes, with an average velocity of 5.0 km/sec. Oceanic layer 3 is composed primarily of gabbro, having velocities greater than 6.6 km/sec. Oceanic crust is overall denser (average greater than 2.8 gm/cc) than continental crust (average 2.65 gm/cc). Crust underlying most of the Gulf of Mexico has not been penetrated by drilling and seismic imaging is poor under areas covered by extensive salt bodies. Therefore, seismic refraction data and gravity data are two tools used to help identify oceanic crust.

Oceanic Crust in the Gulf of Mexico—
A Combination of Rift Propagation and Slow Spreading

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Abstract

The presence or absence of oceanic crust, the location of the continental-oceanic crust boundary, and how spreading centers within the Gulf of Mexico are separated from each other have been matters of conjecture and debate for the past 20 years and are likely to remain so for the foreseeable future.

By combining publicly available topographic, bathymetric, gravity and magnetic data and their derivatives, and by comparing these with analog models from divergent margins across the globe, we suggest a refined model for the opening of the Gulf of Mexico.

Rifting, leading to ocean crust formation, and seafloor spreading in this area, propagated from the west during the Middle Jurassic, reaching the eastern Gulf of Mexico by the latest Jurassic/earliest Cretaceous.

Many authors have suggested that oceanic crust developed as far east as the Henderson and Florida Plain protraction areas. However, we are of the opinion that eastward from central Lund, the crust can best be described as 'proto-oceanic' and, by using the Southwest Indian Ridge as an analog, we can show that ultraslow spreading oriented obliquely to the principal farfield extensional stress orientations, can lead to the features observed in the potential field data from the eastern Gulf of Mexico.

By incorporating the observed data into a global plate tectonic context, we are able to confidently predict the location of oceanic crust in the Gulf of Mexico, as well as the orientations of oceanic fracture zones associated with the opening of the basin.

The Mesozoic Opening of the Gulf of Mexico: Part 1, Evidence for Oceanic Accretion During and After Salt Deposition

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Abstract

Conflicting views have recently been expressed about the deep structure of the Gulf of Mexico, as interpretations cover the whole spectrum from oceanic to extended continental crust. The interpretation proposed here favors the former interpretation, as evidence of the oceanic character is interpreted from both seismic (reflection and refraction) and magnetic datasets.

The core of the interpretation is the recognition of a package of seaward-dipping reflectors (**SDRs**) below the Louann Salt at the base of the Florida escarpment. Gravity and magnetic data and seismic velocity analysis, indicate that this package of seismic events is dense, magnetic, and has high velocities. Therefore, they are unlikely to consist of Triassic siliciclastics. Consequently, it is interpreted that these events correspond to the earliest stages of subaerial accretion of volcanic crust during spreading, before the Gulf of Mexico was in communication with the world ocean.

In the more distal part of the basin, the morphology of the basement on the abyssal plain is considered as representing "classic" oceanic crust having a ridge/transform morphology that is based on structural mapping of seismic data.

Both the **SDRs** wedge and the structural trends observed on the oceanic crust of the abyssal plain indicate a spreading axis roughly trending southeast, indicating that they can be part of the same episode of volcanic/oceanic opening. The 50 km-wide intermediate area between the **SDRs** wedge and the oceanic crust in the abyssal plain, in the absence of good seismic imaging, is interpreted as an area emplaced by volcanic/oceanic spreading in the same episode.

The Jurassic Louann salt overlies the **SDRs** wedge (emplaced in subaerial conditions) and therefore postdates the beginning of the volcanic spreading along the studied transect. It also overlies the intermediate area seaward: salt deposition is therefore interpreted to have ended after the emplacement of about 100 km of volcanic/oceanic crust.

Consequently, volcanic/oceanic spreading in the eastern Gulf of Mexico started before salt was deposited along the studied part of the margin, continued during salt deposition, and ceased in the Early Cretaceous.

The Mesozoic Opening of the Gulf of Mexico: Part 2, Integrating Seismic and Magnetic Data into a General Opening Model

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Abstract

A companion paper (Imbert, 2005, this volume) interprets the abyssal plain of the eastern Gulf of Mexico as an oceanic domain bounded to the northeast by a volcanic margin associated with the initial opening of the basin prior to the end of Louann Salt deposition. This paper explores the consequences of this interpretation on the opening model, at the scale of the entire Gulf of Mexico.

Magnetic anomaly maps are compatible with structural elements derived from seismic interpretations and are interpreted in the deep Gulf of Mexico domain as magnetic stripes recording the reversals of the magnetic field of the earth during the opening of the Gulf of Mexico. This interpretation allows us to closely define the successive stages of opening.

This interpretation is tested against one potential major time line, the seaward limit of deposition of the Jurassic salt. This limit is observed in two domains; the Louann salt in the north and the Campeche and associated salt basins in the south. It is impossible to image the initial depositional limits of the salt due to the limits of seismic visibility. The proposed reconstruction implies a depositional limit of the salt some 100 km inward of the Sigsbee escarpment to avoid overlap. Modeling shows that syn-opening flowage of the salt after the end of evaporitic conditions, under the combined effect of gravity and thermal subsidence of the young oceanic crust, could lead to this order of magnitude of salt displacement. This would also explain why there appears to be more early extension than compression in several areas of the Gulf of Mexico: part of the compression has been absorbed by salt flowage on opening crust (*i.e.*, intra-salt and cryptic).

A general reconstruction of the early stages of opening of the Gulf of Mexico is proposed under these hypotheses.

Regional Geologic and Geophysical Observations Basinward of the Sigsbee Escarpment and Mississippi Fan Fold Belt, Central Deep-Water Gulf of Mexico: Hydrocarbon Prospectivity and Play Types

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Abstract

While most interpretations of the origin of the Gulf of Mexico basin involve rifting by counter-clockwise rotation of the Yucatan block, the exact placement of the ocean-continent boundary has remained controversial. Published interpretations (Bird *et al*., 2005) usually place the boundary near the basinward limit of autochthonous salt. Our interpretation, outboard of salt and southeast of the Mississippi Fan Fold Belt, suggests a more complex assemblage of crustal elements. Seismic interpretation and potential field modeling indicate a zone of highly extended transitional crust dominated by oceanic material although containing large, discreet fragments of continental crust. This domain of anomalous, crustal material displays evidence that emergent to shallow marine conditions lasted longer than currently published interpretations. We believe this area supports a multitude of potential hydrocarbon play types.

Progradation and Retrogradation of the Libyan Shelf and Slope, North African Continental Margin

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Abstract

With the lifting of economic sanctions, western companies have come back to explore for hydrocarbons in Libya, onshore and offshore. However, virtually no modern marine seismic data has been acquired over the past twenty-five years to assist in this renewed exploration effort. During the past year, new 2D pre-stack time migrated seismic data has been acquired and used to examine the large-scale structural and depositional features of the Libyan shelf and slope. The data cover approximately 38,000 line kilometers in water depths ranging between 15 to 2200 meters.

The present day Libyan shelf margin has a demonstrably progradational character. Thick, laterally extensive deltaic deposits dominate the shallow shelf and upper slope. These deposits display classical clinoform geometries that suggest multiple phases of progradation during the past 3-5 Ma. Seismic resolution within the clinoform packages is high, as growth faulting, distributary channels, slump scars, and rotated blocks within the delta front are readily visible.

Clinoform geometries visible below, but truncated by, the Messinian unconformity indicate that the early to middle Miocene margin of Libya was also progradational at certain times.

Recent deltaic deposits sit upon and within a deeply eroded and scarred paleotopography, suggesting large-scale retrogradation of the shelf margin. The erosional surface extends for nearly 500 km along strike in the Sirt Embayment. A 65 km long portion of this erosional surface displays high relief truncated strata, healed fault scarps, and related deep-seated faults. In this area it is likely that a very large volume of shelf margin strata is missing.

The Libyan margin is tectonically active today and has been through most of the Cenozoic. Many faults penetrate from deeply underlying Mesozoic strata to the ocean bottom. The close association of active faults scarps, truncated strata, a potentially large missing section, and a laterally extensive erosional unconformity combine to suggest the possibility of catastrophic margin failure. The exact timing of margin retrogradation is uncertain at present but erosional relationships hint that margin failure occurred either coincident with or following the Messinian salinity crisis.

The Importance of Glacio-Hydro-Isostasy Within the Late Quaternary/ Holocene Sea-Level History of the Gulf of Mexico: Lessons for Stratigraphic Correlation

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Publisher's note: The GCSSEPM Foundation has been sponsoring student research for several years. We have told the students that we would be pleased, when they are done, to present their work at one of our research conferences. The following work represents the results of one of these sponsorships. Alex did his work at Rice University and we are pleased that he will present his work at a poster session.

Abstract

A 30 m discrepancy between sea-level records within the Gulf of Mexico and other "global" records has been known in the literature for over 50 years. Many hypotheses have been proposed to explain this discrepancy including sedimentary loading due to the Mississippi River and the effects of radiocarbon reservoirs. Using quantitative numerical models and over 50 new radiocarbon dates obtained from shallow marine systems across the Gulf of Mexico, we test several hypotheses that might explain this discrepancy. We found that glacio-hydro-isostasy, changes in the Earth's shape due to the shifting of mass on the Earth's surface caused by the waxing and wanning of the last great ice sheets, with an appropriate ice model for the Laurentide Ice sheet provides the best solution. Furthermore, this work has important implications for the ice sheet reconstructions for the Laurentide ice sheet and traditional sequence stratigraphic methods for correlating strata on passive continental margins.

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