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ORAL ABSTRACTS

Continental rifts: Lateral Strength Contrasts in the Lithosphere as a Mechanism for Localizing Necking Instabilities and Deformation

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Besides the effects of intrinsic rheological layering of the lithosphere and its thermal structure, inherited heterogeneities may play an important role in strain localization and strain rate distribution during extension of rifting margins. Here, we consider both inherited small-scale weak zones and the effects of a lateral juxtaposition of lithospheres with differing properties as mechanisms to localize deformation and initiate necking instabilities. Using 2D finite element models that contain lateral lithospheric boundaries, alone and in combination with smaller scale heterogeneities, we illustrate that there are two controls on the style of rifting: Control 1, the stiff/pliable nature of the lithosphere, and; Control 2, the background strain rate in the lithosphere. Control 1 depends on the lithospheric rheology, such that necking instabilities grow faster in materials with high power-law flow exponents (stiff plastic lithosphere) than in those with low power-law flow exponents (pliable viscous lithosphere). Control 2 is important where a strength contrast at a lithospheric boundary influences the distribution of the background strain rate. Necking is a mechanism that amplifies the background strain rate, which implies faster necking in parts of the lithosphere where background strain rates are highest. The finite element models are used to show how these controls act together in the presence and absence of weak local heterogeneities in the extending lithosphere.

Introduction

The large diversity and complexity of the geometry of continental rifts and rifted margins is poorly explained by simple kinematic models such as pure shear (Mckenzie 1978) and simple shear (Wernicke 1985). Here, we consider how final rifted margin geometry reflects strain localization and the growth of necking instabilities. These are a result of background stress in the lithosphere resulting from extensional far-field forces. Lithospheric temperature and rheology affect how fast individual layers thin (neck) and result in depth-dependent extension (Royden and Keen 1980, Fletcher and Hallet 1983, Bassi et al. 1993, Bassi 1995). Furthermore, inherited heterogeneities alter the distribution of stress and the background strain rate. In some instances, this can lead to necking instabilities that localize at the inherited heterogeneities. Our research on the controls of the growth rate of necking instabilities builds on Chenin and Beaumont (2013) and is explained in the next paragraphs.

Control 1: Differential growth of necking instabilities

The temperature and rheology of the lithosphere modulate the growth rate of necking instabilities (Fletcher and Hallet 1983, Schmalholz et al. 2008). Extension of the lithosphere involves a feedback loop between the initial focusing of deformation at the heterogeneities and the way this is amplified by the lithospheric rheology.

The basis for this rheological feedback is that the primary mechanism for deformation of lithospheric rocks is either brittle or ductile. To a first approximation these are controlled by frictional-plasticity or by power-law viscous flow, with large ($n > 1000$) and small ($n \sim$ 3-5) power-law exponents, respectively.

A power-law exponent $n > 1$ results in an unstable flow (Smith 1977, Emerman and Turcotte 1984). Therefore, the existence of pinch and swell (boudinage) structures indicates that the lithosphere is a non-Newtonian viscous fluid with a power-law exponent $n > 1$. Given the right conditions, a perturbation coupled with a background strain rate will grow in size, causing a localized increase in strain rate and starting a positive feedback. At the perturbation, the effective viscosity decreases resulting in an increased strain rate and the growth of a necking instability.

Given that the growth rate of necking instabilities increases with n, we can define 'stiff' lithospheric layers to extend with rapid necking (dominantly brittle, n is large), and 'pliable' lithospheric layers that neck slowly if at all (dominantly ductile, n is small). Here we are using the terms stiff and pliable in relation to deformation of viscous- plastic not elastic materials (Fletcher and Hallet 1983, Zuber and Parmentier 1986). The stratification of the lithosphere into stiff and pliable layers depends on the composition and the temperature variation with depth.

Control 2: Background Strain Rate

The reactivation of pre-existing crustal weak zones has often been invoked to explain rift geometry (e.g. Western Branch of the East African Rift System (Theunissen et al. 1996, Klerkx et al. 1998), and the formation of basins offset from the main locus of rifting along rifted margins (e.g. Fundy Basin in Nova Scotia, Withjack et al. 2010). However, the presence of a favorably oriented inherited weak zone alone is not sufficient to localize deformation.

Since necking instabilities amplify the background strain rate, an additional requirement is that there must be a background strain rate for necking instabilities to localize at a weak zone. Therefore, no necking instability will develop where the background strain rate is zero.

In a laterally homogeneous lithosphere the background strain rate will be uniformly distributed along each layer, allowing weak zones to localize necking instabilities. On the other hand, juxtaposed lithospheres with different strengths will distribute strain such that the weaker, more easily deformable, lithosphere has the higher strain rate. In an end-member case, where the strong lithosphere acts as a rigid block, no necking instability will develop in this region, although inherited weaknesses may be present. For example, a low strain rate in a strong, stiff craton but higher strain rate in adjacent weaker lithosphere will allow necking instabilities to grow faster in the weaker, pliable lithosphere. This seems contradictory to Control 1, which predicts necking instabilities to grow faster in a stiff lithosphere, but instead adds the requirement of a background strain rate in order for a necking instability to grow.

Below, we show that localization occurs at the lithospheric boundary in the presence of an inherited weak zone at that boundary (Figure 1). The growth rate of necking instabilities, controlled by the strength and temperature of the lithosphere, determines: the timescale for lithospheric breakup, the amount of extension required, and the final geometry, wide, narrow or complex, of the resulting rifted margin (Control 1).

In the absence of a weak zone at the lateral boundary (Figure 2), deformation localizes ~150 km away from the lithospheric boundary in the more accommodating, weaker lithosphere (Control 2). This process can act as a protection and preservation mechanism for cratons.

Numerical Modelling: Model Design

We use *SOPALE-nested* (Fullsack 1995, Beaumont et al. 2009); a lithospheric-scale 2D Arbitrary-Lagrangian-Eulerian (ALE) finite element model, which can accommodate large amounts of deformation. The code solves 2D thermo-mechanically coupled, incompressible viscous-plastic creeping (Stokes) flow equations and has frictional-plastic and thermally activated power-law viscous rheologies.

The upper and lower crust extend to 35 km depth and use a ‘Wet’ Quartzite (WQz) rheology (Gleason and Tullis 1995). The upper and lower mantle lithosphere as well as the sublithospheric mantle use a ‘Wet’ Olivine flow law (Karato and Wu 1993). The initial temperature regime is laterally homogeneous with a Moho of 600˚C and the base of the lithosphere at 1350˚C in the models presented. The mantle lithosphere extends to 140 km depth. Extension of the lithosphere is defined by horizontal velocities of 1.0 cm/yr on the right and left horizontal boundaries (total 2 cm/yr).

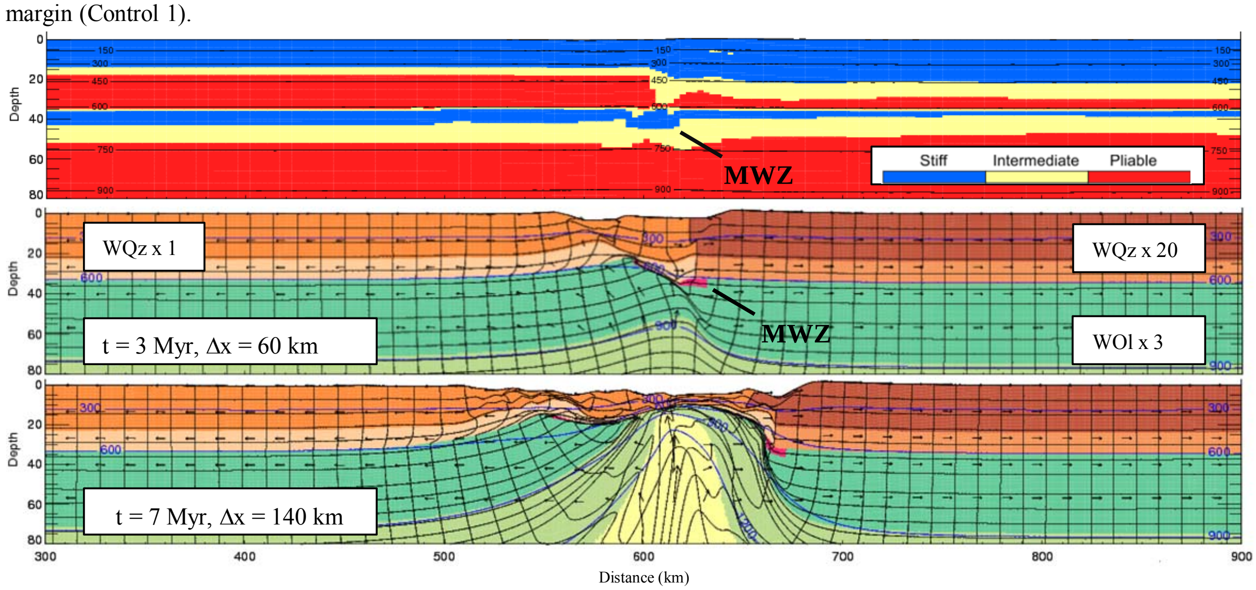

Figure 1: Model result with a small inherited mantle weak zone (MWZ). Upper panel shows the distribution of materials that behave stiff (blue) or pliable (red) at the beginning. The MWZ is at yield and can be seen in blue in the middle of the panel. The middle panel shows rift development after 3 Myr. WQz stands for "Wet" Quartzite, WOl stands for "Wet" Olivine. The lower panel shows the evolution at 7 Myr with significant asthenospheric upwelling (yellow). The pliable nature of the lower crust on the left hand side results in distributed deformation. Extension: 2cm/yr total.

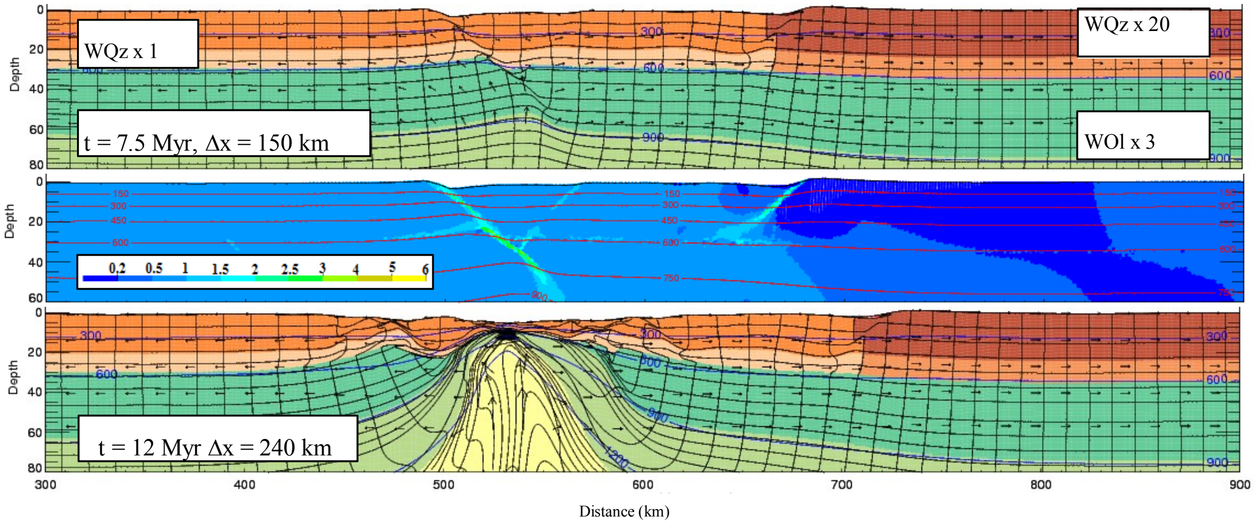

Figure 2: Model without a weak zone at the lithospheric boundary. Upper Panel shows the model after the first strain localization has taken place. WQz stands for "Wet" Quartzite, WOl stands for "Wet" Olivine. The middle panel shows the distribution of accumulated strain after 7.5 Myr. The lower panel shows the localization of deformation ~150 km offset from the lithospheric boundary at 12 Myr. Extension: 2cm/yr total.

The results in figures 1 and 2 consider the particularly simple case, where only the properties of the crust vary across the lithospheric boundary, as a prototype for more general models.

We construct contrasting stiff and pliable behaviour of individual layers and across the main vertical boundary (Figures 1 and 2) by scaling the power-flow law by a factor *f,* 1 and 20 for the crust, which effectively changes the viscosity and “strength” of the layer, and therefore the stiff/pliable nature of the composite layering.

Results: Rift geometry controlled by stiff and pliable behaviour

When a small inherited mantle weak zone is present bridging the lithospheric boundary (Figure 1), it serves to localize necking and the style of deformation is determined by the contrast across the lithospheric boundary and the stiff and pliable behaviour of the layers. For example, in Figure 1 we have a stiff upper mantle lithosphere underlying a pliable crust on the left contrasted with a thicker stiff crust on the right.

The mantle weak zone at the boundary, which is embedded in a stiff layer, becomes the site of localization as predicted by Control 1. Although some strain has localized right at the boundary between the contrasting crusts, deformation is more widely distributed in the weaker, pliable, left crust. Break-up of the mantle lithosphere has occurred by 7 Myr resulting in a highly asymmetric rift partly underplated by lower mantle lithosphere.

There is almost no deformation in the right mantle lithosphere (Figure 1) even though it is stiff and should neck faster under Control 1. The model demonstrates the effect of Control 2, the stiff lithosphere did not neck because the background strain rate was too low. Even the right half of the weak seed remains largely undeformed.

Results: Localization of deformation

In the absence of a mantle weak zone, no necking instability develops at the lithospheric boundary and deformation eventually localizes well away from this boundary (Figure 2). In this case, the background strain rate is higher in the weaker left lithosphere than in the strong right lithosphere, which is indicated by the darker hues of blue in the middle, strain, panel of Figure 2. Although a small amount of strain localizes at the boundary this does not initiate a necking instability. Instead, strain is localized in the weaker, pliable crust subject to a higher background strain rate (Control 2). A shear forms ~150 km away from the boundary and develops into an asymmetric rift by 12 Myr.

Main Conclusions

The presence of a lithospheric boundary imposing a lateral lithospheric strength contrast has significant consequences for rift localization and geometry. The stiff and pliable behaviour of this laterally heterogeneous lithosphere determines rift and rifted margin characteristics such as: symmetry, width, the presence of exhumed mantle lithosphere and the number of riding blocks.

We presented two nearly identical models which differ only in the absence or presence of a small inherited weak zone at the lithospheric boundary. When a small inherited mantle weak heterogeneity at the boundary is present, it is activated because it is in a stiff layer, and results in a highly asymmetric rift (Figure 1) that resembles the Camamu-Gabon margin in the South Atlantic (Blaich et al. 2010).

In the absence of an inherited mantle weak zone the relatively stronger lithosphere remains largely undeformed as the weaker lithosphere accommodates all the deformation, while the strong lithosphere behaves as a rigid block with a low internal background strain rate (Figure 2). This result indicates that a rift located at the boundary of a craton, such as the Baikal rift (Delvaux et al. 1995, Petit and Déverchère 2006), likely localized at a pre-existing weakness, as in the first example (Figure1), as was suggested by Corti et al. (2013).

The results have implications for the preservation of cratons, which are generally acknowledged to be cold and strong, (e.g. Griffin et al. 2008) and probably stiff. Even though they contain inherited weak heterogeneities they are protected by Control 2, provided they are surrounded by weakling lithospheres such as younger orogens.

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Depth-dependent extension, two-stage breakup and depleted lithospheric counterflow at rifted margins

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Uniform lithospheric extension predicts basic properties of non-volcanic rifted margins but fails to explain other important characteristics. Significant discrepancies are observed at ‘type I’ margins (such as the Iberia–Newfoundland conjugates), where large tracts of continental mantle lithosphere are exposed at the sea floor, and ‘type II’ margins (such as some ultrawide central South Atlantic margins), where thin continental crust spans wide regions below which continental lower crust and mantle lithosphere have apparently been removed. Neither corresponds to uniform extension. Instead, either crust or mantle lithosphere has been preferentially removed. Using dynamical models, we demonstrate that these margins are opposite end members: in type I, depth-dependent extension results in crustal-necking breakup before mantle-lithosphere breakup and in type II, the converse is true. These two-layer, two-stage breakup behaviours explain the discrepancies and have implications for the styles of the associated sedimentary basins. Laterally flowing lower-mantle lithosphere may underplate both type I and type II margins, thereby contributing to their anomalous characteristics.

Assessing the influence of orogenic inheritance on the architecture and temporal evolution of hyper-extended rift systems: a combined structural and numerical modelling approach

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The aim of this PhD thesis is to assess the influence of inherited structures and heterogeneities on the architecture and tectonic evolution of hyper-extended rift systems, with special focus on the North Atlantic. To complete this task, we propose a new mapping approach using simple and robust observation-based criteria to identify key features of rift systems, including 1) structural elements of rift domains (e.g. necking zones, coupling points and location of breakup); 2) age of the major rift events (necking and breakup); and 3) key structures and heterogeneities inherited from previous orogenic phases. Based on the analysis of these maps, we will run minimal numerical models in order to constrain the influence of the nature, in-depth location and interactions amongst inherited structures on rift systems.

The first step of our approach consists in highlighting rift systems structural, temporal and inherited characteristics. We distinguish between the different rift domains as a function of the deformation processes they undergo. Three main domains can be identified: 1) the un- or barely thinned *proximal domain*; 2) the unequivocal *oceanic domain* characterized by steady-state seafloor spreading; and, between them 3) the *hyper-extended domain* concentrating most of the deformation. We use gravity, magnetic and reflection and refraction seismic data to identify the necking zone and the continentward limit of unequivocal oceanic crust, which mark the boundaries of the hyper-extended domain. Within the hyper-extended domain, we rely on seismic data (refraction and reflection) to distinguish the area where the crust and the mantle are decoupled from the area where they are coupled, and to identify potential zones with mantle exhumation and/or magmatic additions. Previous studies mapped these domains along the Iberia-Newfoundland and Bay of Biscay. One objective of this PhD is to extend this mapping further to the North, along the Irish, Scottish and Norwegian margins, into domains with polyphase rifting and magmatic additions.

In addition to characterizing the different rift domains, we also aim to assign an age to the two most important events in the development of rifted margins, namely the necking and the breakup. This approach requires us to determine how these two events are recorded in the sediments - including during polyphase rifting - and how they can be mapped in seismic sections. Finally, we map the structures and heterogeneities inherited from previous orogenies that may have influenced significantly subsequent rifting. We consider only features that: 1) are important enough to have had a potential impact on subsequent deformation; 2) are preserved through time; and 3) bear the potential to be reactivated, i.e. that are conveniently oriented and within layers stiff enough so that they can concentrate the stress difference. Using these criteria, we select oceanic sutures, major faults, foreland basins and fold-and-thrust belts.

Several interesting observations emerge from the analysis of these three maps: The Variscan front, which is the limit between the Caledonian and Variscan domains, seems to be a major boundary:

1. It marks the limit between the volcanic margin to the North and the magma-poor province to the South;
2. It separates the polyphase and protracted rift domain to the North from the much shorter and monophase rift to the South;
3. It seems to be a structural barrier preventing the propagation of the Porcupine basin toward the North and the propagation of the North Sea toward the South.

Based on these data and observations, we try to assess under what conditions inherited structures are likely to be reactivated and reconsider how inheritance may be integrated in the understanding of tectonic processes. We will try to link the architecture and evolution of the North Atlantic rift system with the nature and location of weak features initially present within the lithosphere in the light of minimal numerical modelling experiments and use these results as a basis for designing more comprehensive numerical models for the North Atlantic rifting. One of the goals of this work is to highlight potential correlations between first-order changes in the architecture and/or magmatic and/or temporal evolution of the Atlantic margin and first-order features inherited from the Caledonian and/or Variscan orogens. We also aim to assess the importance of inheritance in structuring and controlling the evolution of hyper-extended volcanic versus non-volcanic rift systems.

Continental Margin Syn-Rift Salt Tectonics, Part 1: Intermediate Width Margins

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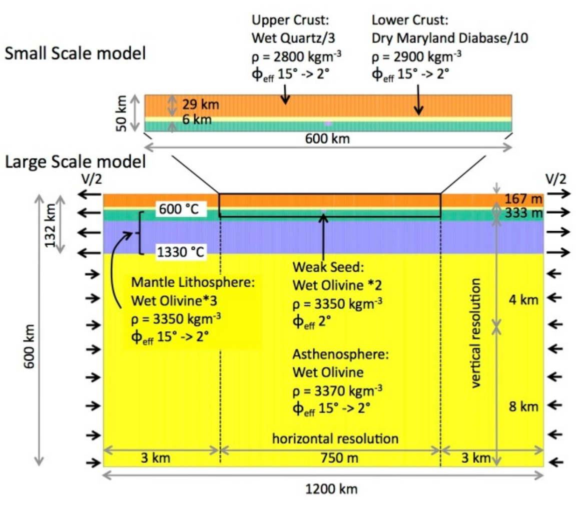
Introduction

Many rifted continental margins are strongly influenced by the deposition and deformation of evaporites. Considerable effort has been directed to understanding controls on the precipitation and deformation of evaporites, generally termed 'salt tectonics', in part due to this topic's importance to the petroleum industry. However, previous studies of salt tectonics at rifted conjugate margins have largely focused on the period after continental break up, when rifting and lithospheric extension are finished. Syn-rift tectonics may significantly impact the original geometry of evaporite bodies, as well as the mobilization of salt and development of salt tectonic structures.

Model Design

In this paper we present dynamically evolving numerical models that superimpose the regional tectonic setting of rifting conjugate margins on the deposition and deformation of evaporites. The nested models span an area 1200 km wide by 600 km deep (Figure 1), and provide high resolution imaging of evaporite basin evolution.



A single crust composition illustrates the roles of 1) timing of evaporite deposition relative to rifting, and 2) subsequent sedimentation, in defining the distribution and deformation of syn-rift evaporites. We contrast evaporite deposition in the early, mid, and late syn-rift periods, and include post-evaporite sedimentation in some models.

Clastic sediments are frictional-plastic and subject to compaction. Salt (halite) has a linear viscous rheology, with viscosity of 10^{18} or 10^{19} Pa s, and does not compact. In our model of the Red Sea we also include a non-compacting, frictional-plastic mixed evaporite that is more dense than halite.

Rifting With and Without Clastic Sedimentation

We define an intermediate continental crust rheology, between the strong and weak crust of Huismans and Beaumont (2011). Our first model considers lithospheric rifting in the absence of sedimentation. Deformation is relatively brittle; the upper continental crust thins primarily through faulting. Depth-dependent stretching is evident, with detachment at the base of the upper continental crust. Diachronous stretching is also apparent; deformation migrates from proximal fault-bounded graben to a narrow area over the rift axis. In the late syn-rift period, thinning of the upper crust is restricted to the most distal margins. When sediments are deposited during rifting, they display a seaward shifting locus of deposition and deformation. Only sediments near the current distal part of the conjugate margin pair are actively deformed at any point in the model evolution. Sediments deposited at the mid-margin during the late syn-rift or post-rift period, when extension is not active at this location, are not faulted. This results in a seaward-younging, sag basin type succession of clastic sediments, faulted throughout its lateral extent, with unfaulted sediments in the upper portion of the succession.

Impact of Timing of Salt Deposition Relative to Rifting, and the Role of Subsequent Sedimentation

Timing of evaporite deposition relative to rifting impacts the geometry of the original evaporite bodies and the development of salt tectonics (Figure 2). The results shown here are for salt viscosity of 10^{18} Pas; results with 10^{19} Pa are considered in the full paper.

We contrast salt deposition in the early, mid, and late syn-rift periods. Salt deposited in the early syn-rift period is focused in a pair of fault-bounded graben in the proximal margin (Figure 2a, b Left/Right). Prograding sedimentation forms an expulsion rollover, leading to thickened salt at the seaward edge of the basin, which later forms a diapir. In the mid syn-rift period crustal thinning leads to subsidence in a region across the rift axis, creating additional accommodation space for salt deposition. Mid syn-rift salt is deposited over clastics in the proximal basins, and on to thinned continental crust over the rift axis. Mid syn-rift salt is more susceptible to later flow, owing to reduced (or non-existent) basement steps (Figure 2c, Left/Right). Prograding sediments further seaward salt flow, resulting in an expulsion rollover and diapir in the left proximal margin, and thickened salt with a tongue of older salt flowing over younger at the right mid margin (Figure 2d, Left/Right). Late syn-rift salt is deposited in a relatively uniform layer across the mid and distal margins, over a thick succession of aggraded clastic sediments. Where late syn-rift salt is thick it readily flows towards the rift axis, forming escarpments where some salt is trapped at the mid margin (Figure 2e, Left/Right). Prograding sediment expels salt seaward, producing thickened salt bodies at the distal margin. Where previous sedimentation provides a barrier to lateral flow, late syn-rift salt remains in the distal margin; otherwise, it may flow over oceanic crust (Figure 2f, Left/Right).

Discussion

This work provides an improved integrated physical understanding of the development of salt tectonics at rifted margins, by allowing salt basin geometry to evolve naturally during extension of the rifted conjugate margins, and by considering the interactions between timing of salt deposition relative to rifting and ongoing sedimentation. Many of the characteristics of our early, mid, and late syn-rift models show good agreement with Rowan's (2014) conceptual model of salt deposition in the syn-stretching, syn-thinning, and syn-exhumation phases of rifting.

The Red Sea: A Natural Example of Syn-Rift Salt Tectonics

The Red Sea is in the late syn-rift to early post-rift stages of continental break up, contains a thick evaporite succession, and is an ideal location to study the interaction between extensional tectonics and the deposition and deformation of evaporites. Understanding the interplay between rifting and evaporite mobilization for the Red Sea will shed light on the relative importance of syn- and post-rift evaporite deformation at more mature conjugate margins, such as the North and South Atlantic. We present a numerical model of the Red Sea with evaporite deposition during the mid to late syn-rift period, preceded and followed by aggrading and prograding clastic sediment, respectively. Evaporite here consists of three phases: halite with a viscosity of 10^{19} Pa s, and frictional-plastic mixed evaporite deposited before and after the halite. Our model captures many of the features characterizing the central Red Sea, including: depth-dependent stretching with decoupling at the base of the upper crust; a thick evaporite package overlying pre-evaporite sediments or thinned continental crust; halite deposition preceded and followed by mixed evaporites; flow of halite towards the distal margin; post-halite sedimentation (mixed evaporites) that sinks into halite and retains a portion of halite at the mid margin (e.g. Mohriak and Leroy, 2012), and; thinning of salt towards the rift axis (Ligi et al, 2012).

Conclusions

1. During rifting diachronous stretching of the crust is reflected in equivalent diachronous stretching and faulting of the overlying sediments, leading to sag basin type deposits cut by a series of abandoned seaward-dipping normal faults, with faults in the most distal region having been active most recently.
2. Timing of salt deposition, relative to rifting, impacts the distribution of salt across the margin pair, and leads to distinct salt tectonics styles. Later salt deposition favors lateral flow and expulsion of salt towards the rift axis. The addition of prograding sediments further mobilizes salt for all deposition times considered, and facilitates the development of more complex structures, including expulsion rollovers and diapirs.
3. The location and style of deformation of salt in the central Red Sea can be approximated by deposition of a two-phase evaporite succession (halite and a frictional-plastic mixed evaporite) during the mid and late syn-rift period.
4. Mobilization of syn-rift salt may commonly occur as a result of extension of the underlying crust with margin-scale gravitational gliding and spreading only occurring later in the salt tectonic evolution.

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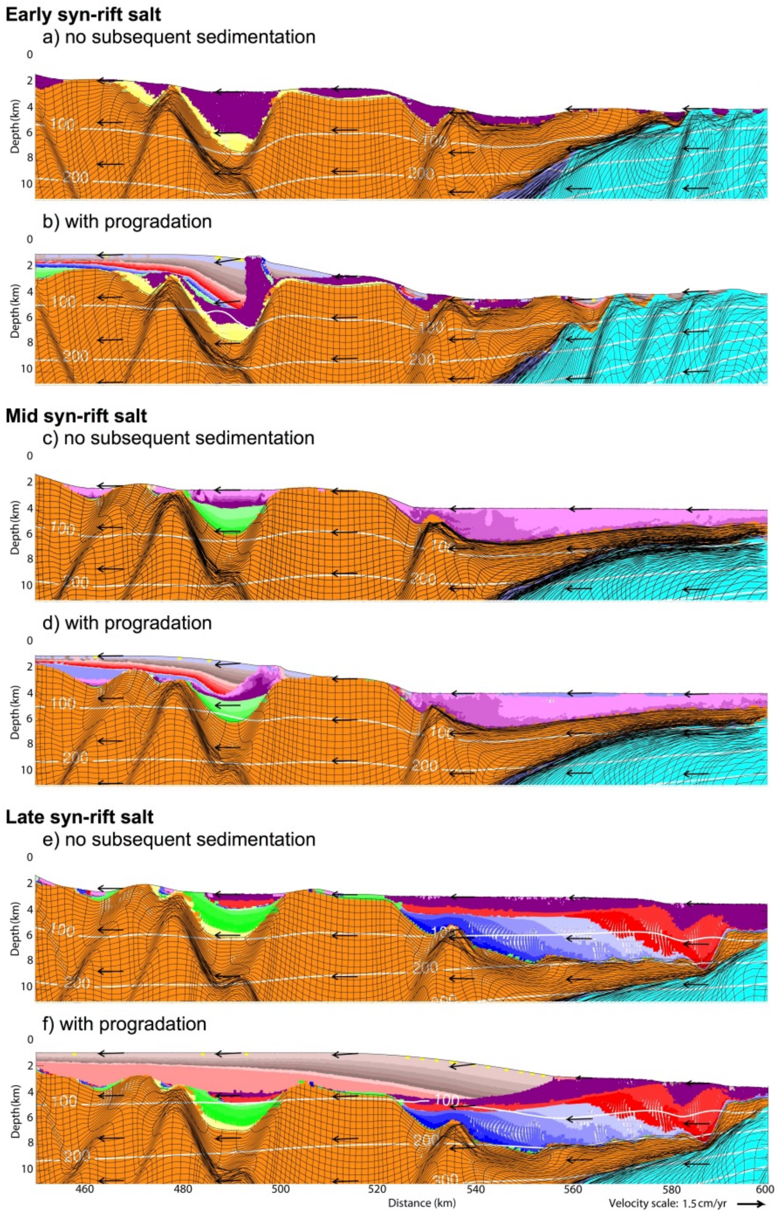

Figure 2, Left: Impact of timing of salt deposition relative to rifting, and subsequent sedimentation, on the distribution and deformation of salt, showing the left margin. Salt deposition is shown for the early (a, b), mid (c, d) and late (e, f) syn-rift periods, with and without prograding sediments following salt. All panels show model configuration after 31 Myr model evolution. Continental crust is orange, oceanic crust is light blue, salt is shades of magenta, and clastic sediments have a rainbow colouration: sand, green, blue, red, pink, and grey, deposited in this order. Vertical exaggeration is 4:1.

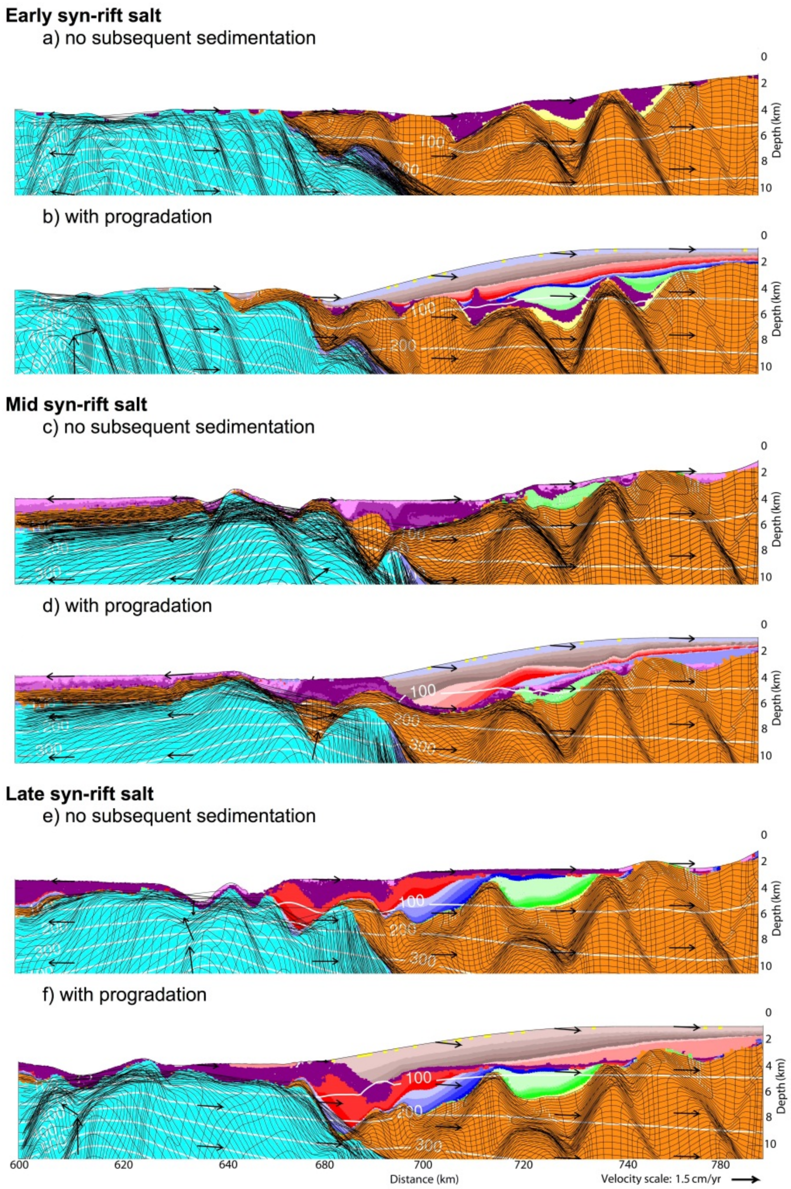

Figure 2, Right: Impact of timing of salt deposition relative to rifting, and subsequent sedimentation, on the distribution and deformation of salt, showing the right margin. Salt deposition is shown for the early (a, b), mid (c, d) and late (e, f) syn-rift periods, with and without prograding sediments following salt. All panels show model configuration after 31 Myr model evolution. Continental crust is orange, oceanic crust is light blue, salt is shades of magenta, and clastic sediments have a rainbow colouration: sand, green, blue, red, pink, and grey, deposited in this order.. Vertical exaggeration is 4:1.

Architecture of West Gondwana prior to the South Atlantic opening in the Rio de Janeiro-Benguela transform zone

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We present here an up-to-date structural configuration of the Gondwana break-up locus, prior to the transform opening between Rio de Janeiro (Brazil) and Benguela (Angola) margins. The evolution and the merging of the different terranes or domains, as well the main sutures and physical discontinuities inheritances are discussed in the Cretaceous break-up scenario.

Introduction

Over the last 20 years, the onshore basement of southeastern Brazil has been the focus of detailed geological mapping with concurrent structural, petrological, geochemical, geochronological studies. A new conception of post Brasiliano/Pan-African orogenic event configuration is presented based mostly on primary data. The database is represented by detailed geological and geochronological works on the Brazilian side, as well as extensive data search from the African side. The integration of such dataset allows the comprehension of the most important mega-structures that make the connections between SE-Brazil-SW-Africa.

Parts of the ties that bind this correlation are covered into the present day passive margins. Also, the amount (under discussion) of the lithospheric stretching during the rift and post-rift phases is still controversial. In order to address this open question, we attempted to draw these main terranes before the break-up, considering not only the boundaries mapped on the onshore area, but also the internal structure of these terranes and the evaluation of stretching rates of different portions along the continental margins, as well as the Continent-Ocean-Boundary (COB) position.

Basement configuration (Brazilian Side)

Before presenting our final results, it is also important to stress the underbalanced dataset on both sides of South Atlantic. The geochronological data (mainly Rb-Sr and U-Pb) point to the major tectonic episodes recorded on onshore basement rocks (Carvalho *et al*. 2000): Lunda-Cuango-Malanje (~2900 Ma), Jequié (Malange-Andulo - ~2500 Ma), Transamazonian-Eburniean (2200-1800 Ma), Kibaran (1500-1300 Ma), Brasiliano-Pan-African (860-500 Ma), Cape Fold belt (330-280 Ma).

On the SE-Brazilian side, Paleoproterozoic rocks with minor Archean inheritance acted as the basement to the Neoproterozoic passive margin basins. Both associations underwent a long and complex period of deformation, metamorphism and magmatism, known as the Brasiliano cycle/event. Three cratonic blocks were preserved from the Brasiliano reworking, São Francisco, Luis Alves and Paranapanema cratons. On the other hand, the margin of the cratonic blocks was involved in different episodes of the Brasiliano Event at ca. 630-605; 605-585 and 535-510 Ma, resulting in deformation, metamorphism and granitic magmatism (of predominant granitic composition – Heilbron *et al*. 2013). The collision episodes resulted from the docking of microcontinents and magmatic arcs that travel from E to eastern border of the São Francisco margin. The Brasiliano metamorphic overprint varies from greenschist to granulite facies from NW to SE, across the Ribeira belt, and from SW to NE, along the Ribeira belt, suggesting a differential uplift across and along its length.

Three major orogenic systems were developed as the result of the Brasiliano convergence: Brasília belt, Araçuaí-Ribeira belts and Don Feliciano belt.

Three cratonic areas, São Francisco, Luis Alves and Paranapanema cratons, remained relatively unaffected by the Brasiliano orogenic cycle deformation and magmatism. Brasilia belt developed between the Paranapanema and São Francisco cratons in the central southeast of Brazil. It has developed as a typical crustal-scale nappe pile, with vergence to the east. In contrast, the Ribeira belt between Luiz Alves craton, Paranapanema and São Francisco cratons, displays quite a different structural style. The Ribeira belt evolved from low angle subduction (?) through a series of continental collisions and accretion of a sequence of magmatic arcs from NW to SE (younger). Luis Alves craton was thrust over the Ribeira belt. A mega-shear zone (suture) marks the former zone of subduction which evolved into steep and locally transpressive mylonitic zones.

Basement Megastructures (Inheriteance)

The aforementioned mega-shear zone can be traced from the south, where it appears from beneath the undeformed Paleozoic sediments of the Parana basin and continues parallel to the southeastern coast of Brazil for over 1000km towards Espírito Santo State, where the structure bifurcates. Older thrust/transpressive shear zones continue towards the north, along the margin of the São Francisco craton, while the younger shear zones carry on to the coast, passing through the south of Vitoria, and continuing offshore. This mega-shear zone separates the São Francisco craton/Brasilia belt/Paranapanema system from the Luiz Alves/Costeiro/Cabo Frio terranes, and it was intermittently active for at least 100My, between 630Ma and 530Ma.

This important NE-SW trending structure can be found at least two places towards the E-W direction, disappearing beneath younger sediments and seawater. The first, near Peruípe, SE São Paulo State, and the other in Espírito Santo State, near Guarapari. At both locations the E-W strike of shear zones, tectonic foliation and lithological boundaries are oblique with respect to the coastline.

The African Side

On the African side, a large portion of Angola and Namibia are underlain by Archean-to-Neoproterozoic rocks, undeformed in the cratonic areas (Congo, Angola and Kalahari cratons) and deformed and with varying degrees of metamorphism within the Pan-African orogenic belts West-Congo, Kaoko, Gariep and Damara). An integrated Geological map of SE-Angola and NW-Namibia (Figure 1) was produced here based on the published material 1:1M scale maps extracted from the geological surveys of the respective countries. Not only this publication on Geology, but also some regional geological maps, as well as sketches from academic articles have been used in this study. There is also additional information from published radiometric ages. Field data was locally collected in SW-Angola coast and central Namibia.

The geological reliability of this integrated map, particularly within Angola, is not as high as the map of SE Brazil geology, in which more recent (and bigger scale) maps are available. However, the map is accurate enough in order to fulfil the purpose of this study. In the northern part of Angola thrusting has placed_the West-Congo belt over Archean basement of the Congo craton to the East. This N-S trending limit of the West Congo belt, parallel to the Angolan coastline was truncated by the E-W trending Malange Horst east of Luanda. Towards the south of Luanda and the Malange Horst, the geology is dominated by Archaen-to-Paleoproterozoic rocks of the Angola Craton. In SW Angola, close to the Angolan-Namibian border, and in Central Namibia, the transpressive Kaoko belt (Goscombe *et al*. 2003) and the Damara belt, respectively, have been thrust onto the Angola craton. The Angola Craton is separated from the Kalahari Craton by the E-W trending Damara belt, which includes tectonically reworked basement of the Angola Craton.

The Gondwana Break-Up

Any correlation between the basement geology of SE-Brazil and SW-Africa must take into account that part of the continental crust is located offshore, where it is often buried under sediments of the marginal basins on both sides of the Atlantic Ocean. Nevertheless, several geometrical/ geographical observations and geological comparisons can be made. There is a remarkable difference between the physiography of the South Atlantic coastlines towards the north and south of Cabo Frio High. Towards the north, the coastlines are oriented approximately SSW-NNE, suggesting rifting/opening of the Atlantic perpendicular towards the two margins. In contrast, to the south, they suggest oblique/opening and result in 700km of the Brazilian coastline, with an E-W to ENE-WSW until Paranaguá, east of Curitiba city, Paraná State.

Kinematic indicators and the geometry of geological structures within onshore basement rocks of Rio de Janeiro State and along the Benguela Coast in Angola indicate that extension began as orthogonal rifting during the early stages of break-up (Jurassic – 190-147Ma), before changing to an oblique rifting (transtensional tectonics) during the Eo-Cretaceous, that was facilitated by tholeiitic magma injections in an en-echelon array. South of São Paulo State triple junction, Ponta Grossa-Guapiara (PGDS) and Florianópolis (FDS) tholeiitic dike swarms indicate that the extension was in two directions NE-SW (PGDS) and E-W (FDS).

Correlation between Rio de Janeiro and Benguela margins

When considering that the Cabo Frio terrane was separated by rifting from the Benguela basement rocks we can suggest that the Cabo Frio terrane was part of Angola Craton. In addition, when considering that the Cabo Frio terrane and the Luis Alves craton overlie the Ribeira belt, it is proposed that the "missing" highly extended continental crust is, predominantly, a Paleoproterozoic cratonic area, which formerly formed part of the Luis Alves-Angola Cratons and the Cabo Frio terrane. This implies that Dom Feliciano, Kaoko and Gariep belts occupy two arms of the triple junction, with the Damara within the third arm.

In summary, two major basement features -Malange Horst in the north and Luis Alves-Bentiaba basement high in the south - controlled the geometry of Gondwana break-up and shaped the present day SE Brazilian and SW African (Angolan) coastlines. This implies that the embayment along Parana (PR)-Santa Catarina (SC) coastline, between Pontal do Paraná and Joinville-SC, corresponds to the headland west of Tombua, and along the southern Angolan coast (Figure 2). Finally, it is assumed that a considerable part of the Luis Alves-Angola craton was stretched and dismembered, forming the basement of the marginal-offshore Santos Basin.

Acknowledgements

We would like to express our gratitude to the Tektos Group (UERJ) and Petrobras for supporting the authors and their research. We are also grateful to Romário Mota and Gabriel Castro for the enlightening discussion about the Espírito Santo and Benguela Geology.

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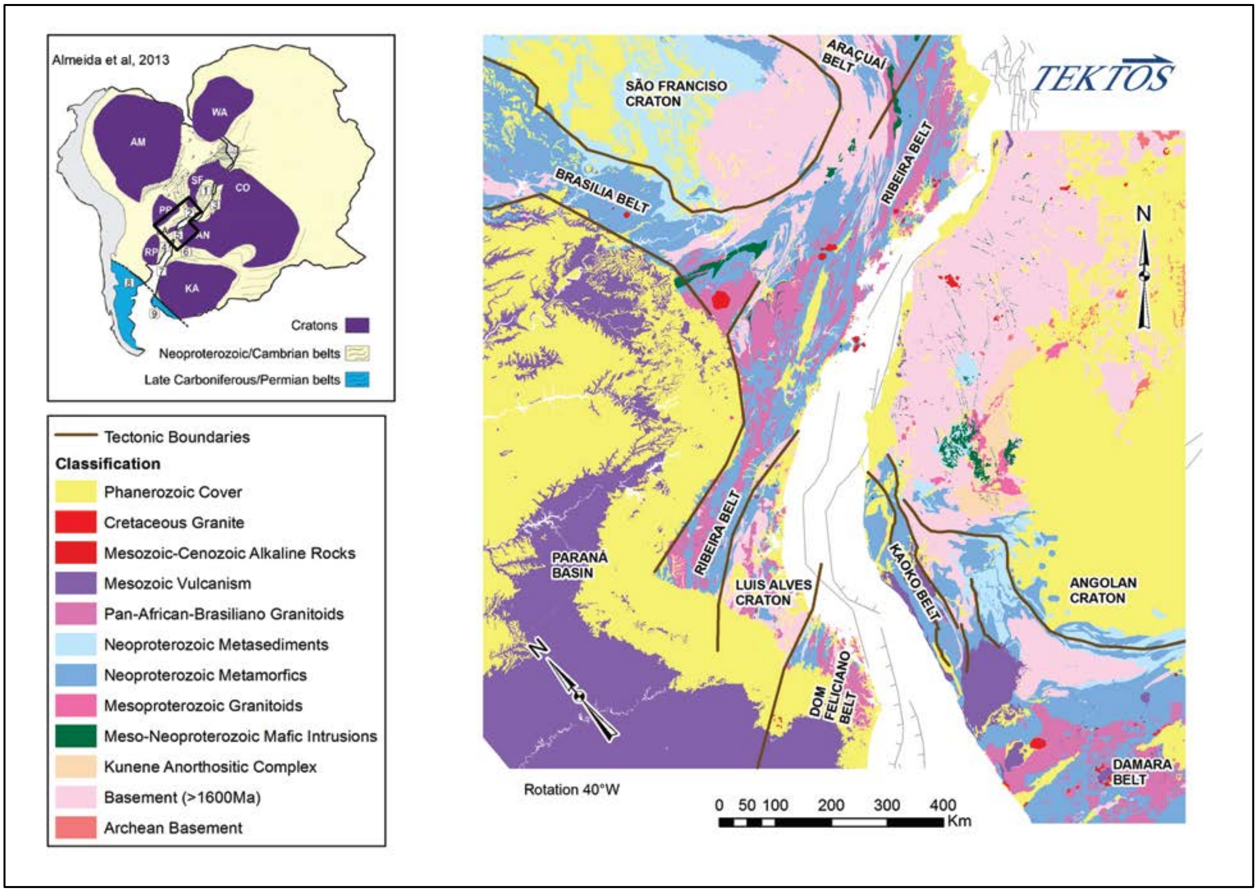

Figure 1: Palinspatic reconstruction of Western Gondwana, focused in Rio de Janeiro-Benguela (Angola) regions. Notice the assymetry of the distribution of the geological terranes: in the Brazilian side, Ribeira belt (Faixa Ribeira) predominates metasedimentary and magmatic (magmatic arcs and intrusives granites) rocks, while in the African side, the Angola craton is exposed and acts as basement of the mesozoic basins.

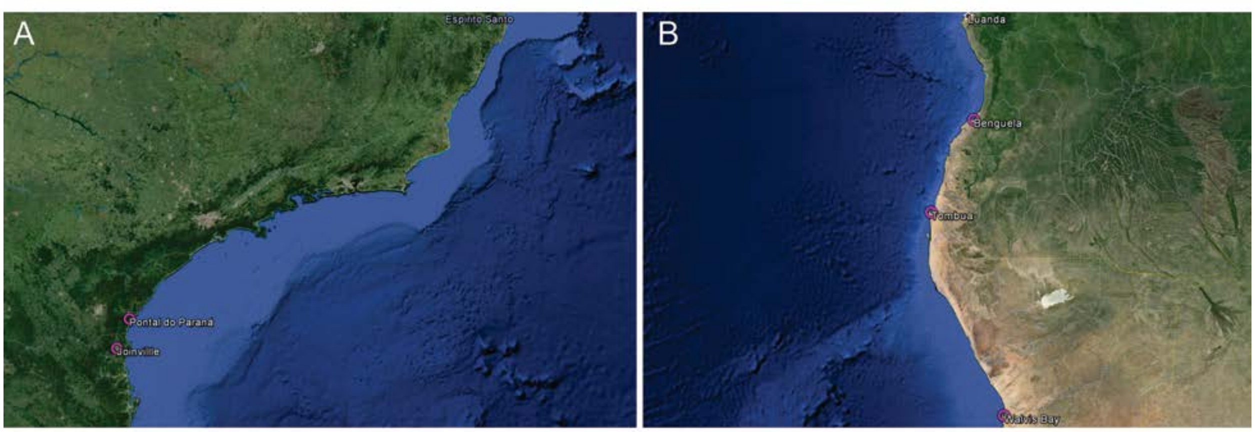

Figure 2: Satelite images (Google Earth) with localization of cities cited on text. Out of scale, North up.

Evidence for hyper-extended continental crust in the East Orphan Basin from seismic reflection data and potential field forward modelling and inversion

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Summary

In 2012 and 2013, PGS, TGS, and Nalcor Energy undertook a large-scale survey to acquire a network of regional long offset 2D seismic reflection and gravity profiles (22,500 km) across the East Orphan Basin, Flemish Pass Basin and Flemish Cap. Seismic interpretation of these lines has revealed regionally-extensive, thick sedimentary basins that can be subdivided into rift and post-rift megasequences. To aid in the seismic interpretation of the top of basement beneath these megasequences, 2D forward modelling of the coincident gravity data was undertaken using the boundaries of these megasequence packages as constraints and representative constant densities for each package. Assuming constant densities for the crust and the underlying mantle, the base of the crust (Moho) was then adjusted to fit the observed gravity data along each line. Insights obtained from the gravity modelling were subsequently used to update the seismic interpretation. Using these complementary geophysical datasets with this iterative approach, clear evidence for an extensive NE-SW-trending zone of hyper-extended continental crust (< 10 km thick) has been identified in the East Orphan Basin. The existence and spatial distribution of this zone was previously predicted based on extreme stretching factors, beta, obtained from regionally constrained 3-D gravity inversion work using satellite gravity data. This zone of hyper-extended crust appears to correlate spatially with overlying Cretaceous fans that exhibit AVO anomalies, suggesting that their evolution may be linked.

Study area

The East Orphan Basin lies at the northeastern edge of thinned continental crust of the Newfoundland and Labrador margin, immediately to the northwest of the Flemish Cap (Fig. 1). The basin was formed and subsequently reactivated during three main rifting episodes that occurred during the Triassic, the Late Jurassic to Early Cretaceous, and the Late Cretaceous. These rifting episodes were oriented roughly NW–SE, W–E, and SW–NE, respectively, resulting in complex faulting within the basin. The sediments of the Orphan Basin overlie basement terranes that were stitched together during the closing of the Iapetus Ocean during the Caledonian-Appalachian orogeny in Paleozoic time. The original Mesozoic opening of the basin occurred along the pre-existing basement structures and tectonic fabrics from the Caledonian-Appalachian orogeny (Shannon, 1991).

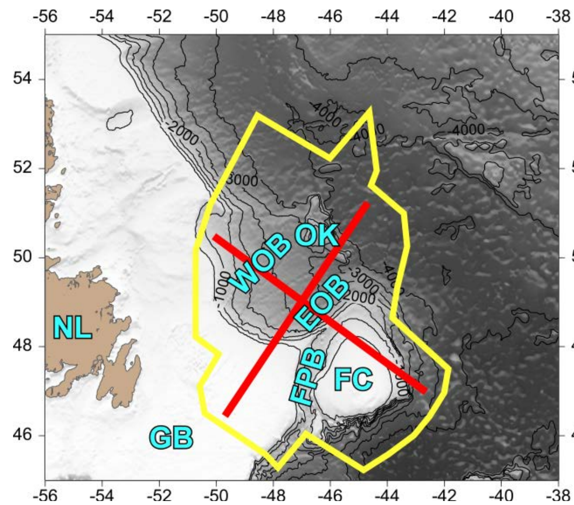

Figure 1: Bathymetric map of offshore Newfoundland and Labrador. The broad outline of the seismic and gravity survey is shown in yellow. The thick red lines show the main orientations of seismic reflection and gravity data profiles. Abbreviations: EOB – East Orphan Basin, FC – Flemish Cap, FPB – Flemish Pass Basin, GB – Grand Banks, NL – Newfoundland and Labrador, OK – Orphan Knoll, WOB – West Orphan Basin.

Data acquisition

Regional long offset 2D seismic reflection and gravity profiles were acquired by PGS, TGS, and Nalcor Energy in 2012 and 2013. A total of 57 lines were acquired resulting in a total coverage of 22,500 km. Lines were oriented either NW–SE or SW–NE and varied in length from 115 to 719 km. In addition to a number of sparsely distributed regional lines, a dense concentration of seismic and gravity lines was focused on the East Orphan Basin and the Flemish Pass Basin. TGS performed the seismic reflection data processing in time and also performed the Bouguer correction of the acquired gravity data (Fig. 2).

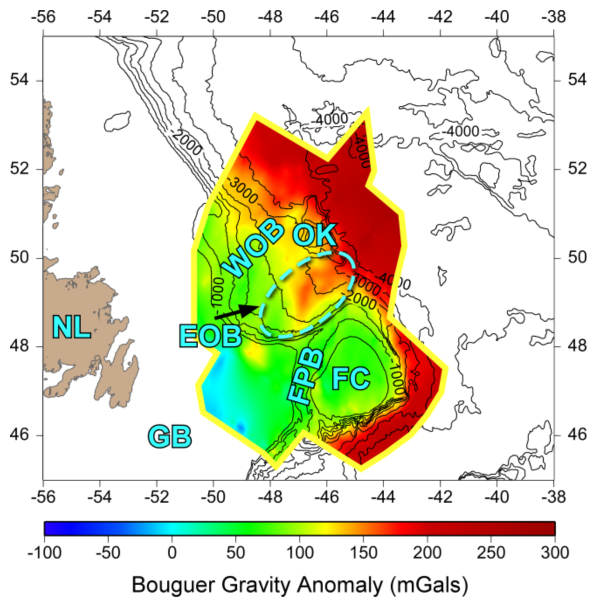

Figure 2: Bouguer gravity anomaly data interpolated across all the 2D profiles. The broad outline of the seismic and gravity survey is shown in yellow. The East Orphan Basin is highlighted with the dashed turquoise oval. Abbreviations are defined in the caption for Figure 1.

Seismic interpretation

Interpretation of the processed time sections from the seismic reflection survey was undertaken at Nalcor Energy with the goal of identifying the main boundaries that subdivided the large sedimentary basins into rift and post-rift megasequences. These boundaries corresponded to the top of basement and the top of the Cretaceous sediments. Interpreting the top of basement was complicated by the complexity of the imaged rifted structures as well as the poorer data quality at depth. Gravity modelling was thus undertaken to reduce uncertainty in the seismic basement pick.

Gravity modelling

In order to construct density models based on the time sections, the horizons were converted to depth using constant velocities for each megasequence. The velocities used in the depth conversion were 1450, 2500, and 2700 m/s for the seawater, the post-rift sequence, and the rift sequence, respectively. Once the depth of the boundaries had been determined, density models were constructed using constant densities of 2200, 2500, 2700, 2870, and 3300 kg/m^3 for the seawater, post-rift sequence, rift sequence, crust, and mantle, respectively. As the Bouguer data were used for the modelling, the seawater density corresponded to the reference density of 2200 kg/m^3 used for the Bouguer correction by TGS. A constant density was assigned to the entire crust for lack of available regional density constraints.

The gravity modelling was undertaken using the GM-SYS Profile Modelling software from GeoSoft Inc. Preliminary gravity modelling was done assuming that all of the interpreted sedimentary horizons were correct and that the depth conversion placed the boundaries at their true depth. The Moho, or base of the crust, was the only part of the model that was adjusted in order to fit the gravity observations. Suspect regions were flagged wherever the crust was effectively pinched out or where no adequate fit could be achieved without altering the sedimentary interpretation. For these regions, the seismic interpretation was re-examined and, if geologically reasonable and consistent with the seismic data, adjusted to better agree with the gravity data. The density models were then updated to reflect the new seismic interpretation. Through several iterations of seismic interpretation and gravity modelling, final density models were developed for all of the seismic lines in the survey (Fig. 3).

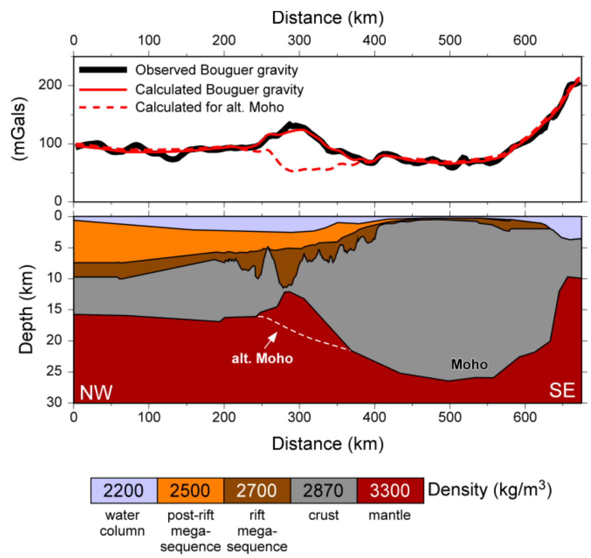

Figure 3: Density model (bottom) based on the seismic interpretation of key stratigraphic boundaries on a NW–SE oriented survey profile, with corresponding observed and calculated Bouguer gravity anomalies (above). To highlight the need for pinching out the crust, an alternative Moho was picked for comparison and the resulting calculated anomalies are plotted with the dashed lines.

The final density models provide basement and Moho depth constraints across the study area. These constraints are consistent with the observed gravity and with the seismic reflection sections. In many instances, the density models revealed Moho depths that were consistent with coherent reflections on the depth converted seismic sections (not shown in abstract). Without the gravity modelling, these coherent reflections could have been erroneously interpreted as sedimentary or crustal structures when they likely correspond to the base of the crust.

Crustal thickness

Once the depth to basement was sufficiently constrained using the seismic reflection data and the gravity modelling, the modelled base of the crust was combined with the depth to basement in order to determine the crustal thickness across the survey area. Along many seismic lines across the

East Orphan Basin, despite shallowing the basement as much as possible to allow for more high densities from the crust to contribute to gravity highs, the Moho also had to be brought up to a shallower depth to provide enough mass from the mantle into the model to satisfy the gravity observations (Fig. 3). Toward the northeast limit of the East Orphan Basin, several of the profiles even required two zones of mantle upwelling to reproduce the observed gravity anomalies.

By combining the modeled results from all of the individual density models, zones of hyper-extended continental crust were identified and correlated across multiple seismic lines, revealing extensive zones of hyper-extended continental crust in the East Orphan Basin (Fig. 4). Such zones had been previously postulated based on derived crustal stretching values, beta, from regional constrained 3D gravity inversion work over the same area using satellite gravity data (Welford *et al.*, 2012; Fig. 5).

The map of crustal thicknesses derived from the individual 2D forward modeled gravity lines shows a zone of hyper-extended continental crust running along the axis of the East Orphan Basin that branches into two zones toward the northeast (Fig. 4). These zones and their branching character show a remarkable correlation with the locations of Cretaceous fans identified on the basis of AVO anomalies. These fans tend to align themselves with the northwestern limit of the hyper-extended zones and even line up with the northwestern limits of the two branches of hyper-extended crust to the northeast. These results suggest a linked evolution between the hyper-extension of the continental crust in the East Orphan Basin and the local emplacement of Cretaceous fans, which requires further study.

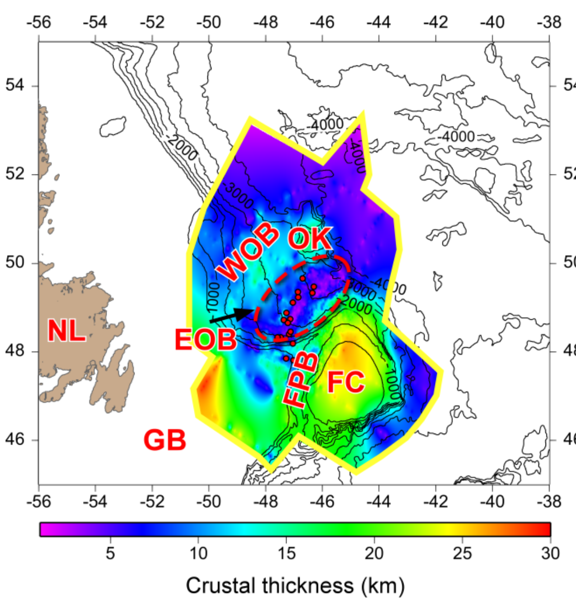

Figure 4: Crustal thickness derived from the seismically-interpreted basement and gravity-modelled Moho boundaries. The broad outline of the seismic and gravity survey is shown in yellow. The East Orphan Basin is highlighted with the dashed red oval. The small red circles correspond to Cretaceous fans inferred from AVO anomalies in the seismic reflection data. Abbreviations are defined in the caption for Figure 1.

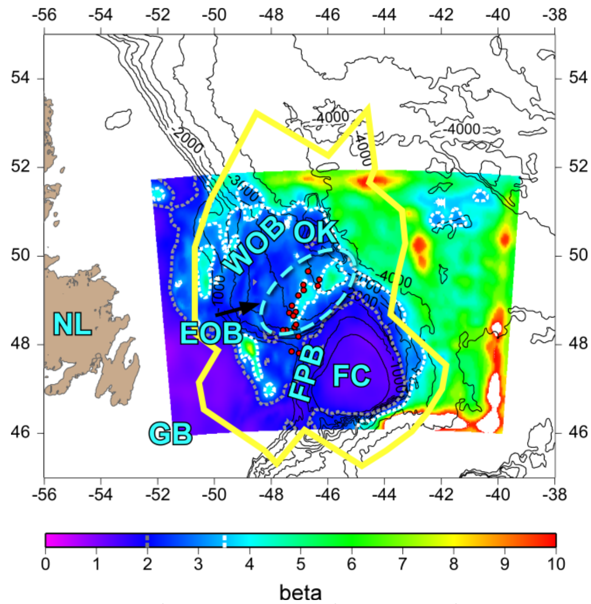

Figure 5: Map of crustal stretching factors, beta, from a regional constrained 3D gravity inversion (Welford *et al.*, 2012). Dashed grey and white contours correspond to meaningful beta thresholds for the presence of polyphase faulting (Reston, 2007) and the possibility of embrittlement of the whole crust (Pérez- Gussinyé & Reston 2001; Pérez-Gussinyé *et al.* 2003), respectively. The broad outline of the seismic and gravity survey from this study is shown in yellow. The East Orphan Basin is highlighted with the dashed turquoise oval. The small red circles correspond to Cretaceous fans inferred from AVO anomalies in the seismic reflection data. Abbreviations are defined in the caption for Fig. 1.

Conclusions

Zones of hyper-extended continental crust have been identified across the East Orphan Basin using an iterative approach of seismic interpretation and 2D forward gravity modelling. The main zone of hyper-extension follows the axis of the East Orphan Basin and branches into two zones toward the northeast. The northwestern limits of these core and branched zones line up with Cretaceous fans identified on the basis of AVO anomalies, suggesting a linked evolution.

This study demonstrates the importance of combining seismic interpretation with gravity modelling in order to increase confidence in the seismic interpretation and ensure that the derived Earth models are consistent with all of the available geophysical information. Without the use of the gravity modelling in the East Orphan Basin, many deep reflectors that we can now recognize as crustal or from the Moho, could have been erroneously attributed to sedimentary structures. A broader understanding of the crustal implications of the seismic interpretation of sedimentary basins can provide greater insight into the tectonic and thermal evolution of a basin or an entire margin.

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The Late Carboniferous Ross Sandstone of Western Ireland: Deepwater insights from Behind Outcrop Drilling

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The Ross Sandstone is one of the most visited deepwater systems on earth due to easy access and perceived high analog potential for many oil and gas exploration targets and development projects. Ross outcrops span the Shannon River Estuary and Atlantic coast of SW County Clare, Western Ireland. Deposition was from a continental scale drainage and within a relatively small, Late Carboniferous intra-cratonic basin experiencing rapid, early post-rift thermal subsidence and high frequency-high amplitude changes in relative sea-level.

In 2009 the research drilling commenced behind the Ross Sandstone outcrops and by 2012 twelve wells had been completed with >1,350m (>4,400ft) of core recovered. The new core and associated petrophysical data are in various stages of evaluation and research is being coordinated by Profs. Peter Haughton and Patrick Shannon at the University College of Dublin, Ireland. Funding is combination of Government and Private grants in Ireland and Statoil ASA. The key objective of the coring program has been to enhance the education and training experience of visiting the Ross outcrops and particularly in their use as subsurface analogs. The Ross deepwater system is a particularly valuable analog for many Atlantic Margin deepwater reservoirs.

Research on the earliest acquired Ross cores has reached a relatively mature stage with a first PhD candidate expected to graduate in 2014. Recent acquired cores are still being processed and evaluation is still in provisional stages via a variety of graduate projects at UCD and TCD, Ireland. However, some early lessons have come into focus and have provided excellent topics for oral and poster presentations at regional and international meetings. This presentation will review some of these findings and context them in our evolving understanding of deepwater sedimentology and stratigraphy and within an historical Ross Sandstone Formation context.

Some of the sedimentology insights revealed by the cores include the following:

- event types, lithofacies and consequently processes are more variable than expected.
- fine-grained lithofacies, in particular, are brought in to sharp focus via the cores with much more gravity flow muds and less hemipelagic/background sediments than expected.
- distribution of event bed types seems to track stratigraphic position and prompts comparisons with similar new insights originating from recent evaluations of subsurface deepwater systems.

Stratigraphic lessons and new understanding includes:

- recognition of higher frequency condensed intervals than the existing outcrop and regional Upper Carboniferous frameworks document.
- an evolution of the Ross system that contrasts with all pre-drill stratigraphic models.
- a long-term vertical distribution of event beds that reflects intra-basinal controls and severely overprints the shorter, glacio-eustatic forced cyclicity of the Late Carboniferous.

Challenges in Exploring for Abrupt Margin Deep water Turbidite Plays in the Atlantic Conjugate Margin

John R. Dribus,
Schlumberger

Since the discovery of the Jubilee abrupt margin turbidite field in the deep waters of Ghana, and the confirmation of the play across the Atlantic in French Guiana and equatorial Brazil, much exploration activity on both sides of the Atlantic has been, and is now being focussed on further exploration of this emerging play. Appraisal of some recent discoveries has also raised important questions about why some of these amplitude-supported basin floor fans are hydrocarbon charged, while others are only partially charged or barren.

This presentation begins with a brief overview of the geological evolution and key characteristics of the Jubilee basin floor fan discovery. Then, a series of seismic dip oriented lines is utilized to tour around the African deep water margin beginning in Morocco and Senegal, then working down through Namibe Basin, Angola, and then on to Orange Basin, Namibia, and then around and northeast to Mozambique examining some of the unexplored and undrilled potential.

In this process, ten key challenges/risks that have been identified during this past year of exploration and appraisal drilling of this play are identified and discussed.

Seismic sections from the Jubilee Field area are utilized to discuss whether or not turbidite sheet traps are primarily stratigraphic in nature, or if a structural component is needed to increase trap integrity. Data from the Jubilee area, and also from the Kilcloher Cliff Section in Ireland, are utilized to raise the question of inadequate internal seals in massive sand reservoirs within high gradient amalgamated basin floor fan systems.

A section from Morocco is then examined to demonstrate the difference between layered pelagic ductile shale and brittle chaotic turbidite shale. The impermeable ductile lithology may play a significant role in limiting migration into prospective reservoirs, while the brittle, less clay-rich facies of the turbidite system may fail as an adequate top seal, allowing hydrocarbons to escape the trap over time.
Then, a dip section through the Sud Profond Block offshore Senegal is utilized to discuss the issue of whether seismic amplitude reflection anomalies always serve as direct indicators of the presence of hydrocarbons (DHI's), or are simply an indicator of porous clastic reservoir rock encased within impermeable pelagic mudstones.

Visual attribute blend displays from the Namibe Basin, Angola showing possible fluid effects are viewed to discuss the risk of on-lapping beds and up-dip pinch-outs as adequate stratigraphic traps for commercial hydrocarbon accumulations.

Moving south, an examination of several seismic amplitude reflection anomalies from Orange Basin, Nambia are viewed to discuss the effectiveness of various thicknesses of overburden rock in containing commercial hydrocarbon columns. The tour ends in the Save Basin, Mozambique where sections are viewed to demonstrate concerns that recent extensional faults that run to or near the sea floor may function as leaks that allow tertiary migration that could jeopardize turbidite trap integrity.

The presentation then summarizes these nine key risk factors described during the tour around the African margin, and then concludes by moving westward, across the conjugate margin to the Americas, and recognizes the importance of adequate clastic sediment supply to form amalgamated reservoirs in the abrupt margin areas.

The final point of the presentation is that there appear to be many transform margin exploration opportunities remaining along the Atlantic margin, particularly offshore Colombia. Perhaps, there may even be a few along the Pacific margin as well.

Hydrocarbon prospectivity along the Atlantic Margin: New results from petroleum system modeling in the Rockall Basin

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Introduction

The Rockall Basin is a rift basin located on the North Atlantic passive margin, west of the UK and Ireland (Figure 1), and considered to be a deep-water frontier basin with only limited heritage seismic and well control. Exploration in the last decades mainly focused on the shallow regions of the continental margin such as in the West of Shetland region. A few discoveries on the eastern margin of the Rockall basin point to working hydrocarbon systems; however, the presence of extensive Paleocene basalt lava successions in some places complicates data interpretation of pre-Tertiary strata and structures. We present a 2D regional model that quantifies and evaluates the individual petroleum systems, burial history, thermal evolution as well as generation, migration, accumulation, and preservation of hydrocarbons.

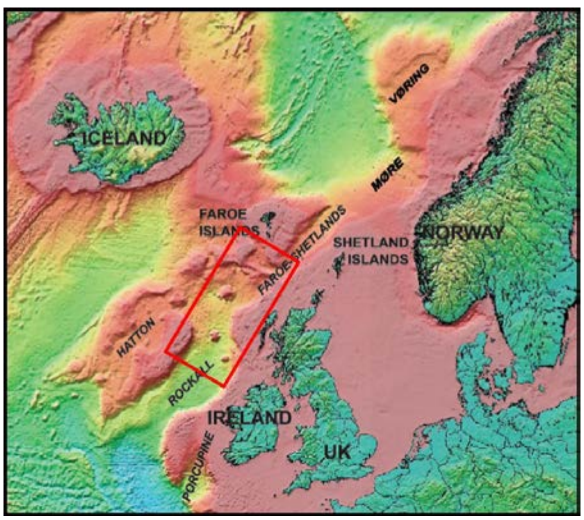

Figure 1: Topography and bathymetry map of the NE Atlantic Margin indicating deep-water areas with underlying rift basins (from Shannon et al., 2005). The study area is highlighted.

Regional Geology and Stratigraphy

During the last two decades, numerous publications have improved the understanding of the tectono-stratigraphic evolution of the Northeast Atlantic Margin and allowed prediction of individual phases of extension and thermal subsidence and the related development of source and reservoir rocks, and trap styles (Naylor and Shannon, 2011; Ritchie et al., 2011; Hitchen et al., 2013; and references therein).

Following the Caledonian orogeny, the area was affected by several rift events during Permo-Triassic, Jurassic, and Cretaceous time. Paleogene extension was associated with extrusion of widespread flood basalts and sill emplacement. Miocene compressional tectonics resulted in uplift and erosion, the formation of anticlines and inversion along earlier extensional faults.

Principal source rocks were deposited in the Early and Middle Jurassic and Late Jurassic/Earliest Cretaceous (Kimmeridge Clay Formation). Reservoir rock deposition was mainly controlled by erosional events related to footwall uplift during rift episodes or tectonic inversion during compressional events. The most important seal rocks are represented by Cretaceous and Tertiary mudstones. Thick Cretaceous and Tertiary successions provide sufficient burial required for source rock maturation (e.g., Ritchie et al., 2011).

Petroleum System Modeling

We applied petroleum system modeling on an 800-km-long regional 2D seismic section into which we integrated geological and geochemical information. The section extends from the Solan Basins (West of Shetland region) across the Northeast Rockall Basin towards the Southern Rockall Basin in Irish waters (Figure 2).

We integrated the southwestern part of West of Shetland into this study because the absence of Paleocene basalts in this region allowed for a more detailed analysis of Mesozoic and Paleozoic play types, and since well information helped i) to calibrate the thermal history, ii) to tie horizons for depth conversion, and iii) to constrain the model with successful and exploration targets (e.g., Strathmore) or dry holes. For the Rockall Basin we included conceptually pre-Tertiary successions with structures and depth ranges based on literature (Hitchen et al., 2013; and references therein).

We evaluated uncertainties, including thermal history including the impact of magmatism and amount and timing of erosion on source rock maturation, ii) presence, depth and properties of source rocks in the deeper undrilled parts of the basins, iii) sealing capacity especially of Tertiary strata, and iv) effect of timing and properties of faults on hydrocarbon charge.

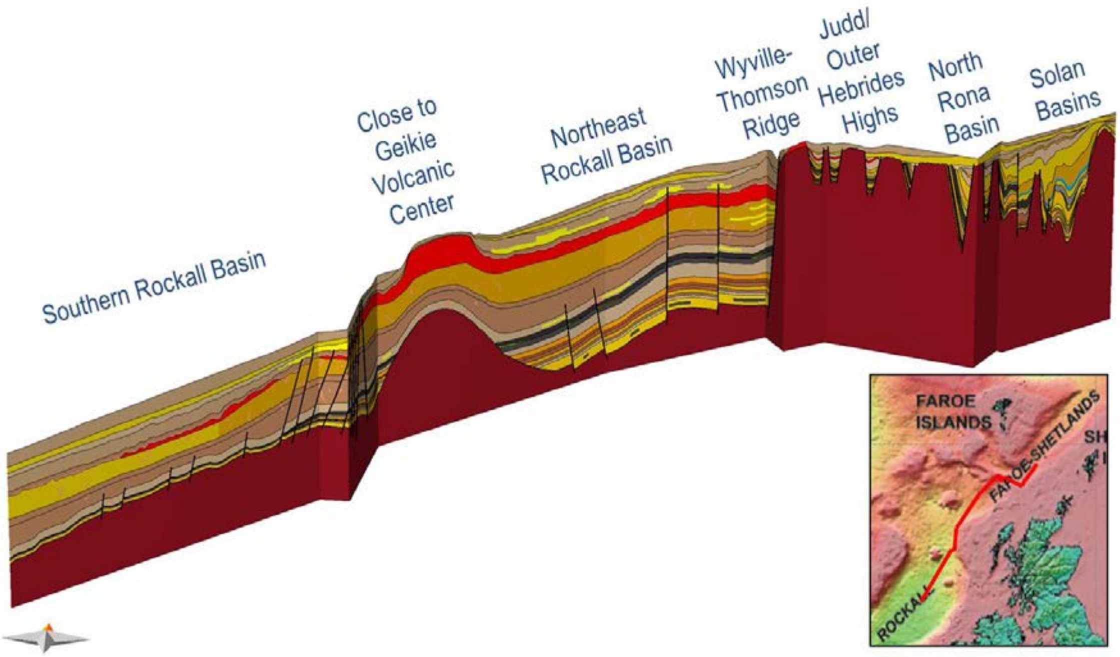

Figure 2: 3D view of 2D petroleum system model section (with facies overlay). Red layer represents successions of Paleocene flood basalts.

Thermal history and timing of source rock maturation is still under debate, especially whether the relatively low maturity values result from unanticipated low heat flow even during rift periods or from overpressure-induced retardation of aromatization reactions during rapid Paleocene burial (see Carr and Scotchman, 2003, and references therein). We thermally calibrated our model for the Solan Basin and simulation results indicate that for this area Jurassic source rocks started to generate during Late Cretaceous (mainly due to massive Campanian to Maastrichtian burial). Because of the lack of calibration data in the Rockall Basin we used the Solan Basin basal heat flow trend as the base case for the Rockall area. We tested several scenarios with geologically reasonable shifts of basal heat to evaluate the timing of source rock maturity. In addition, we studied both the impact of Paleocene flood basalts and the influence of sill emplacement on source rock maturity and hydrocarbon generation.

We analyzed two petroleum systems in the Rockall Basin—Jurassic-Mesozoic and Jurassic-Paleogene—and evaluated the key exploration risks for each system. For the margin of the Rockall Basin and the central part of the Northeast Rockall Basin our model predicts Jurassic source rocks to be in the oil window at present day. Hydrocarbon generation from the Upper Jurassic Kimmeridge Clay Formation equivalent started during Late Cretaceous but sharply increased during Paleocene (Figure 3). This sharp Paleocene increase in hydrocarbon generation was also observed in scenarios with generally reduced basal heat flow trends as well as without consideration of Latest Cretaceous/Paleocene heat flow peak, indicating that thick Paleocene burial (sediments and basalts) is the key parameter for source rock maturity and hydrocarbon generation. Model results show that the flood basalts rapidly cooled at the surface and thermally affected only the adjacent Lower Paleocene sediments. Deeper Jurassic source rocks are not affected by these basalts along the modeled section. This is different from the sills that were mainly emplaced in Cretaceous and Lower Paleocene sediments. These intrusive bodies cooled over a longer period of time and locally matured older Mesozoic strata.

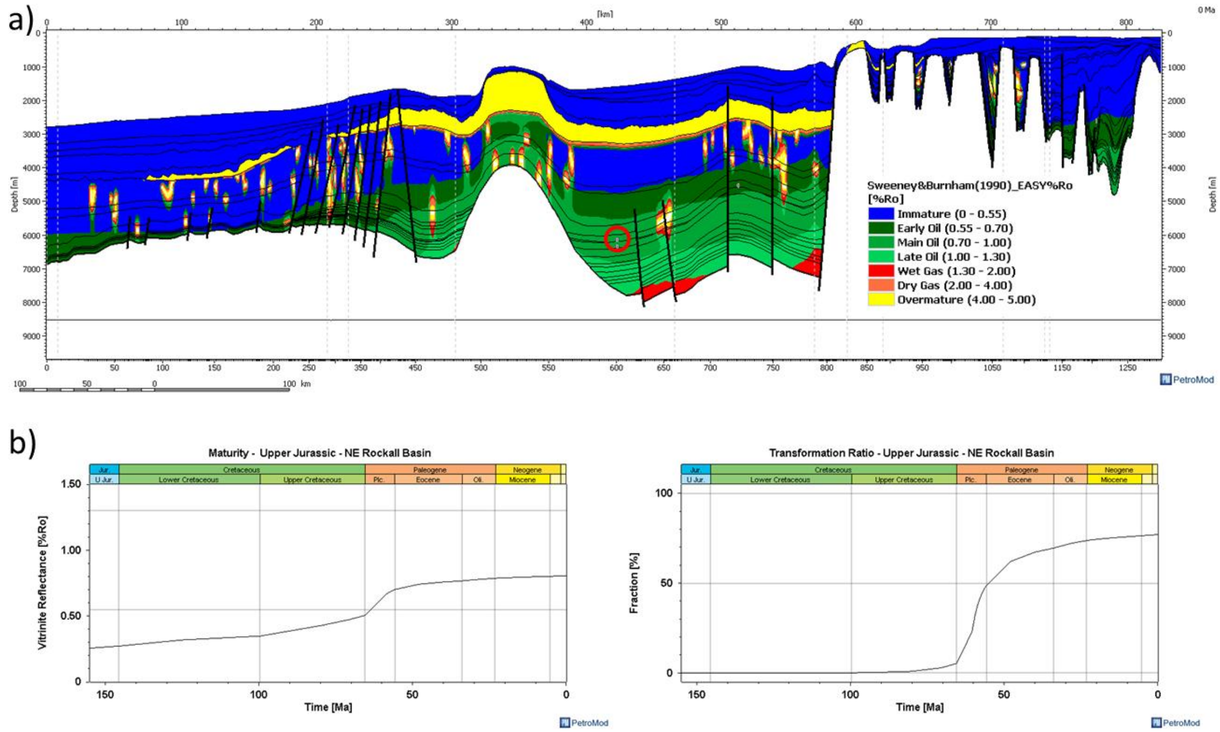

Figure 3: a) Predicted maturity along the 2D section. Note the minor thermal effect of the flood basalts on underlying Paleocene strata. The sills as subsurface emplacements, however, have greater impact on thermal maturity of adjacent sediments; b) time extractions for thermal maturity and transformation ratio of Upper Jurassic source rock from the basin center of the NE Rockall Basin (see red circle in [a]) for location of extractions).

Mesozoic plays are associated with rift-related, rotated fault blocks below Cretaceous sediments. Timing for this Jurassic-Mesozoic petroleum system is favorable because trap formation and sufficient sealing preceded petroleum generation and migration from potential Jurassic source rocks regardless of geologically reasonable variations in basal heat flow (Figure 4). Exploration risks are mainly related to presence and properties of source and reservoir rocks.

Tertiary plays are represented by Paleocene basin floor fans and Eocene fan deposits (Figure 4) in combination stratigraphic structural traps sealed by Tertiary mudstones. Thick Cretaceous strata and—where present—Paleocene basalts complicate charge and migration from potential Jurassic source rocks; faults, however, show the potential for fluid migration. A potential exploration risk is also related to sealing capacities of the Lower Tertiary mudstones.

Conclusions and Outlook

This petroleum system modeling study along the Northeast Atlantic Margin in UK and Irish waters provides the latest geological framework to assess the hydrocarbon prospectivity in this prolific deep-water province. Going forward, new acquisition and processing techniques now offer the ability to image beneath the Paleocene basalt layers as well as to define the major fault patterns and other structural elements of the deeper basin for the first time. This application of new technology promises to enhance our knowledge of the hydrocarbon systems and significantly reduce the exploration uncertainty and risk in this underexplored region.

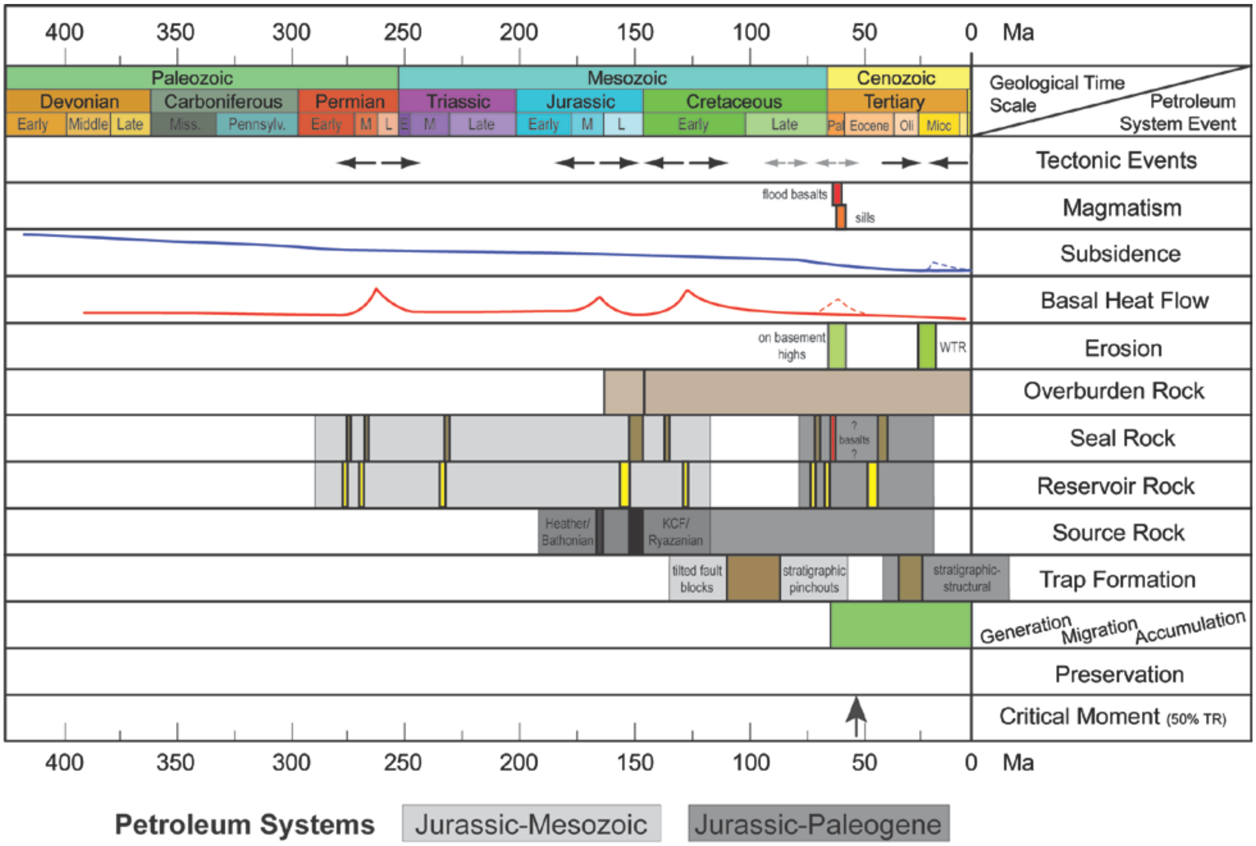

Figure 4: Petroleum system event chart for the Jurassic-Mesozoic and the Jurassic-Paleogene petroleum systems in the NE Rockall Basin and along the eastern margin of the Rockall basin.

Petroleum system modeling results show that for the Rockall Basin thick burial of latest Cretaceous and Paleocene strata controls maturation of Jurassic source rocks regardless of geologically reasonable variations in basal heat flow. Thus, most hydrocarbon generation occurs during a short period during the Paleocene after formation of Mesozoic traps. Paleogene targets also show promise in areas with working seal rocks.

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Producing pore pressure profiles based on theoretical models in un-drilled deep-water frontier basins e.g. Labrador

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Introduction

World-wide, prospectivity has been proven in deep-water and discoveries made. Examples include Gulf of Mexico and West Africa. A frequent problem remains however, that is, these new plays have little if any well calibration therefore making assessment of risk on all levels, problematic.

A classic example is offshore Labrador where there are a number of wells drilled to-date on the shelf, in a series of basins such as Saglek and Hopedale, and a proven hydrocarbon system is present, however, there is no well penetration in deep-water. Recent seismic data has highlighted the presence of deep-sea fan complexes in this deep-water that by analogue with similar features in other basins (Lower Tertiary, Wilcox in the Gulf of Mexico, the Nise Formation in the Vøring Basin) are petroliferous so reservoirs are likely present. Also by analogue, deep-water environments are shale-prone (Figure 1) lithologies and therefore stratigraphic traps can be expected i.e. reservoirs encased in thick shales. The use of analogues for Labrador was highlighted in a recent conference paper by Green et al. (2013).

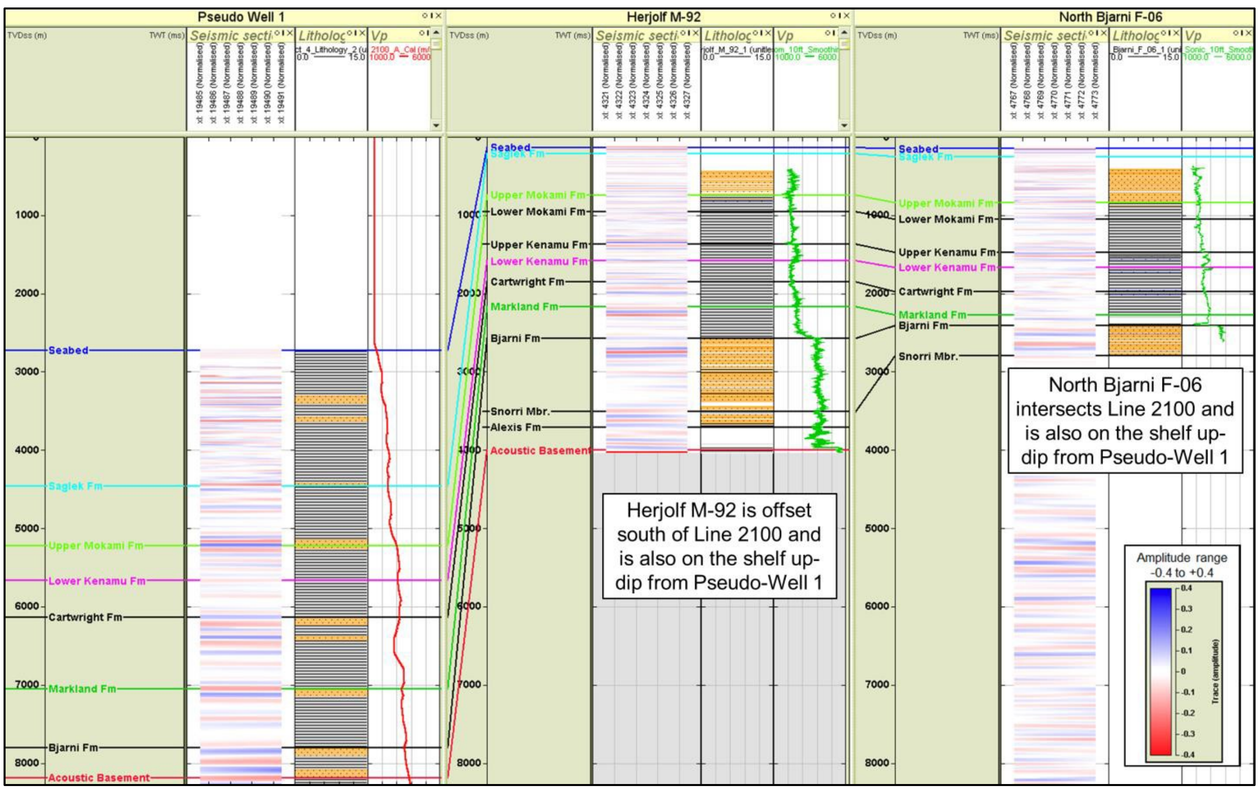

Figure 1: Reflectivity with interpreted lithology and extracted velocity for the shale-rich, deep-water TPP 2 and shallow water sand-prone offset wells North Bjami F06 and Herjolf M-92.

Once a prospect has been identified in the deep-water, the next stage is to de-risk this. One of the key components of this process is to use knowledge of the pressure regime to ascertain (a) the risk of top seal integrity from mechanical seal risking and (b) the drilling window (the fracture pressure minus the pore pressure), if this is too narrow then potentially a prospect is too risky/expensive to drill. Without any well calibration to estimate the likely pressure regime, (a) and (b) become very difficult and/or inaccurate.

To help reduce the risk in these unexplored environments we present in this paper several approaches that can be adopted to model pore pressure in deep-water settings, not just in Labrador, but globally. This theoretical or "geological modelling" approach can then be used to sense-check the pore pressure interpretation from seismic velocity.

Pore Pressure Modelling: Key Stages

Constructing a vertical profile for pressure in the deep-water involves several stages.

1. As lithology has such an influence on the pressure regime, the likely lithology in the deep-water must be understood. Interpretation of lithology is achieved partly from use of seismic reflectivity data and partly from analogue with other deep-water settings.

2. Reservoirs often have very different pressures to their associated shales. They can be lower via lateral drainage (O'Connor et al, 2008) or higher by a process termed lateral transfer (Yardley and Swarbrick, 2000). If the sands are stratigraphically or structurally isolated, they will have the same pressure as the surrounding shales.

3. Models for shale pressure must be produced. Modelling of shale pore pressure in frontier locations is approached using seismic velocity data, often the only data type available, as well as using ages of seismic markers to calculate rates of sedimentation and linking these rates via published datasets in Swarbrick (2012) to produce shale pressure.

4. Many studies of pore pressure assume that rapid vertical loading by sediment and incomplete dewatering of shales, termed disequilibrium compaction, is the only cause of overpressure build up. In fact, other processes such as fluid expansion and load transfer can decrease effective stress and increase pore pressure. These processes occur where shales, dependent on composition and age, are heated such that clay diagenesis and thermal maturation occur.

Therefore in construction of a pressure prediction in frontier regions, these four elements need to be considered and/or incorporated.

Pore Pressure Prediction

As mentioned above there are two principle data types available for predicting the magnitude of shale pore pressure in frontier areas; seismic interval velocities and geological modelling. Seismic data allow for the quantification of the interval velocities but still require a normal compaction trend (or "NCT") from which pore pressure magnitudes can be generated. Geological modelling links the expected facies, i.e. marine shales or basin-floor sands, and structure, based on seismic reflection interpretation, to the expected behaviour of pore pressure within each package.

For shales, the technique highlighted here is termed the Swarbrick or Fluid Retention Depth (or "FRD") model. This based is based on several papers originally proposed by Swarbrick et al. (2002) and more recently Swarbrick (2012) which refined the approach with a larger dataset. All data are of Tertiary age thus the technique is only suggested to be applicable to Base Tertiary. The technique is based on using the rate of sedimentation (from seismic markers) and the shale-type i.e. clay or silt rich (from the facies model), linked together via an empirical dataset to estimate the depth below sea-floor at which overpressure begin to build parallel to the overburden; this is termed the FRD.

In new areas if a key marker, i.e. Base Tertiary (Top Markland in Labrador), can be identified from seismic at a new deep-water prospect location such as the one shown in Figure 1 (Pseudo-Well 1) then the sedimentation rate for that prospect can be estimated. Note that the sedimentation rate is calculated on the compacted thickness following the work by Swarbrick et al. (2002). Once the sedimentation rate is known, the dataset from Swarbrick (2012) can be used to estimate the FRD simply by reading off value(s) from the key chart.

To predict the likely pressure regimes in any deep-water reservoirs, the approach is to use analogues from global datasets. In summary, where the net to gross is low as in the case of mud-rich fans, thin isolated reservoirs are developed. As these are low volume, their pressures are influenced by the encasing shale lithology, leading to high pore pressures (e.g. Lange Formation, Mid-Norway; Akata Formation Niger Delta). By way of contrast, where net to gross is high as in the case of sand-rich or amalgamated fans, single thick sand reservoirs are present (e.g. Nise Formation, Mid-Norway; Agbada Formation, Niger Delta; Wilcox Formation, Gulf of Mexico). These sands can drain pressure towards the onshore via feeder channels. In this case, the shales encasing the sands are more highly overpressured and the sands become pressure sinks. The mixed-sand-mud case leads to thick sands that have the ability to be variably drained, i.e. certain portions of the fan can be normally pressured whereas others are at shale pressure.

Evidence from current well penetrations, Labrador

The only truly deep-water wells in Labrador are located in the Orphan Basin. In other basins such as Saglek and Hopedale water depths are shallow. There is little direct evidence for high pore pressure at depth in any of these wells at current drilling depths (often as the sand content is high), however, in Blue H-28 (Orphan Basin) and Pothurst P-19 (shallow water; Saglek Basin) kicks at depth suggest overpressures of 26850 kPa and 34250 kPa respectively. These kicks are associated with permeable units in thick shale packages. These are the type of packages observed in the deep-water from seismic data.

Using the age of the kick in the Pothurst P-19 well (Lower Tertiary), its depth and the Swarbrick (FRD) approach provides a consistent match. The kick in Blue H-28 is Middle-Cretaceous but was taken close to the Base Tertiary unconformity hence has also been tested using this approach with success (Figure 2).

This evidence suggests that the geological modelling approach has validity in the deep-water regions of Labrador to model shale pressure, at least to Top Markland Formation. Of note is that the geological modelling gives a theoretical, maximum shale pressure assuming minimal pressure dissipation. Any unconformities for instance will reduce shale pressure; however, deep-water environments tend to be less affected by uplift and erosion which are the principle causes of unconformities.

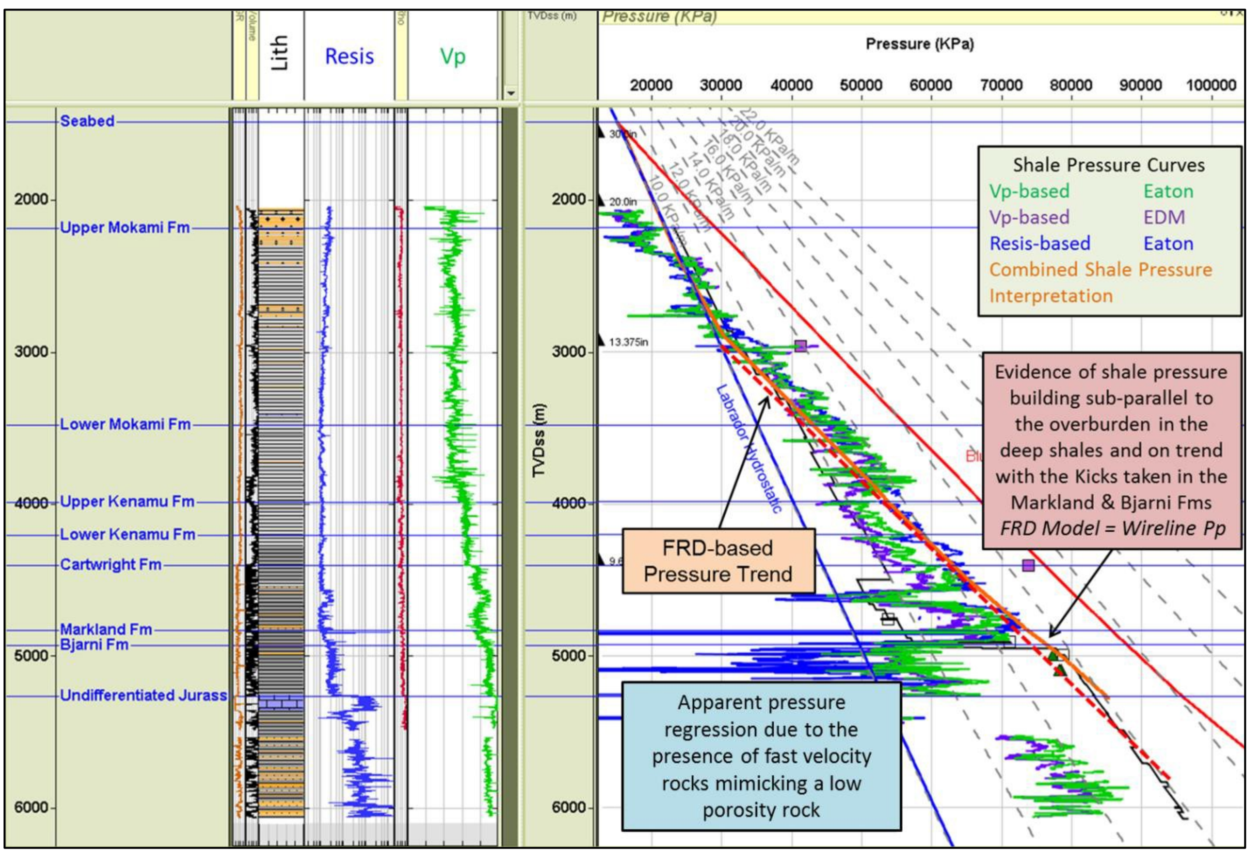

Figure 2: Example of a deep-water well with deep and elevated pore pressure. Shale-based pore pressure predictions from velocity (green/purple) and resistivity (blue) for Blue H-28. Overlain in orange is a simplistic pressure trend from the wireline- based results. The red dashed line is the FRD as calculated showing an excellent agreement with the deep RFT data.

Conclusions

Deep-water settings generally have a series of common features. These features include being shale-prone, having less faulting and less uplift. Evidence for additional mechanisms of overpressure generation rather than disequilibrium compaction is less. All these features all impact the pressure regime, for instance, likely pore pressure regimes in the deep-water are overburden-parallel.

Seismic data from Nalcor Energy has resulted in the identification of new, potentially oil bearing, basins in the deep-water Labrador region. This seismic data has also revealed the similarity between Labrador and basins such as the Vøring Basin in Mid-Norway. In this basin, shale lithology dominate and many reservoirs form stratigraphic traps, where the sands have the same pressure as the shales.

Deep-sea fans are also visible on the seismic. In the case of the these fans, the feeder channel acts as a pressure release value allowing the sands to de-pressurize, creating a mobile aquifer. Similar deep-water hydrodynamic fan systems are reported in the Tertiary of the Central North Sea although present-day water depths are shallow (Dennis et al, 2005), as well as in present-day deep-water plays such as the Gulf of Mexico (Green et al, 2014). In these settings, hydrodynamic trapping, results in tilted fluid contacts. Enhanced seal capacity is also a feature as is primary migration out of source rocks.

The Swarbrick or "FRD" technique is a simple yet powerful method to estimate the likely magnitude of pore pressure in shales within deep-water frontier basins. The distribution of these shales and their associated reservoirs can be derived from use of seismic reflectivity data. The method can allow for operators to recognize high overpressure early in the planning cycle to drill a new well guiding both operations and engineering decisions.

If seismic velocities are present then the geological modelling discussed in this paper can be used to sense-check a pore pressure estimate from seismic velocity data. Care must be taken when using seismic velocity data alone as there are geological reasons for the velocity model to accurately reflect the geology yet fail to reflect the pore pressure, i.e. carbonates which generate fast velocities that mimic low pore pressure but are actually unrelated to the true pore pressure.

Acknowledgements

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A Sequence Stratigraphic and Palinspastic approach to Petroleum Potential of the conjugate margin of North America and North Western Africa

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The Northern and Central Atlantic are enduring areas of interest for petroleum exploration. The exploration history of the margin is varied – the shared geological history of Georges Bank and the Baltimore Canyon Trough on the U.S. Atlantic margin with the petroliferous Aaiun-Tarfaya, Western Saharan Marginal and Mauritanian basins highlights the potential that might be present in the US Eastern Seaboard (currently under moratorium). Proven success offshore Canada continues to ignite interest in the possibilities of the European conjugate margin. Understanding the palinspastic evolution of the Atlantic is critical in order to identify appropriate analogues for frontier areas and to predict the play elements and play types that may be present.

Source rock presence on the North American Atlantic Margin remains one of the exploration risks in the area and can be enhanced by considering analogues from North West Africa and elsewhere on the Atlantic margin. By considering regional and global source rock events within their palinspastic context the timing of these events can be better understood. The mechanism by which organic enrichment occurred and by which organic rich sediments were preserved can also be more accurately modelled when coupled with an understanding of the geodynamic evolution of the margin. A number of potential analogues can be drawn across the Atlantic; The Cap Juby Discovery in the Aaiun-Tarfaya Basin suggests potential for an Early Jurassic source rock event that could be projected to the Northern U.S. Atlantic Margin, in addition to Early Jurassic organic enrichment noted from the Lusitanian Basin and the Moroccan offshore. Synchronous deposition of OAE 1b (Aptian-Albian) and OAE 2 (Cenomanian-Turonian) on both the U.S and African Margins also suggest a wider source rock presence, although thicknesses associated with these events may present some risk.

The widespread development of the Bahamas-Grand Banks Giga Platform during the Middle-Late Jurassic on the U.S. margin is mirrored on the North Western African Coastline acting as a reservoir in the Cap Juby Discovery. Carbonate deposition was then seen to cease on both sides of the Atlantic during the Early Cretaceous with initiation and progradation of clastics manifested in the development of large shelf deltas and turbiditic systems. These are seen offshore Cape Boudjour, Western Sahara and offshore Delaware. The integration of a sequence stratigraphic framework allows the prediction of deposition of key reservoir intervals, both carbonate and clastic, possible on the conjugate margins.

Coastal and Deepwater Sinks of the Northern Gulf of Mexico Cenozoic Margin; Structural and Stratigraphic Controls on Deepwater Fairways

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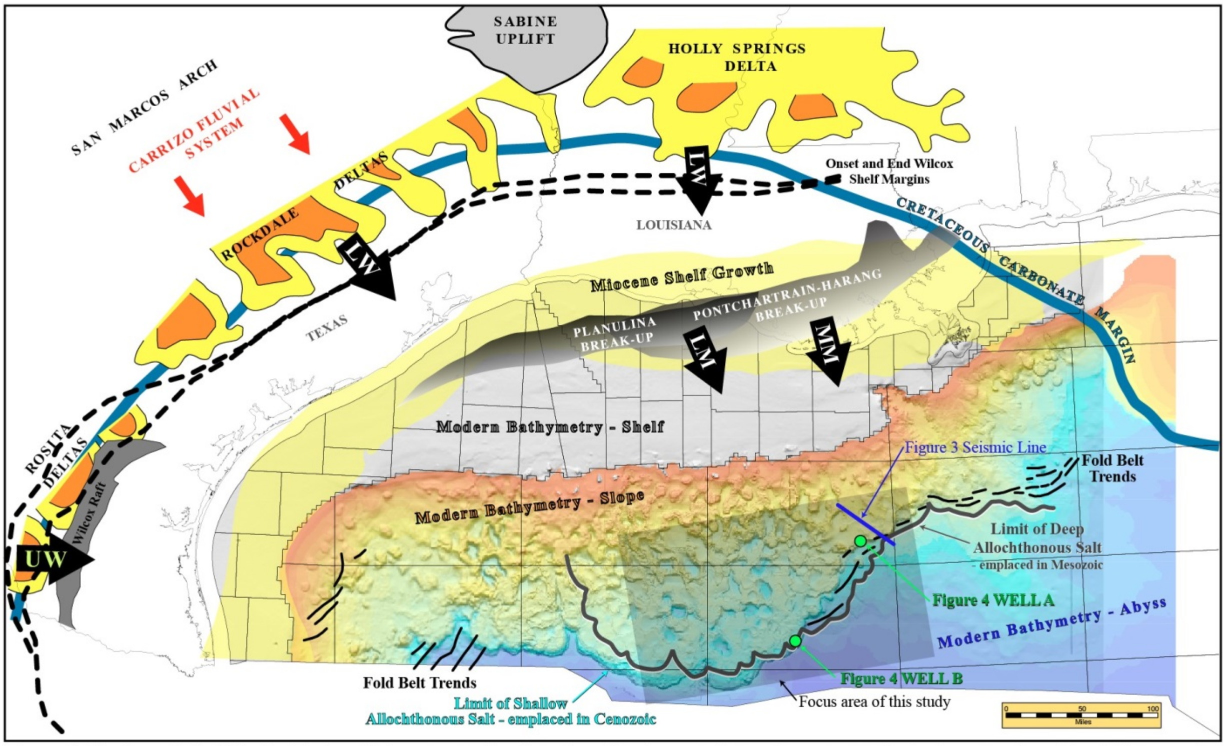

Figure 1: Northern Gulf of Mexico Basin with key structural and stratigraphic elements that are important to the basin center depositional history and petroleum system/s. Key Cenozoic sandy episodes that supplied coarse grained siliciclastics into the ultra-deepwater sectors of the basin are; LW-Lower Wilcox (Late Paleocene), LM-Lower Miocene and MM-Middle Miocene. UW-Upper Wilcox (Early Eocene) sand supply is important on the western side of the basin, but does not extend across the entire focus area of this study. Bathymetry data from NOAA; http://maps.ngdc.noaa.gov
Deepwater fold belts from Rowan et al., 1999; Limit of Mesozoic emplacement allochthonous salt from Hudec et al., 2013; Wilcox deltas from Edwards, 1981 and Glawe, 1995.

Summary

The Cenozoic history of the northern Gulf of Mexico margin has been punctuated by episodes of regional-scale instability in the coastal realms that resulted in conditions that promoted episodic release of copious sands to ultra-deepwater settings down dip. The deepwater settings, especially basin-centered geographies, were well established prior to the Cenozoic and periods of sand supply therefore inherited seascapes that owe their origin to an earlier Mesozoic evolution of post- rift processes, including allochthonous salt emplacement.

This presentation will illustrate the structural fabric of the ultra- deepwater Cenozoic paleogeography's of the northern and central Gulf of Mexico. The reservoir history is placed in context with the structural evolution. Key observations and exportable lessons will be highlighted.

Basin margin instability across the northern Gulf of Mexico has been promoted by tectonic and climate driven periods of extreme sediment supply. The passive margin setting combined with low amplitude and frequency eustatic fluctuations during most of the Paleogene and Neogene are conditions that promoted high stability thresholds for coastal sinks. These thresholds were inevitably exceeded and catastrophic margin collapses resulted. The regional effects of these episodes were felt across the Gulf of Mexico basin and the basin- centered stratigraphy, recently drilled, records exquisitely the details of coastal realm history.

Mapping of key stratigraphic surfaces show the pre-existing paleogeography's inherited by reservoir systems in the Paleogene and Neogene. Modern seismic images document the complex interactions between salt movement and sedimentation. Deep water fields and recent discoveries will be shown in this context.

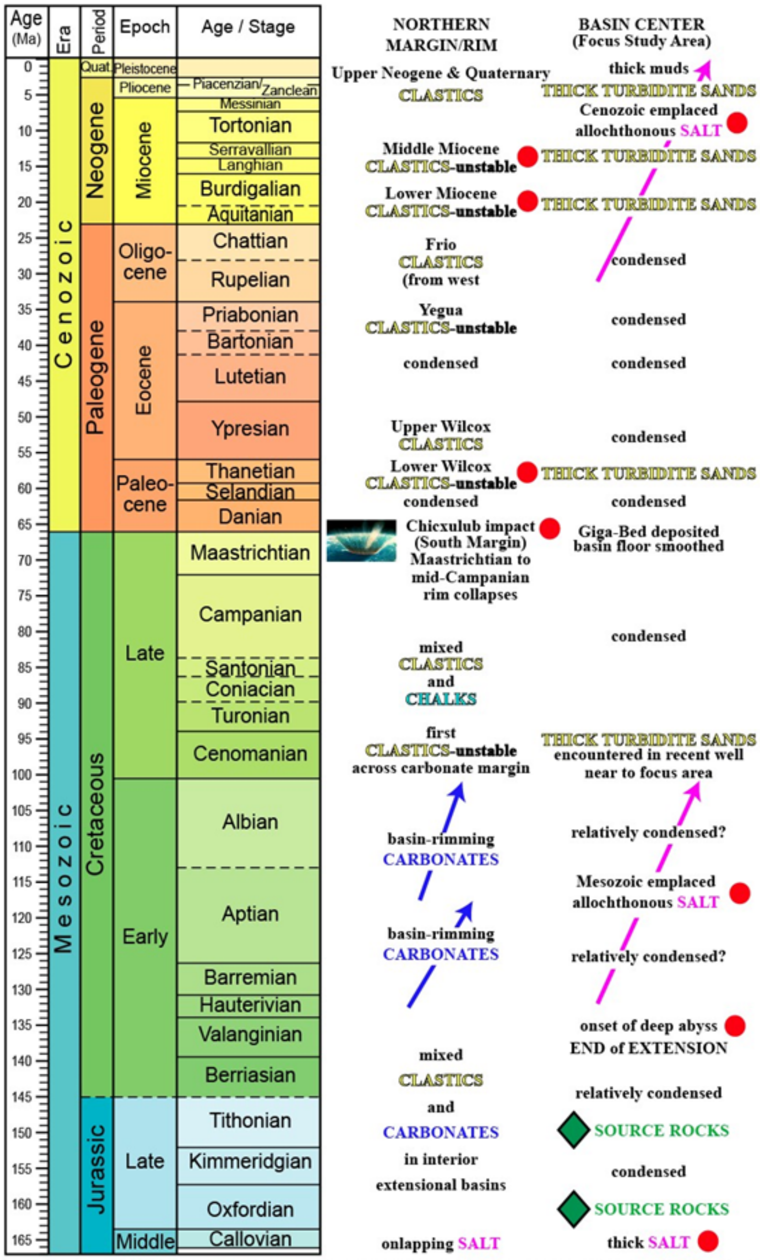

Figure 2: Abbreviated history of the Northern Gulf of Mexico Basin. Key events are marked with a ● and discussed in the text. Time scale from Gradstein et al. 2012.

Tectonic and Stratigraphic History

The key events in the history of the ultra-deepwater Gulf of Mexico Basin are either mapped on Figure 1 and/or highlighted on Figure 2. These events are considered to have contributed most to the stratigraphy and structure recorded in seismic record sections (Figure 3) and recent exploration wells (Figure 4). In stratigraphic order; oldest to youngest, the key events are considered to be:

- Deposition of thick Callovian salt in the early extending basin. This sets the scene for deformation and allochthonous salt during the subsequent Mesozoic and Cenozoic depositional history.
- Maximum rates of subsidence are in the newly created basin center during Jurassic to earliest Cretaceous extension and immediately post-extension. This basin forming episode resulted in a deep basin floor in the region of the focus study area. For the next 135MA this sector of the basin is

the 'catcher's mitt' for gravity driven salt and highest efficiency sediment gravity flows.

- Mesozoic (Early Cretaceous?) movement of salt into and towards the basin center. This period of salt emplacement resulted in bathymetric complexity and future high accommodation for Cenozoic deepest water sediments. Limit of this allochthonous salt (Figures 1 and 3) is at the maximum abyss where the toes of slopes from both north and south converge. Up dip during this period the basin was rimmed by carbonate reefs that aggraded on the limits of weakly attenuated continental crust. This prolonged carbonate-dominated period created a rigid and steep shelf margin that future clastics would negotiate. The first of these clastics are Cenomanian (Figure 2) and thick turbidites of this age have been very recently encountered close to the western edge of the focus study area; possibly a new basin centered, thick system to add to those known from the overlying Cenozoic?

End-Cretaceous impact of a large (10kms diameter) bollide on the southern rim of the basin. This exceptional/extreme event resulted in destabilization of much of the prior 10MA or more of shelf margin and slope deposition, which then relocated into the basin center. The wholesale and regional mobilization of the basin margins created a mega-erosional seascape down into the basin floor where a giga-bed was deposited (e.g. Denne et al, 2013), blanketing prior bathymetric complexity. This catastrophic event sets the scene for the beginning of the Cenozoic; a relatively flat and extensive abyss with a rimming slope that had straight, erosive conduits down into deepest water depths.

The Wilcox clastic supply to the northern basin margin was copious, sandy and driven by Laramide tectonism across the west of the North American continent. The coastal sink/s for these earliest Cenozoic clastics are filled and spilled during the Early Paleocene and a highly unstable basin margin then dominates through the Late Paleocene. High magnitude and high efficiency flows transported huge volumes of sand into the recently created 'Chicxulub' seascape. On the basin floor flows were guided by topography above the shallow-buried allochthonous salt emplaced in the Mesozoic. The regional slopes on the southern and eastern sides of the basin ultimately constrained the depositional limits of this Wilcox mega-fan. Thousands of feet of rapidly deposited sand accumulated in the Early Cenozoic abyss (Figure 4).

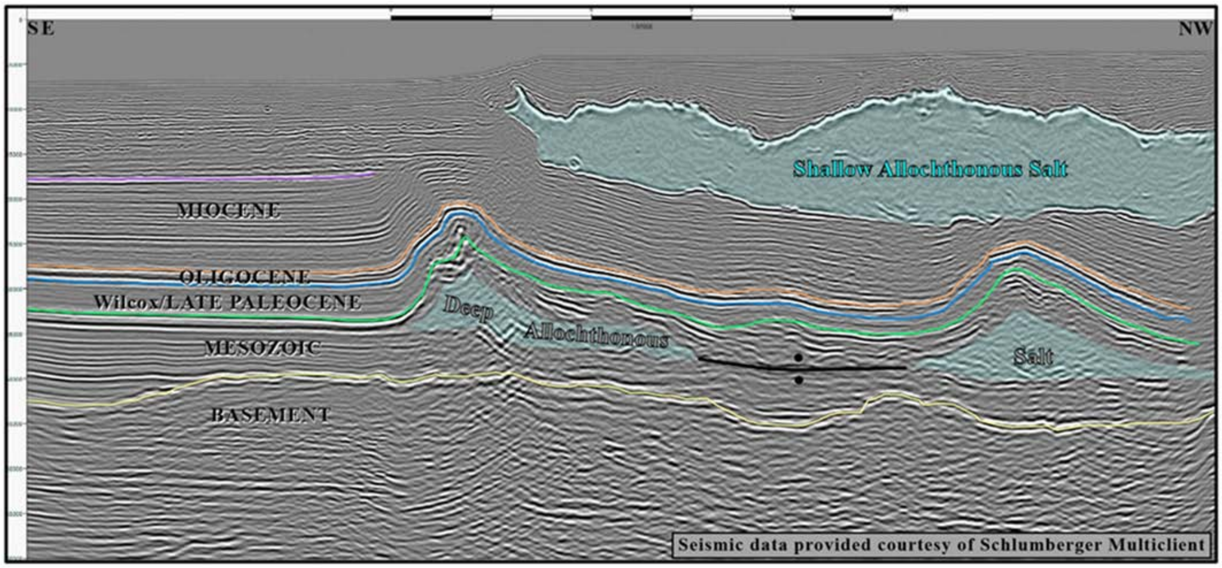

Figure 3: Example seismic reflection data. Location indicated on Figure 1. Salt is Jurassic in age and has extruded from the right of the section during the Cretaceous and also during the Cenozoic; principally during the late Neogene in this geography (see Figure 2). Cenozoic deposition has been rapid and sandy during the Late Paleocene, Early Miocene and Mid-Miocene (Figure 2). In both of the deep structures imaged oil reservoirs are located in the Miocene. Limits of the deepwater sand systems and the allochthonous salts are all in the same abyssal paleogeography, which was established early in the basin history; ~135MA and just after basin formation; post extension. Depth data - to 60,000ft. Scale bar is 15 miles.

At the end of the Oligocene global climate change resulted in an increase in precipitation on the North American continent that was coincident with the establishment of the huge 'Mississippi' drainage basin. A major coastal sink became established on the Louisiana basin margin and subsequent Miocene shelf growth was one of the most rapid in the Cenozoic (Figure 1). The combination of high sediment supply rates combined with an aseismic basin and relatively low amplitude and low frequency glacio-eustatics lead to high instability thresholds being exceeded.

In the Early Miocene (Burdigalian) catastrophic collapse of the margin; the Planulina break-up and subsequent bathyal wedge, lead to huge by-pass of sands into the deepwater (Figure 1). During the early part of the Middle Miocene (Langhian) the coastal sink stabilized.

In the Middle Miocene (Serravalian) a second phase of Neogene catastrophic collapse; the Pontchartrain-Harang break-up and bathyal wedges, lead to renewed huge by-pass of sands into the deepwater settings to the south (Figure 1).

Hundreds of feet of Lower and Middle Miocene turbidite sands (Figure 4) accumulated across much of the central part of the deep basin. Basinward limits to these sands was provided by high accommodation and limits of the allochthonous salt emplaced in the Mesozoic (Figure 3) and the toe of the southern slope of the basin.

The huge coastal sinks and progradation of the northern basin margin during the Miocene (Figure 1) contributed to a new regional and shallow allochthonous salt (Figures 1, 2 and 3). The evolution of this salt canopy ultimately buries the recently deposited ultra-deepwater Miocene sands and it extends, present day, to approximately the same basinward limit of the deeper allochthonous salt emplaced during the Mesozoic (Figures 1 and 3).

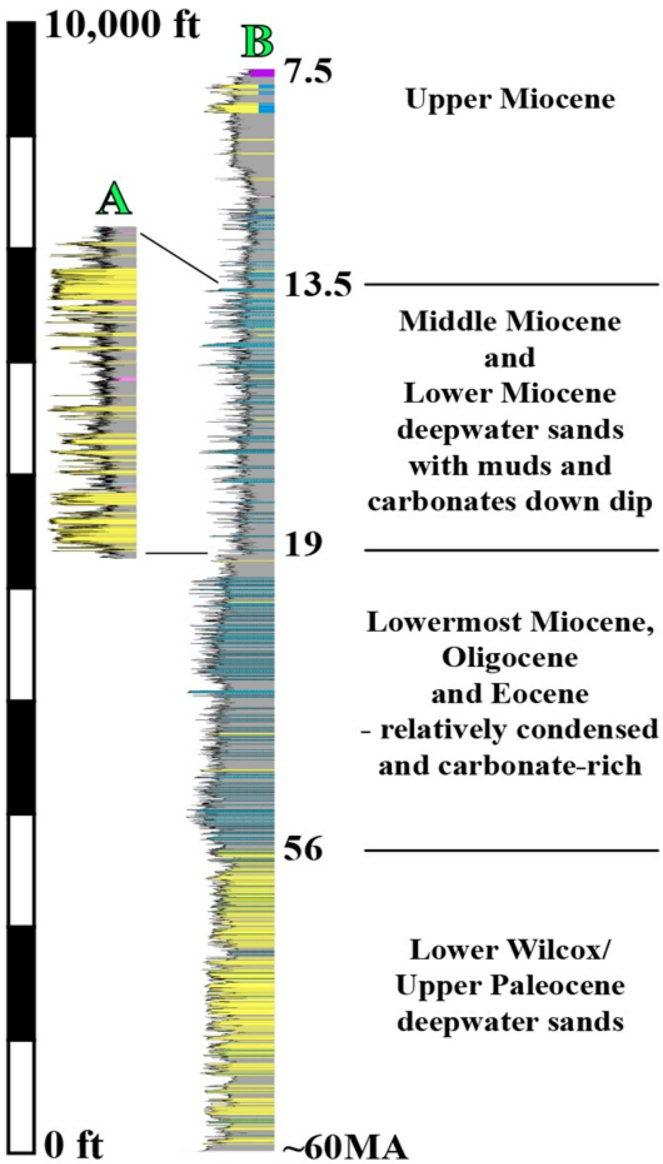

Figure 4: Example well data from study area.
Logs are total gamma. Well locations indicated on Figure 1.

Conclusions and Discussion

The early, extensional history of the northern Gulf of Mexico contrived to establish a relatively narrow deepwater abyss bounded by thick salt in slopes to the north. Mesozoic salt movement emplaced a deep salt nappe into this new abyss with allochthonous limits predetermined by closely spaced north and south continental rises.

The subsequent, largely passive, evolution of the basin margin includes periodic, massive coastal sinks that were unable to accommodate copious sediment supply. Unstable and often catastrophic margin conditions lead to by-pass of sands via high efficiency deepwater turbidite systems into the early established, central basin abyss.

Perhaps underestimated is the importance of the Chicxulub impact at the end of the Cretaceous. This one extreme, basin event reset the regional seascape at a scale that far exceeded the big, but sub-regional Cenozoic margin unstable episodes. Gigantic relocation of basin margin sediments to the basin center broadened and smoothed the prior narrow abyss and created a unique setting into which the later Wilcox sands poured. Thousands of feet of abyssal sand deposition resulted.

Our understanding of the central, deepwater Gulf of Mexico has significant gaps in data. Despite deep wells (>37,000ft TD) there is little known about the pre-Cenozoic stratigraphy. A recent well to the west of our focus study area encountered thick Cretaceous turbidite sands that may link to a Cenomanian unstable, coastal sink. This is only part of 60MA+ of basin history that pre-dates and is equivalent to the length of the Cenozoic history presented in this study. The basin paleo-bathymetry was established before this older episode of deepwater deposition and therefore new sandy deepwater surprises might be in our future.

Acknowledgements

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Seismic stratigraphy of the eastern Scotian Slope: implications for margin stratigraphic and structural evolution

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Two salt tectonic styles dominate the eastern Scotian Slope: (1) a widespread allochthonous salt nappe known as the Banquereau Synkinematic Wedge (BSW; Ings and Shimeld, 2006), and (2) a series of stepped counterregional feeders and associated amalgamated salt canopies to its east. The former developed seaward of an autochthonous salt basin located beneath the outer Scotian Shelf (the Huron Subbasin); the latter formed above and seaward of a primary salt basin located beneath the easternmost Scotian Slope (the southwest Laurentian Subbasin; SWLS). The purpose of this talk is to provide a detailed account of the stratigraphic and structural evolution of the eastern Scotian Slope before, during, and after development of the BSW, and the co-evolution of the SWLS to its east. To do this, we have defined a seven-part seismic stratigraphic framework for Mesozoic and Cenozoic strata on the eastern Scotian Slope. Beginning with an improved understanding of basement structure, we will step through each of these major seismic stratigraphic units and discuss important implications for the structural and stratigraphic evolution of the eastern Scotian margin. Ties to equivalent shelf strata (where borehole calibration is available), coupled with the use of salt contact maps and reconstructed shelf-edge trajectories, allows us to reconstruct the broad-scale history of salt expulsion on the eastern Scotian margin, providing both (a) a clearer picture of the relationship between these two juxtaposed salt tectonic domains and (b) insight into what is driving the abrupt changes in seismic stratigraphy along the eastern Scotian slope.

Plate Tectonics and Organofacies: Mapping Jurassic Source Rock Types and Yields in the Palaeo-Contiguous North Atlantic

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Abstract

The early stages of continental rifting and break-up of the North Atlantic between the late Triassic and Early Cretaceous resulted in the development of sedimentary basins which were episodically connected to, or remained isolated from, oceanic circulation. The source rock geochemistry can imply depositional environments and help understand whether these rift basins were connected to oxygenated oceans, or remained (at least partially) restricted, promoting anoxia and the preservation of organic matter. We use three large geochemical datasets in the Norwegian North Sea, Porcupine Basin and the Grand Banks, together with sparse information from the Morocco, West Iberia and Nova Scotia margins, to compare Jurassic source rocks and estimate potential hydrocarbon yields across North Atlantic conjugate margins in the context of kinematic reconstructions. In the Lower-Mid Jurassic, the combined analysis of kerogen quantity (TOC), type (algal Type I, bacterial-algal Type II or terrigenous plant Type III) and molecular fingerprints (biomarkers), suggests the deposition of a regional, non-marine source rock across the present day Atlantic conjugate margins, in restricted (or partially-restricted) basins in a hypersaline or stratified environment. These rocks are characterized by the presence of Gammacerane, reduced C_{28}/C_{29} steranes and distribution of C_{29}-$C_{34}\alpha\beta$ hopanes in the Porcupine Basin (Ireland), Celtic Sea (UK), Iberia & Morocco and appear to positively correlate to oil/bitumen samples from Nova Scotia and Portugal. In the Upper Jurassic, the North Sea, Jeanne d'Arc and Flemish Pass basins are judged to have remained as restricted based on organofacies, the Porcupine Basin as semi-restricted, while the Rockall Trough and associated West and East Orphan Basin rifts form a more oxygenated link between the Boreal and Central Atlantic seas. In the Jeanne d'Arc Basin, an increase in algal macerals (Type I kerogen) and TOC in the upper sections of the Upper Jurassic Rankin Fm. (Egret Mbr) may be related to a westward jump of the Orphan Basin rift axis, leading to the apparent isolation of the Jeanne d'Arc Basin. Other rifts such as the Whale Basin appear to remain connected to the Central Atlantic and hence remain oxygenated. This tectono-geochemical model allows prediction of source rock quality in the more sparsely drilled or undrilled areas of the North Atlantic.

Introduction

The analysis of conjugate margins when appraising data-deficient basins is a powerful tool for evaluating petroleum potential in prospective areas. For example, the emerging new plays offshore Brazil have been used as proxies for new exploration targets in the conjugate margin of Namibia (Mello et al., 2012). Understanding the geochemistry of source rocks in the context of plate tectonics is crucial when evaluating the exploration potential and risks in frontier basins, such as the Labrador margins and the deep offshore realms off Morocco, West Iberia and Nova Scotia, where there remains uncertainty about the quality, maturity and presence of Mesozoic source rocks.

This study aims to compare source rocks between different margin segments and across conjugate margins by quantifying the hydrocarbon potential of regional source rocks (Fig. 1) and extrapolating this information into conjugate margins in order to help utilise more statistically-significant source rock properties for future exploration.

Database

In the Grand Banks (Canada) the interpretation is based on a large geochemical database which includes publically available data from the Jeanne d'Arc, Flemish Pass, Horseshoe, Carson and Whale basins (IGI's 2014 Grand Banks Database comprising 22,105 rock & 150 oil samples). This is used together with other large geochemical databases from the Norwegian North Sea (7,558 samples) and Porcupine Basin, offshore Ireland (1,177 samples). Sparse data from the Morocco, West Iberia and Nova Scotia margins place further constraints on the regional variation across the palaeo-contiguous North Atlantic and adds credence to published kinematic reconstructions.

We further explore the Grand Banks database, which comprises data from a wide range of analytical techniques, from basic source rock screening and maturity analysis (Rock-Eval, visual kerogen, vitrinite reflectance, etc) to medium-resolution analyses such as gas chromatography and carbon-isotope analysis, to characterise the source rock types and depositional environments.

North Atlantic Kinematics

The North Atlantic margins and peripheral rift basins (e.g. Jeanne d'Arc, Porcupine, Rockall Trough, North Sea Basins) formed through a sequence of extensional pulses interspersed with periods of tectonic quiescence between the Triassic and Late Cretaceous (Ziegler and Cloetingh, 2004).

As a result of this complex tectonic history, rift basins were episodically restricted from oceanic circulation which may have resulted in anoxic conditions favoring the preservation of large amounts of organic matter and the development of regionally significant source rocks. The Rankin and Kimmeridge Clay Fms. are two extensively documented examples of Upper Jurassic deposits, dominating the source-charge in most of the petroleum fields in the Jeanne d'Arc and North Sea basins, respectively (Fowler and McAlpine, 1994; Cornford *et al*. 1998). Though isolated, the Upper Jurassic North Sea rifts were connected to

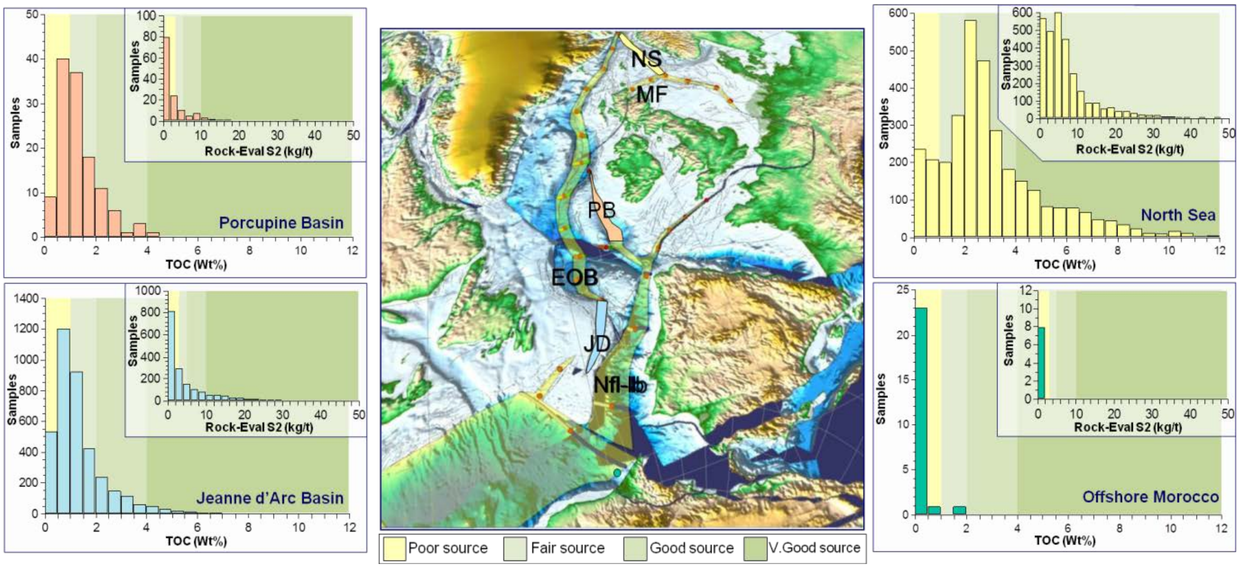

Figure 1:: Hydrocarbon richness (TOC) and yield (Rock-Eval S2) for Upper Jurassic samples in the Porcupine (top left), Jeanne d'Arc (bottom left), Norwegian North Sea (top right) and Offshore Moroccan (bottom right) basins, from IGI's multi-client databases (see References). The palaeotectonic reconstruction at 160Ma is taken from Skogseid et al. 2010: EOB – East Orphan Basin; JD – Jeanne d'Arc Basin; MF – Moray Firth; Nfl-Ib – Newfoundland – Iberia; NS – North Sea; PB – Porcupine Basin

the Boreal Sea to the north, while the Porcupine and Rockall troughs were potentially a more open seaway connecting the Boreal and Tethyan provinces (e.g. Skogseid 2010) at this time. Thus these marine grabens and troughs can be defined as 'restricted' (North Sea, Moray Firth, Jeanne d'Arc basins), or as 'connecting' (East and West Orphan Knoll Basins, Rockall Trough, Porcupine Trough and ultimately the Newfoundland-Iberia Basin).

In contrast, rifting and break-up in the central Atlantic occurred over a single extensional phase during the Late Triassic-Early Jurassic (Sahabi *et al.* 2004), resulting in an open marine, oxygenated depositional environment in the Morocco and Nova Scotia margins.

Upper Jurassic

In the Jurassic and Cretaceous seas of the proto-North Atlantic, preservation (high sedimentation rates, sea bed anoxia) rather than photic-zone bioproductivity seems to control the amount and type of kerogen accumulated (Cornford, 1998). In summary, productivity was adequate for oil-prone source rock accumulation if conditions favored preservation (e.g. anoxia). Figure 1 compares the Upper Jurassic TOC and Rock-Eval S2 yields ("pyrolysate -yield") from samples in the Jeanne d'Arc Basin, Porcupine Basin, Norwegian North Sea and Offshore Morocco using our databases.

There is a good correlation between the TOC (amount) and S2 (kerogen type) distributions in the Jeanne d'Arc and Porcupine Basins, which suggests that the Jeanne d'Arc and Porcupine Basins were partially restricted basins with mean TOC values between 3.00 to 4.75wt%. Despite these similarities, these two basins remained essentially unconnected during the Upper Jurassic, with the Jeanne D'Arc basin closed to the south and the Porcupine closed to the north (Skogseid, 2010). Analogous depositional conditions during this period in the East Orphan, Celtic Sea and Western Approaches Basins suggest that comparable Upper Jurassic organic-richness to the partially-isolated Porcupine Basin may be present here. The Norwegian North Sea has a higher mean TOC value of 5.50% which is likely to reflect the higher degree of bottom water anoxia (preserving organic matter) resulting from a restriction in water circulation associated with extreme distance to open marine waters in the north.

A large sample set of Upper Jurassic carbonaceous shales from the Rankin Fm. (and Egret Mbr) in the Jeanne d'Arc Basin has been used to characterize the quality and quantity of the source rock on the western conjugate margins. Traditionally the Rankin Fm. is described as dominated by Type II kerogen (Fowler and McAlpine, 1994).

Once corrected for maturity, the Rankin Fm. has an average TOC_i of 3.0-3.2wt%, a Rock-Eval $S2_i$ yield of 15-20kg/t, and initial Hydrogen Indices (HI_i) values between 500-550mg/gTOC in the Jeanne d'Arc Basin, indicating a highly oil-prone kerogen. These yields lie between those of partially-connected Upper Jurassic basins such as the leaner Porcupine Basin (TOC_i of 2.8-3.5wt%, $S2_i$ of 9-12kg/t and HI_i of 300-550mg/gTOC), and the richer and closed Norwegian North Sea (TOC_i of 5.0-5.5wt%, $S2_i$ of 22-28kg/t and HI_i of 450-550mg/gTOC).

In Figure 2 we compare the Upper Jurassic Rankin Fm. (Jeanne d'Arc) & Mandal Fm. (Norwegian North Sea) kerogen type using a bulk analysis, Rock-Eval (to derive HI and T_{max}) together with an a subjective visual kerogen analysis.

The visual kerogen analysis tri-plot shows that most Rankin Fm. samples are either rich in liptinitic macerals (oil-prone) or vitrinitic-macerals (gas-prone) in a much more bi-modal distribution than suggested by the HI *vs.* T_{max} distribution. The Lower Rankin Fm. is dominated by a mixture of Type II (planktonic/algal) and Type III (higher plants) kerogen, whilst the upper Rankin Fm. becomes increasingly-rich in Type I (algal) kerogen (HI >650mg/gTOC); particularly towards the centre and north of the basin. This may indicate that during the Late Jurassic the deposition conditions changed from a marine environment (but with high terrestrial input from land plants growing on the basin margins) to an increasingly restricted marine environment where preservation of the bacterial-algal component dominated.

In the kinematic reconstruction of Skogseid (2010), this period corresponds to a westward jump in the rift axis from the West Orphan Basin to the Flemish Pass basin. This 'jump' is confirmed by the dominantly Type II/III kerogen seen in the Porcupine Basin and thus predicted for its southerly extension as the East Orphan Basin (Figure 1).

Since most analyses derive from drill cuttings samples over meter-scale intervals, HI values reflect the mean kerogen type in the composite sample. The database highlights that the Rankin Fm. kerogen is dominantly composed of a bimodal Type I/II kerogen (HI of 550-900mg/gTOC) and Type III kerogen (HI <250mg/gTOC). We suggest that the average 500mg/gTOC HI value is likely to be composed of both a liptinitic and vitrinitic component (Figure 2, insets), giving a composite HI value between 300 – 700mg/gTOC. The HI *vs.* T_{max} plot (Figure 2) shows a wide variation which largely reflects kerogen type (confirmed by decreasing OI with increasing HI) and not maturity (i.e. the T_{max} axis)).

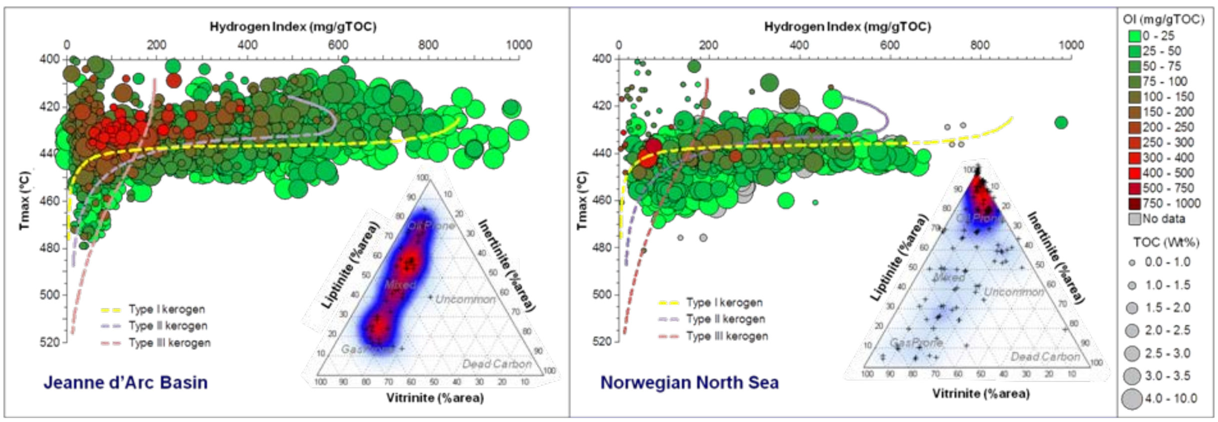

Figure **2**: Evaluation of kerogen type using Hydrogen Index (HI) and Oxygen Index (OI) as bulk-indicators of oil-proneness against Rock-Eval Tmax (maturity) and visual kerogen analysis (inset) in the Upper Jurassic Rankin Fm. (Jeanne d'Arc Basin) & Mandal Fm. (Norwegian North Sea). The visual kerogen colour represents sample density. The Rankin Fm. distribution is largely due to kerogen type while the Mandal Fm. is due to a more dominant Type II kerogen with increasing maturity. All data is sourced from IGI's 2014 Grand Banks Database (see References) & graphs from p:IGI-3© & MatLab©

The geochemical database also highlights differences between sedimentary basins within the Grand Banks. The highest TOC samples (>2wt%) are restricted to the Jeanne d'Arc and Flemish Pass basins, inferring a greater degree of marine isolation than the Whale, Carson and Horseshoe basins which have most TOCs below <1wt% and are therefore thought to be open to marine circulation.

Extensive rifting and subsidence offshore Morocco and Iberia by the Upper Jurassic and the subsequent development of an open seaway to the Central Atlantic basin and Tethys Ocean (and arguably connecting to the Boreal Sea), would lead to well-oxygenated, open marine conditions which are less prone to source rock deposition. The low TOC and S2 values shown from our sparse data most likely result from aerobic bacterial consumption at the sediment surface (Parrish, 1995) despite high photic zone phytoplankton productivity (Cornford, 1998). For this reason the source quality of Upper Jurassic sediments offshore Morocco (Cornford 2014) and Iberia (Spigolon *et al.* 2010) are likely to be generally poor except in isolated sub-basins.

The implications of using the incorrect kerogen type (e.g. Type II rather than a Type and Type III mix) in kinetic models can significantly affect the timing of generation and hydrocarbon quality (e.g. GOR). We suggest a careful consideration of kerogen-type is fundamental to properly appraising the source potential in North Atlantic basins.

Lower/Middle Jurassic

Regional Lower and Middle Jurassic source rocks in the Atlantic margins have been discussed by several authors (Monnier *et al.* 2010; Spigolon *et al.* 2010; Scotchman *et al.* 2001) but are still poorly constrained with respect to quantitative source rock quality values such as TOC, S2 (hydrocarbon yield) and HI. 477 Lower Jurassic and 1,655 Middle Jurassic samples have been characterized based on TOC, Rock-Eval and visual kerogen analysis from 24 wells within the IGI's 2014 Grand Banks database across a 500,000km^2 area.

The presence and quality of regional Lower to Middle Jurassic source intervals is unclear due to poor sample availability, high maturity when sampled offshore and exploration wells terminating in younger sediments. However the presence of a Lower to Middle Jurassic source has been supported by a strong geochemical correlation between source extracts and oil/bitumen samples throughout the North Atlantic margins (Fig. 3).

Biomarkers can provide useful environmental indicators (Fig. 3), with Lower-Middle Jurassic source rock extracts characterised by the presence of gammacerane (associated with stratified and often hypersaline, restricted environments), a C_{28}/C_{29}-sterane ratio below 0.7 (Middle Jurassic and older sources) and the absence of 28,30-bisnorhopane (a compound common in Upper Jurassic source extracts). These biomarker interpretations are consistent with kinematic and palaeo-environmental reconstructions in the Jeanne d'Arc, Porcupine and Lusitanian Basins during the Lower to Middle Jurassic (e.g. Skogseid *et al.* 2010, Sibuet 2012).

The good correlation between Iberian and Nova Scotian source extracts (Fig. 3) could indicate that conditions ideal for source rock formation during this period were replicated over the North Atlantic margins, and may extend as far north as the Porcupine Basin and Slyne Trough (Scotchman, 2001) and west as far as Nova Scotia. The presence of a Lower to Middle Jurassic non-marine source rock has positive implications for future exploration in the North Atlantic, particularly in areas where an Upper Jurassic source is absent or immature.

Once Lower Jurassic samples of the Grand Banks are corrected for maturity using the method of Peters *et al* (2006) the initial TOC (TOC_i) values range from 0.2-3.2wt% with a mean initial value of c.2.5wt%, the HI_i values range between 20-250mg/gTOC and Rock-Eval $S2_i$ yields vary between 0.1-12.5kg/t with a strong vitrinite-rich (gas-prone) kerogen. The kerogen appears mixed with a strong component of non-generative Type IV (inertinite-rich) while organic-rich samples (>1% TOC) contain higher HI values, up to 300mg/gTOC. However these organic-rich samples account for only c.10% of available geochemical samples and are distributed widely across the Grand Banks.

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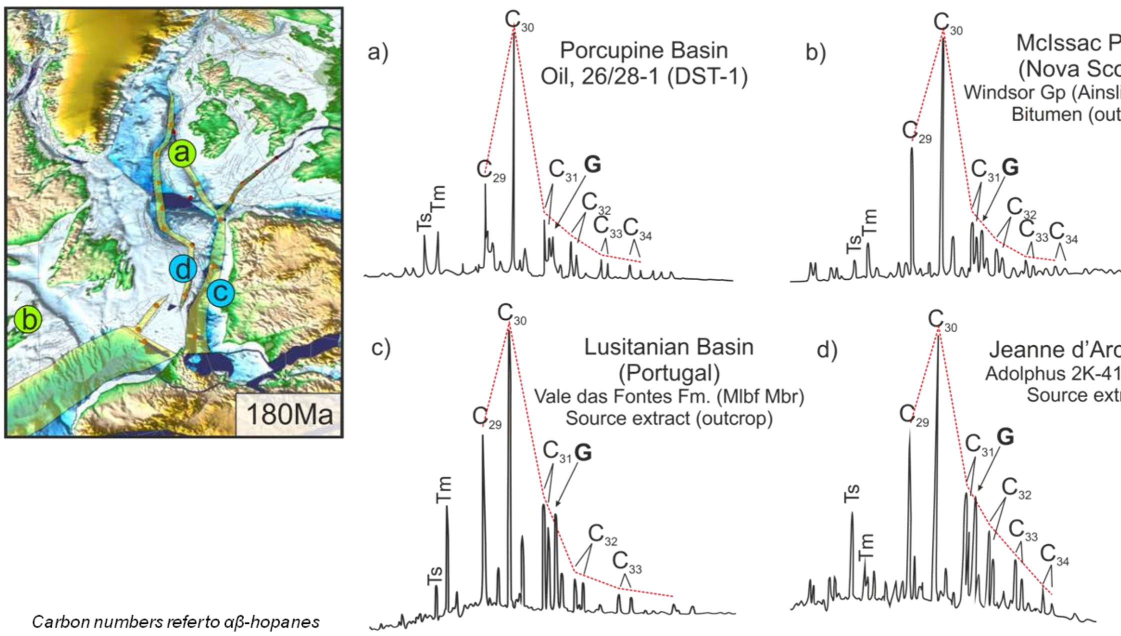

Figure 3: *m/z191 chromatograms (GC-MS) representing terpane distributions showing an excellent correlation between Lower/Middle Jurassic source extracts from the Lusitanian & Jeanne d'Arc basins (c & d) and oil/bitumen samples from the Porcupine Basin and Nova Scotia (a & b). Note the presence of gammacerane ("G") in all samples as well as the common relationship of C_{29}-C_{34}αβ hopanes suggesting that fluids are at least partly charged from a Lower-Middle Jurassic source. GC-MS chromatograms are taken from a) Scotchman, 2001, b) Fowler et al. 1993, c) de Oliveira et al. 2006, d) NRC BASIN database. The palaeo-tectonic reconstruction from Skogseid et al (2010) at 180Ma is shown for context.*

Middle Jurassic samples have corrected TOC_i values between 0.2-5.2wt% (plus two coal samples) with an average value of c.2.0wt%. HI_i values between 0-800mg/gTOC while a mean HI value of c.300mg/gTOC indicates some mixed oil & gas proneness. The $S2_i$ values range up to 51kg/t with a mean value of ~6kg/t, this inferring good oil source rock yields within organic-rich intervals.

However, like the Lower Jurassic samples, the organic rich samples (>1% TOC) comprise only about 10% of the available geochemical samples and again appear to show this distribution across the whole Grand Banks. When combined with the very low source quality of the remaining 90% of samples (low TOC & Hydrogen Index and high Oxygen Index), the implied environmental reconstruction suggests a high sediment-input from a terrestrial source (Type III/IV kerogen) leading to TOC 'dilution'. Periodic phases of hypersaline lacustrine deposition in a syn-rift setting accounts for the sporadic presence of oil-prone Type I or Type IIS kerogen.

Discussion

A comparison of geochemical databases from the Grand Banks, Porcupine Basin and North Sea can be related to plate kinematic reconstructions of the North Atlantic rift and breakup.

Upper Jurassic sources rocks are the major producers of hydrocarbons in the Atlantic margins, with the best quality source rocks accumulating in 'restricted' basins and poorer (or non-source) rocks accumulating in 'connecting' narrow seaways. The geochemistry indicates that the North Sea Central Graben, Flemish Pass and Jeanne d'Arc basins had prolonged periods of marine isolation which promoted anoxic conditions and hence increased organic preservation which are commonly associated with the deposition of algal (Type I) and/or algal-bacterial (planktonic, Type II) precursor kerogens with high oil-generative potential. The Jeanne d'Arc and Flemish Pass basins also had significant woody terrestrial input from eroding sub-aerial continental blocks such as the Flemish Cap and Nova Scotia which resulted in a gas-prone Type III kerogen component.

The tectonic history of Lower-Mid Jurassic evaporite-hypersaline conditions followed by restricted marine Upper Jurassic (before fully open marine conditions are established) means where the Upper Jurassic sourcing is absent or immature, there is increasing evidence of an older Lower-Middle Jurassic, non-marine source below.

Partially connected basins, such as the Porcupine and Western Approaches, may have encountered periodic marine isolation events favoring the preservation of organic matter in dysoxic conditions and are commonly characterized by Type II and Type III kerogen with some oil and gas generative potential. Contrastingly, connecting basins would lead to prolonged periods of well-oxygenated marine environments, and thus poor source rock forming environments (e.g. offshore Iberia/Morocco and Rockall Trough).

The wide-spread correlation between Lower to Middle Jurassic source rock extracts and fluids across the North Atlantic indicates that a source rock deposited in a hyper-saline, restricted environment may be a regionally-significant petroleum source rock. Although in the Grand Banks the available rock data suggests that this earlier source is not as organic-rich or oil-prone as the Upper Jurassic carbonaceous shales.

However, the lateral extent, stratigraphic position and thickness of the Lower to Middle Jurassic sources may make previously disregarded petroleum plays a target for future exploration, not only in mature basins, but in developing basins too.

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Upper Jurassic reservoir and source rocks, age and sequence stratigraphy in the Terra Nova oilfield, Jeanne d'Arc Basin

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The Terra Nova oilfield provides a broad window into the changing geological conditions present in the Jeanne d'Arc Basin during the Late Jurassic, a critical time in the history of the North Atlantic basin development.

Palaeodepositional conditions associated with the oldest strata of the Late Jurassic of the Jeanne d'Arc Basin are marked by a major period of marine flooding across the underlying progradational package of shallow marine to continental sandstones of the Voyager Formation. This early Oxfordian flooding led to the establishment of widespread low to high-energy marine limestones often characterized by common oolites and thick-walled shells. Publically-available geochemical analyses, combined with biostratigraphic studies and wireline log profiles, support the presence of ideal conditions for preservation of marine, oil-prone, hydrocarbon source rocks in the overlying stratigraphic interval known as the Egret Member of the Rankin Formation. Microfossil data indicate that the Egret Member represents a basin deepening, as well as isolation, initiated by the onset of the *eudoxus* Ammonite Zone of the Kimmeridgian (*sensu gallico*), global highstand following a shoaling event marked by a distinctive freshwater to lagoonal ostracod biomarkers (*Darwinula* spp., *Theriosynoecum* spp.). The basin deepening and bottom water stagnation was characterized by a shift to lower energy conditions represented by deposition of thick lime mudstones during the latter part of the Kimmeridgian. The uppermost of these Rankin Formation limestones have been conventionally cored for the first time at the Terra Nova L-98 12Z development well (Figure 1).

In contrast to the preceding patterns of broad subsidence, the Tithonian was characterized by multiple stages of uplift and tilt, leading to exposure and erosion of the underlying Kimmeridgian and Oxfordian Rankin Formation limestones. This exposure created a low-angularity, near base Tithonian unconformity and deposition of the first lowstand fluvial facies of the multi-story Jeanne Formation (*elegans* Ammonite Zone). These basal Jeanne Formation sandstones are laterally restricted to the erosional lows on this early syn-rift unconformity surface and were buried beneath a distinctive organic-rich, micro-laminated shale-marlstone bed that onlapped the sandstones and, southward, onto the unconformity itself. This lowermost organic-rich interval of the Jeanne d'Arc Formation has been cored at the L-98 12Z well where it sits directly atop the near base Tithonian unconformity. Anoxic (or dysaerobic) conditions were short-lived and deposition of organic-lean shales with fish scales and fish bodies was soon established, as recognized in core collected from the Terra Nova F-88 1 well (Figure 1). These shales include microfossils indicating deposition about the *wheatleyensis / hudlestoni* Ammonite Zones. Renewed and enhanced episodic uplift at the south end of the Jeanne d'Arc basin (Avalon Arch), resulted in progressive unroofing of exposed strata and the introduction of pebbles and cobbles of meta-quartzites of probable pre-Mesozoic origin. Thick bimodal (limestone and quartzite) conglomerate beds accumulated as valley floor pavements during the greatest time of uplift and deepest valley incision. The resultant highly angular unconformity underlies the main oil-producing interval at Terra Nova which comprises low-stand braided fluvial sandstones constrained within a set of stacked and offset incised valleys. This major mid-Tithonian unconformity at the base of the stacked reservoir-quality facies has been cored at L-98 12Z, F-88 1, and E-79 (Figure 2) and is observed on 3D seismic data to cut downward across the Terra Nova oilfield to the south where it eventually intersects with, and further incises, the less angular near base Tithonian unconformity. Strata immediately above the mid-Tithonian unconformity include the *fittoni* Ammonite Zone of the Tithonian, equivalent to base Portlandian *sensu anglico*.

Flooding conditions following sediment infill of the valleys occasionally resulted in re-establishment of near-anoxic conditions and preservation of abundant organic material in thin beds of micro-laminated shale-marlstone. While volumetrically minor in the Jeanne d'Arc Basin, the distinctive wireline log signature of these beds provides useful marker horizons for intra-field well-to-well correlations and even across the basin to other fields. The uppermost distinctive source marker within the upper Jeanne d'Arc Formation in the Terra Nova oilfield (labelled TN_K18_SR on Figure 1) is interpreted to have been deposited during the *oppressus / anguiformis?* Ammonite Zones of the Late Tithonian.

In addition to the geomorphological patterns of incised paleovalleys and cross-bedded sandstones consistent with downstream accretion of numerous braid bar forms, there are a number of distinctive geological characteristics of Jeanne d'Arc Formation strata that can, at first, appear at odds with the dominantly fluvial palaeodepositional setting interpreted for the main reservoir facies. Firstly, early dolomite cements in the lowermost conglomeratic basal lag facies have a pendent form. Therefore, rather than representing precipitation in an estuarine mixing zone of fresh and salt water, this early diagenesis is consistent with magnesium-rich runoff from the exposed Rankin Formation limestones and crystal growth in the alternately wet and dry vadose zone of valley floors during their incision. The presence of marine shell debris and glauconite would suggest syndepositional marine conditions if their reworked nature went unrecognized. The local occurrence of trace fossils in transitional fine-grained facies is fully consistent with the interpreted fluvial to floodplain setting through recognition of very low diversity terrestrial ichnological assemblages which include the meniscate trace fossil *Taenidium* that typically were formed in the continental realm by arthropod larvae and beetles rather than marine organisms. Finally, it must be recognized that the shale-dominated facies represent substantial landward shifts of distal settings during late transgressive to highstand conditions between distinct periods of lowstand to early transgressive infilling of incised valleys with coarse-grained, reservoir-quality sandstones. The presence of early diagenetic framboidal pyrite and marine dinoflagellate cysts in the shale-dominated facies in core from Terra Nova L-98 9 indicates connections to marine waters, at least at the bottom water-sediment interface while the presence of thin organic-rich marly units and evidence of fish kill events indicates stagnation in a semi-isolated basin with periodic overturn of a stratified water column. Integration of all these data suggests that, during late transgressive to highstand stages of the early to Middle or Late Tithonian, the Jeanne d'Arc Basin was a semi-enclosed sea, loosely comparable to the modern Black Sea.

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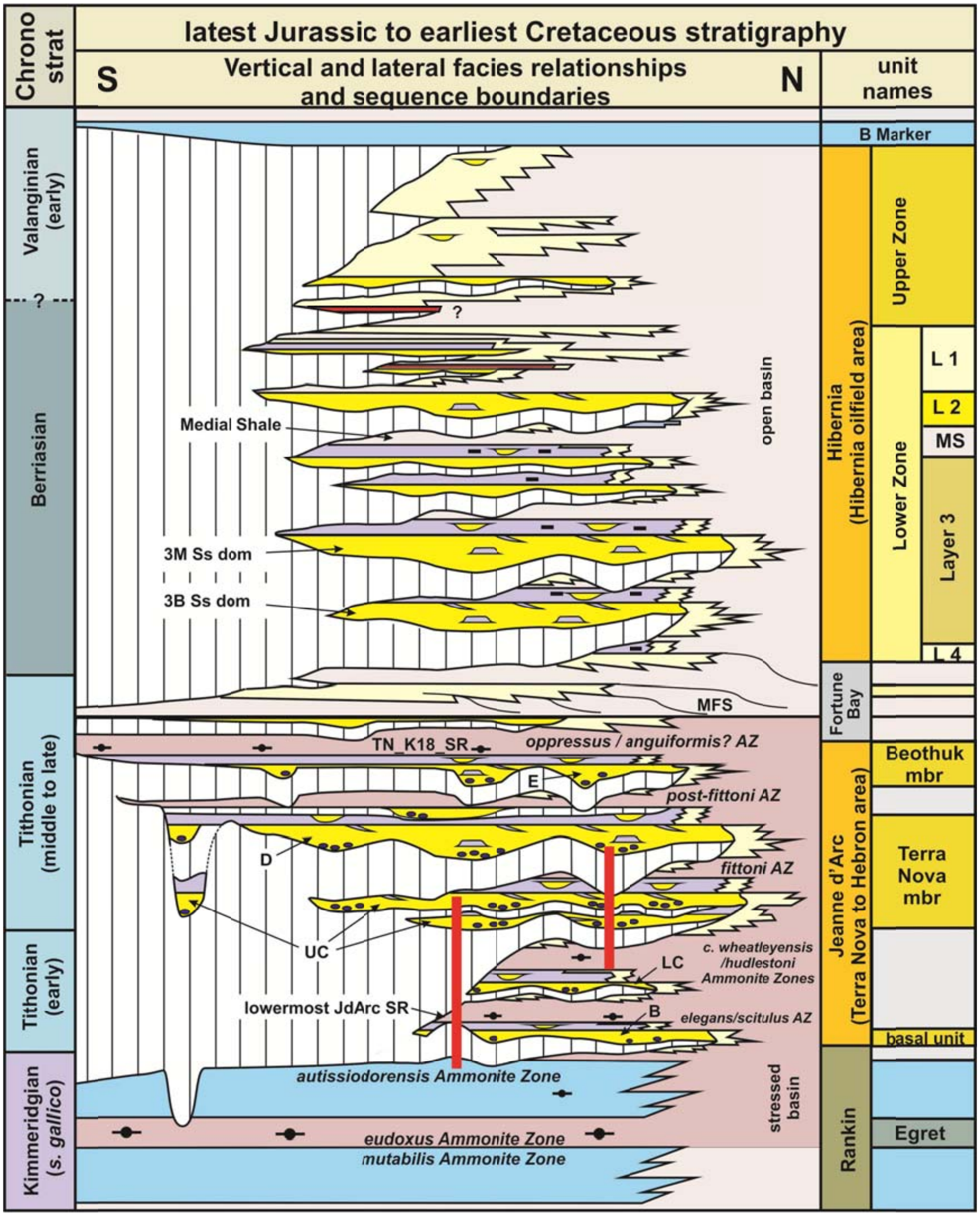

Figure 1: Detailed south-to-north trending stratigraphy across the Hibernia Fm. through the Egret Member of the Rankin Fm. based on Husky Energy commissioned biostratigraphic analyses by Riley and Ainsworth, in combination with published stratigraphic nomenclature of McAlpine 1990, Sinclair *et al*. 1994, Sinclair *et al*. 2005, and Haugen *et al*. 2007. The stratigraphic intervals cored at Terra Nova L-98 12Z and Terra Nova F-88 1 are indicated by the vertical red bars to the left and right, respectively.

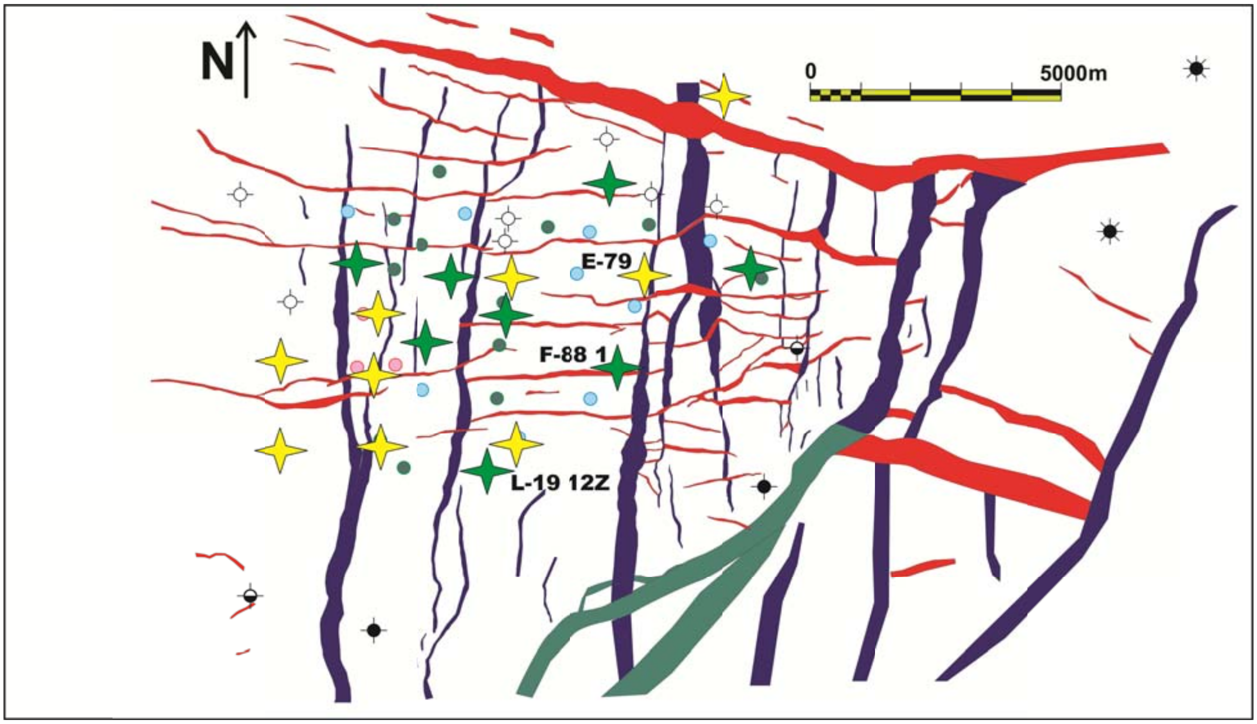

Figure 2: Well and fault location map for the Terra Nova oilfield with wells cored in the Jeanne d'Arc Formation highlighted by stars (yellow for vertical exploration and delineation wells and green for bottom hole location of directionally drilled development wells). Fault map modified after Figure 9 of Ferrill *et al*. (2009).

Lower Jurassic organic-rich intervals along the Central-Northern Atlantic Margin

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The Early Jurassic time interval includes several organic-rich intervals with source rock potential. These are particularly expressive in the European and African margins, where they crop out extensively in several onshore basins. In the Lusitanian Basin (Portugal), the Sinemurian–Pliensbachian is characterized by marine marl-limestone alternations deposited in a carbonate homoclinal ramp environment (Água de Madeiros and Vale das Fontes formations). Other similar organic-rich age equivalents intervals in Iberia are the Camino, Castillo Pedroso (Basque-Cantabrian Basin), and Rodiles (Asturias Basin) formations. Proven Lower Jurassic petroleum source rocks in Morocco occur in the Prerif Basin and Middle Atlas and some oils in Tarfaya and Essaouira basins are thought to be sourced from Pliensbachian to Toarcian shales.

On the other hand, Lower Jurassic source rocks are poorly known in the American margin. The Canada-Nova Scotia Offshore Petroleum Board's (CNSOPB) 2013 Call for Bids NS13-1, based in part on the Play Fairway Analysis (PFA), laid out a compelling case about the probable existence of a Lower Jurassic Source Rock "Complex" (Sinemurian/Pliensbachian/Toarcian) in the Scotian Basin, offshore Nova Scotia (Canada). This complex consists of restricted to near-normal marine series belonging to the Mohican and Iroquois formations' (Sinemurian–Bajocian) distal equivalents, that are expected to have potential for generation of hydrocarbons. It was also hypothesized the existence of local uppermost Triassic–lowermost Jurassic (Argo Formation) organic-rich intervals with potential for source rock. So far, petroleum systems models have been limited to the southwest platform, margin and slope of the Scotian Basin. It is recognised that other regions of the Scotian margin could be locations for the development of a mature source rock. Additionally, the CNSOPB and Canada-Newfoundland and Labrador Offshore Petroleum Board recent Call for Bids opened the concept of an Upper Triassic–Lower Jurassic source rock in other parts of the Canadian continental shelf, namely in the Newfoundland offshore area. Along the Labrador margin, the unbiodegraded oil encountered at North Leif I-05 suggests immaturity, but more mature source rock (most likely of Cretaceous age) and reservoired oil may exist in deeper parts of the basin.

East Coast Magnetic Anomaly: Constraints, Models and Questions

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The East Coast Magnetic Anomaly (ECMA) is a high amplitude curvilinear magnetic anomaly extending from Georgia to Nova Scotia (Figure 1). The ECMA lies within highly extended and/or transitional crust and is sub-parallel to the main structures controlling ~240-190 Ma rifting and breakup. These structures were, in turn, localised along the suture zone of the ~315 - 260 Ma Alleghanian Orogeny. Interestingly, one of the largest Large Igneous Provinces, the ~200 Ma Central Atlantic Magmatic Province (CAMP), coincides with rifting and breakup. It is therefore feasible to propose a source body for the ECMA that is related to the Alleghanian suture, Atlantic opening, or CAMP. As a result, a range of interpretations have been proposed to explain the source of this prominent, continuous magnetic anomaly. Early models involved a major crustal discontinuity (e.g. Keen, 1969) such as the continent ocean boundary, or an edge effect between faulted units of contrasting magnetization combined with intrusion of magnetic material (Alsop and Talwani, 1984). In later works, the source body was interpreted to be related to the Alleghanian suture zone (Nelson et al., 1985; Hall, 1990). Austin et al. (1990) and Holbrook et al. (1994a) proposed that the ECMA was due to a thick volcanic package based on identification of seaward dipping reflectors (SDRs) in reflection seismic and a thick lower crustal high velocity zone from refraction data.

The exact age and source of the interpreted package of SDRs remains unclear, however, some workers propose a link with the wide spread, voluminous magmatism of the CAMP event (Kneller et al., 2012), which is well constrained in age from ~201 to 199 Ma (e.g. Hames et al., 2000). The age relationships between the CAMP event and syn-rift to post-rift sequences provide useful constraints on the nature of the margin and possible interpretations for the ECMA. Although the SDR model for the source body of the ECMA has remained the most popular, there are some inconsistencies in this interpretation. As outlined above, there are a range of interpretations that have been applied to the ECMA but unfortunately there is insufficient data to predominantly support a single model. Therefore, it is worthwhile to review the available data and assess the range of models for the ECMA based on the currently available constraints.

The nature of the Central Atlantic Margin

The Central Atlantic Margin south of Maine has been interpreted as a volcanic margin since the early 1990's. This interpretation is consistent with all of the data available within the central segment from Maine to Virginia, but interpretation of a volcanic margin along the southern segment from North Carolina to Georgia is not as clear cut. Within the central segment, the temporal relationships with the onshore basins suggest that the CAMP event is directly related to development of a volcanic margin. In contrast, temporal relationships in the onshore basins of the southern segment indicate that CAMP postdates the initiation of spreading along this segment and therefore requires an older magmatic event if the >10km thick wedge of seaward dipping reflectors is interpreted as mafic volcanics. Our preferred hypothesis is that the southern segment is a non-volcanic margin and the wedge of seaward dipping reflectors represents a late syn-rift sequence dominated by sediments.

Despite the short duration of CAMP magmatism, this event represents one of the largest igneous provinces documented. Generation of the large volume of mantle melt during the CAMP event is attributed to increased temperatures beneath the large insulating mass of Pangaea with development of craton edge-driven convections cells resulting in linear upwelling beneath the Central Atlantic rift zone (McHone, 2000). CAMP timing and its potential influence are key to understanding the development of the Central Atlantic margin and variations along its length. The formation of a volcanic margin along the central segment can be related to the voluminous CAMP event as outlined below. In contrast, development of hyperextension during the transition to seafloor spreading on the Nova Scotia margin indicates that the generation of mantle melt was low after the short lived CAMP. This leaves the question of the thermal state of lithosphere prior to the CAMP event and whether or not there was potential for generation of significant mantle melt prior to 200 Ma.

Northern and central segments of the Central Atlantic Margin

Collection of seismic reflection and refraction data off Nova Scotia demonstrates that the northern segment of the Central Atlantic Margin is a non-volcanic hyperextended margin (Wu et al., 2006; Funck et al., 2004), and that it is distinct from the central segment which has well developed SDRs and has been interpreted as a volcanic margin (Sheridan et al., 1993). The geometry and structure of the hyperextended margin and the transition to the volcanic margin have been recently imaged in the ION GXT deep seismic survey (e.g. Louden et al., 2013). To the south of Nova Scotia from Maine to around Virginia (Figure 1), 1970-1980's USGS seismic data shows well developed SDR packages just west of the true oceanic crust (e.g. Sheridan et al., 1993). In addition, large offset seismic profiles indicate the presence of a high velocity zone at the base of the crust which has been interpreted as an "underplate" (e.g. Holbrook et al., 1994a).

Age constraints on the rift–to-drift transition in the offshore basins are limited. On the conjugate margin of Morocco, the oldest post-rift strata are Sinemurian or Pliensbachian in age (196.5-183 Ma; Medina, 1995; Hafid, 2000). Detailed mapping of the onshore rift basins provides additional constraints on the duration of rifting and the transition to breakup (e.g. Olsen, 1997; Withjack et al., 1998; Schlische et al., 2003).

1. Syn-rift sequences range in age from 231-196 Ma (Ladinian to Sinemurian) in the central segment and ~237-197 Ma (Ladinian to Hettangian) in the northern segment.
2. CAMP age basalts are interlayered with syn-rift sequences.
3. Many of these basins show a distinct increase in subsidence at ~200 Ma coinciding with the CAMP event.
4. CAMP dykes trend ~NE-SW to ENE-WSW and are consistent with ~NW-SE extension during rifting.

These observations indicate that rifting in the central and northern segments of the Central Atlantic Margin continued during the CAMP event and subsidence increased around the time of magmatism (Schlische et al., 2003). However, the nature of the offshore margin is distinctly different. The central segment is characterised by SDRs assumed to be the same age as CAMP. In contrast, development of a hyperextended margin off Nova Scotia indicates an insufficient generation of mantle melt in the period leading to breakup on the northern segment. This suggests a progression in breakup age (e.g. Withjack et al., 1998; Schlische et al., 2003) with seafloor spreading initiating on the central segment during the CAMP event but later on the Nova Scotia margin following the short-lived magmatic event (around Sinemurian to Pleinsbachian).

Southern segment of the Central Atlantic Margin

On the southern segment of the Central Atlantic Margin from North Carolina to Georgia (Figure 1), 1970-1980's USGS seismic data shows a broad, 10-15 km thick package of reflectors that dip seaward beneath the post-rift section (e.g. Austin et al., 1990; Holbrook et al., 1994b). In addition, refraction data indicates the presence of a high velocity zone at the base of the crust which has been interpreted as an "underplate" (e.g. Tréhu et al., 1989; Holbrook et al., 1994b). Together these observations have been interpreted to indicate the development of a volcanic margin along the southern segment similar to the central segment. The width and thickness of the wedge indicate a very large volume of mafic volcanics. Unfortunately, the seaward dipping wedge is buried beneath a very thick post-rift section and is not fully imaged through to its base so the geometry of the "SDR package" and its relationship to the continental crust and oceanic crust is not fully established.

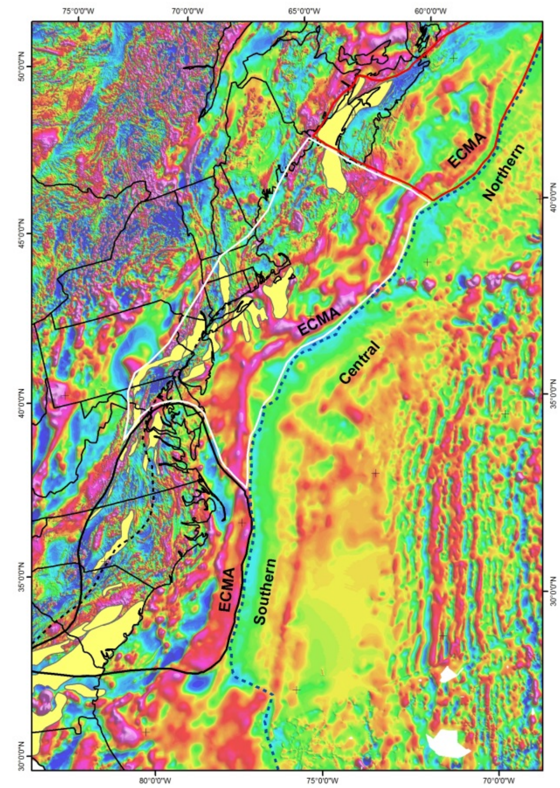

Figure 1: Image showing the location of the East Coast Magnetic Anomaly (ECMA; Reduced to the Pole (RTP) of the Total Magnetic Intensity image). The three segments of the margin are outlined and labelled. Onshore/nearshore basins are shown in yellow. The limit of oceanic crust (LOC) is shown by the blue dashed line and the onshore limit of Cretaceous/Cenozoic cover is shown by the black dashed line.

No age constraints are available for the offshore basins in the southern segment due to limited exploration and the thickness of the post-rift sequence. Detailed mapping of the onshore rift basins provides the only constraints on the duration of rifting and the transition to breakup (e.g. Olsen, 1997; Withjack et al., 1998; Schlische et al., 2003).

1. Syn-rift sequences for the southern segment range in age from 231-213 Ma (Ladinian to Norian). The youngest units have not been preserved but the subsidence patterns suggest that the syn-rift phase ceased close to the Triassic-Jurassic boundary.
2. CAMP age basalts have not been mapped in outcrop (the few basalts intersected in drill holes do not show clear evidence of timing relative to rifting; Heffner et al., 2012).
3. CAMP dykes cut the syn-rift sequences and bounding faults at a high angle, trending ~NW-SE to ~N-S (inconsistent with ~NW-SE extension during rifting).
4. Inversion structures are cut by the NW dykes suggesting inversion initiated pre-CAMP.

The youngest age of syn-rift sequences is not well constrained, however, the key observation is the orientation of the dykes. This orientation implies ~NE-SW to ENE-WSW extension and suggests that rifting had ceased and inversion had initiated in the southern segment by the time of CAMP magmatism (Schlische et al, 2003; Withjack and Schlische, 2005). Thus the timing of the CAMP event relative to the syn-rift to post-rift (and inversion) transition on the southern segment of the Central Atlantic suggests that rifting finished and seafloor spreading had initiated prior to the CAMP event (e.g. Schlische et al., 2003). If the wedge of seaward dipping reflectors represents development of a volcanic margin then a pre-CAMP episode of voluminous magmatism is required. There is no direct evidence for such an event and the >10 km volcanic pile of SDRs interpreted for the southern segment must be considered less likely if its development precedes the CAMP event. The wedge of reflectors that dip seaward can alternatively be interpreted (and modelled with gravity and magnetic data) as a sequence dominated by late syn-rift sediments (possibly including some volcanics) similar to the "sag phase" of the syn-rift sequence on the Angola-Brazil conjugate margins (e.g. Unternehr et al., 2010). The high velocity zone may reflect "underplating", serpentinised mantle or mafic crust related to the Alleghanian suture. The true nature of this syn-rift package will remain uncertain until deep reflection seismic data and additional refraction data is collected along this margin.

If there was sufficient melt generation to develop a volcanic margin along the southern segment prior to the CAMP event then much of the Central Atlantic Margin from Maine to Georgia is a volcanic margin as currently interpreted. Alternatively, if there was not sufficient melt generation to develop a volcanic margin prior to CAMP then the only volcanic margin on the Central Atlantic occurs from Maine to Virginia. In this case, the Central Atlantic Margin can instead be considered as dominantly non-volcanic (possibly hyperextended) with local development of a volcanic margin at 200 Ma during the CAMP event. We favour the later interpretation which is consistent with the lack of documented evidence for mafic magmatism prior to 200 Ma.

Models for the ECMA

The ECMA is remarkably continuous along its length but does vary in amplitude and width. In the central segment the anomaly has a consistently high amplitude and fairly consistent wavelength. Toward the north, the amplitude decreases and the anomaly splits into two less continuous anomalies. Similarly toward the south, the anomaly splits into two peaks and weakens toward the Blake Plateau (Figure 1). Despite these variations, the continuity of the ECMA suggests that a consistent model with continuous or similar source body is preferable. The ECMA is located within the zone of highly extended and/or transitional crust and lies beneath a thick package of post rift sediments (up to 10-15 km; e.g. Sheridan et al., 1988). The wavelength is consistent with a source depth of this order and the amplitude of the anomaly is very high indicating a high induced and/or remnant magnetisation. The most likely source bodies will be mafic to ultramafic in composition

The absence of SDRs on the northern segment offshore of Nova Scotia precludes application of a volcanic margin as the source body for the ECMA in this area, and timing of breakup on the southern segment suggests that a volcanic margin is less likely to provide the source body in this region as well. Although the SDR package and/or high velocity zone within the volcanic margin of the central segment can be modelled as the source body for the ECMA in some areas, in other parts the ECMA is offset from the well-developed SDRs. In addition, this interpretation is not favoured if it cannot be applied to the north or south.

One consistent model that can be applied to all three segments involves structures or crustal zones related to the Alleghanian suture. Mafic to ultramafic source bodies in this setting include: oceanic crust, island arc terranes, or a serpentinised mantle wedge (formed above the subducting slab). Integrated gravity and magnetic modelling indicates that a highly magnetic lower crustal body can explain the anomaly. A second consistent model that can be applied to all three segments involves CAMP magmatism. However, the mafic magmatism will be preserved in different settings in each segment due to the timing of CAMP relative to the diachronous progression of breakup along the margin. Improved data is required in order to test this and other models.

More refraction seismic and higher resolution reflection data are required to properly assess the nature of the southern segment of the Central Atlantic Margin. Reprocessing of older seismic and/or acquisition of new data on the central segment will help clarify the geometry of the volcanic margin. Onshore seismic and drilling will also provide key constraints to better assess the timing of the rift to drift transition in the southern segment. In the meantime, potential field models based on all of the available data can provide testing of the various options.

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Offshore Algarve (SW Iberia): hints of transition to a possible oceanic crust from seismic, gravimetric, and magnetic interpretation.

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Introduction

The study area is located in the Algarve basin, offshore the southern coast of Portugal, and it was the focus of a study performed by Repsol and Partex in 2013 to evaluate its hydrocarbon exploration potential.

The main regional tectonic units in the area are represented by the Rifean-Betic fold and thrust belt, the associated imbricated wedge (olistostrome), and the Guadalquivir and Gharb foreland basins.

A number of shallow biogenic gas discoveries were made along the Guadalquivir basin, both on- and off-shore.

The Repsol-Partex concessions are located further west along this trend, in the Algarve basin, between the southern coast of Portugal and the northern edge of the olistostrome.

The Repsol-Partex concessions include two exploration blocks and, in 2013, three evaluation licenses.

Five wells were drilled in the shelf in the 70's and 80's. None of these wells was a discovery. Gas shows (mainly methane of probable biogenic origin) were recorded in three wells (Imperador-1, Ruivo-1 and Algarve-2). Traces of dead oil were encountered in the Eocene carbonates of the well Algarve-2, indicating that also thermogenic generation may have taken place.

The geological evolution of the basin started with Permian-Triassic to earliest Jurassic rifting, followed by a passive margin stage during the Jurassic-Cretaceous. From the latest Cretaceous onward a convergent margin stage developed in which the Rifean-Betic orogeny and the emplacement of the associated olistostrome took place.

Interpretation and modeling

A regional view of the basin structures can be appreciated on the gravity map in figure 1, generated from satellite data. The most striking feature is a prominent ENE-WSW-oriented anomaly that extends for about 200 km and marks the southern border of the Algarve basin.

On the magnetic intensity map, generated from public domain data acquired by several marine surveys, a concentration of anomalies can be noticed in the same area. They are not as consistent as the gravity anomaly, but this is probably also due to the non-homogeneous nature of this data base.

Gravimetric modeling (figure 2) performed along three dip lines shows that the anomaly can be reproduced only by significantly raising the interpretation of the mantle, hence expressing an important structural feature that marks the transition between different lithospheric domains. North of the anomaly, the model indicates the presence of continental crust with normal thickness, while south of the anomaly the crustal thinning suggests a transition towards oceanic crust.

On 2D seismic, the area of the gravity anomaly is characterized by prominent inverted structures that are associated with pronounced halokinetic features. These inverted structures might be the expression of a transpression zone resulting from the interaction between the African and Iberian plates.

Academic works

Various academic works indicate the presence of a major plate boundary in the offshore Algarve and interpret the existence of a remnant of the ocean that connected the Central Atlantic and the Tethys in the Late Jurassic.
The following is a short description of these works.

Spakman and Wortel, in 2004, interpreted a global seismic travel-time tomography model and identified the presence of a slab of lithosphere in the Gulf of Cádiz, sinking eastward beneath the Rifean-Betic orogen.

Gutscher at al., in 2009, presented a gravity model very similar to the one obtained by Repsol. They observed that an E-W corridor of thin crust (6-10 km) is present in the Gulf of Cádiz, limited between the thicker continental crust of SW Iberia and NW Morocco. They interpreted it as a slab of oceanic lithosphere dipping eastward beneath the Rifean-Betic orogen.

Sallarés et al., in 2011, analysed refraction seismic and wide-angle reflection seismic data along a NNE-SSW profile in the Algarve offshore and identified the transition towards a ~7 km thick crust that, on the base of its velocity and thickness, interpreted as oceanic in nature.

Ranero et al., in 2013, presented a deep seismic profile crossing the Gulf of Cádiz in E-W direction, where it is visible an interval of strong reflectors dipping eastward beneath the Rifean-Betic orogenic wedge. These reflectors are interpreted as Mesozoic under-thrusted sediments on top of oceanic crust.

This interpretation correlates with that of Sallarés where similar strong reflectors are visible in the portion of line characterized by oceanic crust.

In summary, these works concluded that a slab of oceanic crust is present in the center of the Gulf of Cádiz, enclosed between the African and Iberian continental crust, and dipping eastward beneath the Rifean-Betic arc.

Conclusions

The fact that the southern edge of the Algarve basin is bordered by this oceanic slab has certain relevance for the evaluation of its exploration potential, at least for what we could observe in the southern portion of the Repsol-Partex evaluation licenses.

In terms of source rock, this area lies close to what used to be a narrow and segmented ocean in Jurassic time that presumably favoured the accumulation of organic matter.

In terms of deformation, this area appears to be affected by prominent structures of inversion and associated salt diapirism which have developed a large variety of traps. These structures are presumably the result of wrench tectonics developed by the interaction between Iberia and the oceanic slab.

This area is also characterised by the development of a main depocenter which has provided both depositional environments for potential reservoirs and overburden for potential source rock maturation.

All these observations lead to the conclusion that the area with best exploration potential within the licenses evaluated in the offshore Algarve, is located in the southern portion of these licenses, north of the olistostrome edge.

Acknowledgments

We would like to thank Partex Oil and Gas exploration staff for their effective collaboration.

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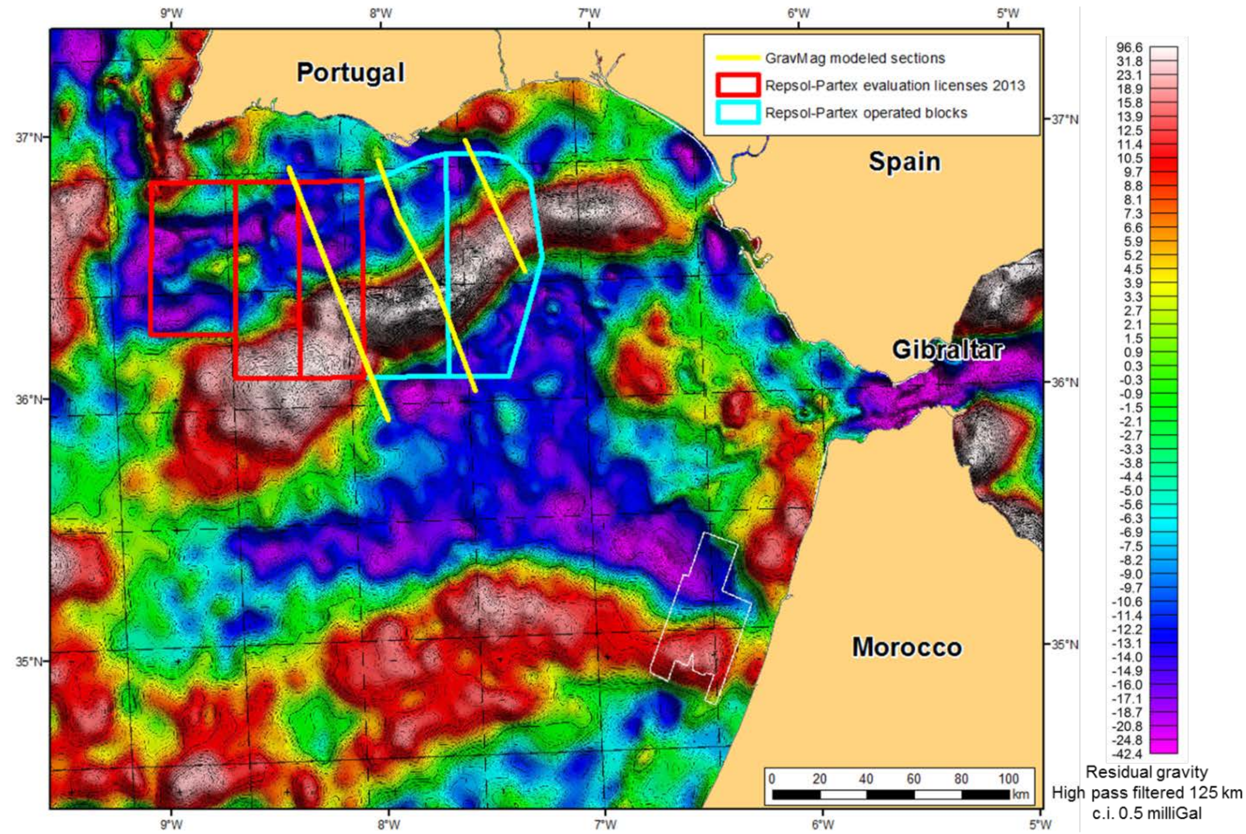

Figure 1: Residual gravity map of the Gulf of Cádiz, showing the study area in the offshore Algarve (red blocks), crossed by a prominent gravity anomaly oriented ENE-WSW, and the three lines for the 2D gravity modeling.

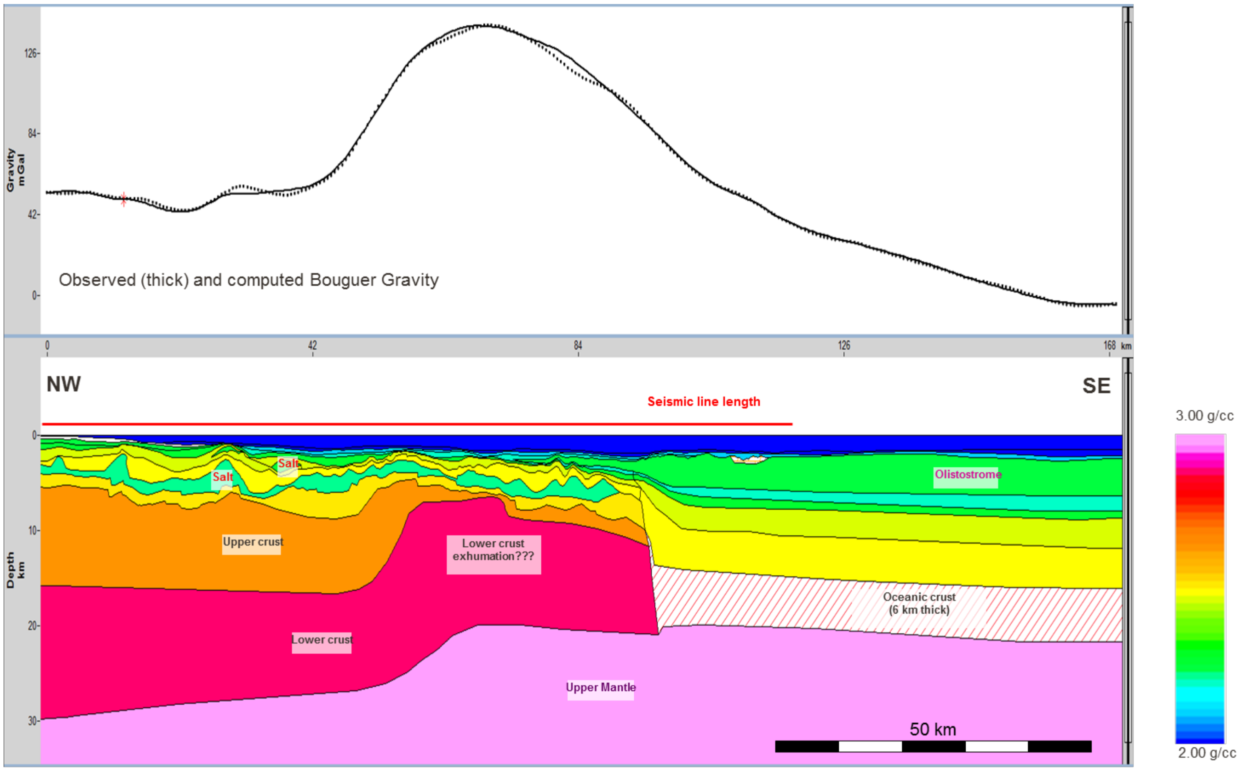

Figure 2: 2D gravity model along the westernmost line; the prominent gravity anomaly can be modeled by significantly raising the interpretation of the mantle; SE of the anomaly, the crust can be stretched to a thickness typical of oceanic crust.

3D Stratigraphic Model and Correlation of the Paraná-Etendeka Province, South Atlantic Margin: Implications for Understanding Volcanic Margin Rift History.

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Introduction

Studies concerning volcanic rocks in Continental Flood Basalts (CFB's) associated with volcanic margins are important to help to understand the pre- rift setting and the transition to rift phases, and can provide important clues in the correlation with offshore sequences. Additionally, the occurrence and role of volcanic rocks in exploration areas (e.g. Angola/Brazil margins) and their potential as reservoir to oil and gas (e.g. China, Argentina) has highlighted the need to better understand the 3D distribution and geometry of such stratigraphic sequences.

The Paraná-Etendeka Province (PEP) is Early Cretaceous in age (cr. 130 Ma) and precedes the fragmentation of the south Gondwana, and consequently the opening of the South Atlantic Ocean (Fig .1). These volcanic rocks cover an area in excess of 1,200,000 km^2 and can reach a maximum thickness of 1,700 m (Melfi et al., 1988). The large portion of the province is located in the South America (90%), in the Paraná Basin, and the eastern- most portion is preserved in the NW of Namibia and southern Angola. Stratigraphic successions also occur in the offshore setting along both margins of the south Atlantic. Offshore the Paraná basaltic plateau was recently demonstrated the presence of widely developed seaward dipping reflectors (SDRs) thick wedges extending through the entire southern Brazil outer margin.

The PEP is composed mainly of tholeiitic basalts and subordinately by andesites and rhyolites/quartz- latites. The basalts are divided into two groups on the basis of Ti contents, High Ti basalts-HTi (TiO_2>2%) and Low Ti basalts-LTi (TiO_2<2%) (Bellieni et al., 1984; Mantovani et al., 1985), which also correlates with similar variations on the African side in the Etendeka (e.g. Jerram et al. 1999). Geochemical correlation models have been used to integrate the chemical stratigraphy of the lavas inside the PEP, however these models ignore the physical heterogeneities inside the volcanic pile, such as architecture and flow morphologies, and how the volcanic rocks relate and inter-finger with sedimentary units, particularly towards the base of the sequence.

Recently new models considering physical characteristics of the lava flow stratigraphy on both sides, Africa and South America, have been built providing a new vision of the volcanic stratigraphy and flow morphologies inside the province (Jerram 2002, Jerram et al., 1999; Waichel et al., 2006).

Many large tectonic structures are found in the Paraná Basin (e.g. Ponta Grossa arc, Torres syncline, Rio Grande arc) that influenced the current limits of the basin and, if active during the syn-volcanic subsidence process induced the formation of sub- basins and was an important role in the structural evolution of the basin. These tectonic structures evolved since the Devonian and were particularly active in Triassic-Jurassic periods (Fúlfaro et al., 1982).

3D Stratigraphic model and correlation

This work presents a new stratigraphic correlation between the two margins of the PEV, integrating the facies architecture, the lava flow morphologies and well data. A 3D model of the volcanic sequence is presented to the Torres Syncline area and the correlation of the Torres section with Awahab section. The 3D model was build using the PETREL E&P Software Platform. Geological sections based on field data and Log data from Paraná Basin (Gama- ray and soniclogs) were used to build the model.

The Torres Syncline is a tectonic structure located in southern Brazil with the main orientation NW-SE (Fig. 1). This structure can be followed in the African side and overlaps with the Huab Basin, NW Namibia. In the Gondwana reconstruction maps this connection is visible both in its overlapping position and with the same orientation of the basin structure. The different thickness of the volcanic sequence marks the main valley of the syncline and the hinges of the structure.

The Torres Syncline is a large structure that constitutes the eastmost outcrop of the Paraná- Etendeka CFB in South American side, and this work focuses the stratigraphy and facies architecture of the volcanic pile in the syncline. The volcanic sequence along the study area permits the division of three regions: main valley, intermediate zone and south hinge, each of them with distinct stratigraphy, which probably reflects the structural evaolution of the syncline. The stratigraphy of the Torres Syncline is composed by: 1- Botucatu palaeoerg; 2- Basic volcanic episode I; 3-Basic volcanic episode II, 4- Acidic volcanic I, 5- Basic volcanic episode III and 6- Acidic volcanic episode II (Fig. 2).

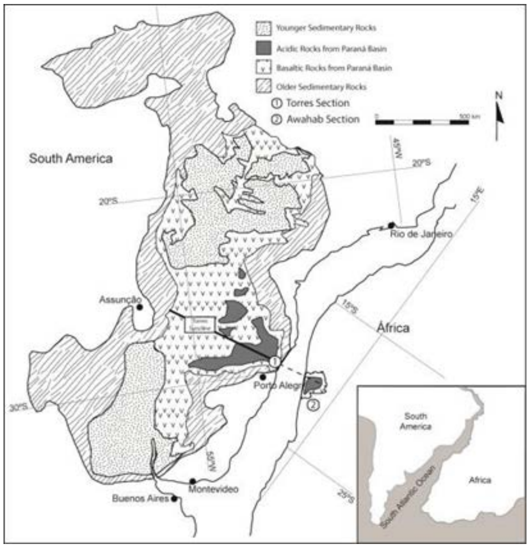

Figure 1- Pre-drift simplified geologic map from the Paraná-Etendeka Province with location of Torres and Awahab sections.

The five volcanic episodes recognized in study area can be related to five volcanic facies architecture: compound-braided, tabular-classic, tabular/lobate escoriaceous, dome-field (acidic lavas) and tabular- flows (acidic lavas). The basic episode I is composed by pahoehoe flows with a compound-braided facies architecture that covered the Botucatu palaeoerg. The basic episode II is a tabular-classic facies architecture predominantly composed by simple flows (10-20m thick) reaching the total thickness of ~250m in main valley. The acidic episode I is exposed in main valley and south hinge, and is composed by acidic lavas forming lava dome-field facies architecture with a thickness of ~150m. The basic episode III is predominantly constituted by rubbly pahoehoe flows with tabular/lobate escoriaceous facies architecture. The acidic episode II is constituted by tabular-flow volcanic facies (acidic flows) and outcrops all along the study area.

The stratigraphy and architecture inside the Torres Syncline is similar to that preserved in the Huab Basin. In both basins the basal portion is characterized by pahoehoe lava flows in a compound braided architecture, followed by rubbly lavas in a tabular classic architecture, and in the upper portions silicic units interbedded with basaltic lavas (Fig. 3).

The basal portion is formed by innumerous pahoehoe flows and flow fields along with interbedded sediments. These first lavas onlapped and buried an aeolian erg (the Botucatu/Twefelfontain Formation), that was active directly prior to the onset of flood volcanism. The advance of lava flows over the unconsolidated sediments generates features of interaction such as peperites lava moulds and preserved dune topography. In some cases the confinement of flows by the topography of the dunes generated ponded lavas.

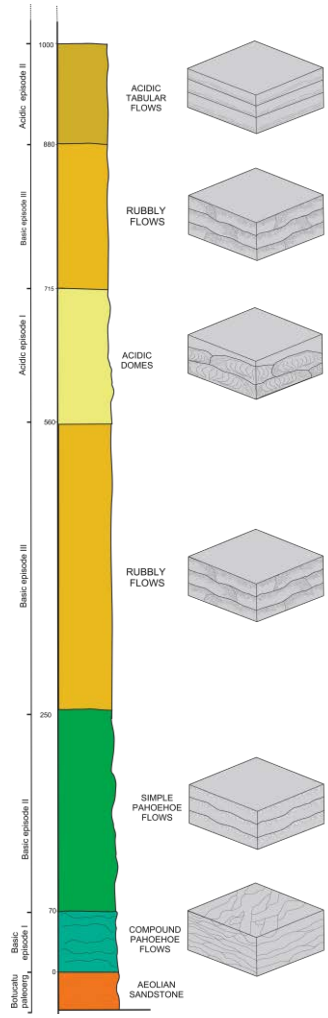

Figure 2- Torres stratigraphic section with volcanic facies architecture.

The central portion of the volcanic pile is characterized by thick tabular lavas with rubbly tops (25-50 m thick). These flows have an internal structure divided in four parts: a smooth vesicular base, aphanitic massive cores with irregular joints, upper vesicular portion and a rubbly top. This unit is thicker along NW-SE axis of the Torres Syncline and represents the main phase of the volcanism. Silicic units occur in the upper parts of the PEP stratigraphy and include lava domes interbedded with basaltic lavas and thick tabular flows.

The Torres Syncline and Huab Basin features constituted one single active structure in the Early Cretaceous and during the main rifting phase. The onset of the volcanism was characterized by low effusion rate eruptions over the paleoerg, forming pahoehoe flow fields in compound braided facies architecture and lava ponds. The main phase of volcanism is build up by thick tabular rubbly pahoehoe flows, formed by larger volume sequences (slightly high effusion rates), that cover the initial pahoehoe flows. At the upper portion of the sequence, the volcanism is more differentiated forming silicic lavas. This evolution of the volcanism in the Torres-Huab area is important to picture the pre- to syn-rift condition preceding the opening of South Atlantic Ocean and can be compared to the present day Djibouti setting with the lava plateau developed adjacent to the SDRs development which precede the installation of the first oceanic crust.

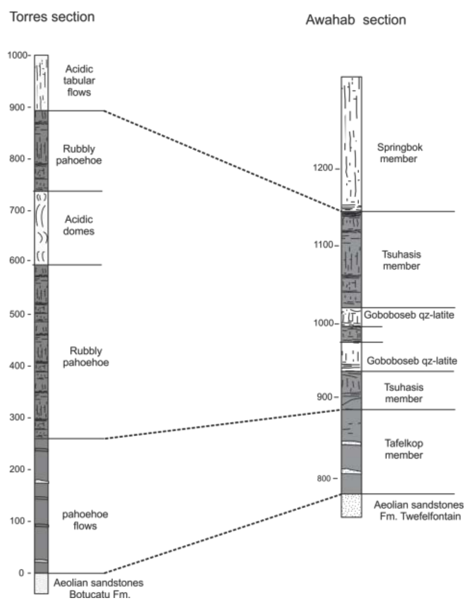

Figure 3- Correlation of Torres and Awahab sections.

The 3D model of Torres Syncline area was built with oil/gas deep wells (PETROBRAS, 18 wells), water supply wells (34 wells) and selected stratigraphic profiles. The six sections in figure 4A permits the reconstruction of the top surface of the Botucatu surface, pahoehoe lavas, rubbly lavas and acidic lavas (Fig. 4B,C,D,E). The Torres Syncline is more expressive in the basal portion of the basin (4B and 4C) and can be divided in two areas. A large uplifted area in north hinge is evident in all stages and a minor area occur at the south hinge in initial stages.

The south hinge exposed in various sections in central portion of Rio Grande do Sul state and show minor tectonics, the basal contact of volcanic sequence with sandstones vary from sea level to ~100
m. The volcanic stratigraphy in the south hinge and main valley is distinct and probably reflects the structural evolution of the syncline, related to normal- faulting processes, and the generation of sub-basins.

The north hinge of Torres Syncline was strongly affected by reverse faults probably related with the break-up process. Additionally, the intrusion of the alkaline Lages Dome affect the sequence and the basal contact of the volcanics and aeolian sandstones is up to 1.000 m high. The inclusion of reverse faults, plotted with base in lineaments observed in spatial images, was necessary to arrange the 3D model.

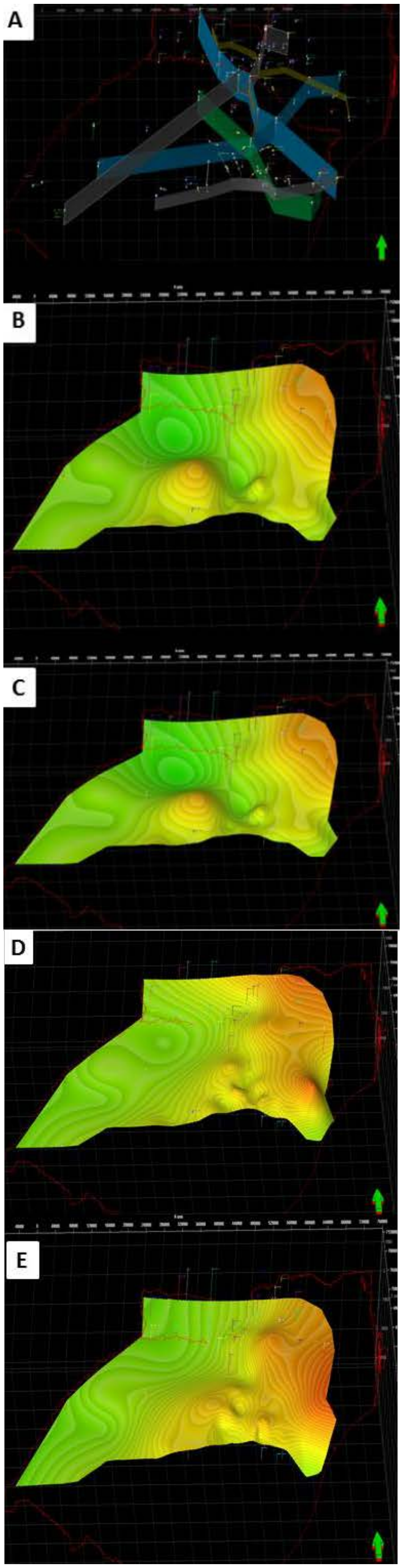

Figure 4- A) Locations of wells and stratigraphic profiles and the six sections. Red lines mark the coastal line (east side) and Rio Grande do Sul and Santa Catarina state limits.
B) Botucatu Fm. Top, C) pahoehoe lavas top, D) rubbly lavas top, E) acidic lava top.

The 3D model of the Torres Syncline area (Fig. 5) was built with the top surface of the four units show in figure 4 (Botucatu Fm., pahoehoe lavas, rubbly lavas and acidic lavas). This first model shows a good agreement with the field geology of South American side and new data from Huab basin (wells and sections) are needed to integrate the African side to the model.

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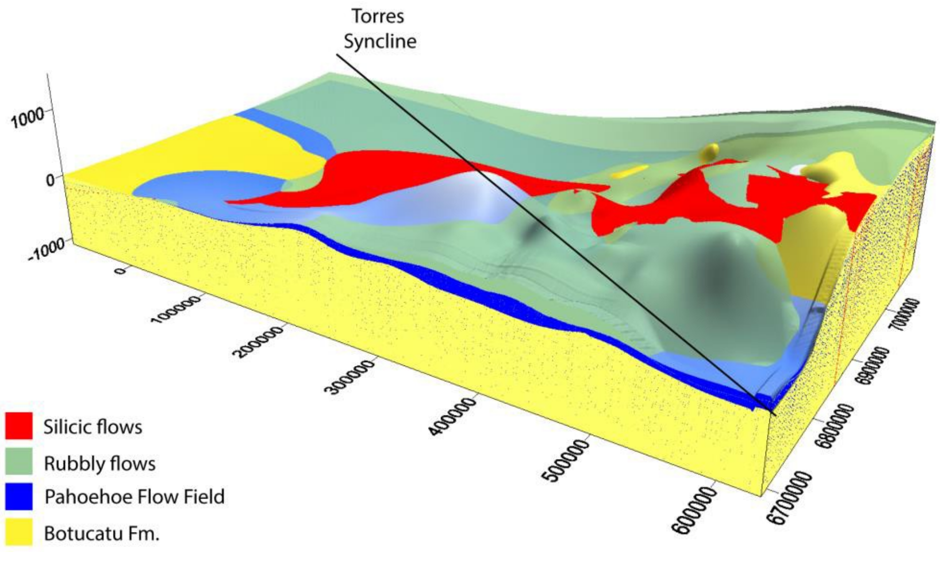

Figure 5- 3D model of Torres Syncline area built with the top surface of the four units show in figure 4 (Botucatu Fm., pahoehoe lavas, rubbly lavas and acidic lavas)

Some Insights into Rifted Margin Development and the Structure of the Continent-Ocean Transition Using a Global Deep Seismic Reflection Database

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Introduction

As deep water continental margins have been opened up for hydrocarbon exploration in recent years, the need to understand the dynamic evolution of continental margins is of paramount importance. ION's BasinSPAN™ programme was borne from the need to understand the nature of the crust across these margins. The BasinSPAN™ dataset consists of regional long-offset 2D reflection seismic, recorded to an average of 18 s TWTT, and then converted to pre-Stack Depth Migration. The data image the entire crustal thickness and complements other datasets (e.g. refraction seismic and gravity) while providing an independent method for investigating the crustal structure across rifted continental margins.

The BasinSPAN™ library covers many of the world's rifted margins (and interior basins), which can be grouped into two main categories; magma-poor rifted margins (MPRMs), and volcanic rifted margins (VRMs). While both margin types represent a transition from stretched continental crust to mature oceanic crust, the nature of the continent-ocean transition and deformation styles between the margin types appear to be quite disparate. There appears to be a fundamental asymmetry that can be observed at MPRMs, while VRMs appear to be relatively symmetric. Here, we will present seismic examples, with conjugate margin data where available, from both MPRMs (Porcupine Basin, west of Ireland; Petrel sub-basin, NW Shelf, Australia; and the E. Indian Margin), and VRMs (W. Indian Margin; and S. Atlantic). We compare and contrast the characteristics of each margin type and suggest potential mechanisms for their causation.

Magma-Poor Rifted Margins

Numerous studies of MPRMs, particularly from the Iberia – Newfoundland conjugate system, have shown there to be strong asymmetry between each of the margins (Reston, 2009; Reston & McDermott, 2011), with strain apparently being focused onto a single structure, or set of structures (Manatschal, 2004, Reston & Pérez-Gussinyé, 2007), that can potentially be matched across intervening oceanic crust (Reston & McDermott, 2011). Palanspastic restorations of interpreted seismic profiles from the W. Iberian Margin restore the crust to only 7 – 10 km thickness (Manatschal, 2004; Reston, 2009), suggesting that the detachment systems at the continent-ocean transition (COT) initiated once the crust had been thinned and embrittled (rheologically coupled due to a suppression of the brittle-ductile transition (BDT) during slow rifting) at a stretching factor (β) of 3, and 4.3, respectively. Both of these estimates for the restoration of crustal stretching above the W. Iberian detachment systems fall within the predicted range for crustal embrittlement, β = 3 – 5 (Pérez-Gussinyé & Reston, 2001), demonstrating the importance of rheological coupling in controlling deformation style within the continental crust, and the change from broadly symmetrical deformation to asymmetric deformation.

We will present profiles from hyper-extended "failed" rift basins where each basin margin forms an unambiguous conjugate pair that is not separated by large expanses of oceanic crust, making these basins natural laboratories in which to observe structures that lead to asymmetric continental breakup.

Data from the magma-poor Porcupine Basin, west of Ireland, and the Petrel Sub-basin, NW Australia, are compared with the magma-poor E. Indian margin, and the well studied Iberia – Newfoundland system.

McDermott (2013) demonstrated that with increasing extensional strain across the Porcupine Basin there is a distinct change in deformation style, likely linked to rheological coupling within the crust leading to total crustal embrittlement. Crustal embrittlement caused a change from (probably) broadly symmetric, distributed extension, to asymmetric extension focussed onto a westerly dipping detachment system – termed the P-detachment by Reston et al. (2001). Subsequent to the activation of the P-detachment strain strongly localised along it (Fig. 1), imparting a strong asymmetry between the basin margins (Reston et al., 2001, 2004; O'Reilly et al., 2006). McDermott (2013) defined stretching domains (I, β ≥ 2; II, 2 ≤ β ≤ 3; III, 3 ≤ β ≤ 5; & IV, β ≥ 5) within the basin where distinct structural styles may be expected to form – i.e. the number of cross-cutting fault generations, and where detachment tectonics initiated (Fig. 1). Here, we can clearly demonstrate these changes, and observe a distinct change in the deformation style with increasing strain, with multiple phases of faulting contributing to the crustal thinning, rheological coupling and crustal embrittlement. Changes in Moho relief are also highlighted for a given stretching domain, with the steepest Moho relief beneath the hangingwall to the P-detachment where the structure roots.

Comparing the observations from the Porcupine Basin, we show that the Petrel Sub-basin shares many characteristics with the southern Porcupine Basin, potentially having a relatively narrow zone of exhumed continental mantle at the proto-COT. Similarly, comparison with the E. Indian Margin demonstrates many of the same characteristics present on the western margin of the Porcupine Basin (as well as the Newfoundland margin). By analogy with the Porcupine data, we suggest that the overall crustal structure results from it forming the hangingwall (or root zone) of an

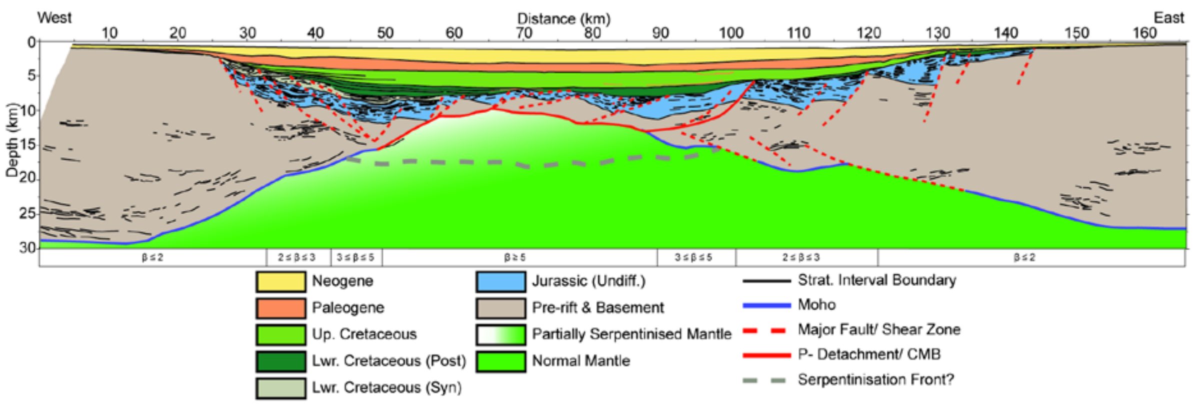

Figure 1: Geoseismic section interpreted from Line IR1-1240 (McDermott et al. in prep), part of the NEAtlanticSPAN™ dataset. Section highlights extremely thin, hyper-extended crust in the central part of the basin (averaging less than 3km thick in places). Note; in basin centre strain is focussed onto the westerly dipping (and isostatically up-bowed), P-detachment system that roots under the western margin. The P-detachment is only present where the stretching factor exceeds 3, and faults can be seen to cut through the entire thickness of the crust signifying rheological coupling has occurred. The overall basin geometry is clearly asymmetric – compare width of stretching domains on either margin. It can be seen that the stretching gradient is far greater on the narrower western margin, the hanging-wall to the P-Detachment, and this is reflected by the steeper Moho.

asymmetric (westerly dipping) detachment system that ultimately lead to mantle exhumation and the eventual establishment of seafloor spreading and oceanic crust formation.

Volcanic Rifted Margins

Recent work conducted by Pindell et al. (2014) using numerous profiles from the BasinSPAN™ library has shown very clearly the crustal structure of VRMs. Interpretations presented by Pindell et al., 2014 are in good agreement with work that has been carried out on many VRMs (particularly in the N. Atlantic using refraction seismic methods – Barton & White, 1997; etc.), and have shown that many VRMs – regardless of the side of the ocean they exist on, possess extremely similar characteristics, and so it is possible that the process of breakup is relatively symmetrical. At VRMs the thermal state is elevated, possibly due to plume related activity impinging on the base of the crust, or potentially from an increased strain rate compared with MPRMs allowing for a stronger asthenospheric upwelling during rifting. Whatever the driving mechanism, very large volumes of magma are produced at VRMs. The most commonly observed features magmatic features at VRMs are probably seaward dipping reflectors (SDRs) – lavas and volcaniclastic material that are erupted onto the surface of the thinning crust (Planke et al., 2000; Pindell et al., 2014) that are very obvious on reflections seismic data, although may potentially be confused with half graben basins. Another common feature, at VRMs high-velocity lower crust (HVLC), or magmatic underplate. The HVLC probably results from large amounts of mafic melt being intruded into the lower crust increasing its density and velocity. Evidence for the HVLC is commonly observed on refraction profiles crossing VRMs (Barton & White, 1997; Vogt et al., 1998; and many others). HVLCs are known from all of the world's VRMs, and have in some cases also been imaged spectacularly on the BasinSPAN™ 2D reflection data, as demonstrated by Pindell et al., 2014.

The COT at VRMs almost invariably contains SDR packages that interact in various ways. We will present data from the W. Indian Margin that may represent a potential COT "type section" for VRMs, recording crustal subsidence as the crust is pulled away from the rift axis and is submerged. We will demonstrate a clear transition from subaerial lava flows (SDRs) to shallow water hyaloclastite mound formation, to deep water pillow lavas and normal seafloor spreading.

We will also present a section passing from the W. Indian Margin, crossing the Laxmi Basin (that we interpret as proto-oceanic – oceanic crust), onto the Laxmi Ridge (interpreted as a micro-continent, that has been deformed during two breakup phases – one to the east and one to the west), and out onto the Indian Ocean. This profile provides an unambiguous conjugate margin pair between the W. Indian Margin and the Laxmi Ridge, and so is an excellent location to study magma-rich continental break up.

We will demonstrate that the margins are broadly symmetrical with the same features observable on each side of the proto/abandoned Laxmi ocean basin. We will present the typical COT of a VRM on both margins; a HVLC forming a relatively gentle Moho topography rising from beneath the Lamxi Ridge eastwards, and from beneath the Indian Margin westwards, to merge with the oceanic Moho beneath the Laxmi Basin. There are also well developed SDRs that apparently thicken towards the Laxmi Basin from each margin, further strengthening the case for relatively symmetrical breakup between the margins. We will also demonstrate the general landward dip of the major rift related faults on the margins (complications due to multiple breakup events notwithstanding) at the Laxmi – India conjugate system, as have been observed on the majority of the VRMs investigated by Pindell et al., 2014.

Variance in Structural Style & Possible Mechanisms

As is clearly demonstrated from the Porcupine Basin profiles (Fig. 1), there is a marked crustal asymmetry observed at MPRMs. This is particularly evident in the hyper-extended, and COT domains where a diverse Moho topography exists. This topography relates to the point at which the crust becomes embrittled, and where the asymmetric (detachment) faults associated with the hyper-extended domain root directly along the crust-mantle boundary (Reston & McDermott, 2011), resulting in a steep Moho topography in the detachment's hangingwall, and a more gentle dip in the footwall. This structure is the same feature that has been termed the outer marginal detachment (OMD) by Pindell et al., 2014.

At VRMs, as will be exemplified by the Laxmi Basin system, the Moho topography is relatively gentle in the COT, with the Moho gradually rising to typical oceanic Moho depths. There appears to be a balance between the thickness of the magmatic addition to the crust (in the form of extrusive material, and intrusive/ underplated material, (Pindell et al., 2014)) and potentially extensional strain rate.

Structurally, MPRMs appear to generally be dominated by faults that dip towards the basin, whereas at VRMs the major faults tend to dip landward. From our observations, we will suggest that these differences are most likely a result of differing thermal states, and strain rates affecting the rheological evolution of a particular margin during rifting.

Where rifting is extremely slow (c.f. MPRMs) it has the effect of suppressing the brittle – ductile transition (BDT) beneath the rift zone forcing it to be deeper in the lithosphere (potentially within the mantle – effectively causing the entire crust to become brittle) than on the basin margins which in turn imparts a riftward dip to the BDT – effectively forming a ductile "detachment" zone. Whereas, when the thermal state (and potentially strain rate) are elevated (c.f. VRMs) the BDT may be uplifted in the central part of the rift (Pindell et al., 2014), effectively forming a ductile detachment dipping landward. The regional dips imparted on the BDT at MPRMS, and VRMs may play a fundamental role in deciding the structural style of the margins. Stewart & Argent, 2000 demonstrated that supra-detachment extensional faults tend to preferentially form synthetically to the regional dip of a detachment zone. Therefore, it is reasonable to assume that the dominant dip for rift related faults at MPRMs will be riftward, and landward at VRMs, just as is observed.

Conclusions

Using ION's BasinSPAN™ long offset 2D data it is possible to confidently compare the overall geometries and crustal structure of rifted continental margins. The structure of Continent-Ocean Transition is very well imaged, and valuable insights to the margin's formation may be extracted.

We have suggested that the strain rate and the thermal state of the lithosphere (i.e., plume, or active asthenospheric upwelling) are key components in the eventual symmetry, or asymmetry that is expected at a given rifted margin. From the profiles we will discuss we will show that magma-poor margins tend to be strongly asymmetric, while volcanic margins appear to be broadly more symmetric. The differences in symmetry appear to apply to both the structural style, and overall margin geometry. We will show that riftward fault dips dominate at MPRMs, with the development of low-angle detachment systems at the COT, and landward fault dips dominate at VRMs, with voluminous magmatic addition forming the characteristic SDRs, and HVLC/ underplated material at the COT. The disparity in crustal structure is also clear from Moho topography at MPRMs and VRMs, with a sharper, more pronounced Moho relief present at MPRMs. The likely cause of this relief at MPRMs is crustal coupling and initiation of detachment tectonics, compared with the more gradual rise in Moho depth at VRMs due to magmatic addition/infiltration at the base of the stretched continental crust, and partially because the Moho is not exhumed to the seafloor.

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Petroleum systems and risk elements of the Central Atlantic Margin- offshore Eastern Canada

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The key elements of effective petroleum systems in the Central Atlantic conjugate margins are the presence of source rock and reservoir. Trap formation and migration are less of a risk with active tectonics along the margin. If there is salt present additional play concepts can be generated. The extensive source rocks and reservoir analogs cropping out on the Western European and African conjugate margins can test play concepts, improving the chances of success.

Coastal exposures of Mesozoic sediments in the Wessex (UK) and the Lusitanian (Portugal) basins provide key insights to the petroleum systems being exploited for oil and gas offshore Atlantic Canada. These coastal areas have striking similarities to the Canadian offshore region, in large measure due to shared tectonic episodes, and provide insight to controls and characteristics of the reservoirs. Outcrops demonstrate a range of depositional environments from terrigenous and non-marine, shallow siliciclastic and carbonate sediments, through to deep marine sediments, and clarify key stratigraphic surfaces representing conformable and non-conformable surfaces. Validation of these analog sections and surfaces can help predict downdip, updip and lateral potential of the petroleum systems, especially source rock and reservoir.

Research in the Basin and Reservoir Lab of Dalhousie University focus on petroleum system and risk element analysis on the Nova Scotia, Newfoundland, and Labrador shelves and deepwater offshore. Research on time-equivalent sedimentary series of cores and cuttings from well data offshore eastern Canada and associated conjugate margins (Morocco, Portugal, Spain and Ireland) within a well-defined stratigraphic framework improves our understanding of source rock, overpressure and reservoir distribution.

The reliance on lithostratigraphy in all areas of the Central Atlantic margin mean that time equivalent lithofacies variations are misinterpreted, for example in predicting overpressure conditions. A number of unconformities are not resolvable on seismic and may be interpreted as one unconformity. These unmapped unconformities are significant and mark the potential for downdip transport of reservoir quality sediments in to the basin. Seismic data can help predict reservoir but seldom aids in defining reservoir quality and on a larger scale, plate reconstructions tend to rely solely on subsurface data, particularly seismic and derivatives of the seismic data for model development.

There is a need to define basin-wide unconformities with greater precision and develop a sequence stratigraphic framework of unconformities and potential condensed sections that can produce source rock. A confirmed petroleum system is present in the Flemish Pass Basin on the Newfoundland Margin that should decrease exploration risk in the adjacent Orphan Basin to the north. Exploration potential is often contingent on the presence of source rock. We can point to downdip deeper water reservoirs that may be sourced from up-dip deltaic systems, e.g. the Sable and Morocco delta systems. These deeper water reservoirs are often encased with excellent seal rocks and within the fetch of condensed sequences that may form potential source rocks. What new exploration concepts and play types are possible?

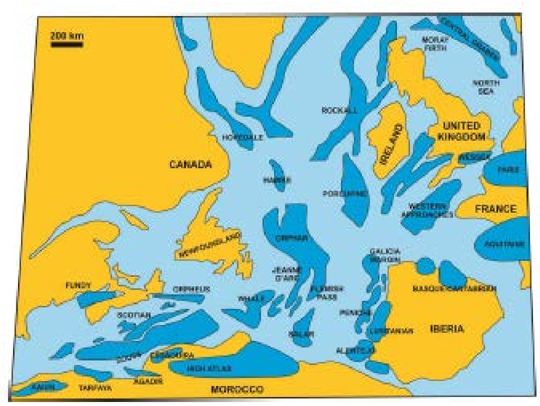

Figure 1. Location of several sedimentary basins formed by the rifting and seafloor spreading that began in the Late Triassic, leading to the opening of the Atlantic Ocean (modified from Tankard and Balkwill, 1989; Decourt et al., 2000, among others).

Go Deep - Status of Exploration Offshore Ireland and a Major New Seismic Survey

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Successful promotion by the Irish Government in recent years, focussed principally on the prospectivity of Ireland's offshore, has been a positive factor in attracting increased interest in exploration investment. This was and continues to be supported by research initiatives aimed at deepening the understanding of Ireland's offshore petroleum potential.

The results of Ireland's most recent Licensing Round, in 2011, were positive. The 2011 Atlantic Margin Licensing Round resulted in 13 new exploration authorisations being awarded compared with 1 following the 2009 Rockall Round and 4 following the 2007 Porcupine Round. A wide variety of exploration targets are recognised from Tertiary to Permo-Triassic; from non-marine fluviatile & aeolian to basin-floor fans with a significant proportion of the Licences having Cretaceous deep marine sandstone objectives. The number of companies and exploration authorisations now in place is at the highest level since exploration began in the 1970s. Furthermore, the recent entry of new exploration companies to the Irish Atlantic Margin, namely Cairn Energy, Kosmos Energy and Woodside Energy; all with significant international deepwater exploration experience is testament to the success of the Round. These new entrant companies are being attracted in part by new exploration targets.

To the south, interest in the Celtic Sea area has re-ignited, partly due to the drilling success at Barryroe and a record number of new Licensing Options, with associated substantial work programmes, including seismic acquisition, have been awarded in the Celtic Sea and the Fastnet Basin.

2013 saw a marked increase in the level of new 2D and 3D seismic acquisition offshore Ireland. A total of 13,650km of 2D and 5,500km^2 of 3D seismic data were acquired, compared with a total of 1,500km^2 of 3D and no 2D acquisition for the previous three years. In 2013 the first phase of a major, Government designed, 2D regional seismic survey was carried out in the Atlantic, with over 10,000km of new data acquired across the Atlantic basins including the Porcupine, Rockall, Hatton, Fastnet, Clare Basins and along the conjugate margin. This is the largest 2D seismic survey acquired to date in Irish waters. The second phase of this survey is being carried out in 2014. The new data from this survey will fill data gaps and aid research in petroleum systems.

On 18 June 2014 Ireland's Minister for Natural Resources Fergus O'Dowd announced the details of the 2015 Atlantic Margin Oil and Gas Exploration Licensing Round. The Round will include all of Ireland's major Atlantic basins: Porcupine, Goban Spur, Slyne, Erris, Donegal and Rockall. The form of concession on offer will be a two year Licensing Option. For the 2015 Round the overall Atlantic Margin is divided into three regions. The maximum number of blocks that can be applied for in each region is as follows:

- For the Donegal Basin , Erris Basin and Slyne Basin Region, a limit of four blocks applies, due to the smaller size of these basins;
- For the Porcupine Basin and Goban Spur Basin Region, the approach of the 2011 Round is repeated and applications can be made for up to six blocks; and
- For the Rockall Basin Region, the maximum area that may be applied for in a single application is up to ten blocks. The increase in the maximum number of blocks per application to ten in the Rockall Basin is intended to stimulate exploration in a relatively underexplored frontier area of Ireland's offshore.

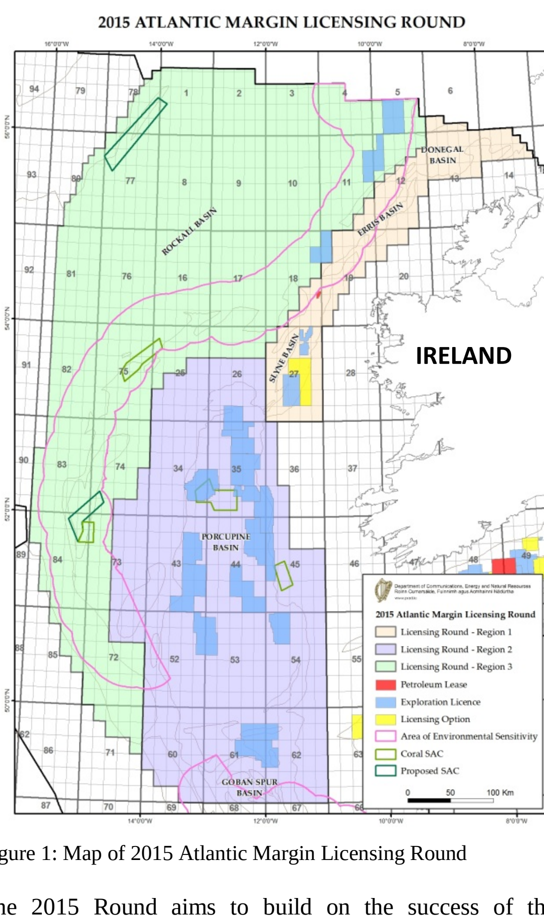

Figure 1: Map of 2015 Atlantic Margin Licensing Round

The 2015 Round aims to build on the success of the previous 2011 Atlantic Margin Licensing Round.Data from the Department's new regional seismic survey will be available and should help inform applications to be made under the Licensing Round, which closes on 16th September 2015.

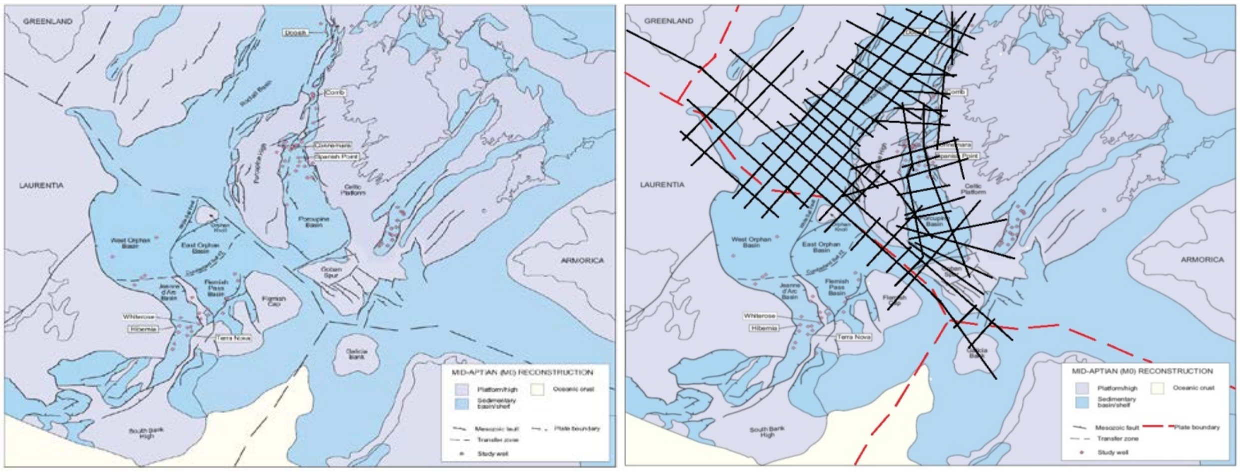

Figure. 2a and 2b: Plate reconstruction of the North Atlantic shows a juxtaposition of the Rockall and Porcupine basins with the Orphan and Flemish Pass basins offshore Newfoundland in Mid-Aptian time. Figure 2b shows the extent of the newly acquired regional seismic survey acquired in 2013 and 2014 by Ireland's Department of Natural Resources and Eni. The combined plate reconstruction data and new mega-regional seismic data will give fresh insights into the distribution of exploration plays, including depositional environments and reservoir prediction, between Atlantic Ireland and the more mature petroleum provinces of eastern Canada.

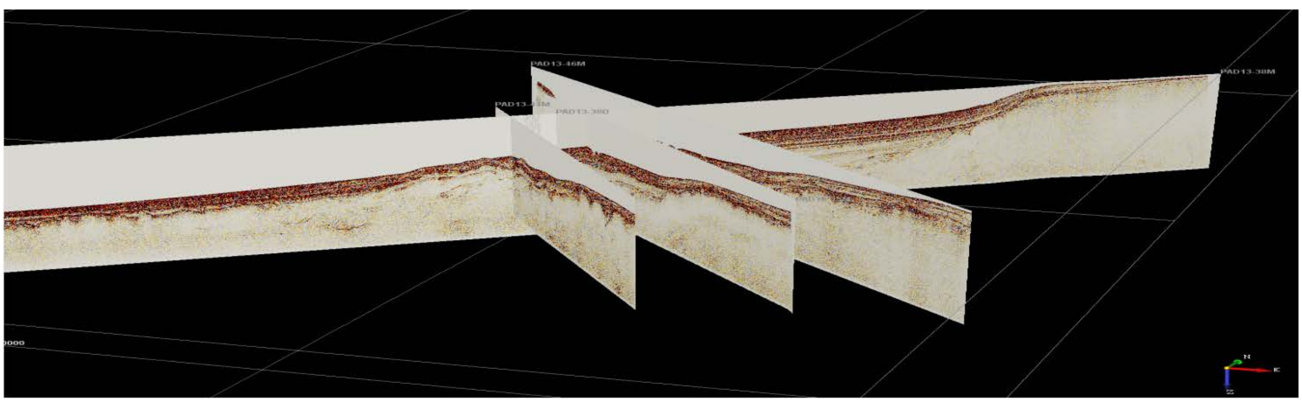

Figure 3. Illustrates the regional extent of the new seismic dataset and long cable deep imaging. The longest line in the survey is 1338km.

This upswing in exploration effort offshore Ireland, both in terms of number and strength of exploration companies active in the Irish offshore and in the level of new seismic acquisition is hoped will, in due course, lead to increased drilling levels, which are currently very low. However, despite this continued low level of drilling activity, it is encouraging that the current exploration status offshore Ireland is healthy and the exploration momentum continues to increase.

Carson Basin, Offshore Newfoundland: an Underexplored Basin with Significant Petroleum Potential

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Jeanne d'Arc and Flemish Pass basins and the Central Ridge are the oil proven subdivisions of the Newfoundland Continental Margin. The Carson Basin is a lateral branch of the same Mesozoic rift system.

Location

The Carson Basin is a complex basinal area located on the eastern divergent margin of the Grand Banks and extending from the continental shelf to the abyssal plain, in water depths from 100 to 4,000 m (Figure 1). The deep part of the basin was earlier described in detail by Tucholke et al. (1989) and, Austin et al. (1989), while Enachescu (1992) provided a regional overview of the basin.

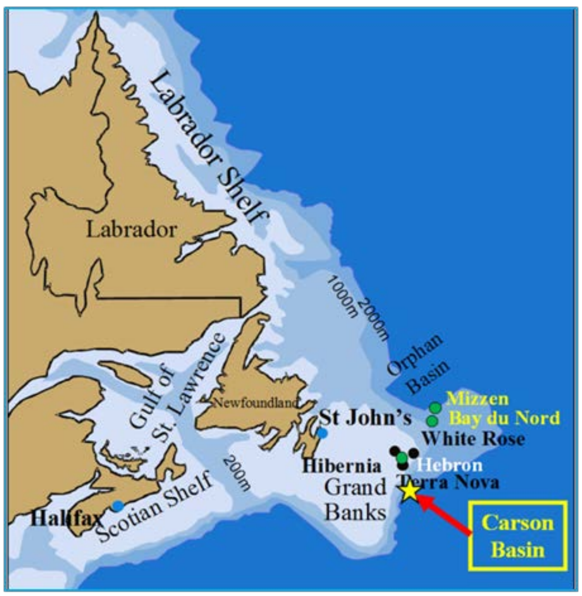

Figure 1: Location of Carson Basin, offshore Newfoundland. Producing oil fields are Hibernia, Terra Nova and White Rose (black dots). Hebron field is in development and Mizzen and Bay du Nord are new oil discoveries in Flemish Pass Basin(green dots).

Regional Setting

This approximately 30,000 km^2 large basin is a Mesozoic extensional area developed over stretched Precambrian to early Paleozoic meta-sediment to sedimentary basement, now found on the continental shelf, slope and rise of Newfoundland. Situated geographically in front of the Grand Banks of Newfoundland, the Carson Basin is another branch of the North Atlantic Mesozoic rift network, which developed on continental and transitional crust and extends out to the first occurrence of oceanic crust.

The boundaries of the Mesozoic Carson Basin are loosely defined. Based on tectonic and structural setting, the position on the continental margin and composition of sedimentary fill, the Carson Basin can be divided into three distinct sectors (Figure 2):

1. *The shelfal sector,* located on the easternmost part of the Grand Banks of Newfoundland that has been severely eroded by both Albo-Aptian-aged Avalon and Base Tertiary unconformities. The sector is separated from the Jeanne d'Arc Basin by a basement ridge trending approximately NE-SW and from the slope part of the basin by a basement ridge capped in places by Late Triassic Argo Formation salt. Late Triassic to Quaternary successions were drilled in this sector of the basin, however Late Jurassic source rocks are absent at the well locations, likely due to non-deposition on basement highs or erosion in the proximity of the Avalon Uplift;
2. *The slope and upper rise sector,* separated from the on-shelf part by a basement ridge trending approximately NE-SW (hinge zone) and from the deepwater basin by a tortuous fault zone and high ridge, both mapped in deepwater. Seismic data suggests that this sector contains the entire Mesozoic sedimentary section including Late Triassic beds and remarkable salt features. Large and complex structures are mapped in this sector including roll-overs in front of deep penetrating listric faults. This sector has high petroleum potential;
3. *The deepwater sector,* located east of a fault system dividing the deepwater region and generally containing a thinner Mesozoic section. The sector is complexly structured. Tilted basement blocks, circular salt structures and transitional zone-like mounds (peridotite mounds?) intertwined with minibasins containing deformed Mesozoic layers are mapped in the deepwater sector. Some of the blocks show slight inversion probably due to transtension or isostatic rebound.

The slope and upper rise sector together with the deepwater sector form what is known in the literature as the Salar Basin and in the industry as Deepwater Carson Basin. For simplification of nomenclature and ease of reference we recommend the term **Carson Basin** to be used for the entire sedimentary area stretching from the Grand Banks shelf to the first occurrence of uncontested oceanic crust (Figure 2).

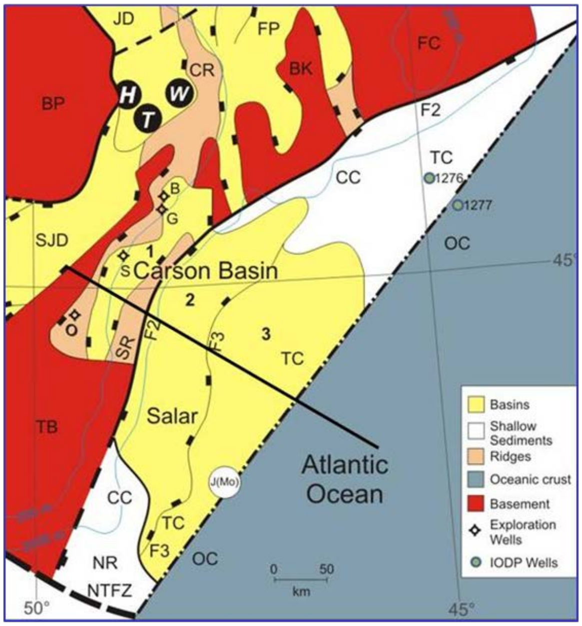

Figure 2. Location of Carson Basin in continuity with other Grand Banks shelf and slope basins and subbasins (modified after Enachescu, 1988, 1992a and b). Subdivisions are marked as 1) On shelf sector, 2) Slope and upper rise sector and 3) Deepwater sector. Exploration wells are: O = Osprey H-84, S =Skua E-41, G = St. George J-55 and B = Bonnition H-32. Notations are: NTFZ = Newfoundland Transform Fault Zone (continent/ocean), NR = Newfoundland Ridge, TB = Tail of the Bank, SR = Salar Ridge, SJD = South Jeanne d'Arc Basin, JD = Jeanne d'Arc Basin, FP = Flemish Pass Basin, CR = Central Ridge, BP = Bonavista Platform, BK = Beothuk Knoll and FC = Flemish Cap. CC = continental crust, TC = transitional crust and OC = oceanic crust. F2 and F 3 are major fault trends in the basin. Producing oil fields are: H = Hibernia, T = Terra Nova and W = White Rose. The black line shows the track of the generalized geological cross-section illustrated in Figure 3.

Basin Evolution

The Late Triassic to Early Jurassic rifting of Pangea created a chain of NE-SW oriented intracratonic basins extending from the Gulf of Mexico to the Barents Sea. The Carson and Lusitanian basins were joined and aligned parallel to the main NE-SW Mesozoic rift trend (that included the Jeanne d'Arc and the Flemish Pass basins) (Enachescu, 1987 and 1992a). The Carson Basin was a parallel trough of the main rift branch. In the late Early Cretaceous the basin detached from its Iberia pair and drifted northwestward during the North Atlantic Ocean opening. Unlike its Iberia conjugate basins, the Carson Basin was subsequently not affected by the Alpine inversion that influenced the late evolution of most of the European offshore basins.

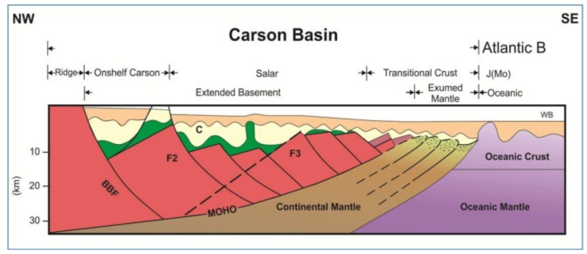

Figure 3. Schematic geological cross-section of the Carson Basin (modified after Enachescu, 1992a and b). Location of cross-section is given in Figure 2.

Currently the Carson Basin represents the eastern arm of the intra-cratonic network of rift basins that was initially developed on the Canadian margin during Late Triassic-Early Jurassic. The basin shared a common tectonic, structural and stratigraphic evolution from Late Triassic to late Early Cretaceous with several of the Grand Banks' basins including the oil prolific Jeanne d'Arc and Flemish Pass basins.

The geological evolution of the Carson Basin was largely characterized by repeated intra-continental Mesozoic rift stages, intermediary postrift episodes, oceanic rifting and drifting and final post-rift thermal sag Based on regional drilling and seismic mapping on the Newfoundland margin, it is assumed that the Carson Basin generally accumulated a similar sedimentary successions that filled the Jeanne d'Arc and Flemish Pass basins.

Lithostratigraphy

The basin's fill includes Late Triassic to Mid Jurassic red beds, salt, limestone and dolomites, followed by Late Jurassic to mid-Cretaceous predominately clastic sequences. A mostly shaley sequence which includes several slope and basin-floor fan sequences that may contain quality sandstone reservoirs characterizes the Late Cretaceous to Quaternary cover (Grant et al., 1988; McAlpine, 1989 and 1990; Hogg and Enachescu, 2007 and 2008). Some of these sequences that included sandstone reservoirs were encountered in the wells drilled on the shelfal basin (Figure 4). The lithostratigraphy displayed by the C-NLOPB on its website that is characteristic for the Jeanne d'Arc Basin and environs can be cautiously applied to the Carson Basin.

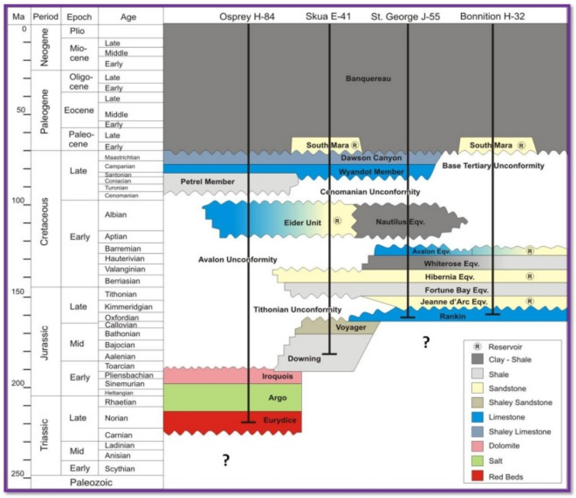

Figure 4. Chronostratigraphy of main geological formations intersected by the four exploration wells drilled on the Carson Basin shelf. These formations were described in detail by Grant et al. (1988) and McAlpine (1990). The Eider Unit is a southern Grand Banks succession-time equivalent to the Ben Nevis Formation from the Jeanne d'Arc Basin (figure modified after Grant et al., 1988 and Solvason, 2006).

Petroleum geology

Four early exploration well penetrations, in the 1970s and 1980s, were unsuccessful in the shelfal portion the basin intersecting good quality reservoirs but did not intersect the source rock, probably due to wells being positioned on basement highs or salt diapirs (Figure 4).

Source Rocks. The most significant source rock in the basin is almost certainly to be the Egret Member of the Rankin Formation of Kimmeridgian age or its equivalent. This unit is the prolific source rock that sourced all the discoveries of the Jeanne d'Arc Basin. The Egret source rock is an oil prone, marine-derived Type II carbonaceous shale with up to 9% (average 4.5%) Total Organic Carbon (TOC). Over 25 exploration wells have penetrated the Egret Member source in the Grand Banks and environs. Another possible source rock is the Turonian to Albian black shale intervals drilled by IODP during Leg 210 at sites #1276 and #1277 (Arnaboldi and Mayers, 2007), although in most parts of the basin it will be in immature to early mature window.

Reservoir Rocks. Reservoir rocks in the Carson Basin should be good quality, quartz rich sandstones deposited in marine shoreface to deepwater settings. The resulting reservoirs will be high porosity and permeability sandstones of Late Jurassic to late-Early Cretaceous age similar to that encountered in the neighboring basins. Two of the wells drilled on the shelf of the Carson Basin, Bonnition H-32 and St. George J-55, encountered Late Jurassic and Early Cretaceous sandstone reservoirs equivalent in time to the Jeanne d' Arc, Hibernia and Avalon sandstones which are all producing oil in the discovered fields of the Jeanne d'Arc Basin. These wells also intersected Late Cretaceous and Early Tertiary reservoir units (Grant et al., 1988; McAlpine, 1989 and 1990; Solvason, 2006).

Seals. Seal should not be a problem for hydrocarbon traps within the Carson Basin as its Extensional and Thermal subsidence stages (Enachescu, 1992) contain regionally distributed successions of very fine clastics, lithified sandstones and regional tight deepwater carbonates. Good seal intervals such as the Downing, Rankin, Fortune Bay, Whiterose, and Nautilus formations were found in the four wells drilled in the Carson Basin (Figure 4). The postrift Petrel Member, Wyandot Limestone and the thick syndrift Tertiary fine clastics of the Banquereau Formation are basin-wide seals.

In a Geological Survey of Canada study, Wielens et al. (2004 and 2006) have considered that an Egret Member or an Egret equivalent source rock distributed on the slope and in the deepwater basin and having 4% average TOC, a Hydrogen Index (HI) of 600 and a thickness of 50 m could have generated 200 billion barrels of oil equivalent (GSC Open File 4739). Their model assumes a closed, non-breached system, which is highly unlikely to exist in the faulted and salt intruded, late synrift and postrift sequences of the basin. However, a material volume of hydrocarbons may have been preserved and is now accumulated in sandstone reservoirs within structural traps located in deeper water. This is the most coveted hydrocarbon play in the basin.

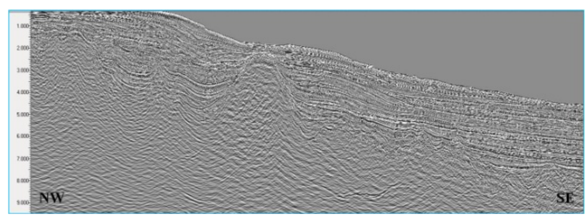

Figure **5.** Regional 2D dip seismic line crossing the shelf, slope and rise of the Carson Basin with examples of undrilled structural and stratigraphic traps (seismic line provided by TGS).

Hydrocarbon Traps. The numerous structural traps found in the Carson Basin are associated with 1) basement highs due to recurring rifting of the Atlantic Margin, 2) gravity faulting, 3) minor transtension and inversion features, 4) differential subsidence and tilting, and 5) gravity-induced movement of the Argo evaporites. The main structural trap types are extensional anticlines, roll-overs, faulted anticlines, faulted and tilted blocks and elongated horsts that may involve the basement or are restricted to the synrift sequences (Figures 5 and 6). Stratigraphic traps are also be widespread in the Carson Basin. Paleo-valleys, basin margin and basin floor fans are interpreted on seismic data available in the basin.

The basin's typical hydrocarbon play is *a structural high (extensional anticline, roll-over anticline, horst, rotated block, faulted anticline, salt anticline or drape anticline),* *with any of the Jeanne d'Arc, Hibernia, Avalon equivalent*

sandstones (primary target) and/or Late Cretaceous and Paleocene sandstone (secondary target) sourced from Late Jurassic marine source rocks.

A numerical 4D basin model for the frontier Carson Basin was produced by Baur et al. (2009) to provide a fast and inexpensive resource assessment. They used a Type II kerogen with a homogenous TOC of 4% and a Hydrogen Index of 60 in the model. The modeling showed that significant volumes of hydrocarbons may have been generated, from an "Egret equivalent" source rock mainly during the Late Cretaceous-Early Tertiary (also Wielens et al., 2006). Due to migration inefficiencies (seeps, alteration, etc.) the volume of oil that will be trapped is reduced to about 10%, meaning that about 5 Bbbls could be present in the reservoirs of the Carson Basin (Baur et al., 2009).

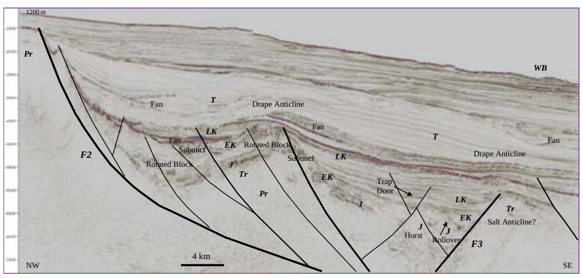

Figure **6.** Interpreted 3D dip seismic line with examples of undrilled structural and stratigraphic traps in the northern Carson Basin (seismic line provided by C-NLOPB). F2 and F3 are major faults shown also in Figures 3, 12 and 13. Notations are: Pr = Precambrian basement, Tr = Triassic, J = Jurassic, EK = Early Cretaceous, LK = Late Cretaceous, T = Tertiary, Subuncf = subunconformity trap.

Conclusions

Carson Basin, a divergent margin basin, had a similar tectonic and structural evolution with adjacent Jeanne d'Arc and Flemish Pass basins, including basement extension, synrift sediment deformation and salt diapirism. Basin fill and stratigraphic divisions are also similar with the neighboring Jeanne d'Arc and Flemish Pass basins and include equivalent reservoir and source rock formations.

To date, no wells have been drilled on the slope, upper rise or deepwater sectors where seismic data indicates presence of thick Mesozoic successions including Late Triassic salt and Late Jurassic sediments that should contain Egret Member source rock or equivalent organic rich shales. Large and complex structures are mapped in this sector including roll-overs in front of deep penetrating listric faults as well as a multitude of combination structural/stratigraphic and stratigraphic traps.

The Carson Basin is a high-risk/high-reward exploration area and is unique in that its slope and deepwater are practically unexplored. The basin is close to the major producing fields of the Jeanne d'Arc Basin, located just south of the Flemish Pass Basin's new discoveries and also close to North America's largest petroleum markets.

Acknowledgements

Thanks are due to NL Department of Natural Resources, C-NLOPB and TGS. Karen Waterman of DNR helped with two illustrations and Steve Whidden of TGS provided a regional seismic line.

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Application of CSEM along the Conjugate Margin.

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EMGS is a publicly-traded Norwegian geophysical company focused on the acquisition, processing and interpretation of marine electromagnetic (EM) data. Receivers are deployed on the seafloor in a grid pattern and then an active EM source is lowered into the water and carefully towed above the receivers. The source transmits a specific EM signal which enters the subsurface and the resultant data is processed to detect changes in resistivity in the subsurface. EM data, when properly integrated with other data types such as seismic and well log data, can provide significant insight into the geological picture, including the possibility of high resistive hydrocarbon accumulations. The data can also be used to better refine the geometries of deep geologic structures which in turn can lead to a better overall image of the subsurface.

EMGS is currently acquiring a 3D multi-client EM survey offshore Newfoundland. This survey represents the first in a series of planned regional EM acquisitions that will tie subsurface resistivity signatures with other key exploration data elements in the area. The first survey will include the recent discoveries in the Flemish Pass basin as well as open acreage that will be made available in the upcoming lease round in 2015.

The status of the ongoing survey will be presented as well as data from a similar multi-year EM campaign in the Barents Sea where there has been over 30,000km2 of data acquired and processed over a 5 year period.

Comparisons between the Deep Crustal Structure of Magma-Poor and Volcanic Passive Margins

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Zag Consulting in Petroleum Exploration Ltda., Rio de Janeiro, Brazil

Introduction

Studies carried out by academic organizations and petroleum industry companies in the conjugate continental passive margins of Iberia-Newfoundland and of the South Atlantic, together with field studies dealing with the reconstitution of ancient passive margins present nowadays as tectonic relicts in fold-and-thrust belts such as the Alps and the Pyrenees, yielded a clearer image of the crustal structure underneath magma-poor margins. This type of passive margin is characterized, from onshore to offshore, by a horizontal zoning constituted by: (1) the original unstretched continental crust with thicknesses varying between 30-40 km; (2) stretched continental crust, where stretching is already significant (few minor grabens) but thinning is not; (3) thinned continental crust, where both stretching and thinning are very significant (several major deep grabens) and, eventually, aborted necked regions (**H-Blocks**) are preserved as aulacogens; (4) the final stretch of continental crust where hyper-extension dominated, where both the upper elastic and lower plastic crusts are deformed by brittle processes (several shallow highly rotated grabens) due to their extreme thinning; (5) exhumed mantle, under the form of a belt of varying width (up to several tens of kilometers), presenting or not overlying grabens, and; (6) oceanic crust, with crustal thicknesses ranging between 9-11 km. The COB is usually placed at the external limit of the exhumed mantle.

On the other hand, field studies carried out by academic institutions in the eastern and western margins of Greenland and by petroleum industry companies in the conjugate continental margins of the Pelotas Basin, in Brazil, and off the Namibia coast in Africa, displayed the rather different crustal structure underneath volcanic margins. This type of passive margin is characterized, from onshore towards the offshore direction, by a horizontal zoning constituted by: (1) unstretched continental crust covered by extensive traps of basaltic lava flows (pre-rift volcanism), (2) a significant necking zone where the thickness of the continental crust diminishes from 40 km to around 20 km in a short distance, where extremely deep grabens may develop (up to 20 km thick), (3) thinned to hyper-extended crust covered by large and highly rotated grabens filled entirely by volcanic material (SDR, seaward-dipping reflectors, basaltic lava flows interlayered with volcaniclastic material), and, (4) oceanic crust. The COB is usually marked where the increasingly shallowing-upwards Moho below the continental crust is flattened around 12-15 km of depth. No signs of exhumed mantle are found in volcanic passive margins.

This work presents and discusses idealized crustal structure models for both end-members of passive margins: Magma-poor (or Sedimentary) and Volcanic Passive Margins. Transitional forms between the end-members, Transitional Passive Margins, are also presented. Brazilian offshore sedimentary basins are used as basis for this sub-division.

Magma-Poor Passive Margins

Magma-poor Passive Margins were defined and have been extensively studied in the last 10 years (Manatschal, 2004; Manatschal et al., 2007; Péron-Pinvidic and Manatschal, 2009 and 2010; Péron-Pinvidic et al., 2013). These studies relied on: (1) the results of deep sea drilling in the conjugate margins of Iberia and Newfoundland, and (ii) on field studies carried out in the Alps and Pyrenees, where ancient Tethyan passive margins are exhumed and preserved amidst intensive folding and thrusting. Ultra-deep seismic sections available to the petroleum industry were interpreted and analyzed utilizing these new concepts, mostly in the South Atlantic. The scant publication of these results show a good correlation between the theoretical concepts and the crustal structure underlying the Brazilian and West African passive margins (Zalán et al., 2009 and 2011; Zalán, 2013; Unternehr et al., 2010; Kumar et al., 2012).

In the Southeastern continental margin of Brazil, the prolific Santos, Campos and Espírito Santo Basins constitute prime examples of Magma-Poor Passive Margins (Zalán et al., 2009 and 2011; Zalán, 2013). Based on the results obtained by these authors in the interpretation of ultra-deep seismic sections shot by ION/GXT an idealized model for these types of margins was developed (Figure 1). Going from onshore to offshore, the following domains of the underlying continental crust can be usually recognized in an overall taper profile: (1) the **original, unstretched continental crust**, with thicknesses in the order of 32-35 km, eventually 40 km; followed by a first mild necking zone, where the crust thins from 32 to around 25 km, above which a hingeline in the shallow basement marks the border of the sedimentary basin, succeeded by (2) **stretched continental crust**, where stretching is significant (with several grabens on top) and thinning is not, although clearly present. The next domain is (3) thinned crust, where both stretching and thinning are very significant. It can be represented by a single significant necking zone amidst the stretched continental crust, above which an aulacogen is developed (**Block H** of Manatschal and co-workers) or as a gradual continuation of the taper profile from stretched to thinned crust. The rule in these three Brazilian basins is that a **continental ribbon** (with thicknesses close to original crust) of resistant continental crust follows the internal necked zone (thinned crust). The continental ribbon passes abruptly into the (4) **hyper-extended crust**, most of the time via two large-scale crustal faults. The hyper-extended domain is characterized by extreme thinning of the crust and the coupling of lower and upper crust into a single unit that displays extreme extensional brittle strain. Several highly rotated seaward-dipping normal faults seem to detach in the Moho. Its thickness may vary from 10 to 0 km in a highly variable horizontal distance (narrow to wide). Numerous deep grabens developed on top of this region. As the hyper-extended domain thins away (tapers out) (5) **exhumed mantle** invariably follows, forming a continuous belt of variably serpentinized material circa 1500 km in length and 15-70 km wide. The exhumed mantle displays the same brittle strain of the adjacent hyper-extended crust and may hold grabens of significant size atop of it. The COB is usually placed at the external limit of the exhumed mantle. (6) **oceanic crust** follows, with crustal thicknesses ranging between 9-11 km.

This idealized profile (Figure 1) may show some variations. For instance, in the Espírito Santo Basin there are no clear H-Block and continental ribbon. The overall profile is a narrow continental margin with a regular high taper profile (original, to stretched, to thinned and then to hyper-extended crustal domains). The Santos Basin is a very wide continental margin with an overall boudinage crustal profile of very low taper, constituted by two necking zones and two intercalated continental ribbons

Volcanic Passive Margins

Volcanic Passive Margins have been less studied and understood than Magma-Poor Margins. The field works carried out by Prof. Laurent Geoffroy in both Eastern and Western continental margins of Greenland and in the Afar Triangle are examples of such studies (see, for example, Geoffroy, 2005). They had shed some light on the structure and composition of these margins. Ultra-deep seismic sections available to the petroleum industry were interpreted and analyzed utilizing the concepts developed in these works, mostly in the South Atlantic. The Pelotas Basin in Brazil and the Namibian margin in West Africa are prime examples of Volcanic Passive Margins. The recent publication of these results (Stica et al., 2014) allowed the establishment of an idealized crustal structure model for Volcanic Passive Margins (Figure 2). These authors concluded that that this type of margin shows an abrupt and dramatic crustal thinning, passing from an original, unstretched crust directly into hyper-extended crust. The distance between this pivotal thinning and the COB may vary considerably along the strike of the basin (from 50 to 200 km) and it is not related to a “normal” rheological taper profile, as in Magma-Poor Margins. These differences in the width of the margin may be explained by intensive injection of dykes in the continental crust causing more or less lateral dilatation, or by regional variations in the rate of crustal stretching. The rift faults dip invariably landwards and the sequences filling the grabens in such margins are nearly entirely made up of SDRs (Seaward-Dipping Reflectors). Field exposures of SDRs in Greenland are entirely volcanic in origin (basaltic lava flows and intercalated tuffs).

In the model idealized for Volcanic Passive Margins (Figure 2) three major domains in the continental crust are characterized, from onshore to offshore: (1) **Proximal Domain**, constituted of original (circa 40-45 km thick), practically unstretched crust, with few small grabens (filled mostly by sediments) preserved on top of the flat crystalline basement, followed by (2) **Necking Domain**, formed by a striking necking zone where the thickness of the crust diminishes from 40 km to around 20 km in a short distance. In this domain extremely deep grabens may develop (up to 20 km thick). The filling of these grabens is made up of seaward-dipping reflections that ressemble enormous SDR wedges. We speculate that some of the filling in the inner parts of the grabens may be sedimentary in origin, but still secondary in relation to the volcanics. The deep and ultra-deep waters are the realm of the (3) **Distal Domain**, dominated by hyper-extended, roughly tabular continental crust with thicknesses in the order of 10 km or less. Huge packages of typical SDRs dominate entirely the grabens developed on this domain. The Oceanic Domain (4) is formed entirely by oceanic crust, which displays a markedly tabular geometry with thicknesses varying from 11 to 7 km, very gently tapering towards the mid-oceanic ridge.

Transitional Passive Margins

Transitional Passive Margins, displaying internal grabens filled with sediments resting side-by-side with external grabens filled with SDR packages, have been frequently observed in the seismic sections of the Ceará, Potiguar, Sergipe-Alagoas and Jacuípe Basins of Northeastern Brazil (Figure 3). Moreover, interdigitation of Volcanic and Magma-Poor Passive Margins may occur, creating a transitional passage between basins, such as is the case in the fuzzy geological boundary between the Pelotas and Santos Basin in Southern Brazil. We consider such margins as transitional stages between the two end-members described above.

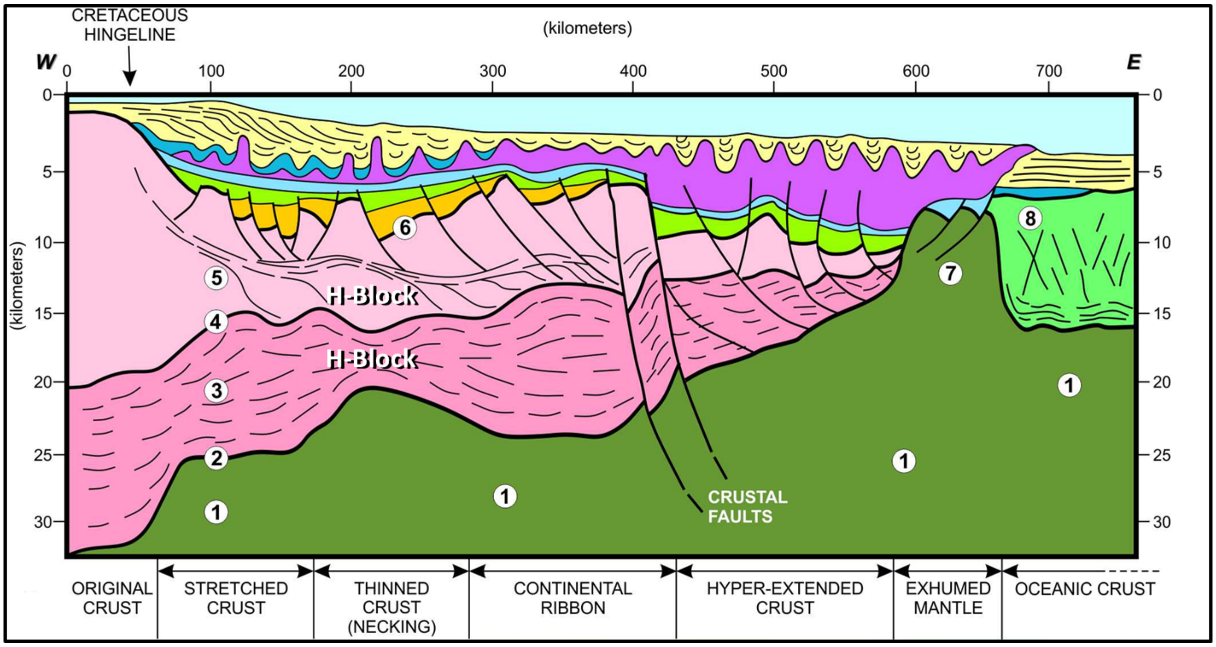

Figure 1 - Schematic W-E geologic profile valid for the Magma-Poor Santos, Campos and Espírito Santo Basins of SE Brazil, displaying the common strain domains of the continental crust (pink colors) and its contact with oceanic crust via an intervening exhumed mantle. Elements numbered as (1) mantle, (2) Moho, (3) lower ductile crust, (4) Conrad, (5) upper brittle crust, (6) top of crystalline basement, (7) exhumed mantle, and (8) oceanic crust. Sedimentary packages above (6) represent Barremian early syn-rift (dark yellow), Early Aptian climax syn-rift (green), Late Aptian late syn-rift (light blue), Latemost Aptian syn-rift evaporites (purple); Albian drift carbonates (dark blue), Cenomanian-Recent drift siliciclastics (yellow). Based on Zalán (2013).

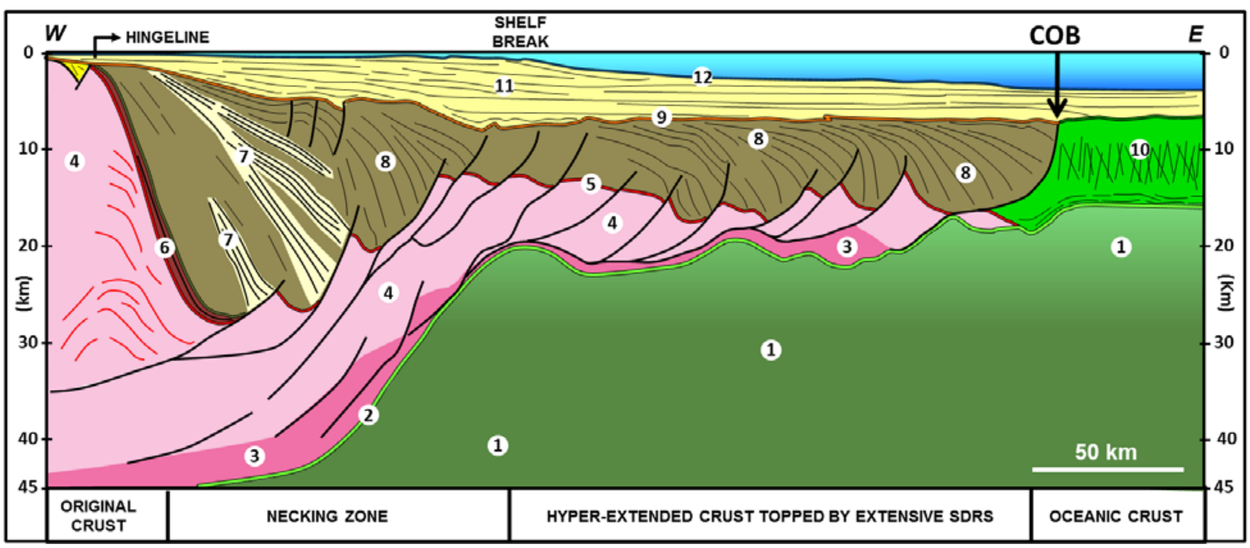

Figure 2 – Schematic W-E geologic profile valid for the Volcanic Pelotas Basin of Southern Brazil displaying the strain domains of the continental crust (pink colors) (line drawings partly based on Line 130 from ION-GXT Pelotas SPAN). Elements numbered as (1) mantle, (2) Moho, (3) lower ductile crust, highly reflective, (4) upper brittle crust, (5) top of crystalline basement, (6) pre-rift basalt traps, (7) possible syn-rift sedimentary facies, (8) syn-rift SDRs, (9) post-rift unconformity, (10) oceanic crust, (11) Drift Sequence, and (12) sea bottom. Interpretation of strain domains partly based on Stica et al. (2014).

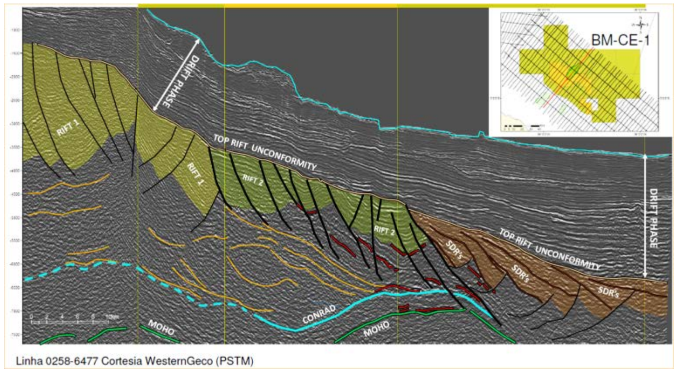

Figure 3 – Interpreted TWT seismic section from the Ceará Basin showing sedimentary grabens side-by-side with SDR-filled grabens (uninterpreted seismic section from Haeser, 2013).

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The crustal structure of the Norwegian continental margin – comparison of refraction seismic and other geophysical data sets

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Geological Survey of Norway

The Mid Norwegian offshore domain is one of the world's most densely covered by seismic (refraction and reflection) and potential field surveys. The rifted system encompasses wide and narrow continental margins (the Møre, Vøring and Lofoten margins) as well as the sheared margin of the West Barents Sea. These margins are structurally distinct, displaying important variations in crustal thickness and the extent of a high-velocity lower crust (HVLC) as well as complex basement and sediment geometries.

The new NAGTEC data compilation makes it now possible to compare data sets of different sources in a consistent manner. An important link between the data sets is provided by isostatic balancing, which puts constraints on the Moho depth, bathymetry and gravity. Structural elements are in parts reflected in the magnetic and gravity signal and are compared to the respective data sets. These comparisons make it possible to isolate areas of inconsistencies, e.g. in the borders of the structural elements or between the crustal structure and anomalously low or high bathymetry. These inconsistencies can reflect a number of circumstances: insufficient mapping (e.g. of HVLC extent), false interpretation (e.g. top basement, oceanic crust), or application of erroneous concepts (flexure, crustal stretching). By identifying these areas, we aim to improve the understanding of the Norwegian margin and to shed better light on its rifting history.

Araripe Basin, NE Brazil: A rift basin implanted over a previous pull-apart system?

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Introduction

Studying the tectonic origin of the basins in Northeast Brazil can provide important data to understand the continental processes related to the South Atlantic's opening. These basins are located where the southern and equatorial branch regions intersect with several yielding substantial structural data that constrain the temporal and spatial influence of the tectonic phases. The pre-Cambrian basement and its structural framework have a strong influence on the formation of these intracontinental basins. It suggests that pre-existing crustal weakness zones, such as the Neoproterozoic Pernambuco and Patos shear zones of the Brazilian/Pan-African orogeny, controlled the development of intracrustal faults (De Castro et al., 2012).

The Araripe Basin (ca. 8,000 km^2) represents the largest interior basin of NE Brazil, and is positioned between the Patos and Pernambuco shear zones, which divide the Borborema Province in three (north, central and south) domains (Fig. 1). These shear zones strike E-W and have a dextral cinematic(BritoNeves et al., 2000).

The main phase of sedimentary deposition in the Araripe Basin occurred between the late Jurassic and early Cretaceous (Assine, 2007). However the basin also contains an important Paleozoic (Silurian-Devonian) sedimentary succession.

The Araripe Basin can be divided in two main sub-basins, the Cariri (East) and the Feitoria (West), which are separated by a regional structural high referred to as the Dom Leme (Assine, 1992; Neumann, 1999).

There are three models proposed for the tectonic evolution of the Araripe Basin. The first is based on a NW-SE initial extension (Matos, 1992, 1999), which reactivated the Proterozoic shear zones. The second involves the reactivation of the dextral E-W shear zones and the sinistral NE faults (Françolin et al., 1994). The third model, recently proposed by Miranda et al. (2012), argues that the Araripe Basin was formed as a pull-apart system between the two shear zones, Pernambuco and Patos.

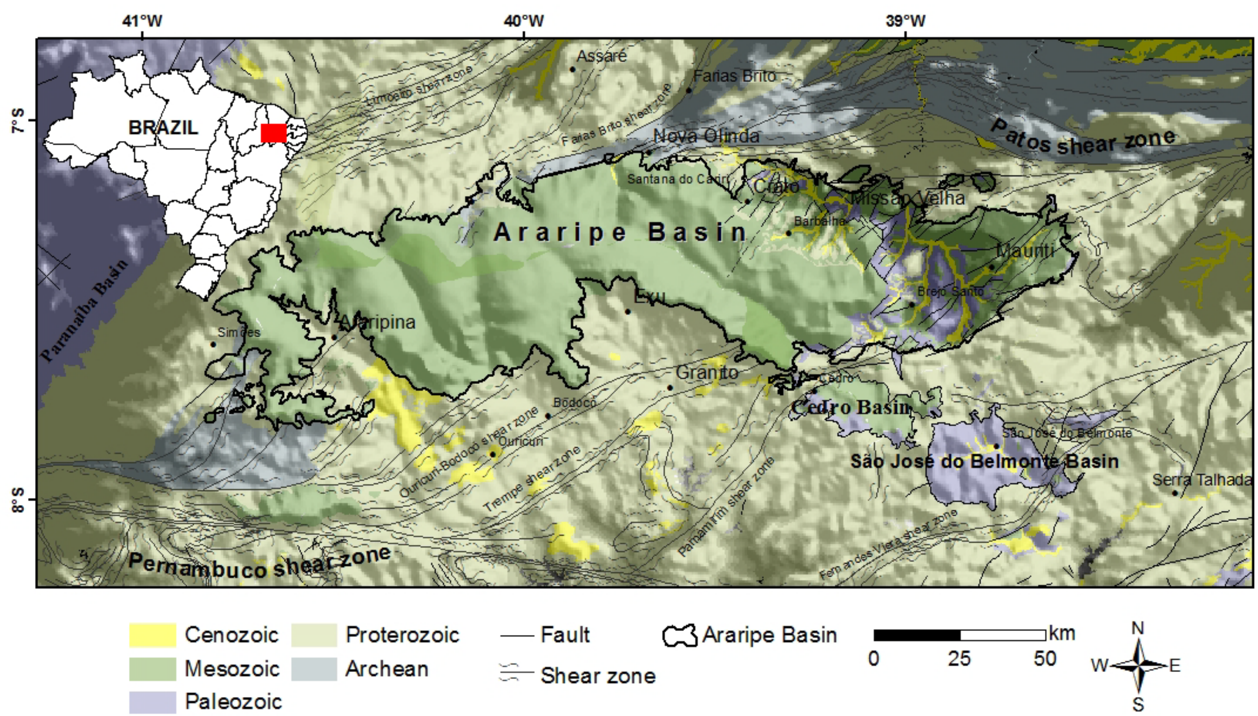

Figure 1 - Simplified geological map of the Araripe Basin

Methodology

We undertake a gravity and tectonic data analysis of the structural network of the Araripe Basin's basement through satellite-derived gravity anomalies and the geological characterization in outcrops. For the gravity data we used a 2' square grid of gravity/bathymetry, which is derived from satellite geodesic data (Scripps Institution of Oceanography, University of California San Diego) measured with GEOSAT and ERS-1 satellites and the error in this gravity data is around 5 mGal (Sandwell and Smith, 1997). We then generated a Bouguer gravity anomaly and also performed a regional-residual separation of this map using the Gaussian method. The residual component was selected in order to mitigate the gravity effect of the crust-mantle interface.

During fieldwork we focused on collecting structural data in order to perform the geological characterization of the gravity anomalies.

Results

Figs. 2 and 3 show the Bouguer and residual gravity anomaly maps, respectively, for the Araripe Basin and adjacent areas. The Bouguer anomaly documents the effects of density variation whilst the residual gravity map shows mostly the superficial anomalies.

Three main observations from the gravity maps and tectonics analysis stand out in our results. 1) The Araripe Basin is rhomb shaped, probably due to movement along the sandwiching Patos and Pernambuco shear zones. 2) NW and NNW gravity anomalies inside the basin are suggestive of *en echelon* arrays, interpreted at Riedel shears. 3) Other gravity anomalies trend E-W and NE-SW in and around the basin, indicative of crustal extensional deformation, strongly influenced by the Neoproterozoic shear zones. This interpretation is substantiated by the fact that the NW (R_1) and NNW (R_2) oriented structural trends became reactivated as normal faults (Paleozoic pull-apart phase). The E-W and NE-SW gravity anomalies show potential sites for transfer faults or accommodation zones, which could be associated with the Lower Cretaceous rifting system.

Conclusion

We concluded that the Araripe Basin had two main tectonic phases: Stage one involved a pull-apart system, which generated the rhomb-shaped configuration during the Paleozoic, through the displacement at the step-overs of the Patos and Pernambuco shear zones. Stage 2 saw the reactivation of the shear zones during the Cretaceous due to the South Atlantic's opening.

Acknowledgements

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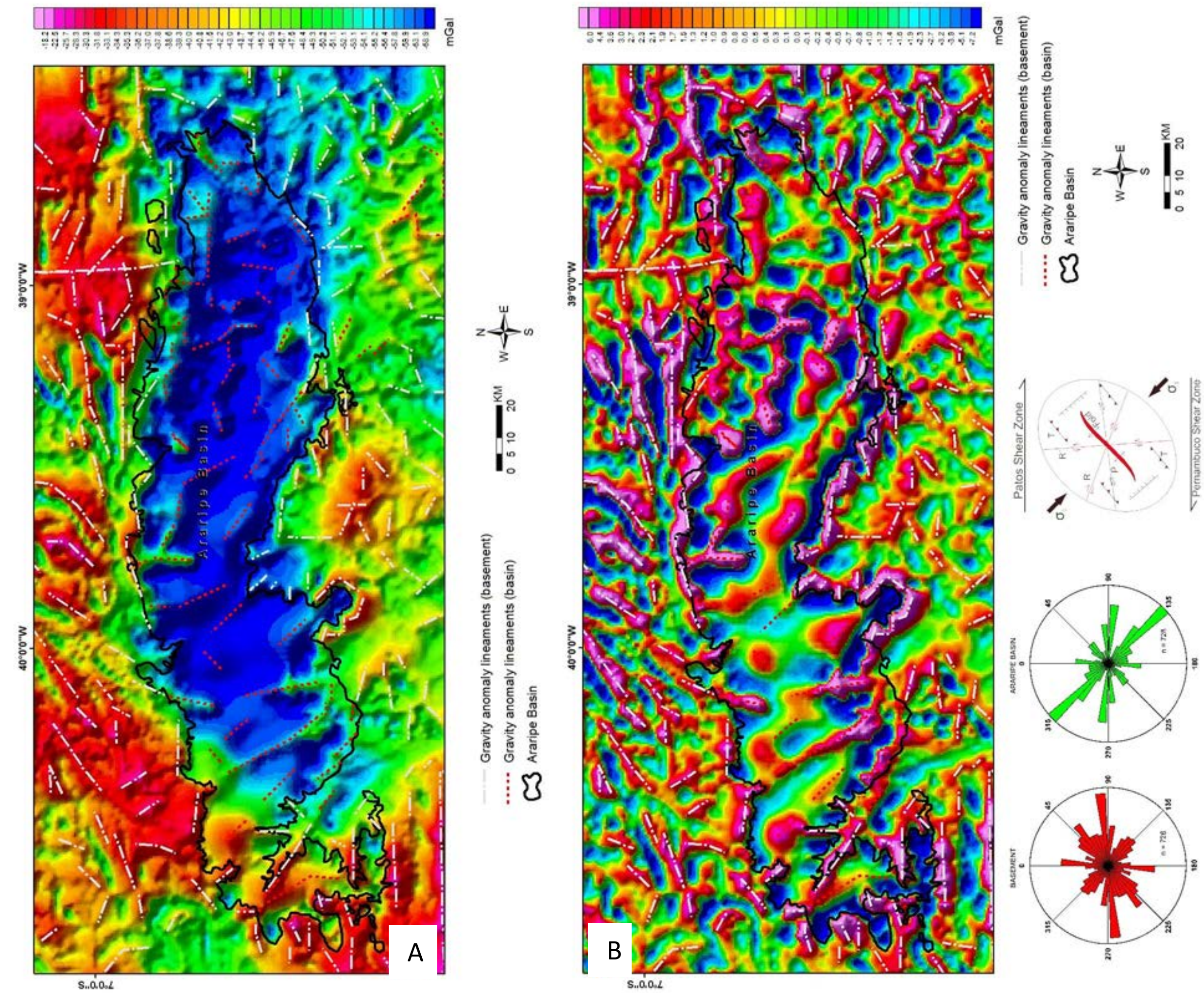

Figure 2 - A) Bouguer gravity anomaly map of the Araripe Basin and adjacent areas showing the basin's rhomb shaped, gravity anomalies trend E-W and NW-SE in and around the basin. B) Residual gravity map of the Araripe Basin and adjacent areas showing the superficial structural anomalies which strike NW (R_1) and NNW (R_2) represent reactivated normal faults (Paleozoic pull-apart phase) and also the E-W and NE-SW trends show the influence of the Lower Cretaceous rifting system.

Construction of magmatic rifted margins in the North Atlantic Volcanic Province

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The North Atlantic is rimmed by archetypal volcanic rifted margins. These are marked by relatively wide belts of magmatic crust, formed during the change from continental rifting to seafloor spreading. Thus seaward-dipping basalt flows (SDRs) directly overlie gabbro accreted by extensional shearing with no intervening sheeted dykes.

We have used seismic interpretation of the volcanic conjugate margins of East Greenland and Vøring Basin (Fig.1), in conjunction with structural reconstructions and viscous fluid analogues, to develop a generic model for the evolution of the continent-ocean transition in magmatic oceanic basins. This shows that, in moderate- to fast-separating plates, when the continental rift splits, a central magma chamber rises beneath paired, outward-dipping normal faults defining an axial horst (Fig.2). The faults are a hybrid of low angle detachments, accommodating the construction of new crust by propagating away from the continent as the plates diverge. Melt flows to the inherent low pressure zone beneath the footwalls where space is created for magma to collect as the faults move, a process we term magma-assisted extensional growth.

A melt lens forms at the top of the growing magma chamber from which dykes are intermittently sourced, traversing the axial horst and erupting as sub-aerial basalts (Fig.2). These collect as lava flows in the hanging walls on either side of the horst and become seaward-dipping due to roll-over, forming SDRs. As each normal fault continues to move, the SDRs eventually meet the upper edge of the magma chamber, welding onto cooling gabbro where the fault detaches. Deformation continues down each side of the magma chamber in the form of a dilational shear zone where melt is accreted, transferring gabbro from the footwall to the hanging wall as the shear zone moves. Eventually, when the mantle lithosphere has thinned to a critical point, the axial horst splits to form an embryonic mid-ocean ridge, and from then on normal oceanic crust is constructed by seafloor spreading associated with sheeted dykes.

A number of important implications arise from this work, both for the North Atlantic and for plate tectonics in general which we will expand on in the presentation.

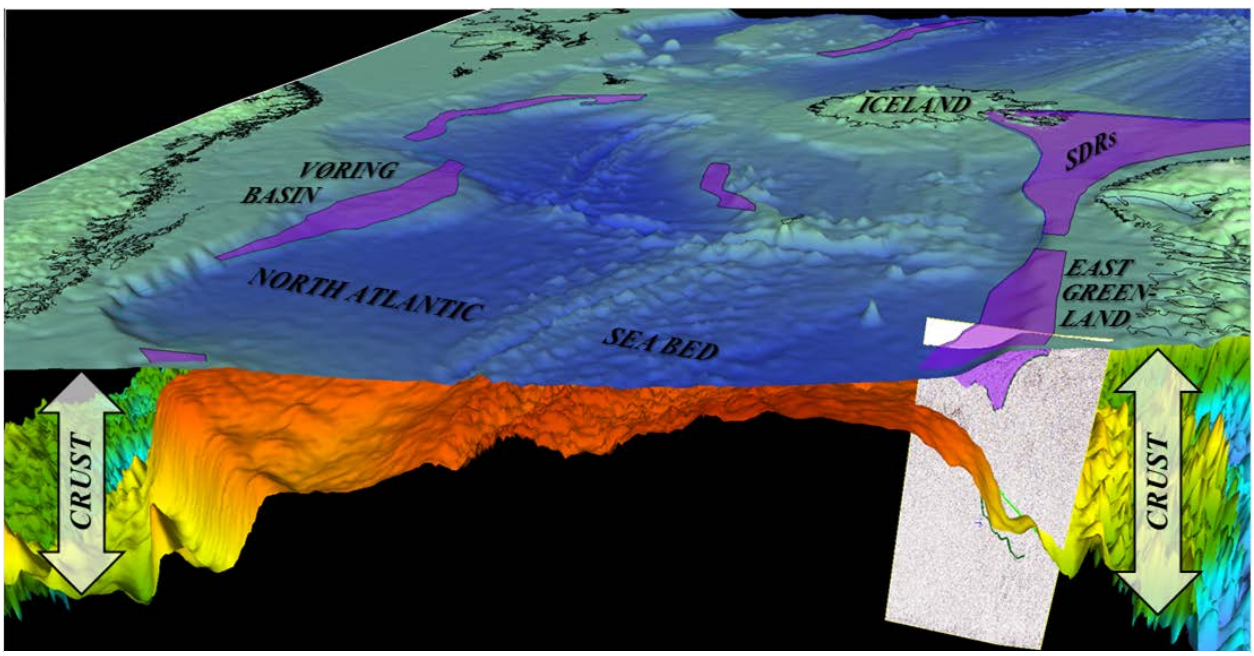

Figure.1. Southward-directed view of the North Atlantic from seabed to base of crust. SDR-bearing transitional crust is highlighted in purple

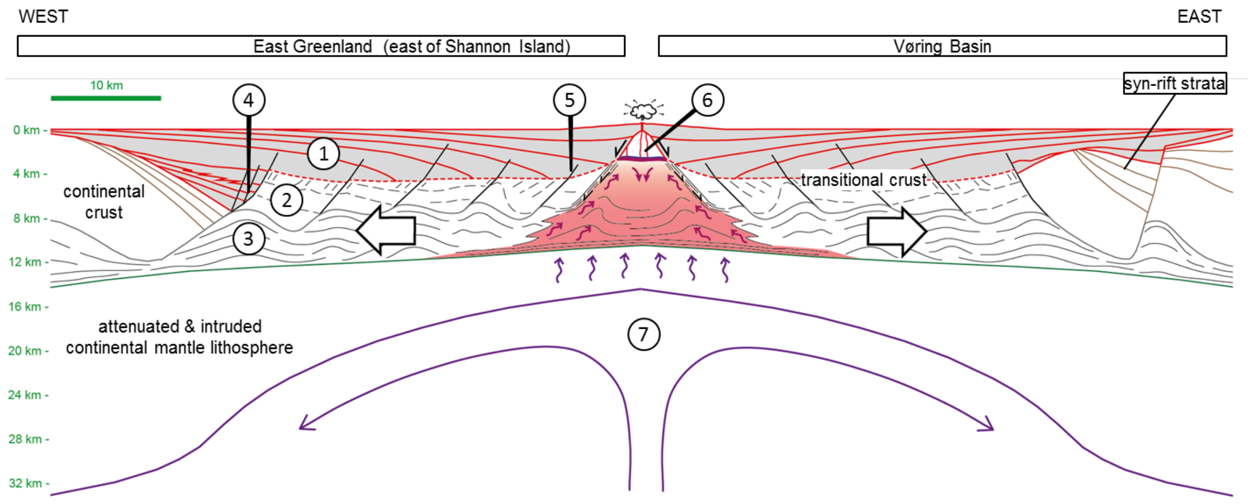

Figure 2. Model for formation of SDR-bearing transitional crust during plate separation, specifically magma-assisted extensional growth around a pluton-cored axial horst.

Key:

1 - SDRs (sub-aerial basalt lava flows).
2 - mid-crust imbricate layer (sheared / foliated gabbro).
3 - lower crust mobile layer (layered gabbros underlain by mafic and ultramafic cumulates and sills).
4 - break-up fault.
5 - abandoned normal fault.
6 - axial horst traversed by dolerite dykes and underlain by melt lens (top of magma chamber, red shading).
7 - upwelling, convecting asthenosphere.

Green horizon - Moho.
Purple wavy arrows - porous flow of melt.
Red wavy arrows - melt migrating through magma crystal mush to low pressure zones beneath footwall crests.
Open black arrows - extension direction.

Complexity of pre- and early volcanism in NAIP

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One of the challenges in creating the new volcanic facies maps in the NAGTEC Atlas was constraining the onset or base of the volcanism associated with NAIP. Even though the geophysical methods and the understanding of the igneous geology has come a long way since exploration started in the area in the late nineties [*Gallagher and Dromgoole*, 2009] there are still many unanswered questions. Seven exploration wells are drilled within the Faroese area of the Faroe-Shetland Channel, where six of the wells are drilled into and in some cases through the volcanic unit [*Varming*, 2009].

It is clear that the seismic interpretations and understanding of the dynamic geological processes are to some degree fragmented and over simplified. The base basalt is, contrary to common belief, a zone of complex interfingering between a volcanic system of lava flows and intrusions, volcaniclastic sandstons and hyaloclastites with a siliciclastic depositinal system. The aim of this presentation is to shed more light on, and hopefully improve the understanding of the complexity of some of the elements during early volcanism.

The new NAGTEC volcanic facies map shows that the volcanism in the NAIP is asymmetric with significantly larger volumes of volcanic material emplaced on the south-eastern (i.e. NW European) margin, compared to the north-western (i.e. Greenlandic) margin.

By looking at the present day active rift system in the East African volcanic provinces [*Morley et al.*, 1999] some of the early phases in the NAIP might be better understood, and the dynamic processes in this developing province can be studied to a closer degree.

Exploration of hydrocarbon in igneous provinces is challenging and areas within the North Atlantic Igneous Province (NAIP) on the north-east Atlantic margin including the Faroe-Shetland Channel are no exception. Therefore understanding the geological history and the evolution of the igneous geology during the pre- and early rift volcanism plays an important role in future development of the hydrocarbon exploration. It will also enable more optimized input parameters when processing geophysical methods in volcanic provinces.

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Sourceland controls on reservoirs sandstones in NE Atlantic Margin basins: filling in the blanks?

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[4]*Geological Survey of Ireland, Beggars Bush, Haddington Road, Dublin 4, Ireland**The northeast Atlantic margin comprises underexplored sedimentary basins and poorly-characterised submarine basement highs. Recent work has suggested that these basement highs strongly influenced the supply of sediment to basins during the Mesozoic (Tyrrell et al., 2007, 2010). Their composition, therefore, is a possible first-order control on the quality and distribution of potential reservoir sandstones in the adjacent Porcupine and Rockall basins. Furthermore, determining the age and affinity of the pre-Mesozoic rocks offshore western Ireland may allow for improved pre-rift correlation with the eastern conjugate margins, with implications for constraining shared basin histories between the Irish offshore and the Canadian Maritimes.*

The onshore geology of the North Atlantic margins comprises a complex assembly of geological terranes, reflecting multiple cycles of orogenesis and ocean opening/closure. These are bounded by lineaments and sutures, the offshore extensions of which are poorly constrained. Tracing the offshore continuation of such boundaries is clearly important as they define the extent of discrete crustal blocks and zones. These lineaments and sutures likely also directly influenced basin evolution and drainage through the Mesozoic in controlling structural trends and sediment transport pathways.

Interest in the offshore basement highs has accelerated in recent years. The Rockall High (Figure 1) was the target of a shallow drilling programme during the early 1970s with subsequent work in the 1990s revealing a Palaeoproterozoic to Mesoproterozoic history to this area of crust (Morton and Taylor, 1991; Daly et al., 1995). More recent work in the area, including analysis of detrital samples likely derived from basement highs west of the Rockall High (e.g., the Edoras and Hatton highs; Morton et al., 2009), has further supported the broader presence of Palaeoproterozoic crust in these areas (Scanlon and Daly, 2001, Morton et al., 2014).

To the south and east of the Rockall High, the Porcupine High (Figure 1) is contiguous with the Irish Continental Shelf, yet the affinity of this area of crust has, until very recently, been very poorly constrained. Direct drilling (MeBo) of a submarine outcrop on the northern flanks of the Porcupine High in 2006 revealed a high-grade metamorphosed granitic orthogneiss. Ion microprobe U-Pb zircon dating indicated a crystallization age of 1310 Ma, signifying a period of magmatism not previously recognized in the region (Daly et al., 2008). Metamorphism, of probable Grenville age, is manifest by ringlets of garnet developed around plagioclase ("rapakivi") rims on K-feldspar megacrysts. *In situ* laser-ablation Hf isotopic analysis of the zircon suggests that the orthogneiss is derived from the melting of pre-existing continental crust, such as the Palaeoproterozoic of the Rockall High or the Annagh Gneiss Complex (AGC), onshore NW Ireland.

Thermochronological work has indicated that the northern Porcupine High has a complex uplift history and did not always act as a discrete single block. This has important implications for the nature, amount and timing of sand delivered westwards and northwards into the Rockall Basin, and eastwards and southwards into the Porcupine Basin. Interpretation of these data also suggests uplift events during the Jurassic and Cretaceous, and highlights the potential to link these events with the delivery of sand to the surrounding basins at these times.

In May 2011, as part of a Geological Survey of Ireland-led ground-truthing programme, rock samples were collected from an E-W transect along the top of the northern Porcupine High, south of the area targeted by MeBo drilling (Figure 1). These revealed the presence of previously unknown metasedimentary rocks, mainly psammites, which, with the support of geophysical evidence, are interpreted to represent significant areas of in-situ bedrock. SEM imaging, petrography and geochemical analyses show that these rocks are of low-metamorphic grade and quartzo-feldspathic in composition with abundant accessory minerals suggestive of a granitic/gneissic source (titanite, epidote, zircon and tourmaline). The Pb isotopic composition of detrital K-feldspars corresponds well with the AGC onshore western Ireland, indicating that the feldspar could have been sourced from the AGC itself or from an equivalent terrane. U-Pb ages of detrital apatites fall predominantly in the range c.1000-900 Ma, suggesting a broadly Laurentian provenance and indicating that subsequent (Caledonian) deformation was not sufficient to reset U-Pb apatite systematics. U-Pb geochronology of detrital zircon from eight samples yields consistent age spectra, also indicating a Laurentian provenance, similar to the Moine Supergroup or the Grampian Group of the Dalradian Supergroup (Tyrrell et al., 2013). The youngest detrital zircon is ~874 Ma, providing a maximum age for the deposition of these rocks and supporting the idea that they represent a previously unrecognised part of the lowermost Dalradian Supergroup. The integrated geochemical data suggests that this metasedimentary sequence is a possible equivalent to the Erris Group (Ireland) and the Grampian Group (Scotland).

In addition to the characterisation of economic basement through direct sampling and analysis, ongoing provenance work on the Mesozoic infill of the various sedimentary basins in the region continues to reveal clues as to the nature of the surrounding hinterland. The Pb isotopic composition of K-feldspar grains is, for example, being widely applied in these areas to constrain sediment dispersal patterns (e.g., Tyrrell et al., 2007). This approach has revealed distinct grain populations which cannot be linked to known basement sources in the region and must, therefore, represent sources that are, as yet, unrecognised and uncharacterised. Key unknowns include the nature of the economic basement on the southern part of the Porcupine High, the shelf area east of the Porcupine Basin, and on the eastern margins of the Rockall Basin. For example, data from Permo-Triassic and Middle Jurassic sandstones from the Dooish well (12/2-1z) on the eastern margins of the Rockall Basin includes coarse granitic and gneissic detritus which is a likely proxy for the geology of the adjacent Erris High (Tyrrell et al., 2010).

The ultimate aim of this work is to understand the "source to sink" evolution of basins offshore western Ireland and to constrain the distribution and quality of reservoir sandstone intervals. This can only be achieved if the nature and palaeoposition of potential sourcelands are better understood and delineated; hence there is a clear synergy between the characterization of offshore basement highs, reconstruction of the pre-rift configuration of the conjugate margins and the assessment of sediment routing and sand dispersal patterns.

This presentation will review the current status of our knowledge of pre-Mesozoic basement offshore Ireland, highlighting these uncertainties. A focused programme of research, funded through the Petroleum Infrastructure Programme (Ireland), will commence in September 2014 with the aim of addressing some of these issues - utilising a novel, multi-proxy geochemical approach. This new programme is a collaboration between researchers in the National University of Ireland Galway, University College

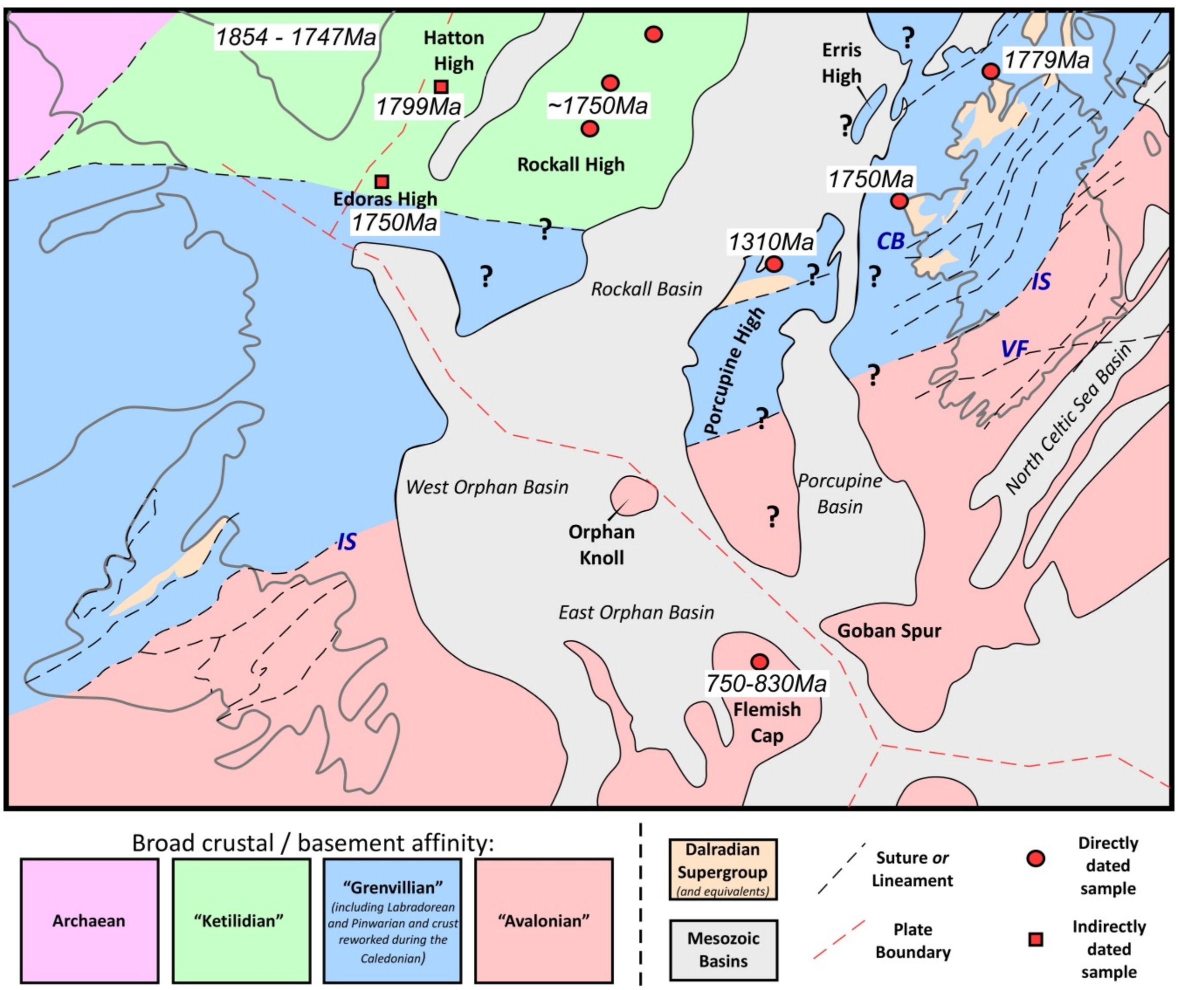

Figure 1: Lower Cretaceous (Aptian) reconstruction of the North Atlantic (after PAD 2006) showing the position of basins, offshore crustal blocks, major sutures and lineaments and broad crustal/basement affinity. The distribution of the Dalradian Supergroup and putative equivalents is also shown. Age determinations from offshore basement highs (Daly et al., 2008; King et al., 1985, Morton et al., 2009; 2014) are highlighted. CB = Clew Bay – Highland Boundary suture; IS = Iapetus Suture; VF = Variscan Front.

Dublin, Trinity College Dublin, Memorial University Newfoundland, Heavy Mineral Research Associates and the Cambridge Arctic Shelf Programme (CASP).

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Revised stratigraphic framework of the Labrador Margin through integrated biostratigraphic and seismic interpretation, Offshore Newfoundland and Labrador

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The Carboniferous to Neogene stratigraphy of seven offshore Labrador wells (Hare Bay E-21, Herjolf M-92, North Bjarni F-06, Ogmund E-72, Pothurst P-19, Roberval K-92 and Snorri J-90; Figure 1) has been re-evaluated based on new micropalaeontological, palynological and lithological analyses. Regional cross-sections, which have been integrated with wireline log and seismic data, allow the recognition of regionally correlative sequence boundaries and an assessment as to the time / spatial distribution of potential hydrocarbon reservoirs.

The oldest rocks occurring on the Labrador Shelf comprise the Pre-Cambrian gneisses and granites. Localised Palaeozoic sediments (Ordovician carbonates and Late Carboniferous argillaceous and arenaceous deposits) are also recognised in a number of wells (Roberval K-92 and Hare Bay H-21 respectively).

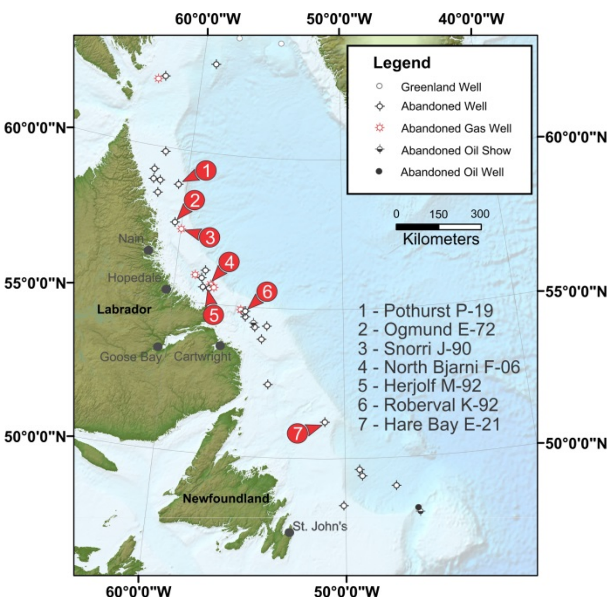

Figure 1: Location map of the wells analysed.

The synrift sequence encompasses the mainly volcanic rocks of the Alexis Formation (Neocomian - Albian), the coarse grained arkosic sandstones, claystones and bedded coals of the Bjarni Formation (Barremian to Late Albian / Early Cenomanian) and the claystones and subordinate sandstones of the "Lower" Markland Formation (Coniacian to Maastrichtian).

The Snorri Member of the Bjarni Formation was defined by Umpleby (1979) as the lowermost siliciclastic interval which is shale and coal dominated within the Snorri J-90 well. Emended herein is the addition of coarse grained feldspathic sandstones and matrix supported conglomerates of Barremian to ?Early Aptian age.

The argillaceous sediments within the Markland Formation are here informally subdivided into "Lower" and "Upper" members. This is due primarily to the identification of a marked intra-Markland regional unconformity; recognised both biostratigraphically and as a strong regional marker on seismic data, with the Early Paleocene Danian representing a period of non-deposition or erosion. This subdivision places the "Lower" Markland sediments within the rift sequence and the "Upper" Markland sediments (Late Paleocene, Selandian) within the drift sequence of the Labrador margin. Localised marginal marine to shallow marine Freydis Member sandstones are developed within the "Lower" Markland Formation. The Markland Formation is interpreted to be deposited in deep water environments with the upper to middle bathyal paleodepths with localised sandier units.

The remaining drift sequence comprises the claystones of both the Cartwright (Late Paleocene, Thanetian) and the Lower Kenamu (Early – Middle Eocene, Ypresian - Lutetian) Formations; with the former (as emended herein) encompassing localised Gudrid / Gudrid Equivalent and Uivak Member sandstone developments.

The post-drift sequence comprises the claystones of the Upper Kenamu (Middle Eocene, Bartonian), with its Leif and Roberval Member sandstones (new member status herein; the Roberval Member is defined in the Roberval K-92 well as the coarsening upward package at the base of the upper Kenamu Formation – Middle Eocene, Bartonian in age); plus the silty / sandy claystones of the Lower and Upper Mokami (Late Eocene – Middle Miocene, Priabonian – Serravallian) and arenaceous Saglek Formations (Late Oligocene, Chattian – Early? Pleistocene). This interval is largely preserved along the margin except for the northernmost extent of the study area.

In this region, as observed in the Pothurst P-19 well, the entire Miocene interval has been removed leaving the Pliocene – Early Pleistocene Saglek Formation resting unconformably on a thin remnant of lowermost Mokami Formation. While this is a change over past interpretations, it is in alignment with recent work off Western Greenland where uplift and erosion related to hotspot migration has led to limited mid-Eocene to mid-Miocene section (Knutsen et al., 2012).

The study area has a number of marked unconformities which have been recognized seismically and confirmed by biostratigraphy (herein and McWhae et al., 1980; Balkwill et al., 1990; Dickie et al., 2011; Figure 2).

a. An unconformity between Palaeozoic / Mesozoic sediments and the underlying Pre-Cambrian Basement, and also between the Alexis Formation (Early Cretaceous extrusives) and the underlying Palaeozoic sediments / Precambrian basement. This approximates to the Labrador Unconformity of McWhae et al. (1980).
b. An unconformity between the Early and Late Cretaceous, no older than Coniacian in the present study wells separates the Markland Formation and the underlying Early Cretaceous (Albian) Bjarni Formation.
c. The Base Tertiary Unconformity, an intra-Markland unconformity; between the “Upper” Markland (Selandian) and the “Lower” Markland Formations (Maastrichtian).
d. A mid-Paleocene unconformity (approximately equivalent to the Bylot Unconformity in northern extents); between the Cartwright Formation and the underlying Markland Formation.
e. An unconformity between the Mokami Formation and the underlying Kenamu Formation. Early Oligocene - Late Eocene, Priabonian - Rupelian, in age, approximately equivalent to the Baffin Bay Unconformity.
f. A mid-late Oligocene, Chattian unconformity; between the “upper” and “lower” Mokami Formations.
g. An unconformity between the Saglek Formation and the underlying Mokami Formation (equivalent to the Beaufort Unconformity in northern extents). A major Miocene unconformity is recognised within the area of the more northerly Pothurst P-19 well and close similarities are noted with the Neogene succession of offshore Greenland.

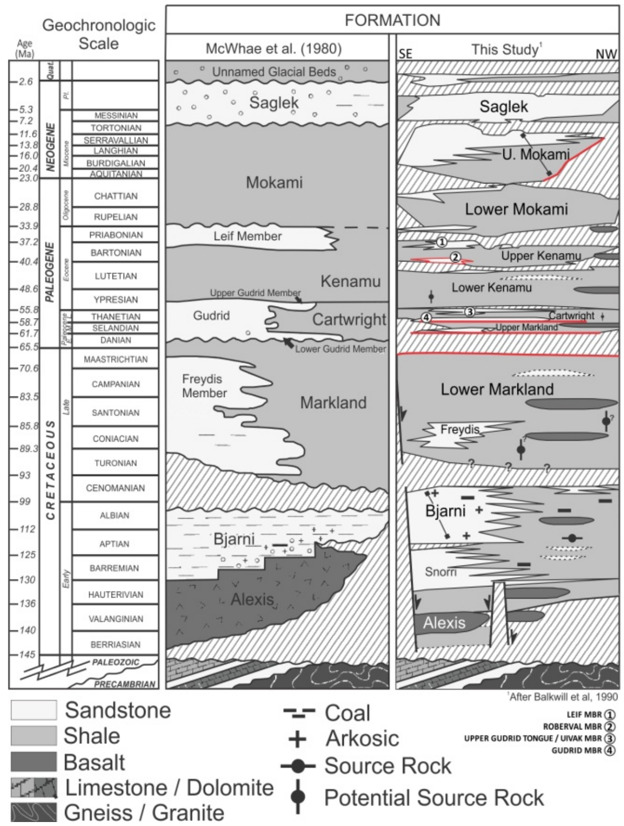

Figure 2: Comparative stratigraphic column. Red markers highlight modifications.

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US East Coast: From regional framework to FTG applicability evaluation

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ARKeX

Summary

It seems more and more likely that the US East Coast will reopen to hydrocarbon exploration within a few years. The new exploration stage of this vast region has two major challenges: to be cost-effective and ensure the smallest possible environmental impact both for people and wildlife of the region. Both challenges require a focused exploration approach.

This paper will illustrate some steps of an exploration workflow from a regional assessment of existing data to introduction to the full-tensor gravity gradiometry (FTG) technology and its applicability to the East Coast.

Introduction

The US Atlantic margin has received little exploration attention for over 25 years with most available seismic surveys dating back to 1970s. Starting in 1974, 5 COST (Continental Offshore Stratigraphic Test) and 46 exploration wells were spudded offshore US East Coast with no commercial discoveries and the last well drilled offshore New Jersey by Shell in 1984 (Wilmington Canyon). However, all drilling was focused within three areas: Georges Bank Basin, Baltimore Canyon Trough and Southeast Georgia Embayment leaving a vast part of the region untested (Figure 1). In a recent estimate released by the US Bureau of Ocean Energy Management (BOEM) there are 3.3 Bbo and 31.28 Tcf of gas in undiscovered and technically recoverable resources offshore the US East Coast.

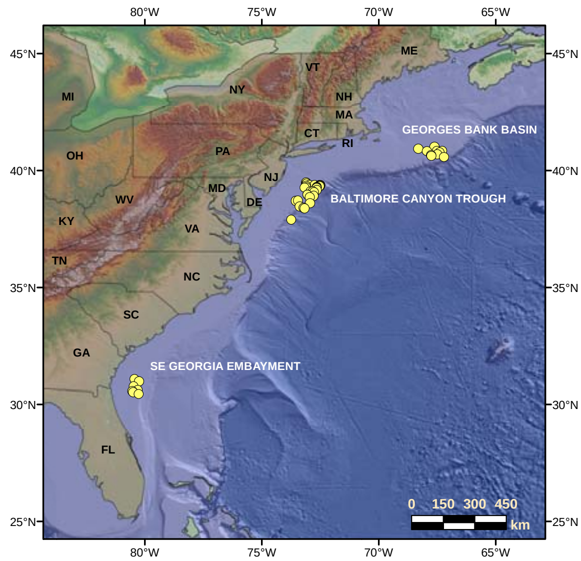

Figure 1: Terain map of the eastern US and offshore. The exploration drilling offshore US Atlantic coast to date was focused on three areas: Georges Bank Basin, Baltimore Canyon Trough and SE Georgia Embayment. Yellow circles are well locations.

The early exploration phase needs to start with analysis of existing and newly available data, not only within the region, but both northward along the coast, where exploration has been active during the dormant period offshore the US, and across the Atlantic, at the African conjugate margin, for analogs. The oceanic fracture zones which are easily mapped using satellite altimetry-derived gravity data are used to juxtapose the US East Coast to North- Western Africa with distinct sea-floor segmentation (Figure 2). Although depositional systems of conjugated segments may differ due to initial tectonic mechanism, e.g. pure shear vs. simple shear causing symmetrical vs. asymmetrical spreading geometries, or local sedimentation history, the analysis of the conjugated segments should be one of the primary objectives. In the South Atlantic, this approach has proven itself over the years, culminating in subsalt discoveries offshore Angola (from Cameia-1 in 2011 to Orca and Bicuar in 2014), based on analogs to their geological counterparts offshore Brazil (with the most famous Tupi field discovery in 2007), and more complex relationship discoveries along the Equatorial Atlantic margins, e.g., Venus (2009), Mercury (2010) and Jupiter (2012) in the offshore Sierra-Leone – Liberian basin and Zaedyus (2011) offshore French Guiana.

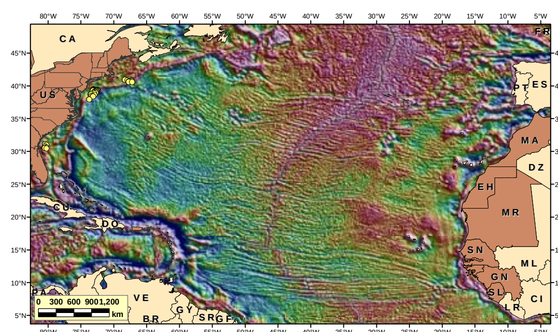

Figure 2: Satellite altimetry derived gravity is a key dataset in mapping fracture zones across the Atlantic and juxtaposition of conjugate margins.

To date, the success rate offshore the North-Western African margin has been modest with only a few sizeable discoveries offshore Mauritania, Gambia and Senegal. However, this region is still underexplored. These areas, as well the frontier Moroccan Atlantic margin have experienced periods of exploration activity, with hydrocarbon shows reported from many of the wells. One such period is currently taking place (over 10 wells will be drilled offshore Morocco within the next two years) and will provide valuable additional information for studying the North Atlantic conjugated margins.

Compilation and analysis of existing and newly available data is the first step of any new venture effort. The ultimate target of this work is to identify areas of focused interest for further exploration program, which often includes magnetic, gravity and 2D regional seismic data acquisition, eventually, leading to positioning of 3D seismic surveys and exploration wells.

Being passive technologies, the gravity and magnetic methods have a minimal environmental footprint. They are also cost- and time effective methods of exploration. The exploration targets that, under right conditions, could be mapped through the combination of gravity and magnetic data include salt, igneous intrusions, basement horsts, rotated basement blocks and carbonate build-ups/reef complexes developed within the paleoshelf and along the edge of carbonate platform.

Geological Assessment

The North American Atlantic margin formed during the North America – Africa rifting initiated in Late Triassic-Jurassic time. The preceding tectonic events culminated in Alleghanian Laurentia-Gondwana collision (Carboniferous-Permian) forming supercontinent Pangea. This final collision of two continents and series of smaller terrain accretion lead to formation of the Appalachian fold and thrust belt, which, in turn, played role of creating a continental zone of weakness and sediment provenance during the subsequent rifting. It makes the formation of this margin somewhat unique as part of the extension was accommodated along pre-existing sutures and thrust fronts, forming the onshore Mesozoic basins (e.g. Withjack et al., 2012). The exact distribution of these rift basins and their offshore extent is obscured by a thick Mesozoic-Cenozoic sedimentary section reaching in places over 15 km in thickness. The distribution of magnetic anomalies (with widely known and discussed East Coast and Blake Spur Magnetics Anomalies) and in places seaward-dipping reflectors (SDR's), are often used to map the continental-oceanic boundary.

According to BOEM nomenclature, five post-rift Jurassic-Cenozoic depocenters are outlined: Georges Bank Basin, Baltimore Canyon Trough, Carolina Trough, Southeast Georgia Embayment, and Blake Plateau Basin. Three of these areas were drilled penetrating Tertiary, Cretaceous and in most cases Jurassic sediments with few wells within Georges Bank Basin and SE Georgia Embayment reaching underlying Paleozoic metasediments. The thickest penetrated a sedimentary section of 6584 m was reported in the Baltimore Canyon Trough area.

Whereas the Cenozoic thickness varies from almost none to 1500 m and the Jurassic from 1500 to over 5000 m (with exception of SE Georgia Embayment where it is absent in places), the Cretaceous section seems to have a more consistent thickness throughout the drilled areas, averaging between 1500 to 2000 m. The offshore sediments are clastics and carbonates deposited in typical rifted-to-passive margin environments displaying coastal and deltaic sequences to shallow marine to deep marine sedimentation.

Within the syn-rift section lacustrine deposits are expected. Both the Georges Bank and Baltimore Canyon Trough exploration areas are characterized by carbonate-dominated sediments within the Jurassic-Early Cretaceous sections, which forms the carbonate platform extending all along the North American Atlantic margin. The overlaying Cretaceous sediments are predominantly clastics with some carbonate, anhydrite and coal interbeds and lenses. The Cenozoic section is dominated by shales and muds with some sands and minor limestone within the Georges Bank and Baltimore Canyon Trough areas, and by limestone and chert overlain by mostly sandy clastics within the Southeast Georgia Embayment.

A number of plays were identified and tested during the previous exploration phase. The pinnacle reefs along the Mesozoic carbonate platform edge were drilled resulting in dry holes attributed to an absence of a hydrocarbon charging system. An interpreted river sedimentation system outboard of the carbonate platform was also tested with disappointing dominance of shales and siltstones and absence of good quality reservoir rocks. Structures related to igneous dykes and interpreted salt diapirs (which are now reinterpreted not to be present in the Baltimore Canyon Trough basin) were also tested. The only proven play system with gas discoveries was related to listric fault-bounded structure within the inner shelf. However, along with this proven play, most of these plays are considered prospective in different parts of the region and classified as conceptual plays by the BOEM assessment (2012).

Gravity and Gravity Gradiometry

The latest satellite altimetry derived gravity data have improved the data resolution reaching 1.5 mGal and 7 km half wavelength (Figure 3). The increased satellite track coverage also improved datasets along the coasts, where tide-related variations of sea surface negatively influence data resolution. Although satellite altimetry derived gravity data are extremely useful at regional exploration scales and allow mapping of major geological structures, the conventional airborne/marine gravity data provides higher resolution with reported half wavelengths of 3-5 km (at appropriate survey line spacing) and also higher confidence in shallower water.

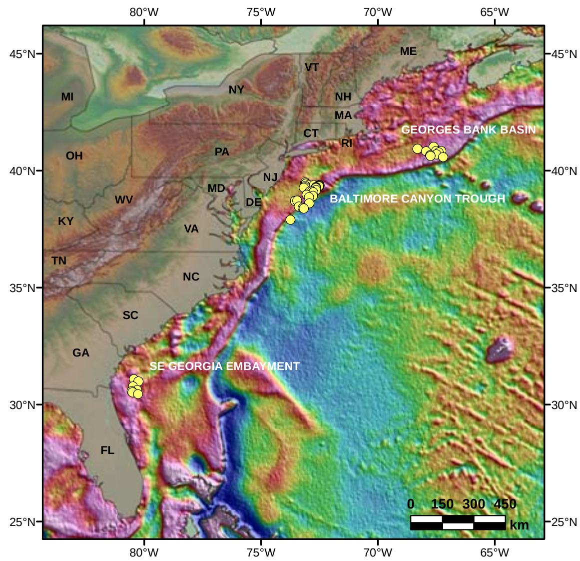

Figure 3: Satellite altimetry derived gravity offshore US Atlantic coast.

Over the last 15 years an advanced gravity measurement technology - gravity gradiometry - has been implemented in both frontier and explored areas with over 4 million line kilometers of data collected by airborne and shipborne systems. The most notable contribution of the technology was in the structural mapping of the East African Rift system leading to a number of significant discoveries.

The deployment of full-tensor gravity gradiometry (FTG), resolving half wavelengths of around 200 m, in frontier exploration areas could be even more effective in certain geological settings vs. conventional gravity by providing a comparatively higher bandwidth and higher-resolution dataset. The high resolution is achieved by measuring directional gravity field gradients (Figure 4), which provides reduced sensitivity to aircraft accelerations as well as detection of off-flight-line anomalies.

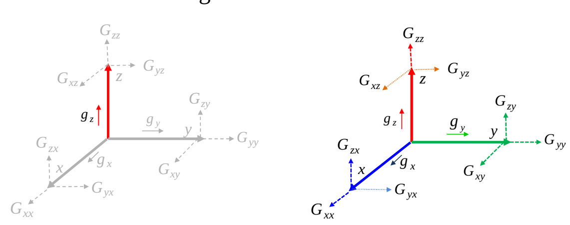

Figure 4: Components of gravity field. Conventional gravity measures one vertical component (Gz). Full tensor gravity gradiometry measures six independent curvature components providing a full Cartesian tensor derivation.

FTG Feasibility Modeling

Feasibility modeling is an important exercise to evaluate the applicability of the method for resolving geological features and to develop an optimal survey design (Figure 5).

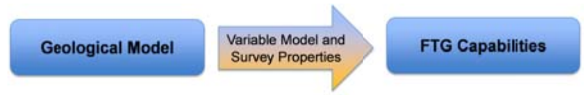

Figure 5: Simplified FTG feasibility modeling workflow.

The measured gravity field contains a contribution from the combination of structural configuration and density contrasts within the sub-surface. These gravity anomaly causing combinations could be intra-sedimentary or related to sediment/basement interface.

Based on the available information, the intra-sedimentary exploration targets of the US East Coast are structures related to igneous intrusions, salt diapirs, inner-shelf clastic depocenters, outer carbonate platform clastic depocenters, carbonate platform edge and associated reefs, inner-shelf reefs, intra-sedimentary anticlines and faults. Extension-related basement structures could be contributors to the measured signal, when they are relatively shallow as demonstrated by our modeling.

The above-mentioned structural features and densities (inferred from lithology information) were combined into a generalized geological pseudo-3D earth model which was then used for the feasibility study (Figure 6). Besides the geological model, the acquisition parameters such as line spacing and orientation, flight altitude, aircraft speed and instrumentation/acquisition noise were also included in order to provide a reasonable representation of the signal detection and resolution capability of an actual survey.

The analysis of the model response (Figure 7) shows that under favorable conditions a number of exploration targets

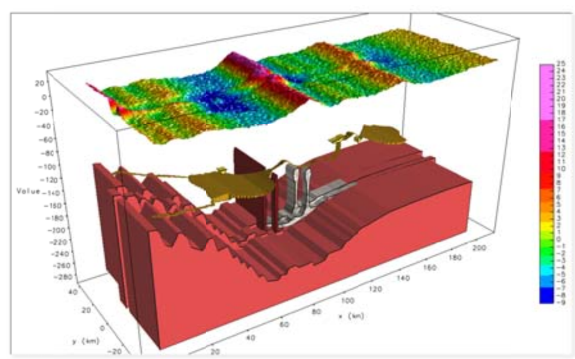

Figure 6: Generalized pseudo-3D geological model for the offshore US coast was built to evaluate FTG applicability in the area.

may be detected and mapped. These include relatively shallow basement horts and rotated blocks, intra-sedimentary dykes, carbonate platform edge, diapiric salt, reefs and possible clastic depocenters.

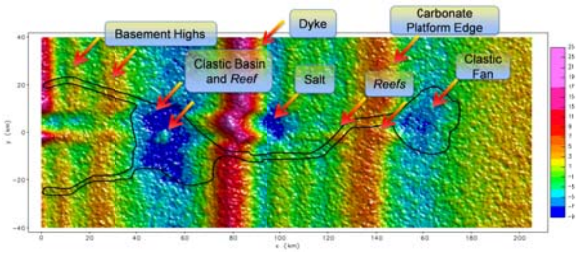

Figure 7: Expression of modeled geological features in calculated FTG Gzz map.

Conclusions

The vast area offshore the US Atlantic coast remains underexplored. The information and knowledge acquired from previous stages of exploration in the region and in the analogous areas as well as utilization of low impact technologies such as airborne FTG are important in development of optimized and environmentally responsible exploration effort in the future.

The FTG feasibility model shows that under favorable conditions, geological features of importance to hydrocarbon exploration could be detected and mapped. Thus, the application of the technology may provide an additional geophysical dataset both in this region and similar settings.

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Basement control on strain localisation during Greenland-Canada breakup

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Basement terranes of eastern Canada and western Greenland are dominated by Archean cratons and orogenic belts. Archean blocks include the typical competent-rounded cratons with minimal reworking, as well as large elongate blocks that have been reworked during the Paleoproterozoic assembly of Laurentia. Orogenic belts range in age from Paleoproterozoic (~1900-1750 Ma) to Mesoproterozoic (1600-950 Ma). Terrane boundaries are defined by changes in orientation and/or magnitude of magnetic and gravity anomalies. Gravity data highlights the similarity of the linear pattern of the Baffin Bay and Labrador Sea regions with other orogenic belts in the region. East to ENE-trending basement fabric of onshore Archean belts in SW Greenland are clearly truncated by the dominant NNW trend of magnetic and gravity orogenic signature offshore. The presence of an orogenic belt between the exposed Archean terranes of Canada and Greenland makes a significant difference to the interpretation of the region. Extension in both Baffin Bay and Labrador Sea was localised on the NNW-trending mobile belt.

Based on the interpretation of gravity data, Baffin Bay is underlain by highly thinned continental crust along with exhumed mantle. The interpreted extinct ridge (NW-trending gravity high) is distinctly asymmetric (NE-dipping) in contrast to normal oceanic spreading centres which are generally symmetric. The asymmetry of gravity across Baffin Bay is consistent with a set of fault blocks and low angle or detachment faults. Published data on the Labrador margin highlights the very rapid thinning of the continental crust. Crust thins from ~40 km to ~10 km over ~25 km width similar to that observed on the Newfoundland margin to the south. Current models for hyperextension tend to have a starting model that consists of horizontally layered crust that requires an initial structure to localize strain. Real continental crust is much more complex and more often has dipping or vertical layering. When basement terranes are taken into account, strain localization is shown to focus on terrane boundaries. Partitioning is strongest on those boundaries with the greatest rheological contrast. Thus mantle exhumation on magma-poor margins is more likely to develop at the boundary of a craton or in narrow mobile belts between cratons where rheological contrast is the highest.

Is there a relationship between mantle serpentinization and compressional deformation on the NE Atlantic margin?

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The NE Atlantic passive margin contains numerous compressional structures possibly dating from the Late Cretaceous onwards (Lundin et al. 2013). Recently Lundin and Doré (2011) proposed the hypothesis that the locations of many compressional structures coincide with pre-breakup hyperextended basins. The authors suggest that hyperextension (with stretching factors of 3-4 or more) results in partial serpentinization of the uppermost mantle, leading to lithospheric weakening that leaves the hyperextended area prone to compressional deformation. A new regional data compilation (The NAG-TEC Atlas) is used to evaluate the proposed spatial association of hyperextension and compressional structures across the NE Atlantic margin from the Irish margin to northern Norway and NE Greenland. Newly collated and standardised seismic refraction and gravity models allow the investigation of crustal thickness variations and identification of areas of hyperextension/serpentinization.

The NAGTEC structural compilation identifies, locates and provides ages of formation for compressional features. The Lundin and Doré (2011) hypothesis has some support offshore Norway (e.g. Lundin et al. 2013) but less so in other hyperextended areas such as the southern Rockall Basin, which does not appear to display significant compressive structures, and where relatively strong lithosphere has been inferred (Kimbell et al. 2004). Furthermore, numerous Cenozoic (and older) compressive domes and ridges are also present around the margins of the northern Rockall and Faroe-Shetland basins, where hyperextension does not appear to be widespread (e.g. Johnson et al. 2005; Tuitt et al. 2010).

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Uplift along Atlantic margins, changes in plate motion and mantle convection

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The origin of the forces that produce elevated, passive continental margins (EPCMs; Fig. 1) is a hot topic in geoscience. It is, however, a new aspect in the debate that episodes of uplift coincide with changes in plate motion (Japsen et al., 2012a, 2014). This has been revealed, primarily, by studies of the burial, uplift and exhumation history of EPCMs based on integration on stratigraphic landscape analysis, low-temperature thermochronology and evidence from the geological record (Green et al., 2013). Colli et al. (2014) provides one of the first attempts to understand these episodic, vertical movements from a geodynamic perspective.

Post-breakup uplift of the margins of Greenland and the spreading history of the NE Atlantic

Late Eocene, late Miocene and Pliocene events of uplift and erosion (beginning at c. 35, 10 and 5 Ma) affected the margin of southern East Greenland after opening of the NE Atlantic at the Paleocene–Eocene transition (Fig. 2; Bonow et al., 2014; Japsen et al., 2014). Based on a synthesis of geological observations, stratigraphic landform analysis and apatite fission-track analysis data, Japsen et al. (2014) showed how these regional phases shaped the margin: (1) During breakup, the margin underwent burial below voluminous flood basalts that erupted onto a largely horizontal lava plain near sea level as well as below younger Eocene lavas and sediments; (2) after late Eocene uplift a regional erosion surface (now the Upper Planation Surface, UPS) was graded to the base level of the adjacent ocean; (3) late Miocene uplift of the UPS led to formation of the Lower Planation Surface (LPS) by incision below the uplifted UPS, and (3) Pliocene uplift led to incision of valleys and fjords below the uplifted LPS, leaving mountain peaks reaching 3.7 km above sea level.

These regional uplift phases are synchronous with phases in West Greenland (despite the asynchronous histories of drifting west and east of Greenland), overlap in time with similar events in North America and Europe and also correlate with changes in plate motion. For example, the late Eocene uplift event that affected Greenland as well Scandinavia (e.g. Green and Duddy, 2010) correlates with the significant change in spreading direction in the NE Atlantic around Chron 13 time at ~33 Ma (Gaina et al., 2009). Sea-floor spreading west of Greenland ceased at this time and the plate reorganization was preceded by a marked drop in spreading rates. The much higher elevation of East Greenland compared to West Greenland suggests dynamic support in the east from the Iceland plume.

Post-breakup uplift of the Atlantic margin of NE Brazil and the spreading history of the South Atlantic

In the Campanian, Eocene and Miocene, events of uplift and erosion (beginning at c. 80, 45 and 15 Ma) affected the margins of Brazil and Africa after Early Cretaceous opening of the South Atlantic (Fig. 3; Japsen et al., 2012a). A synthesis of geological data, stratigraphic landscape analysis, and paleothermal and paleoburial data revealed that NE Brazil underwent a four-stage history since breakup: (1) After breakup, the margin underwent burial beneath a thick sedimentary cover; (2) uplift episodes in the Campanian and Eocene led to almost complete removal of these deposits; (3) the resulting large-scale, low-relief erosion surface (now the Higher Surface, HS) was deeply weathered and finally reburied at the Oligocene-Miocene transition; and (4) Miocene uplift and erosion produced a new, lower level erosion surface (the Lower Surface, LS) by incision of the uplifted and re-exposed Paleogene peneplain (Japsen et al., 2012a).

The uplift phases in Brazil coincided with main phases of Andean orogeny which were periods of relatively rapid convergence at the Andean margin of South America (Fig. 4; e.g. Cobbold et al., 2007). Because Campanian uplift in Brazil coincides not only with rapid convergence at the Andean margin of South America but also with a decline in Atlantic spreading rate, Japsen et al. (2012a) suggested that all these uplift events have a common cause, which is lateral resistance to plate motion. Because the uplift phases are common to margins of diverging plates, it was also suggested that the driving forces can transmit across the spreading axis; probably at great depth, e.g. in the asthenosphere.

Uplift due to compressive stresses at the edges of cratons

Japsen et al. (2012b) pointed out that EPCMs are typically located above thick crust/lithosphere that is closely juxtaposed to thinner crust/lithosphere. The presence of mountains along margins in the Atlantic domain (e.g. Norway, Brazil, East and West Greenland, eastern Canada) close to where continental crust starts to thin towards oceanic crust, illustrates the common association between EPCMs and the edges of cratons. These observations indicate that the elevation of EPCMs may be due to processes operating where there is a rapid change in crustal/lithosphere thickness. Vertical motion of EPCMs may thus be caused by compressive stresses at the edge of a craton (e.g. Cloetingh et al., 2008). The synchroneity between changes in plate motion and uplift events along conjugate margins indicates immediate, far-field transmission of momentum through the upper mantle (H.-P. Bunge, pers.comm., 2013). The compression may be derived either from orogenies elsewhere on a plate or from differential drag at the base of the lithosphere by horizontal asthenospheric flow (Green et al., 2013).

The observations reviewed here indicate a connection between vertical movements along passive continental margins, changes in plate motion and mantle convection.

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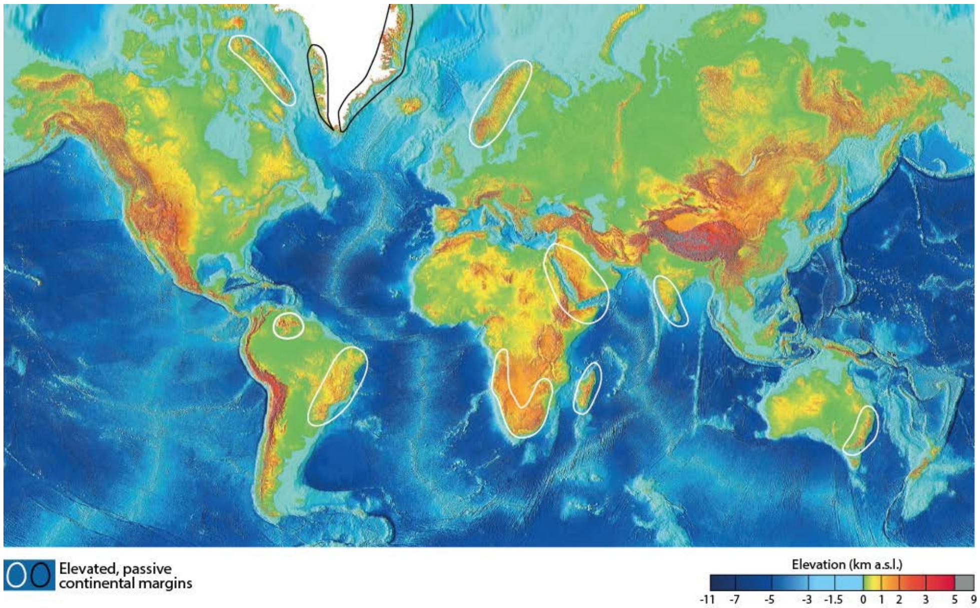

Figure 1: Topography of the Earth showing elevated passive continental margins (EPCMs). Only Atlantic-type margins that can easily be connected to the corresponding spreading centre are indicated and only elevated margins that reach 2 km a.s.l. in more than a single summit. Study areas in East Greenland and Brazil are indicated. Modified after Japsen et al. (2012a) and Green et al. (2013).

Figure 2: Gåseland, East Greenland (70°N), looking north-west. The dominant 1900-m plateau (the Upper Planation Surface, UPS) is an erosion surface that truncates basalts that were erupted at 56 Ma during North Atlantic breakup. The basalts cover the undulating, weathered basement in the foreground. After uplift which started in the late Eocene (~35 Ma), the UPS was formed by fluvial incision and slope processes, and ultimately graded to sea level. The landscape was then uplifted again in the Miocene and incised by rivers. The present plateau is smoothed by periglacial processes and the river valleys have been widened and deepened by glacial erosion. From Bonow et al. (2014).

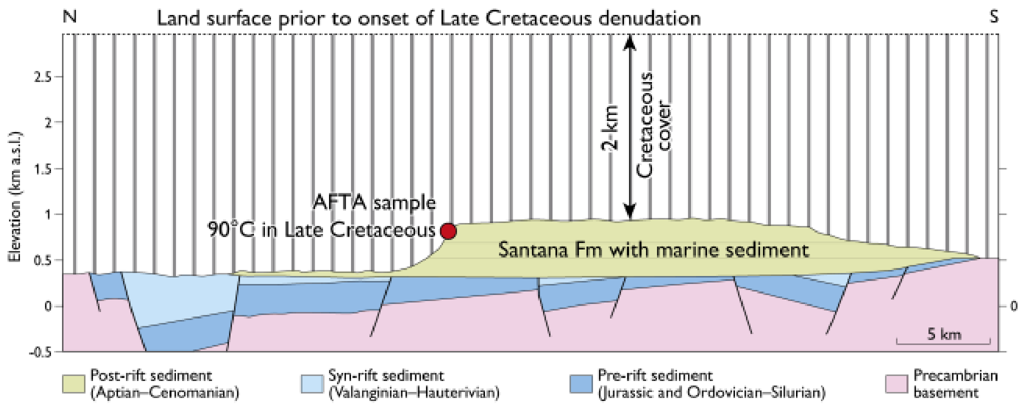

Figure 3: Araripe Plateau, NE Brazil (7ºS, 400 km from the Atlantic margin). The post-rift Santana Formation of early Albian age contains unambiguous marine strata (e.g. echinoids) at an elevation of c. 600 m a.s.l. (Assine, 2007; Martill, 2007; Morais Neto et al., 2006). These observations testify (1) to post-rift subsidence and (2) to subsequent significant uplift. Thermal history interpretation of apatite fission-track analysis (AFTA) samples from the post-rift sequence of the Araripe Basin shows that this sediment reached palaeotemperatures of 80–100°C in the Late Cretaceous in close agreement with vitrinite reflectance values of 0.56% corresponding to a palaeotemperature of 93°C (Morais Neto et al., 2006). These observations show that burial of the Araripe rift continued after break-up at the Aptian–Albian transition and after the deposition of the Cenomanian sediments that are the youngest preserved today. The thickness of the cover removed above the present-day surface of the plateau since the onset of Late Cretaceous denudation thus amounts to c. 2 km (1.8–2.5 km for a palaeogeothermal gradient of 30°C/km and a palaeosurface temperature of 25°C). After Green et al. (2013).

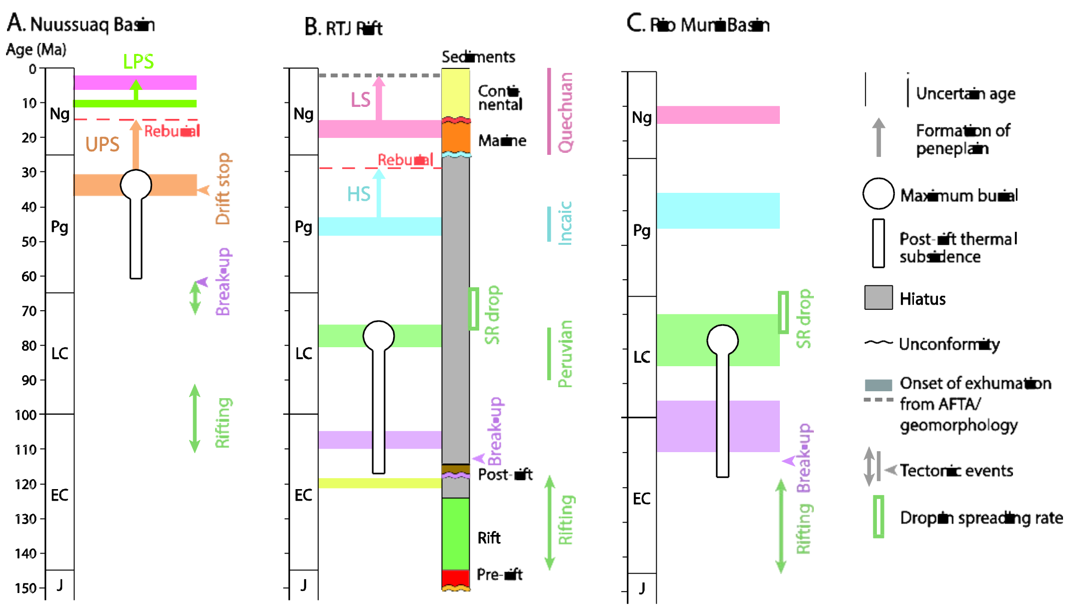

Figure 4: Comparison among timing of uplift events, formation of peneplains, and tectonic episodes along margins in the Atlantic domain. The present-day landscapes in West Greenland and NE Brazil were formed millions of years after breakup when regional peneplains were uplifted and dissected during the Neogene. (A) Nuussuaq Basin, West Greenland (70°N; Japsen et al., 2006). The Upper Planation Surface (UPS) defines the plateau, whereas the Lower Planation Surface (LPS) is a system of paleovalleys (e.g. Bonow et al., 2006). (B) Recôncavo-Tucano-Jatobá Rift (RTJ), NE Brazil (12°S; Japsen et al., 2012a). The Higher Surface (HS) defines the plateau whereas the Lower Surface (LS) defines the plains between the plateaus. Main phases of Andean orogeny: Peruvian, Incaic, and Quechuan (e.g. Cobbold et al., 2007). (C) Rio Muni Basin, West Africa (2°N; Turner et al., 2008) (conjugate margin to NE Brazil). The colors of the vertical bands indicate onset of uplift events and the interpreted correlation between events on the conjugate margins in NE Brazil and West Africa. Changes in plate motion are after Chalmers and Pulvertaft (2001) and Torsvik et al. (2009). SR—spreading rate; AFTA—apatite fission-track analysis. After Japsen et al. (2012a).

A Re-evaluation of the Exploration Potential of the Baffin Bay and the Labrador Sea Based on a New Deformable Plate Reconstruction

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Introduction

Baffin Bay and the Labrador Sea have been the focus of a renewed exploration effort over the last decade which has resulted in a vast amount of new geological and geophysical data. At the same time non-rigid / deformable plate modeling methodology has advanced, so that the complex interaction between rifting, strike-slip fault zones, and Cenozoic compression can now be modeled. This deformable plate reconstruction study of Baffin Bay and the Labrador Sea uses newly developed methods to more accurately determine the structural development and basin geometry. The area of the study is shown in Figure 1.

The structural and geological development of the Baffin Bay - Labrador Sea area are also discussed in the wider regional context of the Arctic and North Atlantic. The relationship with the plate tectonic evolution of the Greenland, North American and Eurasian plates can be clearly demonstrated. The relevance of hyper-extension and failed rift margins are also discussed.

Discussion

The timing of breakup, and the extent of hyper-extended crust and mantle exhumation in the ocean basins, have been re-defined as a result of the study. The complex interaction between rifting, strike-slip fault zones, and Cenozoic compression in north Greenland and Ellesmere have also been modeled. The northward propagation of the rift system shows a progressive development of structures which influence deposition and potential trap integrity. Mapping the geometry and connectivity of the rift basins helps to assess the critical marine connections to the Arctic and Atlantic oceans.

The area can be subdivided into four distinct geological provinces which have a different geological development resulting from the opening of the Labrador Sea and Baffin Bay ocean basin from south to north. These geological provinces are the result of south to north propagation of the rift system. As a result each of these areas have a different exploration potential.

A series of palaeogeographic reconstructions provide a detailed analysis of the geometry of the basins at the time of deposition. The plate reconstruction results are used to model palaeogeography and the marine connection between the Labrador Sea and Baffin Bay, and between Baffin Bay and the Arctic Ocean.

Structural trap development also varies from south to north in the Labrador Sea – Baffin Bay region. Lower Cretaceous non-marine sandstone reservoirs are sealed by thick Upper Cretaceous shale in tilted fault blocks in many of the Labrador Sea discoveries. In West and NW Greenland tectonic activity continued throughout the Late Cretaceous into the Palaeogene making this type of Cretaceous tilted fault block trap less effective in these areas. New evidence from the non-rigid/deformable plate reconstruction suggests that break-up did not take place until the latest Paleocene, which is later than previously thought. Structural inversion becomes more prevalent northwards in the area as the Greenland plate moved northward in the Eocene and collided with North America forming the Eurekan thrust belt on Ellesmere Island.

Conclusions

Deformable plate reconstruction methods can be applied successfully in the Baffin Bay - Labrador Sea area and have provided new insights into its geological development. Modeling the area within a larger regional Arctic-North Atlantic context is important in determining the relative motion of the plates and the amount and timing of deformation on the plate margins. The development of the new deformable plate model has resulted in a re-evaluation of the Baffin Bay-Labrador Sea margins.

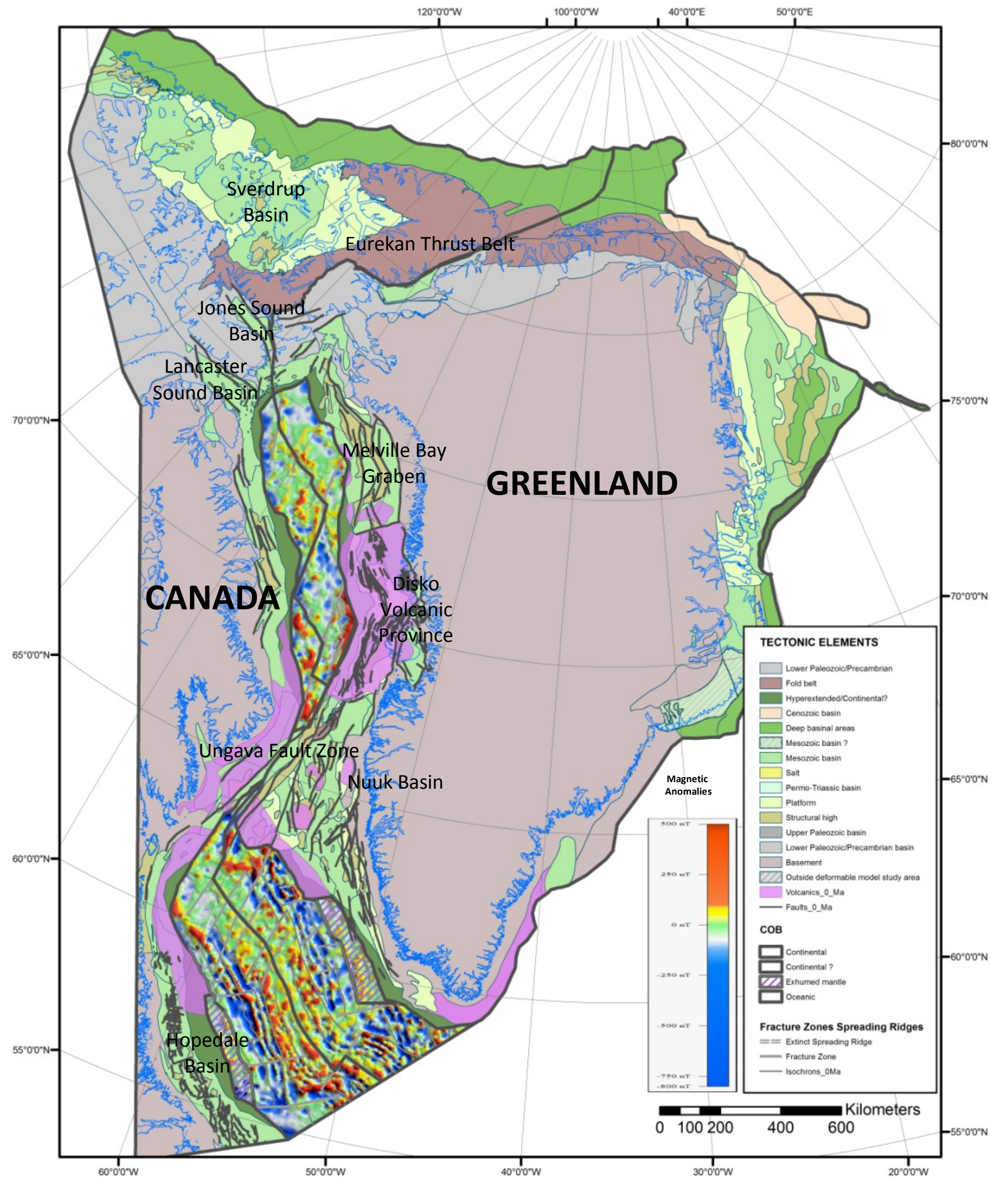

Figure 1: Labrador Sea - Baffin Bay deformable plate reconstruction study area. The figure shows major tectonic elements and magnetic anomalies.

Labrador Sea to Greenland: structural-stratigraphic interpretation and seismic facies analysis provide further understanding of the depositional and tectonic evolution of the basin

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The Labrador Sea developed when the Greenland and North America plates separated. The basin developed in two stages of rifting, an initial period of stretching in the Early Cretaceous with the formation of fault blocks that were filled with Lower Cretaceous sediments, followed by thermal subsidence and a second period of rifting in the Late Cretaceous - Early Paleocene, culminating in the onset of sea floor spreading in Mid Paleocene. Along the Labrador and southern West Greenland margins, oceanic crust is separated from continental crust by highly stretched but non-magmatic transition zones which developed before sea-floor spreading (Chalmers and Pulvertaft, 2001).

Exploration offshore Labrador has been confined to the shelf with no test of the deep water potential conducted. The hydrocarbon potential of the shelf has been proven by 6 significant gas discoveries. The last well drilled offshore Labrador was in 1983. The West Greenland margin is also significantly under-explored. Only seven wells have been drilled and the seismic coverage is still very regional (less than 85,000 km 2-D seismic data). No wells have been drilled on the southern West Greenland Margin.

A multi-client long offset 2D seismic survey (totalling 22,167 line km) acquired by TGS in partnership with PGS in 2012 and 2013 in the Labrador Sea has provided the opportunity for deep sea exploration. This new seismic dataset and the West Greenland data (2001-2005) acquired over slope and deep water regions provided new insights into the structural and stratigraphic development of the Labrador Sea (Figure 1.).

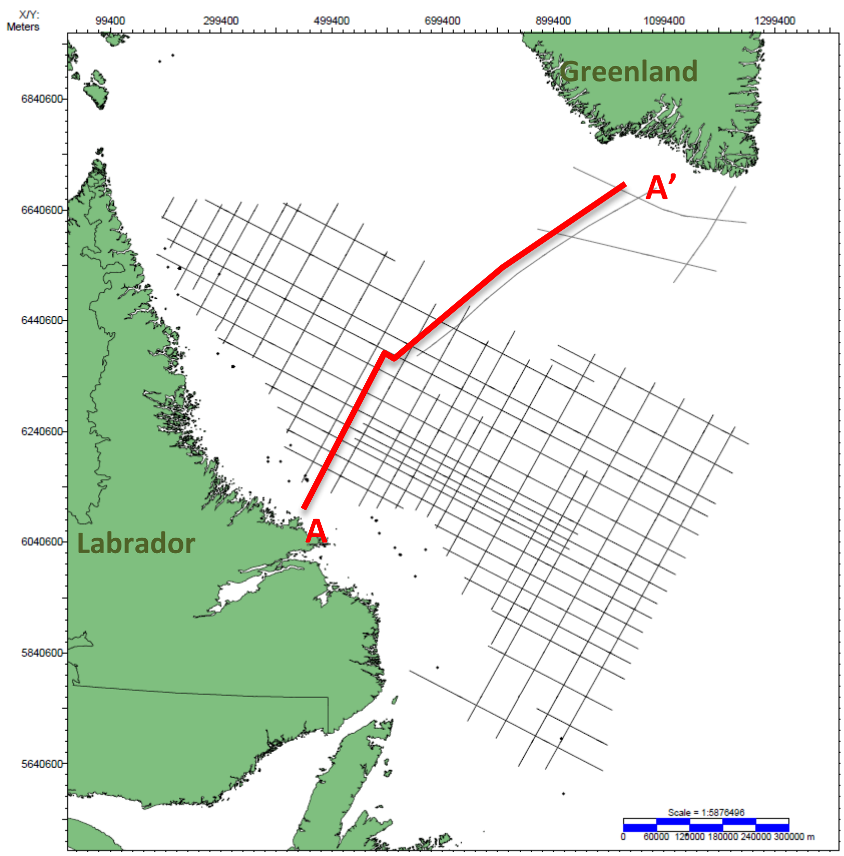

Fig 1. Labrador Sea location map; multi-client long offset 2D surveys and regional 2D surveys offshore Labrador and southern West Greenland respectively with well locations on the Labrador Shelf. A-A' Transect Line from Labrador Shelf to Greenland Shelf

A sequence stratigraphic and depositional environment interpretation of the Labrador passive margin was conducted. Detailed interpretations and computerised petrophysical evaluations were completed on well log data from 31 wells across the Hopedale, Saglek and St Anthony Basins, along with a detailed structural and stratigraphic interpretation of the regional multi-client 2D seismic data set.

The detailed interpretation of the well log data and the 2D seismic data set provided the basis for a comprehensive seismic facies analysis study to be undertaken from the Labrador Shelf to the median line with West Greenland. The seismic facies analysis together with a potential fields modelling study provided further understanding of the depositional environments and tectonic evolution of the Labrador Sea basin (Figure 2.).

A number of potential source rock intervals within the Late Cretaceous and Early Tertiary have been identified. Thermal modelling results indicate that these source rocks are likely to be mature for oil expulsion in the deep water part of the basin.

Play fairway analysis was undertaken for seven sequences over the Labrador shelf, slope and deep water area that assessed the prospectivity (hydrocarbon potential) of this large under-explored frontier margin. The maps produced combine reservoir, seal and source facies; which were then used to create common risk maps for reservoir, seal and source presence. Additional common risk maps were constructed for source rock maturity. The play types represent different lacustrine and marine systems. Due to the sparse well data coverage typical of frontier basins, the play models are seismically driven, resulting in high-level qualitative risk assessments, dividing the plays into low-, medium-, and high-risk categories.

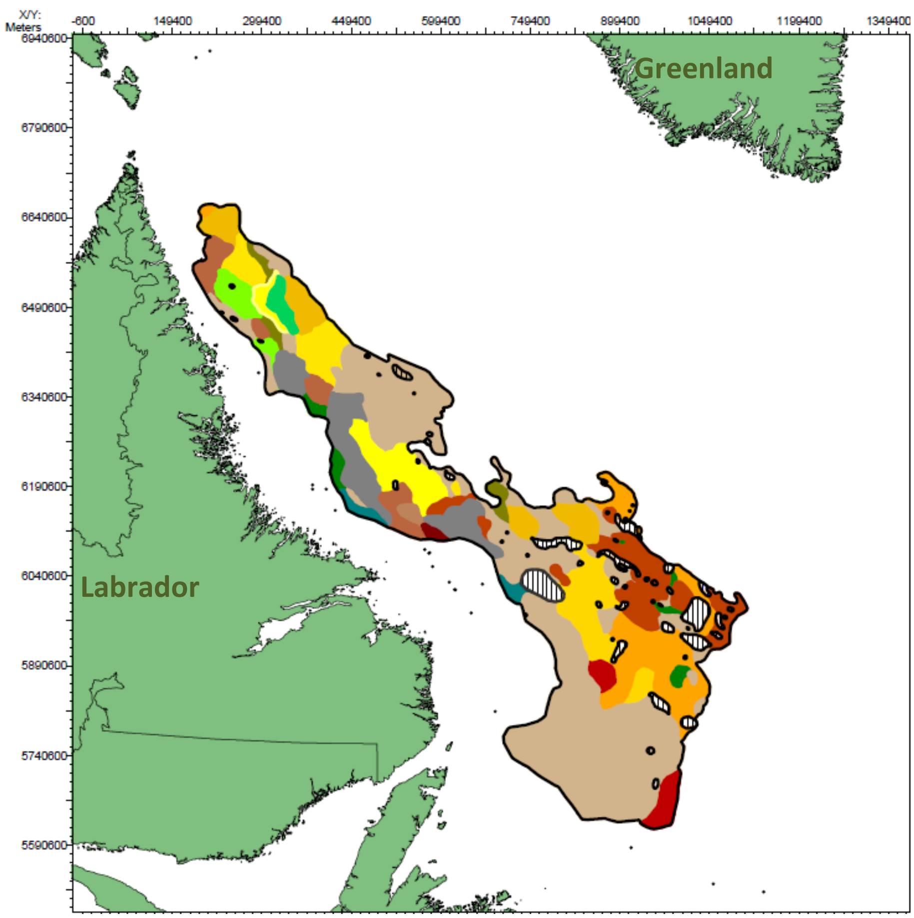

Fig 2. Late Cretaceous formation SFA/GDE map used in Play Fairway analysis. Colours represent lithologies and depositional environments

In order to develop a further understanding of the evolution of the Labrador sea and the depositional environments of the closely related margins of Labrador and West Greenland, a seismic profile transect across the conjugate margins was created using the recent Labrador Sea data of 2011/2012 and West Greenland data acquired between 2001 and 2005 (Fig 3., see Fig 1. for location). This profile was interpreted by tying the existing Labrador Sea interpretation across the extinct spreading centre to the southern West Greenland shelf and performing seismic facies analysis to identify similar depositional environments from the Labrador to Greenland shelf (Figure 4.).

The development of the Labrador Sea and the continuity and distribution of sediment supply between the conjugate margins allows for a seismically driven interpretation of the depositional environments of the sediments on the southern

West Greenland Margin**.** The earliest sediments are the syn-rift Bjarni Formation on the Labrador shelf (Early Cretaceous Kitsissut and Appat sequences, Greenland margin). The units are overlain by the Markland Formation of the Labrador shelf (Late Cretaceous Kangeq Sequence, Greenland margin). Rifting was renewed in the Early Paleocene with mixed clastics being deposited**.** After the end of the Paleocene there was little rifting in the region, but compressional structures were formed locally as a response to transpression related to strike-slip movements that transferred plate motion from the Labrador Sea to Baffin Bay (Chalmers et al. 1993).

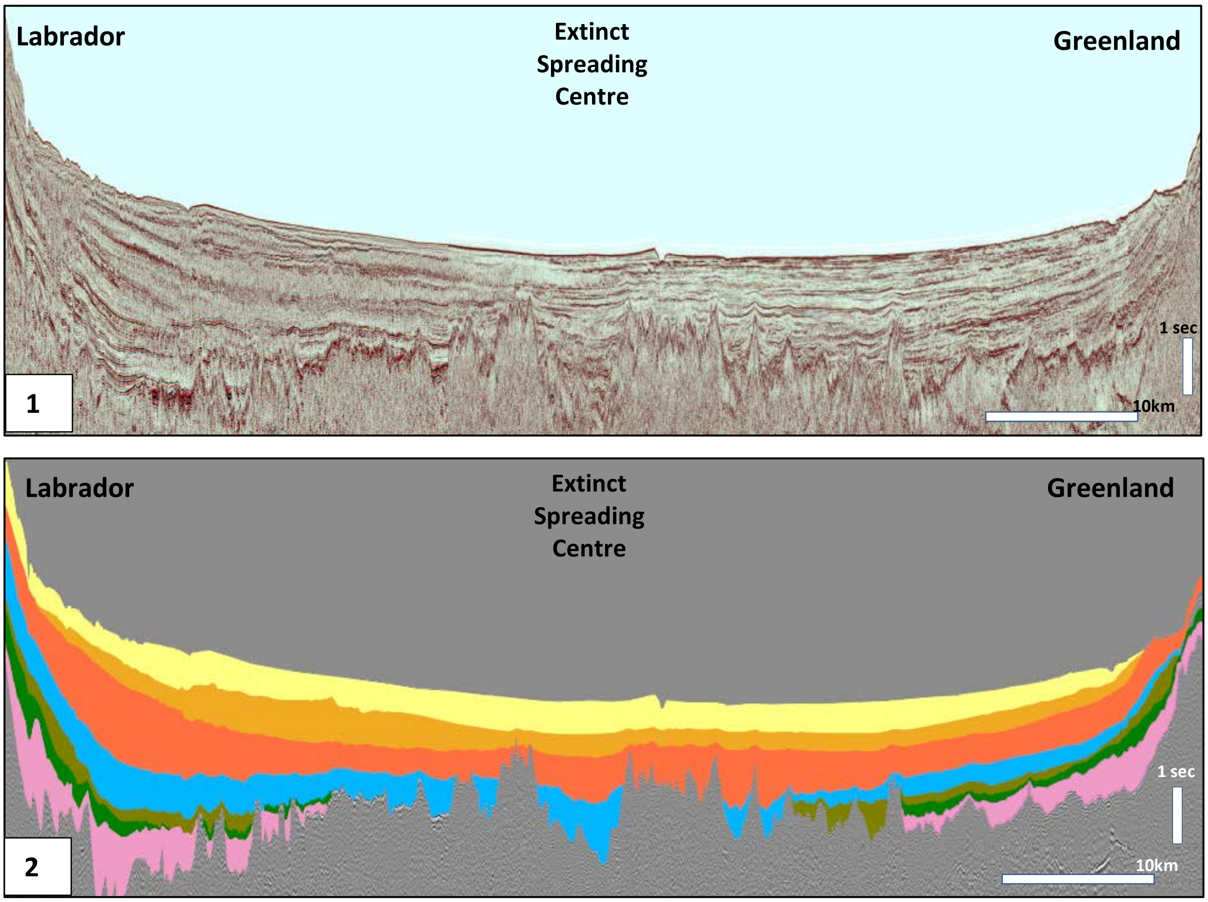

Figure 3. Section A-A’ Labrador Shelf to Greenland Shelf. 1. Uninterpreted transect. 2. Interpreted transect; Colour = Labrador name (Greenland name); Yellow = Saglek (Pliocene), Dark yellow = T6.5 (Late Miocene). Orange = Mokami (Mid-Miocene-Oligocene), Blue = Kenamu (Eocene), Olive Green = Cartwright (Paleocene), Dark Green = Markland – (Kangeq), Pink = Bjarni (Kitsissut & Appat)

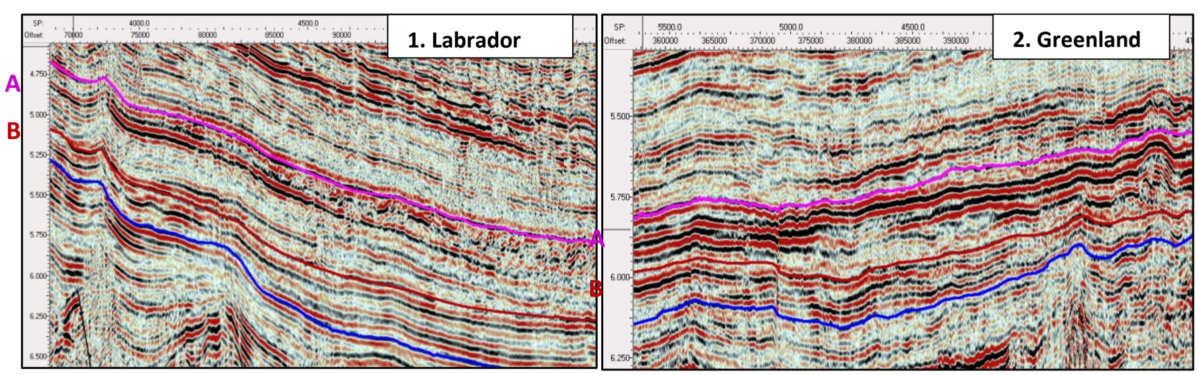

Figure 4. Top Eocene, Mid Eocene, Top Paleocene. SFA (Seismic Facies Analysis), GDE (Gross Depositional Environment). **A:** SFA = Upper: Moderate to high amplitude, good continuity, sub-parallel Lower: (locally) Low amplitude, poor continuity, sub-parallel. GDE= Upper Slope (SA1) – Fan Complex, Sand in upper section, shale with silt locally in lower section. **B:** SFA= Moderate amplitude, good continuity, parallel to

sub-parallel. GDE= Upper to Lower slope (SA1-SA2): sandy turbidite. There is potential for a larger abundance of sand on the Greenland Margin for this particular facies.

This transect was also used for gravity and magnetic forward modelling to derive a subsurface model across to the conjugate margin. The results of forward modelling several density and magnetic cross sections in the Labrador Sea supported the interpretation and provided further constraints on the extent of the continental to oceanic transition zone and provided a more detailed model of the crustal configuration and distribution across the two conjugate margins which is broadly consistent with previous published studies (Alsulami et al, 2013)

Different crustal domains in the South and North of the Labrador Sea were identified and compared to West Greenland. The published results of an analyses of gravimetric and magnetic domains offshore West Greenland (Planke et al, 2004) were used as a guideline for frequency analyses performed in the Labrador Sea and offshore southern West Greenland. The result was a detailed interpretation of the gravity and magnetic anomalies on the conjugate margins in the area of interest surrounding the transect.

The seismic facies maps and the crustal distribution resulting from the gravity and magnetic modelling provides support for the interpretation of the depositional evolution and its effect on continuity and distribution of sediment supply between the conjugate margins.

The Labrador seismic data set, available well data and gravity and magnetic data has allowed for a comprehensive interpretation to be undertaken from the Labrador Shelf to the median line with West Greenland. In addition, this survey was tied to regional seismic data from West Greenland and allowed for a continuous transect to be made from the Labrador shelf across the entire width of the Labrador Sea to the southern West Greenland shelf, which provided important new constraints to the depositional environments and the evolution of the basin. This comprehensive interpretation is essential in helping to better understand the distribution of the substantial undiscovered resources believed to be offshore West Greenland and Labrador.

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Late Jurassic to Early Cretaceous Structural Development of the Celtic Sea Basin Offshore Ireland Based on New 3D Seismic Acquisition

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1,920 sq. km. of new 3D seismic acquisition acquired by Fastnet Oil and Gas Plc in 2013 represents the largest and most recent 3D seismic database in the Celtic Sea offshore Ireland.

Interpretation of these data has greatly improved the seismic imaging of the Late Jurassic to Early Cretaceous interval in the basin, which has led to an improved understanding of structural development and of the petroleum system relative to its conjugate margin counterpart in the Jeanne D'Arc and Flemish Pass Basins offshore Eastern Canada. Significant additional hydrocarbon resources were recently discovered in 2013 in the Flemish Pass Basin.

The 2013 seismic data has facilitated the identification of new and existing prospective structures as well as imaging deeper structures that have never before been targeted by legacy drilling. The potential for deep oil and gas beneath the long-producing and giant Kinsale gas field has also been enhanced together with a better appreciation of the potential for attractive reservoir development. The oil column identified, but never conclusively tested, in the first well ever to be drilled on the flank of the Kinsale Structure (48/25-1) is now shown to be within and on the edge of a structurally controlled closure. This sequence was never reached and tested in any of the later Kinsale wells.

Linking regional tectonic events with the stratigraphic succession and subsidence history of Orphan Basin, offshore Newfoundland, Canada

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Orphan Basin, on the Atlantic continental margin offshore eastern Newfoundland, is a large rift basin that formed during multiple rift phases (Fig. 1). Extension from the Jurassic through the Early Cretaceous (Aptian) resulted in faulting and thinning of the continental lithosphere within the basin. Subsequently, extension was focused east of Orphan Knoll with the onset of seafloor spreading beginning at least by the Santonian (chron 33R). These regional tectonic events may be recorded in the stratigraphic succession of Orphan Basin. We have integrated seismic and well data with revised palynological dating to develop a regional stratigraphic framework and to identify basin-wide unconformities and syn-rift sedimentary packages. Combining the stratigraphy with analysis of the subsidence history allows us to make inferences on tectonic influence.

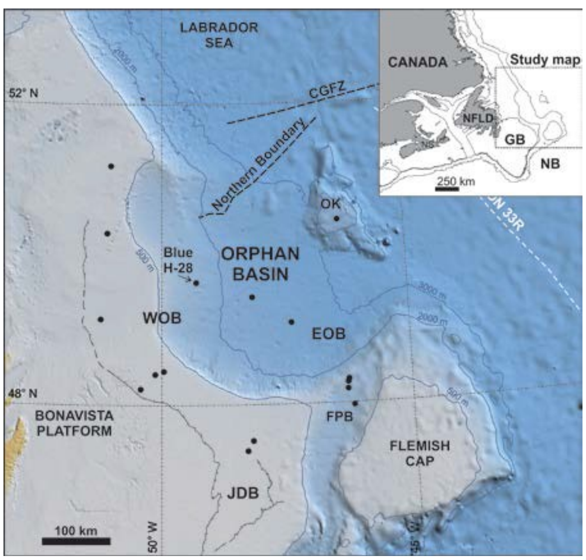

Figure 1: Study area with well locations shown. CGFZ=Charlie- Gibbs Fracture Zone, JDB=Jeanne d'Arc Basin, EOB=East Orphan Basin, FPB=Flemish Pass Basin, GB=Grand Banks, NB=Newfoundland Basin, NFLD=Newfoundland, OK=Orphan Knoll, and WOB=West Orphan Basin.

A basin-wide unconformity and correlative conformity, of Aptian-Albian age (AU), is associated with erosion in the central, high-standing part of the basin (Fig. 2). On seismic data, the Aptian-Albian event appears to mark the end of crustal thinning and rifting and is consistent with a breakup unconformity. Following this, there was a delay in thermal subsidence that is normally associated with post-rift deposition. Albian through Santonian aged deposits reflect shallow-marine to shelfal (< 200 m) paleowater depths during a period of minor sag basin development (Fig. 2). A Santonian-aged unconformity and its correlative conformity (SU) represents more localized erosion atop basement highs (Fig. 2), along the western basin margin and on Orphan Knoll. Major thermal subsidence began in Late Campanian-Early Maastrichtian times, when a significant transgression took place across the basin (Fig. 2), culminating in the development of the Base Tertiary (BT) event. This prominent seismic event records bathyal water depths and development of a condensed section representing basin-wide maximum flooding.

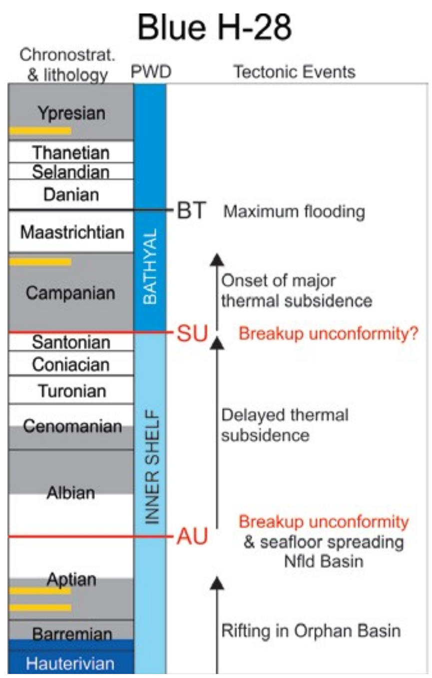

Figure 2: Chronostratigraphic succession in the Blue H-28 well. The paleowater depth (PWD) and major stratigraphic events are denoted, as well as major tectonic events. Lithology depicted: shales are grey, sandstones are yellow, limestones are blue and missing section is shown in white.

We propose that the major stratigraphic events in Orphan Basin reflect the breakup of crust and/or lithospheric mantle on a broad regional scale. A mechanism is required to explain the delayed post-rift subsidence in the basin and the development of the Santonian event. The Aptian- Albian unconformity reflects the end of crustal extension within Orphan Basin. To the south, in the Newfoundland Basin, this time reflects the initiation of seafloor spreading; however, complete lithospheric breakup east of Orphan Knoll may have been delayed until Late Cretaceous time when thermal subsidence begins.

The tectonic subsidence histories at the wells and from backstripping 2D profiles support the recognized period of delayed basin subsidence. We have modeled this using depth-dependent extension models, which show that extreme mantle thinning is needed to satisfy the observations. Furthermore, the mantle thinning must persist into the post-rift period, some 30 million years after crustal extensiohn ceased.

Delayed post-rift subsidence has been observed at other magma-poor rifted margins (Franke, 2013). The Orphan Basin, however, is much wider (~400 km) than most continental margins, which limits direct application of conceptual and quantitative models to the region. We favour the counterflow of depleted, buoyant, continental mantle (Huismans and Beaumont, 2011) below Orphan Basin to explain the prolonged shallow water depths. However, other processes are also viable. Whatever the mechanism, it appears that mantle, as well as crustal, processes controlled the nature of Mesozoic and earliest Cenozoic stratigraphy.

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History, character, and implications of fault growth in the Terra Nova oilfield, Jeanne d'Arc Basin

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An integrated understanding of variations in stress state and structural deformation through time is required to accurately constrain the influence of plate tectonic extension on the character, distribution and compartmentalization of source and reservoir facies within the Jeanne d'Arc rift basin. Multiple, high-quality 3D seismic cubes, combined with numerous, relatively closely-spaced well penetrations achieved during exploration, delineation, and development stages of the Terra Nova oilfield, provide a data-rich opportunity to evaluate and illustrate this complex history of episodic tectonism. Prior evaluations of the Terra Nova structural character include Wilcox *et al*. 1991. Sinclair 1995, Haugen *et al*. 2007, Ferrill *et al*. 2009. Richards *et al*. 2010.

The following list summarizes the deformational components that ultimately define the reservoir character of the Upper Jurassic Jeanne d'Arc Formation at the Terra Nova oilfield.

1. Pre-depositional inherited structures
2. Syn-depositional conjugate extensional faults
3. Syn-depositional intra-sedimentary faults
4. Post-reservoir deposition extensional faults and interaction with existing structures
5. Post-depositional oblique-slip deformation
6. Post-depositional compactional fault propagation

Development of the Jeanne d'Arc rift basin was strongly influenced by the structural grain of the basement established through accretion of crustal plates during the assembly of Pangea. This inherited pattern of sinuous lineations of compressionally folded Devonian and older strata is observed along the length of the North American eastern seaboard and continues across the Grand Banks as illustrated by large-scale aeromagnetic trends. NW-SE-oriented extensional forces locally re-activated some of these pre-existing compressional structures as normal faults during the Triassic to earliest Jurassic time. As a result continental red beds and thick layers of halite accumulated in the fault-bounded and segmented Jeanne d'Arc and associated rift basins. Many of these initial Mesozoic rift-driven faults became inactive and were buried during the Middle Jurassic but they remained structural inhomogeneities available for subsequent reactivation. (see label "1" on lowermost section of Fig. 2).

Following deposition of the economically important Egret Member source rock during the Kimmeridgian (*sensu gallico*), the Terra Nova Field area experienced extensional fault growth within the sedimentary column. This shallow expression of extension is attributed to renewed stretching at depth within the continental crust and deformed Lower Paleozoic and older strata present beneath thick Upper Triassic to Lower Jurassic salt beds. Northerly-trending normal faults of opposing dip grew laterally, as well as vertically, such that they commonly intersected, thereby acting as conjugate fault pairs. The main East-dipping fault is dominant (i.e. through-going) at the N-S-oriented conjugate fault pair labeled "2" on Figure 2 but along strike to the North, the west-dipping fault becomes dominant, demonstrating their coeval growth. This style of fault growth and interaction is demonstrated to have spanned deposition of the Jeanne d'Arc, Fortune Bay and Hibernia formations (green interval between the Tithonian unconformity and B Marker surfaces on Fig. 2). Differential subsidence on adjacent fault blocks is demonstrated by abrupt thickness variations of Tithonian to early Valanginian strata, along with enhanced section thinning in areas of crossing faults. The growth of the northerly-trending set of syn-depositional faults created the primary spill point to the Terra Nova field along its western margin (westernmost blue fault of Fig. 1).

Tectonically-driven regional basin tilt and local fault block rotation with associated seismic activity (i.e. earthquakes) are furthermore interpreted to have combined with incision-induced gravitational instabilities to have caused intra-sedimentary slump faulting into syn-formed valleys. This resulted in updip extension and down-dip small-scale toe thrusts on intra-sedimentary listric faults. Growth of such intrasedimentary detached faults is evidenced by strata-bound rotated and distorted layers of shale-prone beds beneath major sequence boundaries. One such example was cored at Terra Nova L-19 12Z (box folding seen on Fig. 3). Seismically-derived maps of the incised valleys on the SW flank of the Terra Nova Field in the area of the King's Cove A-26 were first published by Enachescu (1993, 1994).

Post-depositional arching induced by transpression and fault block rotation during subsequent mid-Aptian to Albian rifting (yellow interval on Figure 2), inter-acting with numerous inherited structures, combined to generate the ultimate trap shape for the field. Note the complex patterns of Aptian-Albian strata on the hanging wall of the Voyager fault zone. The lower interval thickens toward this major basin-bounding fault(s) while the overlying syn-rift strata thin toward the same fault. This pattern is considered a response to a component of oblique slip along this somewhat sinuous fault. At the same time, a new set of crossing conjugate faults grew during this new episode of crustal extension in response to NE-directed extension (red faults of Fig. 1). Interaction of the older northerly-trending faults with these youngest rift-induced faults combined to significantly compartmentalize, and locally truncate stacked reservoir facies in the field.

Finally, substantial local upward propagation of faults during Tertiary times due to differential compaction altered the shallow sedimentary section but did not provide leak pathways for hydrocarbon loss after source maturation and oil migration into the highly structured field.

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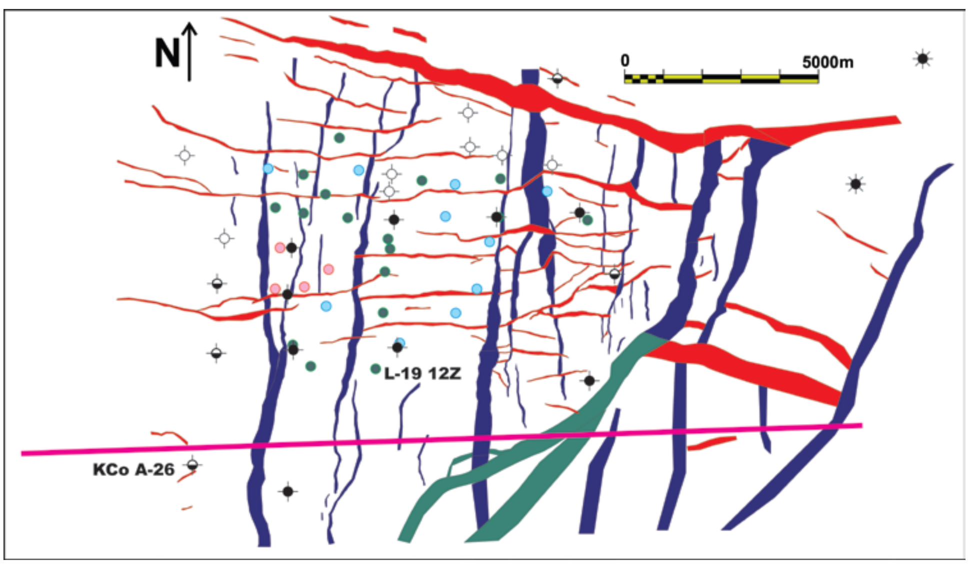

Figure 1: Well and fault location map for the Terra Nova oilfield. Bottom hole location of directionally drilled development wells indicated by coloured circles (green – producers; blue – water injectors; red – gas injectors). Magenta line represents location of Fig. 2 seismic profile. Fault map modified after Figure 9 of Ferrill *et al*. (2009). Blue polygons represent normal faults active during the Late Jurassic to Early Cretaceous; red polygons represent normal faults active during the mid-Aptian through mid to late Albian; green polygons represent segments of the oblique-slip Voyager fault zone also active during the mid-Aptian through mid to late Albian

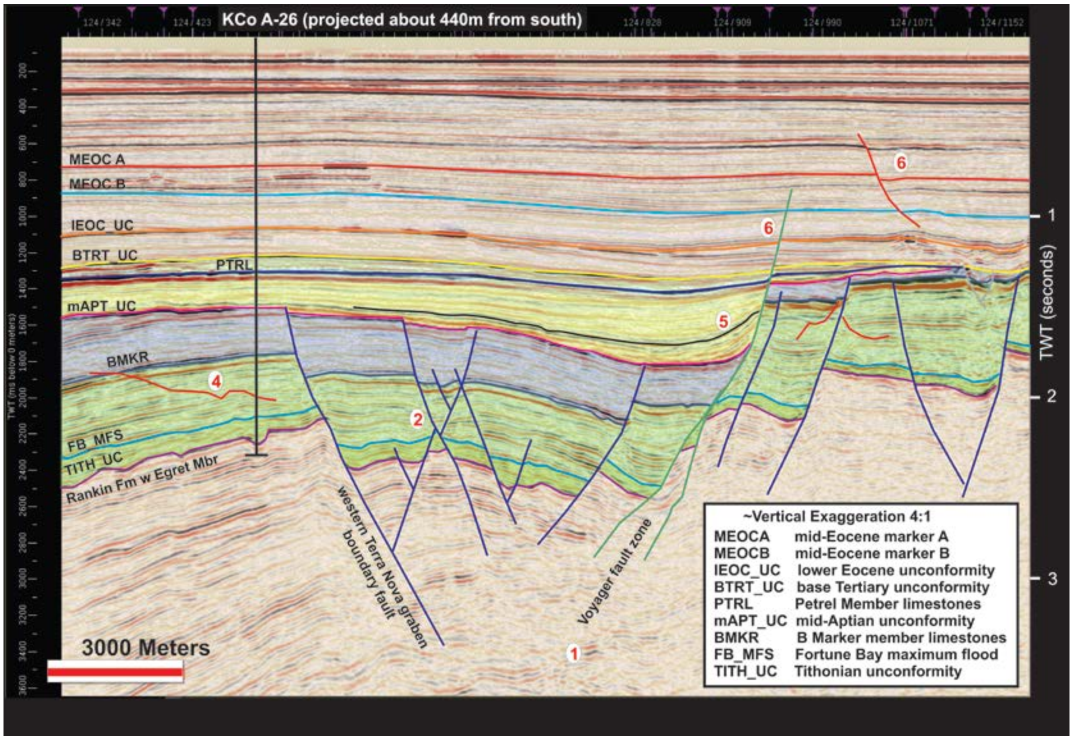

Figure 2: West to East (left to right) seismic profile across south end of Terra Nova field (location on Fig. 1) from 1997 3D survey in time. Deformational components numbered as in text. The green fault segments are components of the Voyager fault zone aligned with inherited Triassic rift structures, later re-activated with a small oblique component and finally compactional propagation into post-rift Upper Cretaceous and Tertiary strata.

Figure 3: Intra-sedimentary box fold interpreted to be at toe of a slump rotated block of lower Tithonian shales of the Jeanne d'Arc Formation that were destabilized by substantial valley incision at the major middle Tithonian unconformity (as cored at Terra Nova L-98 12Z). Strata above and below the deformed zone are consistently low-dipping.

First cycle supply to the Cretaceous Scotian Basin resolved using Pb-isotopes in detrital K-feldspar grains

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Introduction

One of the more challenging problems in determining the provenance of sandstones is that much of the detritus may be of polycyclic origin, reworked through older sedimentary deposits. Such polycyclic sandstones are much more fertile as a source of many heavy minerals than are first cycle (crystalline basement) sources. Thus resistant heavy minerals from polycyclic sandstones can dominate the heavy mineral assemblage in a deposit and better resist the ravages of diagenesis than less stable first-cycle minerals. Yet the distribution of crystalline basement in a drainage basin is generally more informative in tectonic reconstructions than are older sedimentary basins. Feldspars are the second most important framework grains in many sandstones, after quartz. Feldspars are more likely first cycle, derived directly from crystalline sources and, given their mechanical and chemical instability, will rarely survive second cycle erosion and transport. Pb-isotopes in K-feldspars provide an effective means of discriminating between sources, with older sources generally being less radiogenic.

The Scotian Basin, offshore eastern Canada, accumulated several kilometres of deltaic sandstones and shales in the Upper Jurassic–Lower Cretaceous, reflecting tectonic processes associated with the extension and separation of Europe and Greenland from North America. Several lines of evidence suggested that much of the sediment was derived from the Appalachian orogen: heavy minerals can be linked to Appalachian sources (Tsikouras et al., 2011), euhedral and subhedral zircons in many wells mostly have ages in the range of 400–700 Ma characteristic of the Appalachians, and most monazite is also in the same age range. Only in a few wells did Mesoproterozoic monazite and euhedral-subhedral zircon predominate, suggesting a source in the Grenville province of southern Labrador and outliers in western Newfoundland.

The purpose of this study was to test the hypothesis that volumetrically the bulk of sediment in the Scotian Basin was derived from the Appalachians, with lesser contributions from the Grenville of Labrador. More generally, the study demonstrates the utility of Pb-isotope analyses as a tool to complement other studies of detrital mineral chemistry and geochronology.

Materials and Methods

Nine samples of sandstone were analysed from the Scotian Basin, several corresponding to previous heavy mineral chemistry and zircon geochronology determinations, but two contained no analyzable K-feldspar, apparently because of early diagenetic destruction by meteoric water. K-feldspar can, in some situations, dissolve or be albitised at depths in excess of 3 km. However, the controls on this effect and its impacts on the integrity on the Pb isotopic composition of feldspar are not yet fully understood.

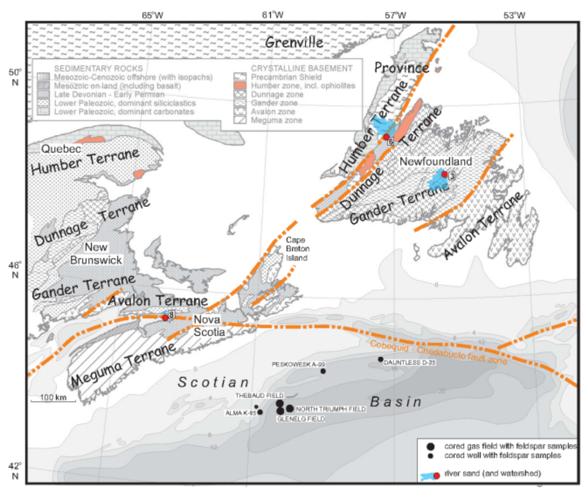

Figure 1: Map showing location of wells and river basins sampled in this study (modified from Tsikouras et al. 2011)

In addition, three samples collected from sandy bars in rivers (Fig. 1) were analysed to provide typical Pb-isotope signatures for the Avalon terrane of Nova Scotia, the Central Mobile Belt of Newfoundland, and the Long Range complex with inboard Appalachian terranes and Grenville inliers in western Newfoundland

K-feldspars were imaged on an SEM using backscattered electrons prior to analysis. The Pb isotopic composition of individual grains was determined using LA-MC-ICPMS, with laser trackways targeted so as to avoid any imaged intra-grain heterogeneities. A total of 140 feldspars were analysed from the seven sandstone samples.

Results

Most feldspars fall in the range $^{207}Pb/^{204}Pb$ of 15.15–15.55 and $^{206}Pb/^{204}Pb$ of 15.4–18.0, with a smaller cluster in the range $^{207}Pb/^{204}Pb$ of 15.55–15.7 and $^{206}Pb/^{204}Pb$ of 18.0–19.0 (Fig. 2). Comparison was made with published analyses of K-feldspar and galena from southeastern Canada by Ashwal et al. (1986), Swinden et al. (1988), Ayuso and Bevier (1991), deWolf and Mezger (1994), Ayuso et al. (1996), and Dostal and Chatterjee (2010). Unexpectedly, most samples contained predominantly feldspars of Grenville origin and a few less radiogenic feldspars may indicate a Paleoproterozoic or even Archean source (Table 1). A few samples have common Appalachian feldspars, most of which correspond to the central and northern terranes of the Appalachians. Such Appalachian feldspars are most abundant in the middle Missisauga Formation at Thebaud I-93 (~50%) and the upper Missisauga Formation at North Triumph G-43 (~45%). Elsewhere in the upper Missisauga Formation, Appalachian feldspars make up <15% of the feldspars in four different wells and the Cree Member at Peskowesk A-99 also has <15% Appalachian feldspars.

Discussion

Comparison has been made with zircon (Piper et al., 2012) and monazite (Pe-Piper et al., 2014) geochronology from the same or nearby samples (Table 1). Abundance of particular detrital minerals depends on the fertility of source rocks in those minerals and the breakdown of minerals during weathering and transport. Much of the detrital zircon is polycyclic, and Piper et al. (2012) regarded only euhedral to subhedral zircons, with limited rounding, as being first cycle. Most monazite is thought to be first cycle. Monazite is also susceptible to chemical weathering during weathering of source rocks and during transport, but is probably more stable than K-feldspar.

The two samples with a high proportion of Appalachian feldspars, from Thebaud I-93 and North Triumph G-43,

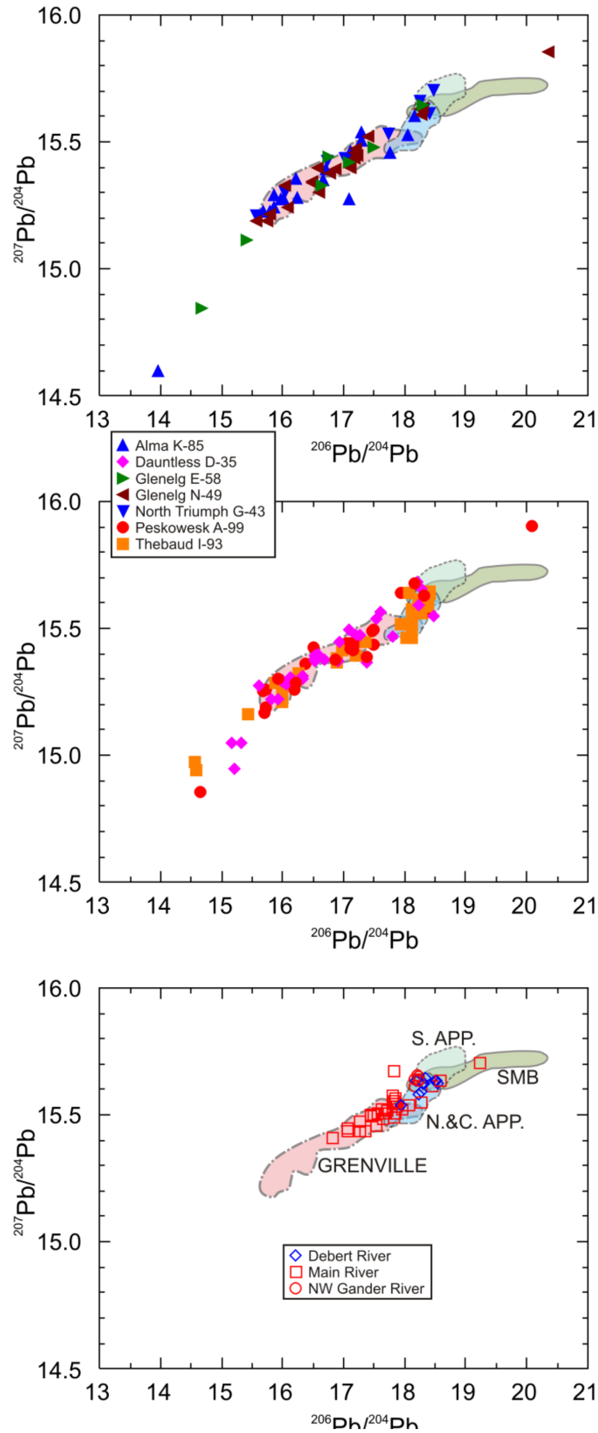

Figure 2: Pb-isotopes from wells and modern river samples, compared with fields for different source areas based on the literature.

Well	Depth (m)	Number of grains in each age group: less radiogenic or older			Grenville			Appalachian			more rad.
		Feldspar	Zircon	Monazite	Feldspar	Zircon	Monazite	Feldspar	Zircon	Monazite	Feldspar
Alma K-85	3075.47	**1**	2	n.d.	**16**	8	n.d.	**1**	0	n.d.	**0**
Thebaud I-93	3080.38	**2**	3	1	**12**	4	2	**15**	2	6	**0**
Glenelg E-58*	3709.78	**1**	n.d.	3	**5**	n.d.	15	**1**	n.d.	45	**0**
Glenelg N-49	3642.9	**0**	0	n.d.	**17**	15	n.d.	**3**	2	n.d.	**1**
North Triumph G-43	3283.3	**0**	4	2	**5**	16	3	**4**	3	10	**0**
Peskowesk A-99	2228.82	**1**	3	11	**19**	22	8	**4**	6	6	**1**
Dauntless D-35	3166.1	**3**	1	n.d.	**24**	8	n.d.	**4**	1	n.d.	**0**
River samples	*Tsikouras et al. (2011)*										
NW Gander River	3	**0**			**0**			**6**			**0**
Humber River	6	**0**			**25**			**4**			**1**
Debert River	8	**0**			**0**			**10**			**0**

Monazite includes all dated grains; zircon includes only euhedral, subhedral and subhedral-rounded grains within 10% of concordancy.
* monazite 100 m shallower

Table **1**: Analysed samples, showing numbers of grains of Appalachian and Grenville origin. Feldspars from this study; zircon from Piper et al. (2012), only euhedral, subhedral and subhedral-rounded grains within 20% of concordancy; monazite from Pe-Piper et al. (2014)..

have a relatively higher proportion of interpreted first cycle Grenville zircons, but a relatively higher proportion of Appalachian monazite. Whether these differences between minerals is related to source rock fertility is uncertain. It is also possible that some of the older zircons interpreted as first cycle are in fact polycyclic.

The three samples from the central basin with predominant Grenville K-feldspar (Alma K-85, Glenelg E-58. N-49) show a similar relative abundance of interpreted first cycle zircon. Only one sample has monazite analyses and these show a higher relative proportion of Appalachian monazite. The two samples from the eastern basin (Peskowesk A-99, Dauntless D-35) likewise have zircon abundances similar to the K-feldspar, but in the one sample with monazite determinations (Peskowesk A-99), again the proportion of Appalachian monazite is higher. This sample also has a disproportionately high abundance of Paleoproterozoic monazite, with more distant sources in central Labrador. This observation suggests that the greater abundance of Appalachian monazite is not due to weathering and break-up of Grenville monazite during transport.

Conclusions

The advantage of K-feldspar as a tracer for provenance is that its abundance in source rocks is readily assessed from geological maps showing the distribution of granite. The Appalachians and the Grenville province have broadly comparable abundances of granitic plutons. Our K-feldspar data show that the Grenville province was the principal source of feldspar to the Scotian Basin in the Early Cretaceous. Abundance of zircon is more difficult to interpret because of uncertainty as to which zircon grains are first cycle. The disproportionate abundance of monazite of Appalachian and Paleoproterozoic origin is likely related to greater fertility in these tectonic units. Uplift of the Grenville province in the Labrador rift may have created better conditions for supply of fresh feldspar than from more weathered basement horsts in the Appalachians.

This study has demonstrated the utility of Pb-in-K-feldspar analysis as a provenance indicator and has shown the predominance of Grenville sources to the Early Cretaceous Scotian Basin, related to uplift of the Labrador rift. It has also provided further information on the range of feldspar compositions from particular terranes of the Appalachians.

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Mineralogy, texture, and provenance of Kimmeridgian hydrocarbon source rocks in the Flemish Pass Basin and Central Ridge, Offshore Newfoundland, Canada

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Introduction

The prolific Kimmeridgian source rocks of the Grand Banks of Newfoundland have received considerable attention as they are the primary oil source rock for this significant petroleum district. This unit has been studied in detail in the Jeanne d'Arc Basin, where four producing fields exist and a fifth is scheduled to begin production in 2017. Nearby basins contain similar geology and structures, and are thought to hold significant promise for hydrocarbon discoveries. However, these nearby basins have been studied only in limited fashion (Enachescu, 2012). The Flemish Pass Basin, in particular, has yielded significant hydrocarbon discoveries in the Mizzen area in 2010 and the Harpoon and Bay du Nord areas in 2013; it has garnered some interest for industry exploration as well as academic research (Lowe et al., 2011). The Flemish Pass Basin is separated from the Jeanne d'Arc Basin by a topographic high called the Central Ridge, where significant hydrocarbon discoveries have also been made (Enachescu, 2012). The primary source for the oil is considered to be a Kimmeridgian organic-rich shale, likely equivalent to the Egret Member in the Jeanne d'Arc Basin (Fowler et al., 2007). The Egret Member consists of brown to grey shale of marine origin, marlstone/limestone, and fine-grained sandstone and siltstone (Bateman, 1995).

Previous work on the Kimmeridgian source rocks in the Flemish Pass has been focused on the organic geochemistry and hydrocarbon source potential of the unit (McCracken et al., 2000; Creaney & Allison, 1987). This study presents new data on the lithogeochemistry, U-Pb detrital zircon geochronology, and detrital heavy mineralogy to contribute to the understanding of this important interval within the basin. This information provides a framework and procedure for working with heavy minerals in fine-grained sedimentary rocks. The provenance and heavy mineral data enable a more accurate prediction of prospective areas for hydrocarbon exploration.

Methods

Panther P-52, South Tempest G-88 and Baccalieu I-78 from the Central Ridge and Flemish Pass Basin are the wells studied to date. The available cores and cuttings were viewed and sampled at the CNLOPB Core Storage and Research Centre in St. John's, Newfoundland. Although samples from conventional core are preferred for this study, the whole Kimmeridgian source rock interval was not cored. Thus, cuttings were also sampled where cores were unavailable. Samples were washed and sieved to a grain size interval of 15 to 180 micrometres. For U-Pb zircon geochronology, grains were mapped and backscattered electron imaged using the MLA-SEM (Quanta 650F) at Memorial University. This was followed by U-Pb dating by LAM-ICP-MS, using a GeoLas excimer (193nm) laser ablation system coupled to a Thermo-Scientific Element-XR magnetic sector ICPMS. Additional samples from conventional core were also powdered for whole rock geochemical analyses by X-ray Fluorescence at Memorial University. The lithogeochemistry supplements the U-Pb zircon geochronology for provenance interpretations. In order to analyze heavy minerals in the Kimmeridgian samples, several different methods of heavy mineral separation were employed to determine the most effective method to concentrate and study heavy minerals within fine-grained sedimentary rocks. In addition to conventional heavy liquid separation, methods such as hydroseparation were also employed. This work is still in progress but initial results indicate heavy liquid separation is significantly less effective in the presence of clay minerals.

Core Examination

Core and thin section descriptions helped to define the mineralogy, textures and structures of individual intervals of Kimmeridgian source rocks, and interpret the depositional environment. Individual cores from Panther P-52, South Tempest G-88 and Baccalieu I-78 demonstrate similar characteristics. The cores are dominated by fine-grained material, but interbedded silts, sands, and coarser material are common (Figure 1A). There are abundant soft sediment deformation features (Figure 1B), and numerous scours, with a distinct lack of bioturbation. In addition, the cores are abundant in terrestrial organic material. The combination of these features, the lack of bioturbation, in particular, indicates that these individual cores were deposited beneath storm wave base. Despite the relatively distal environment under which they were deposited, there was likely a high energy source, as indicated by the coarse-grained material, terrestrial organic material, scours and deformation. Initial interpretations, thus, favour a distal marine environment affected by frequent turbidity currents. This interpretation was also favoured to explain late Jurassic cores in the South Tempest G-88 well by DeSilva (1994).

Lithogeochemistry and zircon grain morphology

Present work involves investigation of provenance of the Kimmeridgian source rocks through detrital U-Pb zircon geochronology as well as bulk rock geochemistry. Initial geochemical observations focused on analyzing provenance-sensitive trace elements. A Zr/Sc vs. Th/Sc plot indicates that the bulk of the detritus delivered to the Central Ridge and Flemish Pass Basin during the Kimmeridgian can be considered first cycle detritus. The samples are not enriched in Zr. This is uncharacteristic for passive margin sediments as they are typically enriched in Zr due to sedimentary recycling. In addition to geochemical trends, this observation is also supported by the morphologies of zircon grains. The majority of zircon grains found in the Kimmeridgian samples are euhedral to subhedral crystals, suggesting the grains are likely not polycyclic. Sedimentary recycling is likely more important for rocks deposited after the Tithonian rifting episode, as demonstrated by Dearin (2007) for Hibernia and Ben Nevis Formation sandstones in the Jeanne d'Arc Basin.

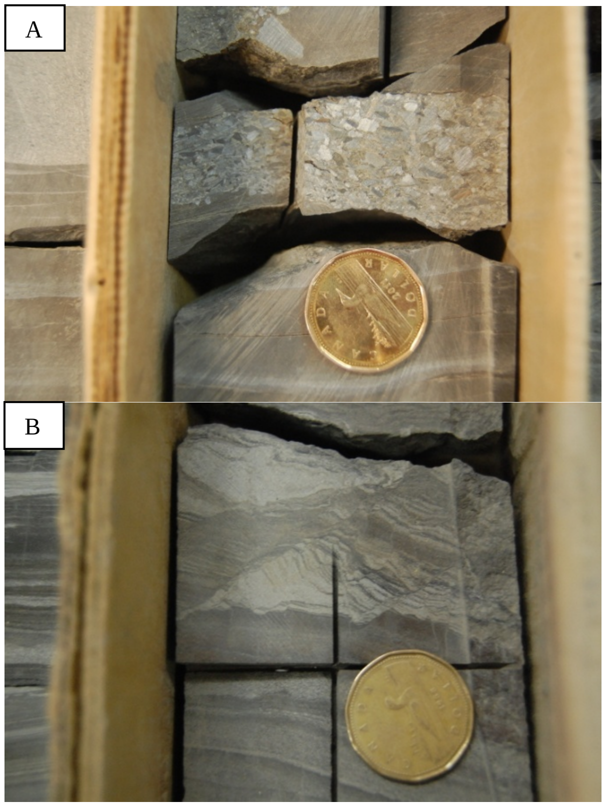

Figure 1: (A) Abundant coarse material in Kimmeridgian cores from well Bacalieu I-78 (B). Common soft sediment deformation in Kimmeridgian cores from well South Tempest G-88

U-Pb zircon geochronology

Ages from 30 detrital zircons were age dated from a single cuttings sample from the Panther P-52 well (3210 m depth) using U-Pb LAM-ICP-MS geochronology. These provide a direct indication of the age(s) and nature(s) of the source region(s). Two major populations were found. Eight of the zircon grains are Neoproterozic, 545-650 Ma, likely derived from Avalonian basement. Seven are Permian-Carboniferous grains, 275-345 Ma, possibly with an Iberian provenance. Also, three end Jurassic grains, 145-150 Ma, were found, which is evidence for basin related magmatism, contemporaneous with Kimmeridgian sedimentation. Avalonian basement is known to exist west, south, and east of the sampled units (Haworth and Lefort, 1979; King et al., 1985,1986; Krogh et al., 1987), and is therefore not overly indicative of drainage orientations.

However, the presence of a large number of Permian-Carboniferous grains suggests that drainage systems during the Kimmeridgian were active from the East, as grains of this age correlate well with magmatic rocks present on the nearest part of the Iberian massif (Priem & den Tex, 1984). Westerly-derived paleodrainage patterns were suggested by Lowe et al. (2011) to explain detrital zircon populations in Flemish Pass Basin Tithonian sandstones. One of the key indicators of the westerly-derived provenance was the presence of Ordovician-Silurian grains, interpreted to be derived from the Central Mobile Belt of Central Newfoundland. The distinct lack of zircons of this age in the Kimmeridgian sample indicates that large westerly-derived paleodrainage systems were not active at this time, and local, Avalonian sources were more important, with input from easterly-derived drainage systems. This interpretation remains to be tested with additional samples from the Central Ridge and Flemish Pass.

Heavy mineral diversity

Cuttings samples from Kimmeridgian intervals in the Panther P-52 well suggest that fine-grained, clay-rich successions and samples from rich source rock intervals preserve more diverse heavy mineral assemblages than from permeable, coarse-grained, non-source rocks. In the fine-grained sample (P-52 (3950m)) diagenetically unstable minerals such as staurolite, titanite, and epidote composed 69 wt.% of the heavy mineral fraction. Diagenetically stable minerals such as zircon, rutile, and monazite composed just 31 wt.%. In the coarse-grained sample, however, (P-52 (3210m)), staurolite, titanite, and epidote composed just 8 wt.% of the heavy mineral fraction with diagenetically stable zircon, rutile, and monazite composing 92 wt%. In coarse-grained, permeable samples, corrosive pore waters are likely causing the degradation of unstable heavy minerals as demonstrated by Morton & Hallsworth (2007) & Morton (2012). However, in fine grained, clay-rich samples, the low permeability inhibits corrosive pore water infiltration and likely aids in preserving more unstable heavy mineral assemblages (Morton, 2012). In addition, the presence of hydrocarbons in rich source rock intervals may also inhibit heavy mineral degradation. If so, this may provide a technique to assess whether hydrocarbons have migrated from the source rocks. If migration has taken place, the expectation is that less diverse heavy mineral suites will be present, as the rock will be unprotected from corrosive pore waters. Future work will assess other wells within the Central Ridge and Flemish Pass Basins and determine whether this is an observable trend.

Acknowledgements

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Stratigraphic distribution mapping in the North-East Atlantic

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As part of the NAG-TEC project, executed by the Geological Surveys of North-West Europe, stratigraphic distribution maps were compiled in the North-East Atlantic region for the following seven chronostratigraphic intervals: Devonian, Carboniferous, Permian-Triassic, Jurassic, Cretaceous, Paleocene and Eocene-Pliocene. These maps concern the distribution of not only the sediments but also igneous rocks of that specific chronostratigraphic interval.

A first step in the map compilation process was a regional stratigraphic distribution mapping executed by the individual Geological Surveys through correlating chronostratigraphic intervals in wells and outcrops, by interpreting seismic data and by using published regional maps and cross sections. The next step was a quality control of these maps by checking the distribution polygons for consistency and fitting at the boundaries of neighbouring countries.

Further an extensive lithostratigraphic well database consisting of nearly 1000 wells was built and converted to its chronostratigraphical equivalents. The use of this well database enabled not only the verification of the stratigraphic distribution polygons but also the quality of the Total Sediment Thickness map, which refers to the entire cover sequence including Cenozoic basalts and sub-basalt sediments. Finally the stratigraphic distribution polygons were checked to align with the boundaries of structural elements. After these quality controls the new stratigraphic distribution maps have been used to update the geological map of the North-East Atlantic area.

All above mentioned maps will be displayed and described in the 'Tectonostratigraphic Atlas of the North-East Atlantic Region' and will support the E&P industry to fully develop the basins in the North-East Atlantic region by careful data-integration and geoscientific effort to discover new oil and gas reserves.

Geology and Petroleum Exploration Play Concepts of the Central Atlantic Conjugate Margins (Nova Scotia – Essaouira-Agadir Morocco): Similarities and Differences

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The Atlantic margin of Morocco extends over 3000 km of coastline. It is one of the oldest existing passive margins, and is partly conjugate to the Scotian margin of North America. Today the Scotian Basin encompasses an area of over 300 000 km^2 beneath the continental shelf and slope, and includes up to 20 km thickness of sedimentary rocks in its deepest areas south and east of Sable Island. Because of their key positions within the Central Atlantic Ocean, and their promising hydrocarbon potential, both margins were, and still the object of extensive research programs and industrial exploration studies. The main objective of this paper is a comparative study of the Atlantic conjugate margins of Morocco and Nova Scotia using the example analogues of the Scotian Basin and Essaouira-Agadir Basin. We focused mainly on the similarities and differences in the general geology, geodynamic evolution, salt tectonics, play concepts, and then petroleum systems in both basins.

The sedimentary fill of the Mesozoic-Cenozoic conjugate marginal basins, Scotian Basin and Essaouira-Agadir Basin, shows a very similar depositional and structural history, especially during their Triassic and Jurassic evolution. Salt movements are well expressed from Early Jurassic to Late Tertiary forming similar salt-related features (pillows, diapirs, canopies, toe) in both basins.
Both the Nova Scotian and Moroccan margins show evidence for elements of working petroleum systems. The Scotian Basin has proven petroleum systems with past production from the Cohasset-Panuke oil fields, ongoing gas production from the Sable Sub-basin and the Deep Panuke gas field, all on the shallow Scotian Shelf. Like the Scotian Basin, the Essaouira-Agadir Basin has proven petroleum systems in the onshore part of the basin with minor oil and gas production in the Sidi Rhalem, Toukimt and Meskala fields. Recently, exploration focus shifted to the deep water on both conjugate margins because of the impressive hydrocarbon discoveries and high success rates in deep water of other circum-Atlantic basins such as the Gulf of Mexico, offshore Brazil and West Africa, and recently Northwest Africa (Mauritania).

Offshore domain of the two homologue basins is still underexplored, only very few deep water wells were drilled in both basins until now. Five play concepts were proven in the Scotian Basin; Early-Middle Jurassic carbonates and sandstones; Oxfordian–Tithonian; Berriasian-Valanginian-Hauterivian; Hauterivian-Barremian; and Aptian-Albian-Cenomanian. While only three wells were drilled in offshore Essaouira-Agadir Basin; Pre-Albian, Salt-related structures during Cenomanian-Turonian and Tertiary stratigraphic play were tested. The main play concepts within the Essaouira-Agadir offshore segment are Salt diaper and Tertiary amalgamated channel play in the inboard area, the Lower Cretaceous Subsalt plays and the Toe thrust play outboard. One major difference between the two basins fill occurred during Cretaceous time where an upwelling process resulted in the deposition of organic rich sediments in Moroccan side. This has probably contributed to the existence of a Cretaceous petroleum system in Morocco especially where adequate burial is bringing into maturity this source rock.

Ongoing detailed studies and analyses are directed by super-major companies such as Shell and BP (Offshore Nova Scotia) and Kosmos, Chevron, BP and Cairn (Offshore Morocco) in both margins to get a better understanding of their hydrocarbon potential.

New Deformable Plate Reconstructions Coupled with Palaeogeographic Mapping and Palaeo-Earth Systems Based Source Facies Predictions: Implications for the Prospectivity of Atlantic Margin Basins

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The break-up history of the Atlantic margin basins provides palaeogeographic controls on basin geometry, bathymetry and timing that are key aspects in the accumulation of marine source facies that are fundamental constraints on hydrocarbon prospectivity. To construct a predictive marine source facies model for application in frontier basins deformable plate reconstructions were used as the basis for palaeogeographic mapping that provided the surface boundary conditions for palaeo-Earth systems modelling (ESM). Palaeogeography and ESM results were then combined to build a predictive tool that includes the processes of organic matter productivity, dilution and preservation.

Reconstruction of tectonic plates and the geological datasets intersected with them is essential for the interpretation of tectonic evolution and for palaeogeographic mapping. However lithospheric stretching and/or thinning at divergent plate boundaries means that traditional, rigid plate reconstructions are unable to provide realistic interpretations of pre-rift and syn-rift plate geometries. To address this problem a new Plate Wizard deformable plate model has been built. Plate boundaries and the continent/ocean transition zone (COTZ) were defined using seismic and gravity/magnetics data sets and rifting histories for each margin have been established. The trajectory of deformation was determined for each rifting episode and stretching factors were calculated and applied within the plate model to deform each plate margin and any associated datasets by the calculated amount. The result is more accurate pre-rift plate geometries, without the overlap and/or under-fit problems that are detrimental for all rigid model plate reconstructions.

The deformable plate model was used to reconstruct well and outcrop data points, and geophysical data, the legacy of over 30 years of petroleum geological studies, to be used as the basis for palaeogeographic mapping. The global database also includes climate proxies and source rock data that were used later to test the veracity of both the ESM results and the source facies predictions. Detailed palaeotectonics and palaeoenvironments maps were prepared and a novel method relating topography and bathymetry to plate tectonic environments was used in the construction of palaeo digital elevation models (DEMs).

The DEMs were coupled with state-of-the-art palaeo-ESMs (UK Met Office HadCM3 palaeoclimate model) and an unstructured mesh model to simulate palaeotides (Imperial College, UK, ICOM tide model). In conjunction with the DEMs, palaeo-ESM results were used to create a new predictive model of organic matter productivity, dilution and preservation. This model defines source facies depositional space for the selected time slices. The combined approach also provides an understanding of regional palaeogeographic and palaeoclimatic geohistory, drainage basin evolution, and the estimation of clastic sediment flux. Predictive mapping is used here to provide an assessment of source rock risk for Atlantic margin basins. The gridded model results provide an objective assessment of lateral variability in source quality that with burial and maturation is the basis for mapping previously unrecognised oil and gas kitchens.

Comparative uppermost Jurassic to lowermost Cretaceous formation and fill of conjugate Iberia-Newfoundland basins

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Summary

Divergent margins are commonly assumed to record diachronous rift-to-drift phases along and across their strike, particularly when comparing crustal segments in which continental breakup is diachronous. However, similar stratigraphic markers are recorded in large parts of NW Europe, Ireland and Canada and these appear to indicate the influence of comparable synchronous episodes of tectonism across broad areas. Borehole and stratigraphic datasets from onshore and continental shelf basins in West Iberia and Newfoundland have recently been combined with high-quality seismic profiles to understand the true significance of the Latest Jurassic-Early Cretaceous stratigraphic interval across the North Atlantic. This approach is important to correctly assess the petroleum potential of both margins, at a time when major tectonic events are known to have important implications in terms of the relative distribution of reservoir units, mass-transport deposits, and OAE's in deep-water margins.

Seismic-reflection, borehole, outcrop, time-structure, isochron and isopach data document common stratigraphic elements between West Iberia and Newfoundland during the Kimmeridgian-Valanginian. In this work, we demonstrate that the evolution of Late Jurassic-Early Cretaceous rifting in West Iberia has strong similarities with Newfoundland. An important conclusion from this work is that stratigraphic unconformities of regional expression, marking episodes of tectonic uplift and relative sea-level fall, can be used as key markers to characterize the tectono-sedimentary evolution across the North Atlantic Ocean, into Newfoundland.

Locally these unconformities reflect five (5) Oxfordian-Aptian ‘regressive events’, which are associated with tectonic uplift of rift shoulder areas to a larger rift axis offshore. In Newfoundland, most of these unconformities have been previously interpreted as reflecting diachronous, if not at all distinct, tectonic events to West Iberia. New data suggest the five unconformities to be represented on both sides of the West Iberia-Newfoundland conjugate. As a result, we suggest large-scale tectonic events to have affected both margins during the Late Jurassic-Early Cretaceous, proving a common evolution for both margins. Significantly, our results suggest that the last syn-rift event preceding continental breakup was initiated in the Late Kimmeridgian (Figs 1 and 2). In this setting, a) the main syn-rift event in the Lusitanian Basin is expressed by younger strata than previously assumed; b) the boundary separating the Tethyan and Boreal realms along the North Atlantic was located in SW Iberia, not in the region of the modern Nazaré Fault.

Stratigraphic markers of Late Jurassic-Early Cretaceous syn-rift across the North Atlantic

a) The S1 event (Oxfordian-Kimmeridgian boundary)
Subsidence in the Lusitanian Basin peaked in the Oxfordian-Kimmeridgian boundary (S1) and is associated with propagation of faults to the seafloor and erosion of adjacent carbonate platforms (Wilson et al., 1989, Alves et al., 2002). An equivalent, synchronous event is recorded in the Porto Basin (Moita et al., 1996), a margin basin extending from the outer shelf to the upper continental slope areas of NW Portugal (Fig. 2). By the end of the Kimmeridgian (end of mutabilis/acanthicum biozones, Atrops and Marques, 1986), a relative sea-level fall occurred on the inner proximal margin (S2) (Alves et al., 2002, 2003). At this time, subsidence curves for the Lusitanian Basin show a strong tectonic pulse associated with the uplift of its western rift-shoulder area (Berlengas Horst) (Hiscott et al., 1990).

b) The S2 event (late Kimmeridgian)
Onshore and on borehole data, the S2 event marks the base of locally unconformable deltaic to alluvial/fluvial deposits prograding into the Lusitanian Basin from the west (Hill, 1989; Alves et al., 2003). On a regional scale, strata overlying S2 are grouped in the Lourinhã formation (Wilson et al., 1989). This unit reflects sediment progradation on the inner proximal margin in response to marginal uplift of rift-shoulder areas due to the onset of extension on the outer proximal margin west of the Lusitanian Basin, i.e. in the region where the rift axis was located during the last stages of continental rifting. Following uplift and sediment progradation, accommodation space in the Lusitanian Basin was mostly filled by the Late Berriasian (late post-rift stage, Alves et al., 2003), prior to a third (S3) basinwide unconformity (Fig. 2).

c) The S3 event (Berriasian-Valanginian boundary)
Alves et al. (2009) interpreted S3 as marking the onset of (post-rift) tectonic quiescence in inner proximal basins, with the exception of the Porto Basin (Moita et al., 1996). Further West in deep-offshore basins, two important events are also associated with S3: a) the initiation of continental break-up in the Tagus Abyssal Plain, SW Iberia; and b) the onset of the final rifting episode (Rift 4) in NW Iberia, in what is called the Peniche Basin (west and south of the Porto Basin).

d) The S4 (Barremian) and S5 (Aptian) events
After the S3 event, subsidence was significantly reduced in the Lusitanian Basin (e.g. Hiscott et al., 1990), while a passive margin was already established in most of southwest Iberia (Fig. 2). Continental deposits covered a great part of the southern Lusitanian Basin with a uniform distribution until the Valanginian, followed by marine/transitional strata

recording an earliest Hauterivian transgression maximum (Dinis et al., 2008). An even simpler facies distribution – with no major variations in thickness – is recorded west of Lisbon after the early Hauterivian, above a maximum flooding surface marked by the Safarujo/Cabo Raso members (Hiscott et al., 1990b) and preceding a) a Barremian regression (S4) and b) an Aptian-Albian 'break-up unconformity' in both NW Iberia and Newfoundland, the S5 event (Soares et al., 2012; 2014).

Evidence for Kimmeridgian-Valanginian syn-rift across the North Atlantic

Based on the identification of events S1 to S5, and after analyzing their tectono-stratigraphic significance along West Iberia (and across the North Atlantic into Newfoundland), we propose Late Jurassic-Cretaceous continental rifting west of the Lusitanian Basin to comprise two distinct pulses. A first latest Kimmeridgian-Tithonian extensional episode records the onset of the main (and latest) episode of rifting north of 38^{0}30N, i.e. north of Lisbon (Alves et al., 2006). This latter event is recorded at ODP Site 1069 (Wilson et al., 2001) and in Leg 103 (distal Galicia margin, Boillot and Winterer, 1988) by the deposition of Tithonian shallow-marine carbonates. The onset of a major episode of rifting in S2 also agrees with Late Kimmeridgian (pre-rift) extensional faulting documented on the western and southern Galicia Bank (Clark et al., 2007). Extension after S2 preceded a stage of marked regression in the Lusitanian Basin (S3) and continental break-up at N40^{0}15' during the Barremian (S4) (Whitmarsh and Miles, 1995), c. 10 m.y. before Late Aptian break-up in Northwest Iberia, where a stretching maximum is recorded during the Valanginian (Groupe Galice, 1979; Murillas et al., 1990; Boillot et al., 1995). This re-assessment of the true extent of syn-rift in West Iberia indicates S1 as being a local rifting event specific to the Lusitanian Basin, and that the main syn-rift event in Central West Iberia spans the interval between S2 and S4 (Figs. 1 and 2).

The second, and ultimate, rifting event that led to complete continental break-up between Iberia and Newfoundland is coincident with the 'break-up sequence' of Soares et al. (2012, 2014) and precedes a developed drift unit whose base is dated at ODP and DSDP drill sites as latest Cenomanian-Turonian. The corollary of this work is that the rifting and break-up histories of West Iberia and Newfoundland are interpreted to be similar, putting to ground the concept of asymmetric (and diachronous) rifting conjugate margins between Newfoundland and West Iberia. Specifically, by comparing Kimmeridgian-Valanginian tectono-stratigraphic units across the Atlantic into Newfoundland, the main conclusion of this work are:

a) The last pulse of extension west of the Lusitanian Basin suggestively occurred before the Valanginian, thus correlating syn-rift successions on the outer proximal margin west of the Lusitanian Basin with equivalent syn-rift strata in the Jeanne d'Arc Basin (e.g. Sinclair, 1995). The 'break-up sequence' of Soares et al. (2012, 2014) effectively marks the last episode of syn-rift in West Iberia and precedes drift unit developed after the Cenomanian-Turonian in Northwest Iberia.
b) This interpretation agrees with the interpreted seismic data, in which two distinct rifting axes are recognized in West Iberia. A first axis relates to Oxfordian-earliest Cretaceous continental rifting and extends from the Porto Basin to the Southwest Iberia. A second axis relates to Late Kimmeridgian to Aptian rifting, extending from the Estremadura Spur to the Galicia Bank. Separating the Tagus Abyssal Plain from Axis 2, a major structural lineament should have developed along the west Iberian margin south of the Estremadura Spur.

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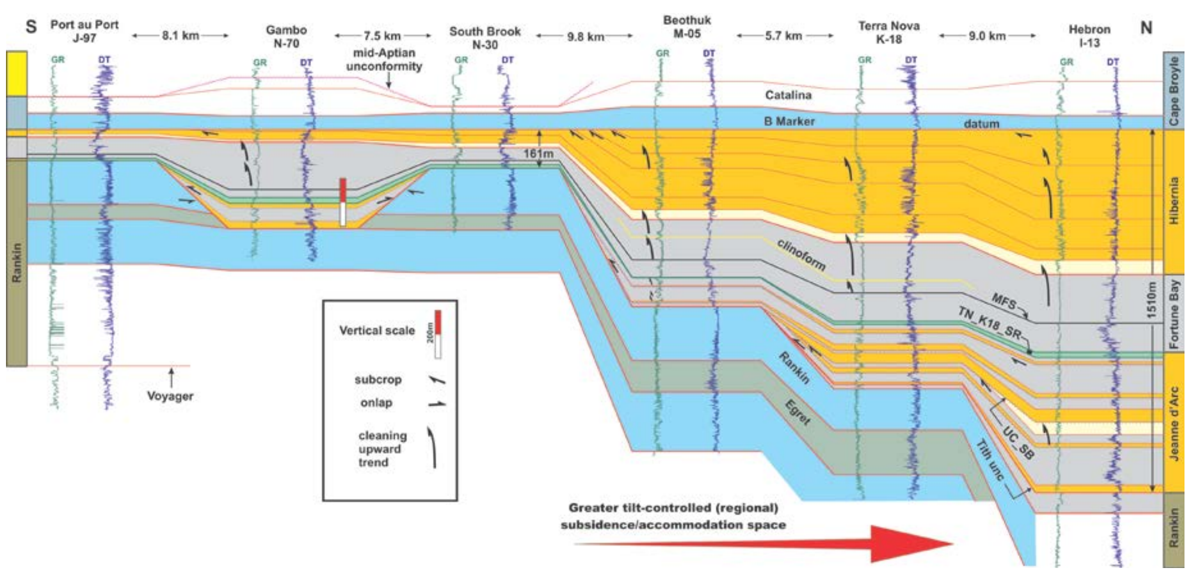

Figure 1: Correlation panel showing the distirbution of latest Jurassic to earliest Cretaceous (Kimmeridgian to Tithonian) units offshore Newfoundland. The figure highlights the high degree of tilt and variations in subsidence/accommodation space recorded during this rift period in the Jeanne d'Arc Basin. The section increases in thickness from 161m to 1510 m from the South Brook N-30 well to the Hebron I-13 well. Compare with Figure 2 from the region South of Lisbon, Southwest Iberian Margin. Modified from Sinclair et al. (1994).

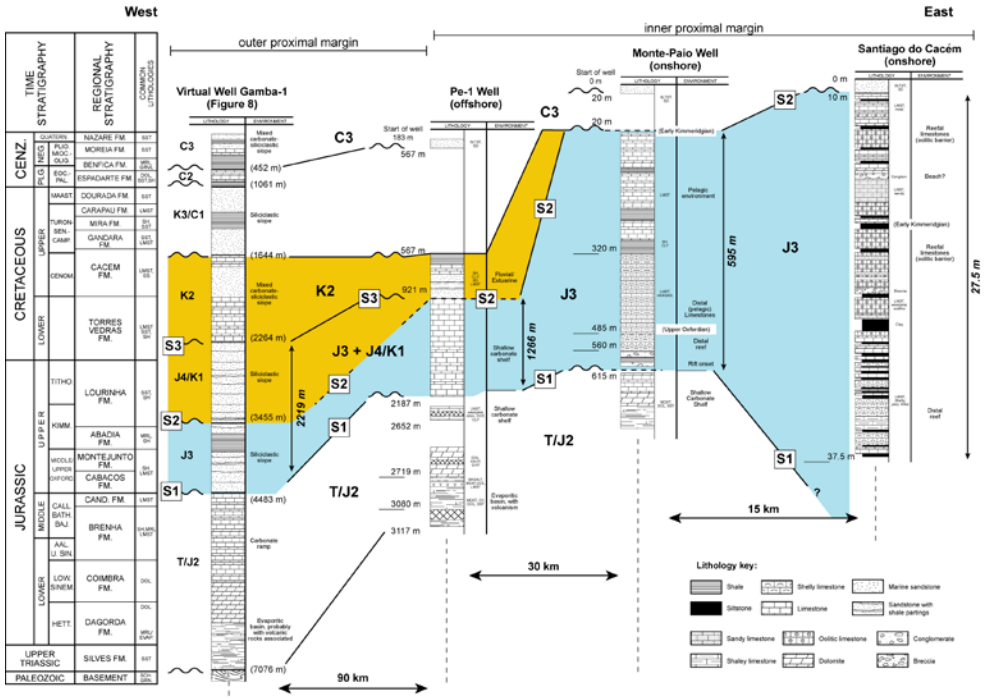

Figure 2: Correlation panel showing the distirbution of Jurassic to Cenozoic units offshore SW Iberia. Variations in subsidence/accommodation space recorded during this main rift episodes in West Iberia are also recorded in this panel. The Late Jurassic-earliest Cretaceous succession increases in thickness from 27.5 m to 2219 m from Santiago do Cacem to well to deep-offshore sub-basins (Gamba-1). Compare with Figure 1. Modified from Alves et al. (2009).

Influence of Gulf of Mexico on Southeast North American Margin: Why Is Florida Still Attached?

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Introduction

Supercontinent break-up is still a poorly understood phenomenon, both as to why and how the continents break-up. The break-up of the supercontinent Pangea at 200 Ma offers an extensive, yet often confusing, array of evidence. Along the United States eastern margin Pangean break-up tectonics left a series of accessible and not so accessible deformational features including rift basins and dikes, that offer clues as to the nature of the break-up, unfortunately, some of the clues in the southeastern United States are contradictory.

The rifting event that stretched the North American continental crust from Texas to New Jersey created initially wide zones of extension generally parallel to pre-existing zones of weakness beginning as early as 230 Ma. These wide zones of extension evolved oceanic spreading centers that separated the Pangea continents, except for the South Georgia Rift (SGR) zone. Despite extensive continental thinning, extension, and magmatism at 200 Ma, the South Georgia Rift zone, between Florida and the continental North America, failed. Instead, a series of ill-defined basins developed around the allochthonous Florida block and it remained attached to North America. The Triassic/Jurassic South Georgia Rift basins are oriented sub-parallel to the NE trending basins of the same age along the east coast of North America and are sub-parallel to the suture zone that connected the Florida terrane to North America during the assembly of Pangea. The basaltic flows and diabase dikes found within the rift appear to be part of the 200 Ma Central Atlantic Magmatic Province and to be from a similar source as flows and diabases found along the southeast to central coast of North America (e.g. Callegaro et al., 2013). Thus, why the rift failed and Florida is still attached to North America, via a much more complicated set of rifting, is poorly understood.

The best evidence for why the South Georgia Rift (SGR) zone did not continue to extend and remove Florida from North America may lie in the diabase dikes that line its margins. Dikes are generally intruded perpendicular to the least compressive stress, thus, dikes associated with rifting events are generally intruded parallel to the rifts. The dikes associated with the South Georgia Rift, dated at 200 Ma, are perpendicular to the rift. These NW trending diabase dikes can be found both within the SGR and to the north of the basins. While not extensively mapped in Georgia and Alabama, they are very clearly delineated on the aeromagnetic anomaly map of South Carolina where they are found across the state and propagating into North Carolina (Figure 1). South Carolina is where the northern portion of the failed SGR intersects the NE trending rifts that became the central Atlantic. This intersection may be marked by a fan of NW to N-S trending dikes visible on the aeromagnetic map. Moving further north along the east coast of North America the NW trending dikes slowly progress to N-S trending and finally to NE trending. All of the dike orientations have been dates as 200 Ma and are from a similar source. The NW-trending diabase dikes

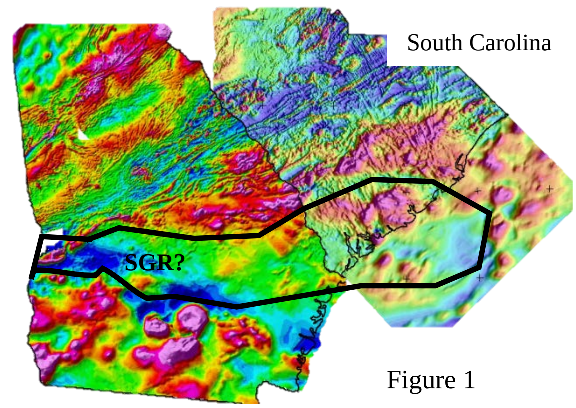


Figure 1

indicate that the stress field that had created the SGR starting around ~230 Ma had changed (suddenly?) around 200 Ma from the least compressive stress being oriented WNW-ESE to ENE-WSW.

Because the rifts along the southeast coast of North America did not fail and the SGR did, the cause of the stress change likely came from the South or Southwest. While many models have been created of the evolution of the Gulf of Mexico and the Yucatan block motion, there continue to be many ill-defined motions and dates. Finite-element models using both large-scale plate motions (North America, Africa, South America) and micro-plate motions (Yucatan, Florida, etc) are used to define viable sequences of events that produce the change of stress state that resulted in NW trending dikes soon after the formation of a NE trending basin, and resulted in the death of the SGR and the retention of Florida by North America.

Methods

To determine a possible cause for the failure of the South Georgia Rift and Florida remaining with North America during the break-up of Pangea existing paleogeographic models were tested with finite element models to determine if the stresses created by these models could a) account for known deformational features and b) could create a stress state such that the SGR would fail. The freeware paleogeographic program GPlates was used to model the motion and velocities of plates during the break-up of Pangea based on 2 existing paleogeographic databases, Wright et al. (2013) and Seton et al. (2012). Plate velocities and locations for North America (NA), Africa (AF), South America (SA) and the Yucatan (YUC) were determined relative to a fixed reference frame. These data were then transferred to a static finite element program where NA, AF, SA, and the YUC were outlined and overlie a weak asthenosphere which is fixed at its base. An assumption was made that the craton of each plate was the driving force behind the plate motion and therefore the applied motions were only applied to these areas.

Because the global paleogeographic models used (and generally found) do not show relative motion between NA and AF/SA prior to 200 (while extensional features exist on land at 230 Ma), the time periods used in this study

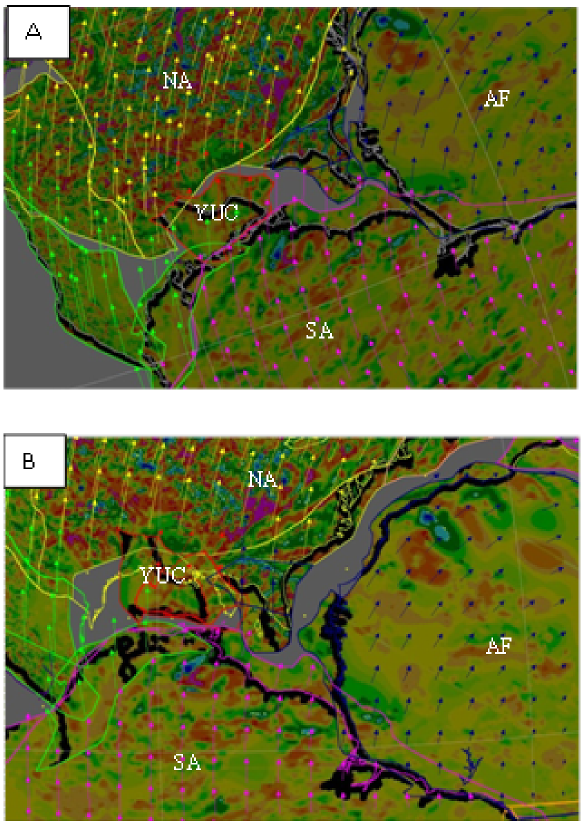


Figure 2 (A,B) Results from GPlates. Background of continents is present day magnetic field of the continent while the arrows represent the motion of each continent or continent fragment to a fixed reference frame. North America=NA, South America = SA, YUC = Yucatan, AF=Africa. Figure A was created using the data from Wright et al. (2013) for 182 Ma, while Figure B was created using the data from Seton et al. (2013) at 184 Ma.

correlate to the onset of discernable relative motion between the plates, which is around 184 for Seton et al. (2012) and around 182 for Wright et al. (2013). When none of the finite element models of the paleogeographic information used could create a stress field to explain the failure of the SGR, two were combined along with data from the Gulf of Mexico (e.g. Pindell and Kennan, 2009). In Wright et al (2013) the Yucatan develops a strong westward motion around 174 Ma, however, in their model the Yucatan is significantly to the west of Florida with a large area of unknown material between them. In our model we combined the motion of the Yucatan at 174 Ma from Wright et al. (2013) with the placement and motion of the continents from Seton et al. (2012) at 184 Ma.

Paleogeographic Results

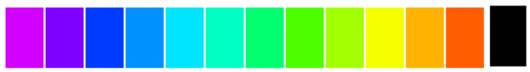
The following images show the absolute velocities of Africa, North America, South America and the Yucatan during the break-up of Pangea as determined by Seton et al. (2012) and Wright et al. (2013). While the overall plate motions are similar, the position and motion of the Yucatan block vary significantly. In these details most of the paleogeographic models varied, including some that had all of Florida moving east during the break up of Pangea.

Finite Element Results

Finite element model results of various paleogeographic reconstructions of the break-up of Pangea are dependent not only on the configuration of the plates and the plate velocity, but also abide by some universal truths about stress. In all models weaker material does not transmit stress as well as strong material, thus a weak area (such as a mid-ocean ridge) will not transmit much stress across it. The result is that no matter the orientation of the plate motion, the initiation of sea-floor spreading reduces the direct influence one continent has on another. For example, the extensional stress along the North American east coast margin drops significantly when a weaker zone between it and Africa develops, suggesting that continental extension would cease with the weakening of the suture between the two (Figure 3B and D). Finite element results of the paleogeographic reconstructions of Wright et al. (2013) and Seton et al. (2012) at various ages and configurations of suture strength were compared and generally displayed the same results; NW-SE extension across the South Georgia Rift and southeast coast of North America until well after separation of the continents, no compression was observed (Figure 3A). Figure 3 A is an example from 184 Ma using Seton et al.'s (2012) reconstructions. Given the general orientations of the stresses, E-W to NE-SW trending extensional features would be expected where the stress concentrations are the highest. In Figure 3A the sutures between the continents were modeled as strong and the plate motion was as in Seton et al. (2012) (black arrows). All stresses in the continental crust were extensional with the intensity shown by the color, strong extensional stress is observed across the South Georgia Rift, along the northern Yucatan border, and across the northeastern United States suture. Not shown, but also modelled was the weakening of the sutures as the continents split (due to very thin crust, extensive magmatism or both). The onset of weakening was modelled in sections (NA-AF etc) as might be expected during rifting. In all instances weakening reduced the stress across that boundary and while it caused no to minor changes in the orientation of the remaining stress fields.

Combined Reconstruction Results

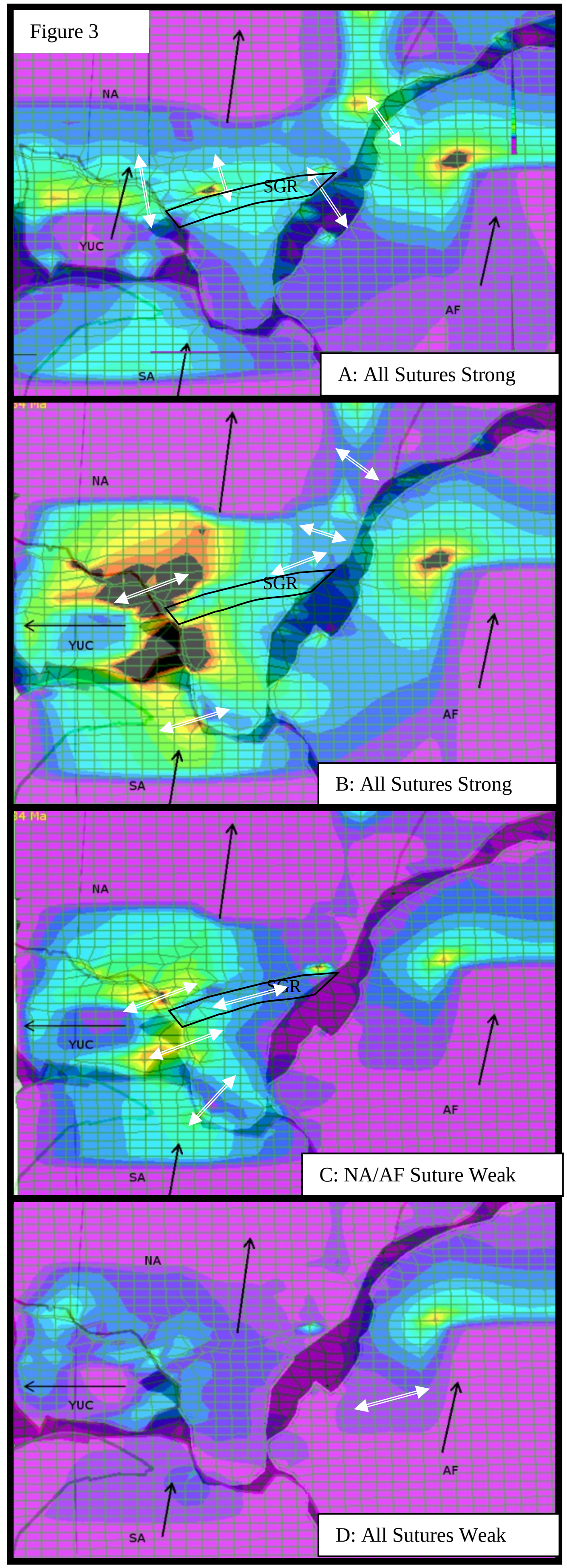
Because the existing paleogeographic models did not produce results that account for all of the observed deformation, namely the NW trending dikes and the failure of the SGR), new combined models were constructed. The motion of the Yucatan from Wright et al (2013) at 174 Ma



Least Extension------Greatest Extension (MPa)

Figure 3: Finite Element Results
Finite element results shown as extensional stress intensity (there were no significant sigma 1 compressional stresses generated in the crust). Black areas are under the greatest compressional stress while purple areas area under the least. The grid pattern represents the x-y portion of the finite element grid used while the long black arrows indicate the orientation and relative strength of the displacements applied to the cratonic regions of each continent. White double-headed arrows indicate the general principal stress (sigma 1) orientation at that location. The location of the modelled sutures between the continents can be seen as shadowed areas. The South Georgia Rift (SGR) is generally outlined and labelled SGR. North America is labelled NA, South America in labelled SA, Africa is labelled AF and the Yucatan is labelled YUC. Figure 3 A: Finite element results of Seton et al. (2013) paleogeographic motion at 184 Ma. In this model all the sutures between the plates were modeled as ‘strong’ only one order of magnitude less than the continents. Figure 3B: Finite element results of Seton et al (2013) paleogeographic motion at 184 Ma combined with a westward motion of the Yucatan. All sutures between the plates are modeled as ‘strong’, one order of magnitude weaker than the continents. Figure 3C: Finite element results of Seton et al (2013) paleogeographic motion at 184 Ma combined with a westward motion of the Yucatan. In this model all the sutures are still modelled as ‘strong’ with the exception of the suture between NA and AF , which is modelled as weak (2 orders of magnitude less than the continental crust). Figure 3D: Finite element results of Seton et al (2013) paleogeographic motion at 184 Ma combined with a westward motion of the Yucatan. In this model all the sutures are modelled as weak.

and the plate motion and plate positions from Seton et al (2012) were used to construct several finite element models. In these the generally N-NE motion of the major plates was retained with their slight deviations from each other and the Yucatan was modelled as close to Florida and moving rapidly to the west. Figure 3B shows the principal stress finite element results of this configuration when all sutures were still relatively strong, as in previous models all stresses are extensional. While there is still extension across the NA-AF border, the locus of greatest extension is across the YUC-NA border and its orientation is WSW-ENE, this stress appears to be causing the extensional stress between NA-AF to swing to be more WSW-ENE than without the Yucatan’s westward motion. This would result in NW striking deformational features (dikes and/or faults). Weakening the suture between NA and AF results in a dramatic stress drop between NA-AF and a moderate stress drop between NA-YUC (Figure 3 C). While the NW



trending deformation would continue to develop between NA-YUC, this would cease along the east coast of NA. Weakening all sutures between NA, AF, YUC, and SA results in a dramatic drop in all extensional stresses except for the ones generated at the top of the applied displacements in Africa (Figure 3D).

Discussion

The late Triassic/early Jurassic paleogeographic reconstructions of Wright et al. (2013) and Seton et al. (2012) do not create the stresses necessary to form the observed deformation when modelled using a 3-D finite element model. While the ENE and NE trending extensional basins that range from North Carolina to New England would be likely be formed in all the existing paleogeographic models tested, as NW and WNW trending stresses dominate the margins of North America (Figure 3A), none of the existing models can account for the NW trending dikes in the southeastern United States. Nor can any of the existing models explain why the South Georgia Rift, which is subparallel to all the other east coast rifts, failed.

Thus, two paleogeographic models were combined with other works on the evolution of the Gulf of Mexico to construct a displacement model that might recreate the observed deformation (e.g. Pindell and Kennan, 2009). By combining the plate motions and positions of Seton et al. (2012) with the westward motion of the Yucatan plate of Wright et al (2013), a plausible stress field was generated in the area of the SGR that would account for the NW trending dikes and the failure of the rift and the formation of rifts around Florida.

However, none of the paleogeographic models used has the same timing as the observed features. According to radiometric dating and field work extension began as early as 230 Ma in the southeastern United States and the NW and NE trending diabase dikes were intruded at 199 Ma (e.g. Callagaro et al., 2013). None of the paleogeographic models used, or investigated, has enough motion between NA-SA-AF to create the massive continental extension seen at 230 Ma until 200 Ma at the earliest and 178 Ma at the latest (e.g.; Wright et al., 2013; Seton et al., 2012 Golanka, 2007). Based on the results of these finite element models and the observed deformation, I propose the following scenario and revision of the dates. Around 230 Ma the relative motions of NA-AF-SA begin to deviate from each other, resulting in the formation of NE-SW and ENE-WSW trending basins in the southeastern United States. By around 200 Ma continental extension has created enough continental thinning that a massive magmatic event from the Gulf Coast of the United States to the northeastern United States and throughout northern South America and West Africa occurred. At the onset of the magmatic event (the Central Atlantic Magmatic Province) the Yucatan, which is located in the continental United States next to Florida begins to move westward very rapidly, resulting in the end of the South Georgia Rift (SGR), the formation of NW trending dikes perpendicular to the SGR and the formation of N-S trending extensional basins along Florida's west coast. Stress orientations from the finite element models of this scenario suggest that the orientation of the extensional basins in South Florida as well as the drilled diabase (Heatherington and Muller, 1991) may have formed at this time. Eventually, because of the massive magmatism the crust between the various plates was weakened and the motion of the plates away from each other no longer generated enough stress to cause large-scale continental extension.

Conclusions

In conclusion, the South Georgia Rift (SGR) failed because of the onset of westward motion of the Yucatan plate at 200 Ma. The Yucatan must have been adjacent to Florida and embedded in the continent to have exerted the necessary stress to cause NE-SW extension and the formation of the NW trending dikes. Positioning the Yucatan at this location and having it start moving at 200 Ma also would result in extension in South Florida and the formation of the observed extensional basins and diabase flows seen in drill holes.

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Mapping the crust in the Northeast Atlantic Ocean: a comparison of the conjugate margins

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Over the last three years, the geological surveys of the NAG (Northeast Atlantic Geoscience) group compiled a comprehensive tectonostratigraphic atlas of the Northeast Atlantic Ocean. This atlas project is referred to as the NAG-TEC initiative. As part of the project, a detailed database of the crustal structure has been compiled based on more than 200 seismic refraction profiles. Maps of Moho and basement depth were compiled from this data set employing kriging techniques. This method proved to be very successful on the unevenly spaced and regionally sparse data as can be seen by comparison with a gravity inversion carried out over the same area.

The crustal thickness map shows a fairly continuous zone of thinned crust along the NW European margin, extending from Rockall Trough and the Faroe-Shetland Channel to the mid-Norwegian basins. This zone of hyperextended crust is underlain by partially serpentinized mantle in Rockall Trough. Off mid-Norway, any serpentinization process beneath the hyperextended crust was probably overprinted by the breakup-related volcanism forming a widespread high-velocity lower crust. Our compilations also indicate possible zones with hyperextended crust beneath the wide NE Greenland shelf. However, there is no information on the presence of serpentinized mantle or high-velocity lower crust due to the lack of appropriate seismic refraction lines.

Based on the refraction database, a total of ten conjugate transects could be assembled that show various degrees of symmetry and asymmetry. A review of these conjugates indicates that the NE Atlantic is still waiting for a set of truly conjugate lines, acquired with a similar data quality and density, modelled in a consistent way on either side, and long enough to extend across the entire margin from proximal to distal regions.

No prominent sedimentary basins are known along the Southeast Greenland continental margin. However, gravity data calibrated with nearby refraction seismic lines indicate a 2 to 3-km-thick basin south of Ammassalik. This basin extends ~200 km along the margin but the only available reflection seismic data have poor penetration. Based on the seismic data, it was hypothesized that this basin could be a failed rift arm. The basin is referred to as Ammassalik Basin and plate reconstructions show it just north of the Hatton Bank at the conjugate Faroe-Hatton margin.

3D partitioning of deformation and magmatism in a V-shaped propagating hyper-extended rift system: Examples from the southern North Atlantic.

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Rifted continental margins are relics of extensional tectonic and magmatic events leading to continental breakup and seafloor spreading. The project aims to analyse and characterise the 3D partitioning of deformation and magmatism during continental rifted margin development. A particular focus will be on the study of V-shaped rift and oceanic basins. Studies of rifted continental margins have made substantial progress in recent decades with the improvement of geophysical imaging methods, deep sea drilling and comparison with fossil margin remnants trapped in collisional orogens. However, these studies are usually limited to investigating 2D profiles despite the fact that rifted continental margin formation processes are 3D in space and, if time is included, 4D. It is therefore important to investigate the time/space evolution of these systems in order to describe and understand the propagation and partitioning of the deformation and magmatic processes leading to seafloor spreading.

While divergence between North America and Europe is localized along the Mid Atlantic Ridge, prior to breakup the distribution of deformation was more complex leading to several hyper-extended rift systems. These hyper-extended, magma-poor rift systems distributed along the southern North Atlantic have typically small amounts of magmatic additions that together with good seismic reflection and refraction coverage enable imaging the crustal structure of the deep rifted margin. The products of this complex rift system include the Bay of Biscay, which is a more evolved V-shaped ocean basin formed by Cretaceous seafloor spreading. In contrast other branches of this hyper-extended system show only hyper-thinned crust and possible locale mantle exhumation (e.g. E and W Orphan, Porcupine, Rockall Through). The strain accommodated and partitioned among these basins is important but difficult to quantify and to include in regional restorations. The analysis of these poly-directional and polyphase extensional systems will provide new insights into the evolution and propagation of the southern North Atlantic rifting predating breakup and onset of seafloor spreading.

The observation-driven approach combined with geophysical methods used in our project will enable to describe how deformation and magmatism are partitioned in time and space and how these processes determine the evolution of rifted continental margins. Because seafloor spreading initiation in the southern North Atlantic developed during the Cretaceous magnetic quiet zone, an important challenge is to determine block motion in the absence of oceanic magnetic anomalies. Observational methods will include crustal thickness mapping based on 3D gravity inversion corrected by lithosphere thermal gravity anomaly (Greenhalgh & Kusznir, 2007; Chappell & Kusznir, 2008) and 2D flexural backstripping subsidence analysis (Kusznir et al., 1995). 2D seismic reflection lines combined with deep borehole data indicate the duration of the deformation which is of prior importance to understand the evolution of the system. And published refraction line will be used to constrain the deep structures of the margins. This geophysical database is used as a tool to investigate the rifting and hyper-extension processes, but geological field work data are also included in the scientific reflection, as they are with boreholes the only direct access to rocks nature.

In order to restore rifted domains, fixed boundaries are set on the proximal slope break of the necking zone, on the first clear oceanic anomaly (C34 in the southern North Atlantic) and on the interpreted last continental crust. These boundaries delimit different domains which correspond to different modes of deformation and different phases of the rifting process. Therefore each domain has to be analysed separately on multiple 2D lines, extracted from the crustal thickness map, to retro-deformed the rifted margin. The project will focus on the deformation of this rifted domain, in particular in areas where the fixed boundaries are not parallel and where strike slip movements could occurred, those settings are characteristic of V-shaped hyper-extended systems. The second challenge is to link the deformation with time by using regional stratigraphic unconformities, reflecting deep tectonic processes. This work will try to provide a method to analyse the kinematic of continents before the oceanic accretion.

Preliminary results show that former continental shapes are easy to restore with the crustal thickness, obtained by 3D gravity inversion, when the margin is parallel to the first magnetic anomaly. Whereas, in oblique settings the reconstructed shape are depending of the orientation of the restored lines. Therefore different hypothesis have to be tested to understand the deformation of V-shaped propagating rift systems. Observation and quantification of pre-breakup deformation of continental rifted margins is a prerequisite to develop a consistent kinematic model of the southern North Atlantic opening.

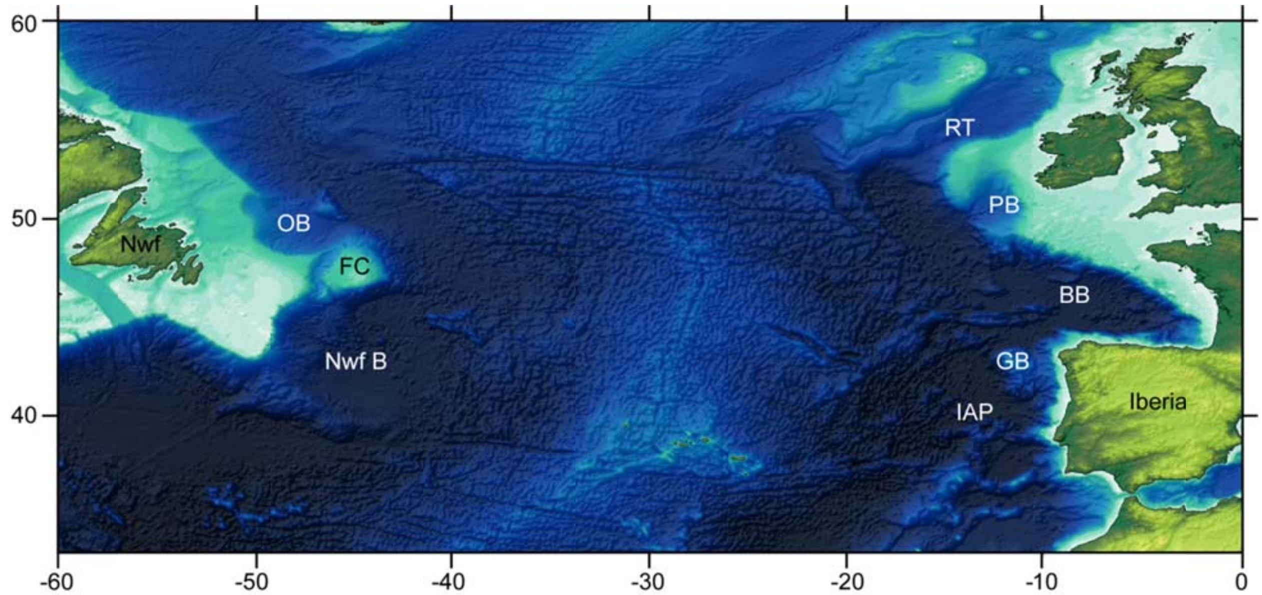

Figure 1: Bathymetric map of the southern North Atlantic. BB: Bay of Biscay; FC: Flemish Cap; GB: Galicia Bank; IAP: Iberia Abyssal Plain; Nwf: Newfoundland; Nwf B; Newfounland Basin; OB: Orphan Basin; PB: Porcupine Basin; RT: Rockall Through.

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Igneous Geochemistry from the Faroe-Shetland Basin and the Davis Straights: an insight into the opening of the North Atlantic

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The Palaeocene, North Atlantic Igneous Provence (NAIP) stretches from the Baffin Island, to the Faroes-Shetland Basin and northwards, to the Vøring Basin. It is widely accepted that the NAIP was the result of a mantle plume. However, there is still discussion concerning the initial position of the plume and about its chemical and thermal evolution. This study is based on the interpretation of new geochemical analyses carried out on igneous samples from oil exploration wells in the Davis Straights and the Faroe-Shetland Basin, including the 4.2km deep 6104/12-1 well which penetrates 1690 metres of volcanic material, together with data from the literature (Figure 1), and charts the changing chemistry of the plume using.

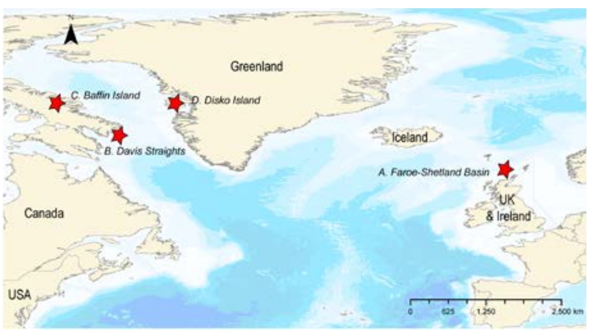

Figure 1: Location Map showing the datasets used within this study. A. Faroes-Shetland basin, B. Davis Straights, C. Onshore Baffin Island, D. Disko Island W. Greenland

It has previously been suggested that an ascending plum will have a carapace of mid-ocean ridge basalt (MORB) type depleted mantle, riding atop of the more Nb and La rich plume which is now the dominant component exhibited in Iceland today (Fitton et al., 1997). This study suggests that the depleted mantle, which was being uplifted and heated by the underlying plume, became hemmed in by the thick sub-continental lithosphere underlying Greenland, Scandanavia and Scotland. This material was unable to escape, except by flowing under a thinner part of the Greenland lithosphere towards West Greenland and Baffin Island, where it re-melted, causing the eruption of depleted picritic lavas.

This study utilises the previously defined parameter, Δ-Nb, which measures the Nb content of the magma, relative to its Zr and Y and compares it with the present day Iceland values (Fitton et al., 1997). In addition to the new parameter, Δ-La, which characterises the curvature of the rare earth element (REE) patterns. Together these parameters show that despite early entrainment of Nb and La rich material, which dominates the Iceland plume today, this component did not dominate the eruptive products of the plume until about 55 Ma, when the Norwegian Sea began to open.

Materials and Methods

During the drilling process the drill bit descends through the rock and produces homogenised samples, unfortunately barite based drilling compounds are used during the drilling, leading to a contamination issue with barium. Consequently, barium ratios and discrimination plots are avoided for the purpose of this study. For this study one hundred and ninety-four basalt samples were collected from ditch cuttings obtained from hydrocarbon exploration wells within the Davis Straights and the Faroe-Shetland Basin. The ditch cuttings were examined under a binocular microscope, removing visible contamination. Reference was made to the wireline gamma ray log to mitigate the risk of analysing caving.

After drying the samples were fused following the lithium-tetraborate method described by Jarvis and Jarvis (1992a; 1992b), the resulting glass bead is then dissolved in nitric acid. The solution is then analysed by inductively coupled plasma optical emission spectrometry (ICP-OES), which analyses the major elements as well as some trace elements, and inductively coupled plasma mass spectrometry (ICP-MS), which analyses the trace and rare earth elements. The samples for this study were analysed by a Thermo ICAP6500 radial ICP-OES and ThermoX X series 2 ICP-MS (*Origin Analytical, Welshpool*) with a total of ten major elements, twenty-six trance elements and fourteen rare-earth elements. In addition, the data was also combined with published datasets to give a comprehensive study across the North Atlantic (summarised in Table 1).

Results & Discussions

Figure 2 shows the geochemical data plotted on the Nb/Y vs. Zr/Y plot, proposed by Fitton et al. (1997), which is used to distinguish between Icelandic basalts and those basalts derived from N-MORB.

Locality	Rock Type	Figure 1 point	Number of Analysis	Reference
Faroe – Shetland	Basalt	A	161	This Study
Davis Straights	Basalt	B	33	This Study
Baffin Island	Picrite	C	36	Starkey *et al.*, 2009
Disko Island	Basalt	D	63	Lightfoot *et al.*, 1997

Table 1: Summary of data used in this study

This diagram makes this distinction between the Icelandic and N-MORB basalt based on the behavior of Nb during the melting process (*opt. cit.*). Furthermore, the geochemical plot proposed by Fitton et al. (1997) is insensitive to low-pressure fractional crystallisation and within this diagram all variations amongst Iceland and N-MORB basalts caused by degree and depth of partial melting and source depletion, through melt extraction, are all contained within their respective linear arrays (Fitton et al., 1997).

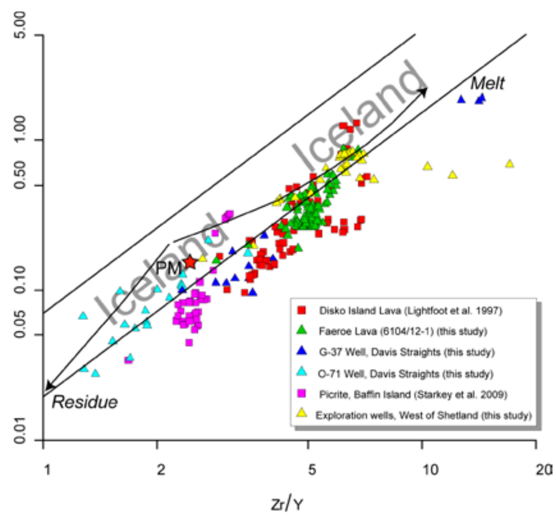

Figure 2: Nb/Y vs. Zr/Y plot proposed by Fitton et al. (1997) with the Iceland array.

The volcanic samples analysed here, and those from the literature cited, plot in a parallel array along the lower boundary. The majority of the samples are N-MORB in composition, although some samples plot in the Icelandic field (Figure 2). The samples which plot in the N-MORB field, Δ-Nb < 0, are interpreted as the carapace of N-MORB material which ascended, riding atop of the plume. Gradually through time the carapace of material was eventually replaced with more Icelandic basalt.

Rare Earth Elements (REE) are typically used to characterise the processes that have affected the evolving magma, such as, fractional crystallisation, crustal contamination, mantle heterogeneity and partial melting, because they are insoluble, likely to resist alteration and have varying degrees of compatibility. Typically, the REE are displayed on Chondrite normalised, logarithmic, diagrams. A key aspect of this diagram is the slope of the REE patter, which here have been abstracted as the Log[La/Yb]-n value; positive values positive values represent LREE enriched patterns, negative values represent LREE depleted patterns and a value of zero represents a flat REE pattern. In addition, the curvature of the REE pattern may also be abstracted, and expressed as a new parameter, delta-La (Δ-La). A mathematically straight line is constructed from Yb through to Sm i.e. the MREE (Medium Rare Earth Elements) and the HREE (Heavy Rare Earth Elements) and predicts the La value that would result. The actual La value is then subtracted from this and recorded as Δ-La. In essence therefore, Δ-La represents the deviation of the pattern from a straight line and hence, if the line is concave upwards Δ-La is positive, if the line is concave downwards Δ-La is negative, whilst a straight line yields a Δ-La value of zero.

Petrogenic processes determine the "movement" of samples on this plot. Garnet removal, or non-inclusion, which is a feature of incremental re-melting, would promote horizontal movement. Furthermore, the removal of clino-pyroxene, and amphibole, which can be associated with fractional crystallisation, and/or contamination, promotes a north-east movement. Interestingly, some of the lavas from well Hekja O-71 plot in the lower left of the diagram (Figure 3), i.e. they have low Log[La/Yb]-n and Δ-La values, which is unusual for Phanerozoic lavas, and are usually the result of re-melting mantle material. Mantle re-melting liquids contain more La, in preference to Yb, while the remaining residue is enriched in Yb. The Δ-La value greatly depends on the ratio of minerals left in the residue, particularly the clinopyroxene to garnet ratio; while the removal of clinopyroxene, which occurs later than olivine, causes the melt position to shift to the top right of the diagram (Figure 3). The distance spanned by some of the wells it too great and would require a large amount of pyroxene to be removed. For such a dramatic shift this study suggests the contamination of the melt, brought about by dissolution of continental crust during ascent, would be a very effective agent moving the melts to the top right of the diagram (i.e. steepening the patterns). In this case, assimilative fractional crystallisation (AFC), the process in which latent heat of crystallisation is used to melt the wall rock of an ascending magma, is suggested as the process.

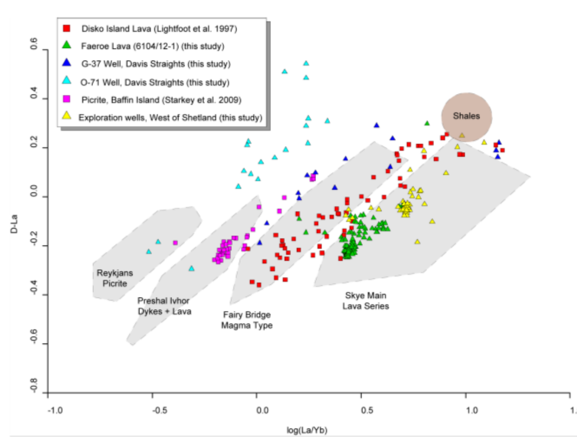

Figure 3: Log[La/Yb]-n vs. Δ-La plot

Figure 3 shows that the individual magmas have separate early histories, most likely the re-melted product an under-plating mantle plume, but all have undergone some later fractional crystallisation and contamination as part of the process. The geographic location of these magmas implies a mantle plume that under-plated Greenland, progressing under the Davis Straights and Baffin Island (Figure 4).

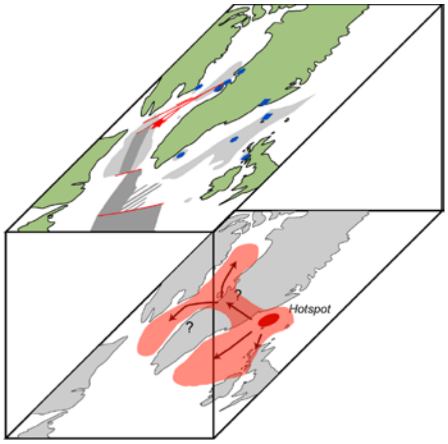

Figure 4: Proposed underplate migration path of the magma originating at the Hotspot (modified after Chalmers *et al.*, 1995). Blue spots denote high temperature mafic rocks, red star denotes sub-aerial sea-floor spreading.

An interesting feature is how two magma sequences, the onshore picrite and the basalt sequences within the G-37 well, can originate from the same re-melt phase. The onshore picrite has been less affected by the AFC process, and has retained its original picrite geochemical signature. To accomplish this the magma would have crossed the Moho as picrite; supper hot this magma would have the necessary heat to assimilate large quantities of crustal material en-route to the surface. Figure 5 demonstrates a possible hypothesis for this fractionation. The magma, which forms from the same re-melt phase, either ascends quickly through the continental crust, without any AFC; while some ascends more slowly, possible through a sedimentary basin, where AFC can take place. Not only have the two wells gone through different fractional crystallisation histories, they were derived from separate volcanic sources. The correlation of the volcanic intervals from the Hekja O-71 and Gjoa G-37 has been discussed by various authors for years (Balkwill, 1987; Roest & Srivastava, 1989; Srivastava & Keen, 1995; Sørensen, 2006). The volcanics of the Gjoa G-37 were initially thought to be the result of subaqueous eruptions, and that the volcanics were underlain by oceanic crust extending from the central part of the Labrador Sea (Roest & Srivastava, 1989; Srivastava & Keen, 1995). However, the sediments that have been found to inter-finger the volcanics, and have now been assigned to the Danian, formally assigned to the Maastrichtian (Nøhr-Hansen, 2003; Klose et al., 1982; Chalmers & Pulvertaft, 2001). Sørensen, (2006) suggested that no oceanic crust was present within the area, and that the boundary between the continental and oceanic crust in the Labrador Sea must have been further south. Rare earth elements curves (not shown) highlight the possible contamination with continental crust by geochemical features, such as; enrichment in light rare earth elements, negative niobium anomaly, and depletion of titanium, phosphorus and strontium. Contamination with continental crust would support the hypothesis of Sørensen, (2006). In addition, there are three samples identified as volcaniclastic within the Gjoa G-37, these cluster separately (Figure 2 & 3). Interestingly, these samples are enriched in niobium and could represent the niobium enriched tail of a plume (Fitton et al., 1997).

The occurrence of picrite implies that the mantle was hotter than normal; typically normal mantle has a potential temperature of 1280ºC and typically generates dry melts with 11% MgO. However, mantle temperatures which are 200ºC hotter generate melts which have been identified on Baffin Island and W. Greenland (Chalmers et al., 1995, *and references within*). There are two models of mantle plumes, active and the static (Campbell & Griffiths, 1990; White & McKenzie, 1989), both of which make predictions to the temperature distributions; the peripheral margin of the plume head should be several degrees lower than that of the center. Therefore, picrite occurrence should be limited to above the central plume stem. The distribution of picrite within the northern North Atlantic is inconsistent within this statement. There is also a timing issue; neither of the models can account for the early volcanism at the plume margins by 6 to 7 Ma (Chalmers et al., 1995). Chalmers et al. (1995) proposed a model to account for the distribution of the picrite within the northern North Atlantic area; the 'big hot head' model, which suggests that as the lithosphere under the volcanism was thin and that very high temperatures where sustained in the upper asthenosphere for at least 2000 km. High Mg-magma was then sourced from the mantle close under the plume, a short migration distance produce picrite. However, this study demonstrates, that through the use of the REE's, and the newly identified Δ-La parameter, the re-melt phases which can be identified; with increasing distance from the plume location there is a corresponded increase in the Log[La/Yb] as different melt phases are removed, and the residue advances.

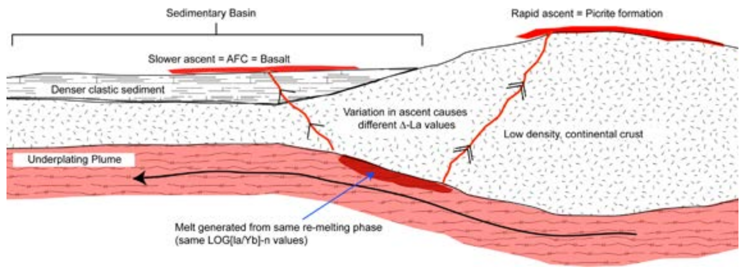

Figure 5: Proposed hypothesis for magma differentiation

Conclusions

This study demonstrates the new parameter Δ-La which can highlighter different melting phases, and demonstrates how mantle underplating could produce different magma re-melts with an ever increasing Log(La/Yb). While the Δ-Nb plot demonstrates that the samples are predominantly N-MORB in composition, and are likely to reflect the initial N-MORB rich carapace, which ascended on top of the plume head.

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Investigating the lithosphere underneath the Orphan Basin prior to, and during, rifting; the Newfoundland margin, eastern Canada.

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Abstract

Sedimentary basins in rifted margins are characterized by basement subsidence and accommodation of sediments during both the syn- and post-rift stages. Quantitative analysis of this subsidence gives insights into the initial thickness and rheological structure of the lithosphere prior to, and during, the rifting process.

The Orphan Basin, located in the Newfoundland rifted margin of eastern Canada, shows highly extended crust and thick sedimentary covers. This makes an ideal case study for examining the primary factors that control lithospheric extension, rifting style and the development of sedimentary basins. Using seismic data (courtesy of TGS), tectonic subsidence analysis, and 2D numerical modelling, we aspired to (i) describe and quantify the syn- and post-rift subsidence in the Orphan Basin, (ii) identify the spatial and temporal distribution of the various rifting phases and the related crustal and subcrustal amounts of thinning, and (iii) investigate the thickness and strength of the lithosphere prior to, and during, rifting.

Our work shows that the pre-rift lithosphere was rheologically strong and thickened prior to rifting. It also indicates that extension in the Orphan Basin occurred in three distinct phases during the Jurassic, the Early Cretaceous and the Late Cretaceous. Each rifting phase is characterized by a specific crustal and subcrustal thinning configuration. Crustal deformation initiated in the east during the Jurassic and migrated to the west during the Cretaceous. It was coupled with a subcrustal thinning which was reduced underneath the eastern domain and very intense in the western domain of the basin. The spatial and temporal distribution of thinning and the evolution of the lithosphere rheology through rifting time controlled the tectonic, stratigraphic and crustal architecture that we observe today in the Orphan Basin.

Volcanic structures (syn-rift and post-rift) in Pernambuco Basin, NE Brazil - 2D seismic data

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Abstract

The Pernambuco Basin is a marginal basin located on the eastern part of the Borborema Province, Northeast Brazil. The Maragogi High represents its south limit and the Pernambuco Shear Zone represents its north limit (Figure 1). Of its total area of 20,800 km2, only 2.8% is located onshore. Despite being critical to the Brazil-Africa conjugate margin story and discussion about the influence of hotspot activity in this region of the South Atlantic rift (which probably formed the Ipojuca Magmatic Suite, ca. 100 Ma), the occurrence of subsurface volcanic structures in the basin is poorly studied. The occurrence of lava flows, sills and dykes in exposures in the coastal zone is abundant, and Barbosa et al. (2014) interpreted the occurrence of sills and dykes on the onshore region using 2D seismic data. However, the identification of volcanic structures on the offshore region was never addressed by previous studies. Understanding this volcanism is important for unraveling the rift history of the basin as well as to any assessment on the region's petroliferous potential.

This study tried to characterize major volcanic features interpreted in a set of 2D seismic surveys covering the Pernambuco Plateau region in deep and ultra-deep waters region. Recent studies showed that the plateau bears the highest oil potential. The database used consists of 40 multichannel, time migrated surveys which covers the northwest and central plateau region (Figure 1). Stratigraphic control of seismic sequences was inferred by the knowledge over the stratigraphic column in the onshore region (exposures and the 2 CP well), once there is no wells in the offshore area (Figure 1). Interpretation issues such as signal attenuation and noise which affects the surveys were minimized by the use of frequency filters (mainly low pass), following the discussion about prospectivity of volcanic basins in Rohrman (2007). The data analysis allowed us to identify various volcanic features such as volcanoes, sill complexes, pyroclastic flows and volcanic vents (Figure 2). These findings are consistent with the analysis of potential field data (MAG and GRAV) which suggests an important amount of volcanic rocks in the Pernambuco Plateau.

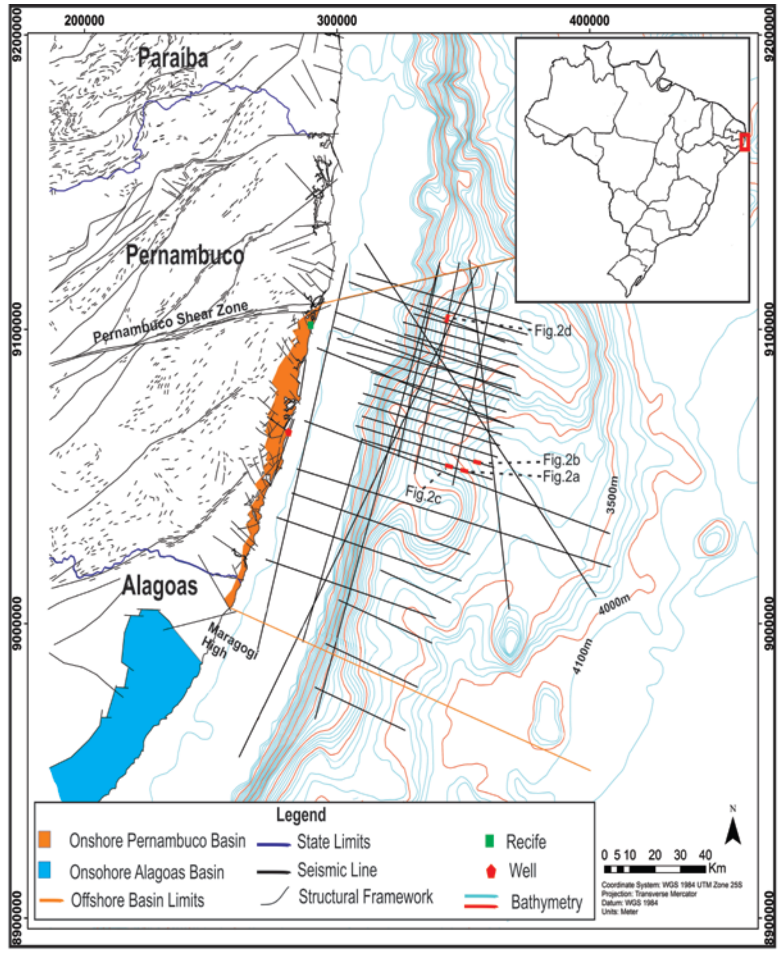

Figure 1 - Location map of the study area with the main geological structures that composes the structural framework of the eastern edge of the Borborema Province and adjacent continental margins. The bathymetry, basins limits, seismic lines analyzed in the study are also plotted as well as the location of the volcanic structures showed in figure 2.

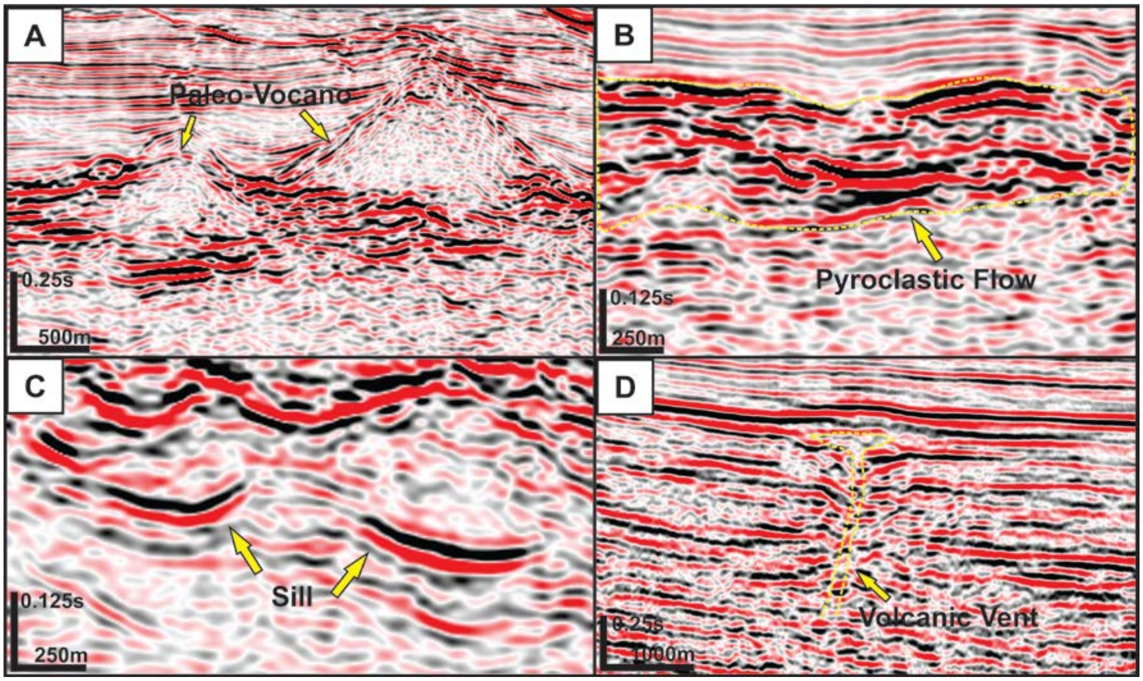

Figure 2 - Examples of volcanic structures present in the Pernambuco Plateau. A) Buried Paleo-Volcanoes. B) Pyroclastic Flow. C) Sills. D) Volcanic Vent. The location of these structures is shown in figure 1.

Dykes were highly visible due to their strong positive reflections and abrupt lateral terminations. Their presence was also detectable via the absence of seismic reflections along a vertical and subvertical section called the 'blindzone'. Sills showed well-defined, strong amplitude reflectors, saucer-shaped with abrupt terminations and laccoliths showed the absence of signals in its core structures flanked by divergent reflectors sets. Structures with conic sections showing internal overlapping strata with inverted 'V' shapes were suggestive of volcanic buildings. Seismic sequences showed strong positive reflections, convolute to fairly continuous internal configuration, abrupt lateral terminations, concordant with the sedimentary strata in the adjacencies of volcanic centers were interpreted as lava flows. Pyroclastic flows are interpreted as seismic sequences that showed chaotic seismic facies with well-defined top and poorly defined base. Volcanic vents showed the characteristic eye-shaped upper part with the sedimentary strata dipping into the vent chimney (Fig. 2).

Despite the huge volume of volcanic activity in the central portion of the plateau, a more detailed interpretation suggest that isolated carbonate platforms developed over some magmatic building in underwater environment. Repeated eruptions could have created topographic highs in the central and border regions of the plateau, where upper portions reached the photic zone and allowed biotic colonization with the development of carbonate fabrics over these structures.

Seismic stratigraphic interpretation, involving the definition of the main tectono-stratigraphic sequences is complicated due the absence of offshore wells. However, a tentative definition of major sequences was achieved based on onshore well correlations - top of rift deposition, top of Cretaceous deposition and the Oligo-Miocene unconformity. Volcanic structures were interpreted as Late Cretaceous in age (possibly Santonian to Maastrictian) and also within the Paleogene. Our results thus show that the magmatism in the plateau extended to younger sequences than is known in the onshore region, the youngest of which are Albian in age. The identification of subsurface volcanic structures will allow us to better understand their genesis and emplacement timing. Also the definition of the volcanic influence in the basin will reduce the exploratory risk and help to determine the role of this event within the petroliferous system.

Acknowledgement

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Bottom current activity as indicator of established lithospheric breakup

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Introduction

Lithospheric breakup has been the focus of intensive research work addressing its triggering mechanisms, kinematical models and structural evolution (e.g. Braun and Beaumont, 1989; Healy and Kusznir, 2007). However, few papers document in detail the seismic-stratigraphic changes occurring on continental margins when of lithospheric breakup (e.g. Péron-Pinvidic *et al.*, 2007; Soares *et al.*, 2012, 2014).

The recognition of the *breakup unconformity* (sensu Falvey, 1974) as a surface defining the exact moment of lithospheric breakup on continental margins has been shown to be an oversimplified model (Manatschal, 2004; Soares *et al.*, 2012). The *breakup unconformity* per se can merely represent the end of activity of local faults, instead of the true end of crustal stretching and the start of the drifting phase of newly formed passive margins.

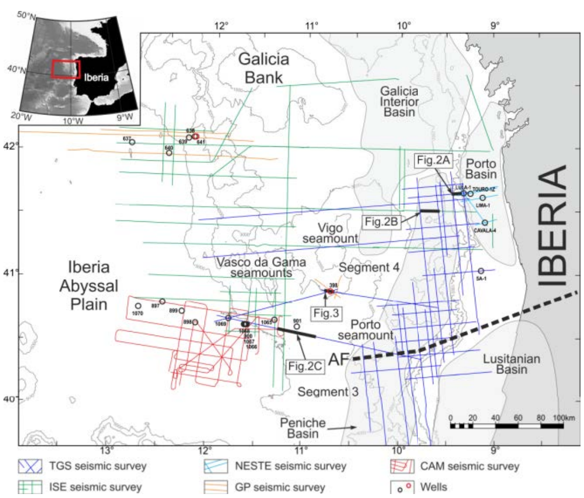

Figure 1: Location of study area and datasets used in this study. DSDP/ODP sites are located west of meridian 10°, with red circles indicating the sites where the breakup sequence was recovered. Industry wells are located east of meridian 10°. AF- Aveiro Fault

Using data from the conjugate margins of Iberia and Newfoundland, Soares et al. (2012) proposed the identification of the *lithospheric breakup surface* and the recognition of the *breakup sequence* for the recognition of strata materializing the transition between syn- and post-rift settings. The resulting substitution of the term *breakup unconformity* with *lithospheric breakup surface* is justified by the fact that on several conjugate margins two breakup events take place: first the continental crust is ruptured, causing exhumation and thinning of lower lithosphere, followed by a second breakup event rupturing the extended lower lithosphere (Boillot *et al.*, 1987). Due to the occurrence of this multiphase breakup events, a migration in the extensional locus progresses from the continental crust to the exhumed lower lithosphere, recorded as by the cessation of most fault activity towards the rift margin (Ranero and Pérez-Gussinyé, 2010). This basinward migration of the extensional locus promotes the generation of a *breakup unconformity* that does not record the end of the rifting process, since regional extension on the rift axis is still going on.

Soares et al. (2012) therefore demonstrated that the final breakup will generate, in premature tectonically inactive regions, a conformable surface rather than an unconformity. The authors also postulated that the use of "lithospheric breakup sequence" (LBS) is a more exact term than *breakup unconformity*, as it refers specifically to the final (lithospheric) breakup and it does not imply an unconformity in all its extension. The LBS can vary between an erosive basal surface of forced regression and its correlative surface on the inner proximal margin, to a conformable surface in deeper parts of the margin. The definition of a "breakup sequence" (BS) is a more comprehensive concept to characterize the transition from syn-rift to post-rift conditions than the sole identification of a LBS.

For this work, we interpreted 2D seismic data from five different surveys and well data from deep sea drilling and industry campaigns, to describe in detail the Albian-Cenomanian BS along the Northwest Iberian margin in terms of its stratigraphic architecture and sedimentology (Fig. 1). Additionally, on the conjugate margin, seismic and deep-sea well data were used. Our focus is on the outer proximal and distal margins, mainly of Northwest Iberia.

Results

Seismic data reveal the presence of three main seismic facies within the BS that are associated with: a) black shales and fine-grained turbidites, b) mass transport deposits (MTDs), and c) contourite drifts. Borehole data show that these facies develop proximally as mixed carbonate-siliciclastic sediments in a forced regression context (Fig. 2A). MTDs tend to occur close to the continental slope together with olistostromes (Fig. 2B). Distally, the MTDs change into organic-rich black shales deposited as fine-grained turbidites (Fig. 2C), followed by the deposition of contourite drifts showing widespread evidence of deep-water current activity towards the top of the BS (Fig. 2C). The seismic character of the BS is not uniform in the study area. However, characteristic seismic facies within the BS can assist its recognition. Seismically, the LBS (The base of the BS) usually comprise a strong reflector separating two well distinct seismic packages (Fig. 2B, C). Below the LBS, the reflections are usually moderately strong and can be chaotic, divergent or parallel (Fig. 2B, C). Distally, the lower part of the BS is often composed of low amplitude, transparent reflections.

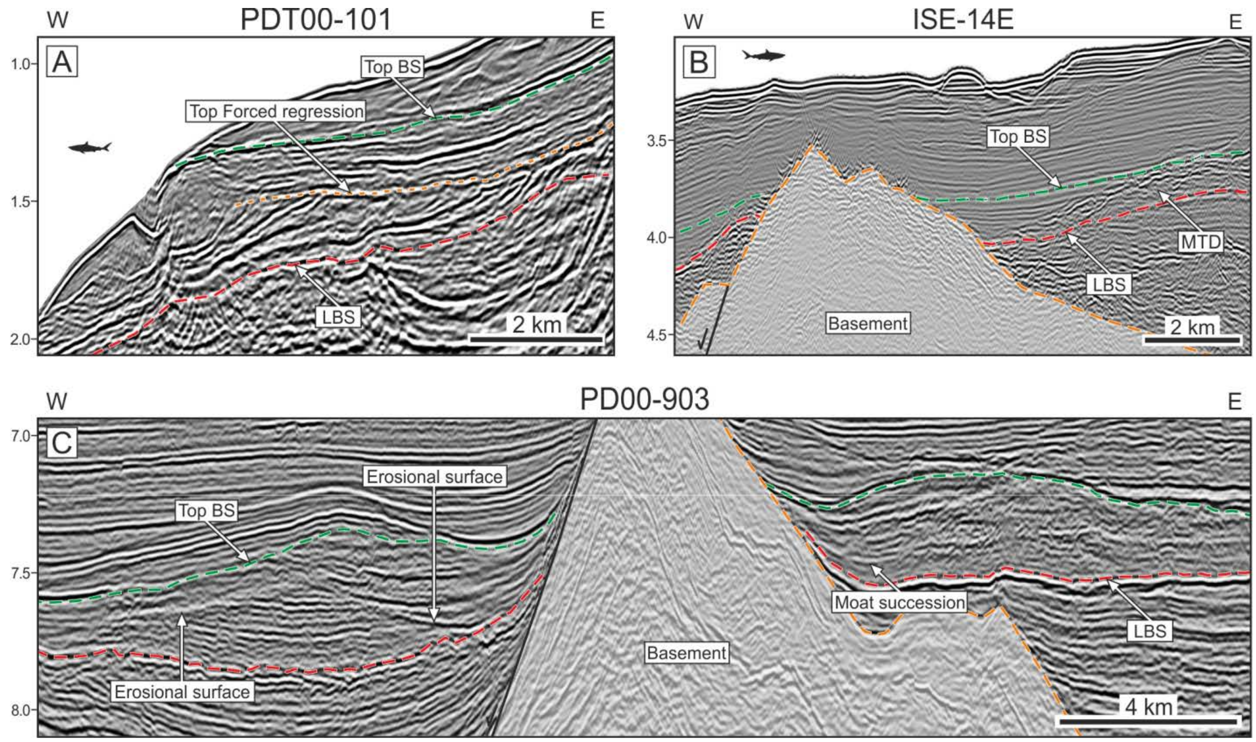

Figure 2: Variability in seismic character of the BS and the LBS present in the study area. A—transition between the inner and outer proximal margins, displaying the basinward edge of the prograding forced regressive deposits identified at the base of the BS. B—MTD within the BS. C—two elongated mounded and separated drifts along a common structural high. Separated by erosional surfaces, several depositional episodes can be observed, particularly on the west side drift. Seismic profiles in two-way time (ms). Location of seismic profile in Figure 1.

Towards the top of the unit occurs a transition, which can be gradual or abrupt to higher amplitude, continuous reflections (Fig. 2C, 3). This pattern can change across the basin with the presence of depositional features such as contourite drifts or erosional surfaces (Fig. 2C). In fact, besides contourite drifts, one of the main characteristics of the BS that can be observed on seismic data is the widespread presence of erosional surfaces within it (left side of Figure 2C). Truncation of reflections below the BS, and onlaping onto its upper surface, are common characteristics observed in Northwest Iberia.

The integration of well data from DSDP Site 398D and seismic data crossing this site allowed the identification of three units within the BS (from bottom to top, Units A, B and C), separated by erosional surfaces (intra BS-1 and intra BS-2 surfaces) (Fig. 3). These surfaces were found to be equivalent to the boundaries of the velocity groups 7a-7b and 7b-8 of Shipboard Scientific Party (1979).

Sedimentological data from DSDP Site 398D show several characteristics that can be attributed to bottom current activity during the BS deposition. The BS displays increasing amount of bioturbation towards its top, particularly after the Intra BS-1 surface. A similar increase in traction structures upwards in the succession is observed in the form of wavy and parallel lamination, especially where silty and sandier beds were deposited. Coarser beds, which can display reverse grading, occur at the base of Unit C. Towards its top, the BS is marked by thin, fining-upwards radiolarian sands, thin mudchip sandstone layers, fining-upwards quartzose sandstone and siltstone laminae displaying cross-bedding and erosional basal contacts (Shipboard Scientific Party, 1979).

In terms of bioturbation, *Chondrites*, *Zoophycos* and other unidentified ichnofossils are relatively frequent towards the top on Unit B, increasing further in frequency within Unit C. This character is interpreted to reflect an increase in oxygenation from the base to the top of the BS, which is also suggested by the decrease in preserved organic matter (Shipboard Scientific Party, 1979). This change is interpreted as related to the presence of bottom currents in Northwest Iberia, replenishing oxygen levels and allowing benthonic organisms to thrive.

At the BS, the scarcity of sedimentary structures in interpreted contourite drifts is in agreement with the presence of muddy contourites, which are less likely to be preserved than in coarser grained contourites and predominance of bioturbation is expected (Martín-Chivelet *et al.*, 2008). Although some of the cored sedimentary structures can also be associated with turbidite deposits, the degree of erosion and extension of erosional surfaces observed on seismic data indicates the action of deep currents activity, rather than then more localized turbidity flows sourced from proximal areas of the margin.

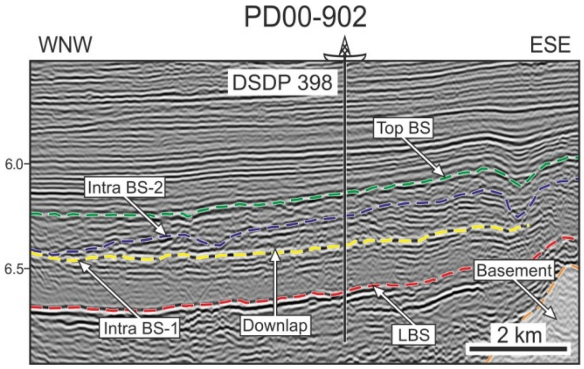

Figure 3: Seismic section crossing DSDP Site 398. Note the intra-BS erosional surfaces. Seismic profiles in two-way time (ms). Location of seismic profile in Figure 1.

Lithospheric breakup as a trigger for deep current intensification

The relationship between tectonics and major oceanographic events, such as the onset of bottom currents, is well known (e.g. Meijer *et al.*, 2004). As lithospheric breakup evolves in Northwest Iberia, the lithospheric rebound occurring in association with this event was able to generate vertical tectonic movements large enough to promote subsidence in deep-offshore depocenters (Braun and Beaumont, 1989; Kooi and Cloetingh, 1992; van Balen *et al.*, 1998). This lithospheric subsidence, altering the pressure gradient of the water masses around the ruptured lithospheric segment could potentially trigger the installation of a more permanent and stronger geostrophic current regime, in contrast with the previous sluggish bottom waters present on the Central Atlantic and its intermittent, presumably rare bottom currents (Tucholke and McCoy, 1986).

Landward, the lithosphere vertical movements promoted widespread rift-shoulder uplift recorded as a widespread forced regression on the proximal margin (Grobe *et al.*, 2014; Soares *et al.*, 2012) (Fig. 2A). This had as consequence the erosion of important volumes of sediment, which bypassing the continental margin, were delivered directly onto the continental slope. This suggests that this period of important sediment influx, transported to deep-offshore depocenters by turbiditic currents, to have masked ongoing bottom current activity during the early stages of the lithospheric breakup.

Later in the BS, the shutdown of continental shelf sediment bypass, reduced the amount of turbidite and consequently the input of terrestrially derived organic matter to deep-offshore basins, allowing bottom current activity to record the stratigraphic architectural expression characteristic of drift deposits, without the "masking effects" of mixed turbidite-contourite deposits. In fact, this gradual transition explicates an absence of more pronounced lower boundaries on the majority of the observed contourite drifts and the vertical change in seismic facies commonly observed in the BS, from a transparent, less structured lower part to sub-parallel reflections in sediment drifts accumulated to the top of the BS (Figs. 2C and 3).

Another plausible reason for this vertical change in seismic facies is, as proposed by Stow et al. (2002), an increase in bottom current velocity. In fact, an increase on the velocity of these bottom currents can be inferred towards the upper part of the BS (e.g. more frequent erosional surfaces and traction structures at DSDP Site 398), which cannot be merely related with the declining of turbiditic activity. It should also be noted that the top of the BS is marked by a regional unconformity resulting from erosion exerted by strong bottom currents (Shipboard Scientific Party, 1979). Most likely, both hypotheses had a part on the formation of the BS in Northwest Iberia.

Conclusions

Our results are important as they demonstrate that the presence of contourite drifts is a ubiquitous feature in Northwest Iberia after the Aptian-Albian lithospheric breakup (Soares *et al.*, 2014). Importantly, turbidite deposition appear to be concentrated in the lower parts of the BS, in opposition to the activity of bottom currents which increases towards the BS top, a character suggesting that the BS comprises a mixed contourite-turbidite system in Northwest Iberia, with contourite drifts becoming more prominent as the newly passive margin evolves.

As a result, we postulate the recognition of contourite drifts in Northwest Iberia as having significant palaeogeographic implications: they materialize the onset of important and widespread deep-water circulation between two rifted continents, thus marking the establishment of oceanic gateways between fully separated continental margins.

Acknowledgements

The authors are grateful to DGEG/DPEP (Direcção Geral de Energia e Geologia/Divisão para a Pesquisa e Exploração de Petróleo) for granting access to their archives and use of their facilities. Halifax 2008 Legacy Bursary and the Atlantic Conjugate Margins Conference 2014-St. John's are kindly acknowledged for their financial assistance in enabling my participation at this conference. Duarte Soares thanks the Fundação para a Ciência e a Tecnologia (FCT) for the SFRH/BD/64127/2009 PhD grant.

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Shale diagenesis and its impact on pore pressure prediction: A case study along the NE margin of Eastern Canada

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Introduction

The dominant mechanism for generating overpressure in shales is disequilibrium compaction (Swarbrick 2012 and references therein). Industry-standard techniques for quantifying overpressures generated from this mechanism rely on a porosity/effective stress relationship. However, at high temperatures (typically >120°C, although dependent on mineralogy and age), thermally-driven processes in the shales can generate secondary overpressure in rocks with low porosity. This overpressure would be significantly underestimated by these traditional methods such as Eaton (1975), as these techniques rely on a porosity anomaly suggesting elevated pore pressure. Such processes, e.g. fluid expansion, gas generation, lead to anomalously low velocity (with no density change) which is often referred to in the industry as "unloading" and featured in papers such as Bowers (1994). Alternatively, other secondary processes can lead to both slow velocity and high density, e.g. load transfer (e.g. Lahann et al, 2001), where shale compressibility is affected. Both these processes can elevate the pore pressure without an associated porosity anomaly. An additional process results in fast velocity and high density, cementation, where there is a possibility of reduced reservoir quality in more permeable units in association with the surrounding shales and overpressure generated by disequilibrium compaction is preserved. This latter process produces "fast" shales such that velocity data (well log, seismic) can no longer be linked to porosity thus overpressure is under-predicted.

The identification and quantification of these processes, some of which result in secondary pressure are therefore vital to accurately predict pore pressures in these thermally active (or older basinal) settings. Furthermore, it is essential to understand these secondary processes since they can impact on the elastic behaviour of a rock and thus may impact on the seismic amplitudes and AVO class.

There are many examples from basins around the world that show where overpressure is high, the associated porosity is also high, as expected. By contrast, the basins along the NE margin of Eastern Canada exhibit high overpressure yet low porosity shales suggestive that secondary processes may be active. The work presented in this paper highlights the method of identifying overpressure mechanisms, suggests that cross-plotting CNL/Rho data should be a regular part of this process in order to remove the effects of lithological variation and then, by means of two case studies, looks into the impacts of these processes along the NE margin of Eastern Canada. This is timely as there is recent industry focus in basins such as the Flemish Pass Basin (e.g. Harpoon and Bay du Nord discoveries) as well as seismic being shot in offshore Labrador.

Identifying Overpressure Mechanisms

A technique used to recognize the presence of these thermally-driven processes is a velocity (Vp) and density (Rho) cross-plot (Bowers 1994; Hoesni, 2004; Swarbrick 2012). The technique relies on cross-plotting data from shales only. However, as Vp and Rho data are also affected by lithology i.e. grain size reflecting more silt/sand or more clay-rich sediments, deviations on a Vp/Rho plot can in fact be simply lithologically rather than pressure associated. These shifts offset data away from the primary trend to a parallel trend, i.e. clay-rich lithologies move slightly towards higher density and slower velocity whereas sand-rich lithologies move slightly towards lower density and faster velocity. Therefore, to establish the presence of secondary processes such plots must be viewed with and understanding of the shale facies variation in any basin.

To help understand the effects of lithology variation on shale velocity with the aim to better identifying potential pressure generation mechanisms another method that can be used to resolve lithology effect in the absence of mineralogical data such as from XRD analysis is to cross plot CNL (Compensated Neutron Log) and Rho (Rider, 1996; Katahara, 2007). Here, the use of the neutron log enables us to understand the variation in porosity and thus identify the lithological variations (with sonic and density) and clay content in shales which can impact on the acoustic impedance and elastic properties of rocks. The neutron log records scatter caused by hydrogen atoms primarily in pore fluids, which gives a proxy for porosity. Thus it can differentiate between clay percentages in shales such that high readings are more clay-rich.

Case Study 1: Labrador Shelf

The well database consisted of 30 wells covering the offshore Labrador and Newfoundland Shelf. Fluid gradients were established for all relevant direct pressure data to determine the reservoir overpressure. This allowed some calibration for shale pressures associated with the reservoirs. Log data such as, Vp, Rho and CNL were carefully conditioned. Ancillary data such as, temperature, stratigraphic markers and geological and drilling reports were also integrated.

Geothermal Gradient

A temperature database was created from data from all 30 wells. The database was predominately compiled from wireline formation tests (e.g. RFT) and their derivative tools such as MDT, RCI and RDT. DST data were used where available. Additional temperature data were compiled from well reports (BHT for instance) and all data were corrected for mud circulation. An average geothermal gradient of 30°C/km was established although this gradient varies across the basins from 22°C/km (Roberval C-02) through to 38°C/km (North Bjarni F-06).

The implications of a geothermal gradient of 30°C/km is that the majority of the wells shows temperatures higher than >100°C below >3000 m TVDml. The variation in gradient allowed for a depth range to be established to capture uncertainty. The implication is that the temperatures are theoretically high enough for secondary processes to be active in the mudstones and shales in Labrador below these isotherms.

Shale Properties

Localized areas, such as the Saglek Basin in the north and Orphan Basin in the south of Labrador, show clear evidence of deviations from a disequilibrium compaction trend allowing us to make inferences on secondary processes that may affect the overall pressure regime of the system.

For example, Vp/Rho cross-plots show the clearest evidence for secondary processes in the Karlsefni A-13 and Gilbert F-53 wells from the Saglek Basin and Great Barasway F-66 and Blue H-69 in the Orphan Basin (Figure 1a). Here, we see a trend whereby there is an overall increase in density (>2.5 g/cm^3) and velocity that is consistent with combined process of chemical compaction with cementation during clay diagenesis. The density in particular is useful as density data of this magnitude are too high to be as a result of purely mechanical compaction and suggest that such low porosity shales have been affected by diagenetic alteration. The increase in both density and velocity suggests cementation has occurred. Such a process is not considered to generate additional overpressure but will significantly impact the permeability in the shales and, potentially, in the reservoirs. This or these processes will reduce reservoir quality and preserve any overpressure generated by disequilibrium compaction by preventing pressure dissipation.

By cross-plotting CNL with Rho reveals that for Great Barasway H-66 (Figure 1b) that there is little variation in clay content and therefore supports the interpretation that the shales are cemented rather than the deviation being related to variation in clay content alone.

Case Study 2: Jeanne d'Arc Basin Shale Properties

The majority of the Vp/Rho cross-plots from wells located in this basin show evidence of disequilibrium compaction despite the majority of the BHT exceeding 100°C. However, Vp/Rho cross-plots from the Trans-Basinal Fault system of the Jeanne d'Arc Basin show 'apparent' evidence of unloading (Figure 2a), e.g. South Mara C-13 and Nautilus C-92, whereby there is a reduction in velocity with little change in overall density with increasing depth.
Cross-plotting CNL and Rho suggests that there is an evident change from lower percentage of clay in shale to a higher percentage (Figure 2b). That is, there may a strong lithological over-print present and that the deviations observed are due to changes in sedimentary provenance or depositional facies change within a single province rather than purely an unloading effect. Abid et al. (2004) report that there are demonstrable changes in smectite to illite distributions within the Jeanne d'Arc Basin. The authors suggest that in the Northern Jeanne d'Arc Basin (e.g. Whiterose J-49 and Conquest K-09 area), the illite content increases linearly with depth. By contrast, in the Trans Basinal Fault Area (e.g. South Mara C-13 and Nautilus C-92) the illite content shows a rapid increase in a short depth interval of approximately 500 m. This provides collaborative evidence for changing shale lithofacies. The authors however attribute the change to diagenetic change i.e. transformation of smectite to illite. The sharper change in the Trans-Basinal Fault area is due to the availability of K+ ions, as a result of percolation of fluids from the basement at depth up faults. The more rapid change to illite by diagenesis may result in elevated pore pressure via unloading, however some of the changes in illite may simply be due to provenance. This is suggested by the shift in Figure 4 and could be due to shifting prograding and retrograding cycles of deposition. Some unloading effects are not ruled out however as these wells such as South Mara C-13 are highly overpressured.

Implications

Low porosity inferred from the density log in shales is not consistent with the typical understanding of disequilibrium compaction where porosity is high and therefore density is low. Therefore, utilizing Vp/Rho and CNL/Rho cross-plots in conjunction proves a useful set of technique that can clarify trends/deviations that could be otherwise attributed to unloading or other processes, rather than simply lithological changes.

Analyses using these techniques with data for several wells located along the NE margin of East Canada, reveals that (a) in some cases, lithological effects are present than evidence for unloading is less compelling, and (b) diagenetic processes are present that will impact on the ability to accurately predict pore pressures by creating artificially fast shales.

Furthermore, as the rock and elastic properties in the sub-surface are also primarily controlled by temperature and pressure then accurate predictions of both can significantly alter the elastic properties; to an extent that can influence the expected seismic amplitude response of hydrocarbons (Avseth et al., 2008) and thus affect the accurate building of rock physics models.

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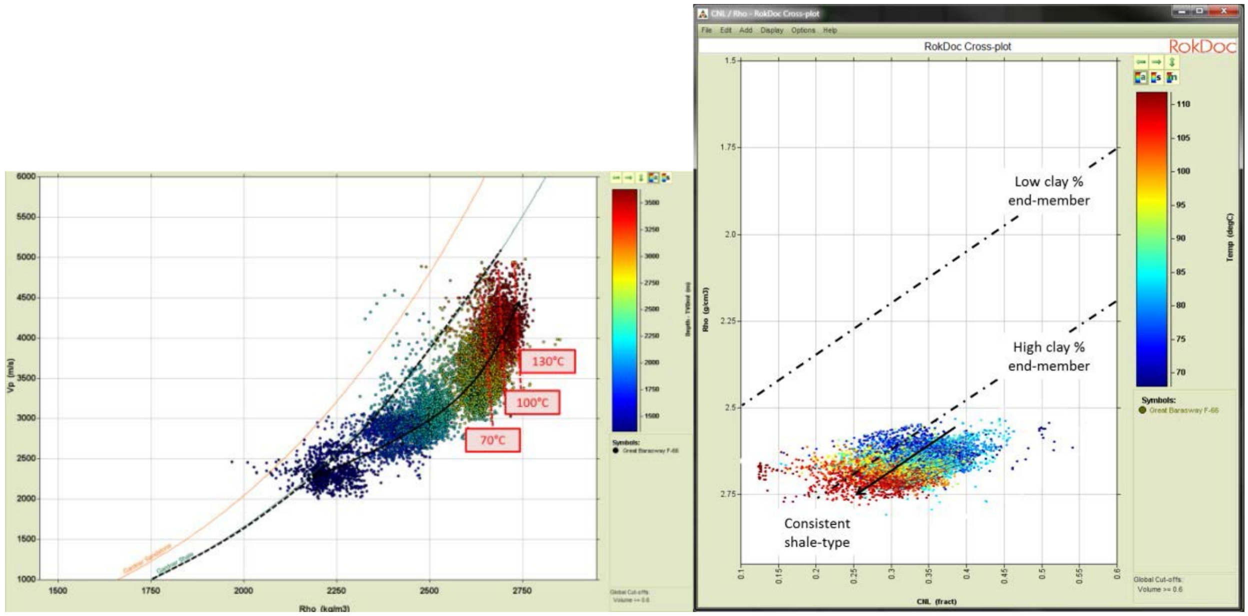

Figure 1a: Vp and Rho cross-plots showing evidence of a hybrid process of chemical compaction and cementation in Great Barasway F-66 (a) (Ikon Science, 2014). The Gardner shale line (black dash). Deviations from this primary trend with temperature occur at a depth of approximately 2600 m TVDml in both wells. A Vshale filter of 0.6 has been applied and the data are coloured by depth below sea floor. Figure 1b: Cross-plot of CNL/Rho for all shales in Great Barasway F-66. The shale content is consistent throughout the well implying that all the shales have the same clay percentage so that any deviation shown in Figure 1, for instance, cannot be attributed to a lithological effect.

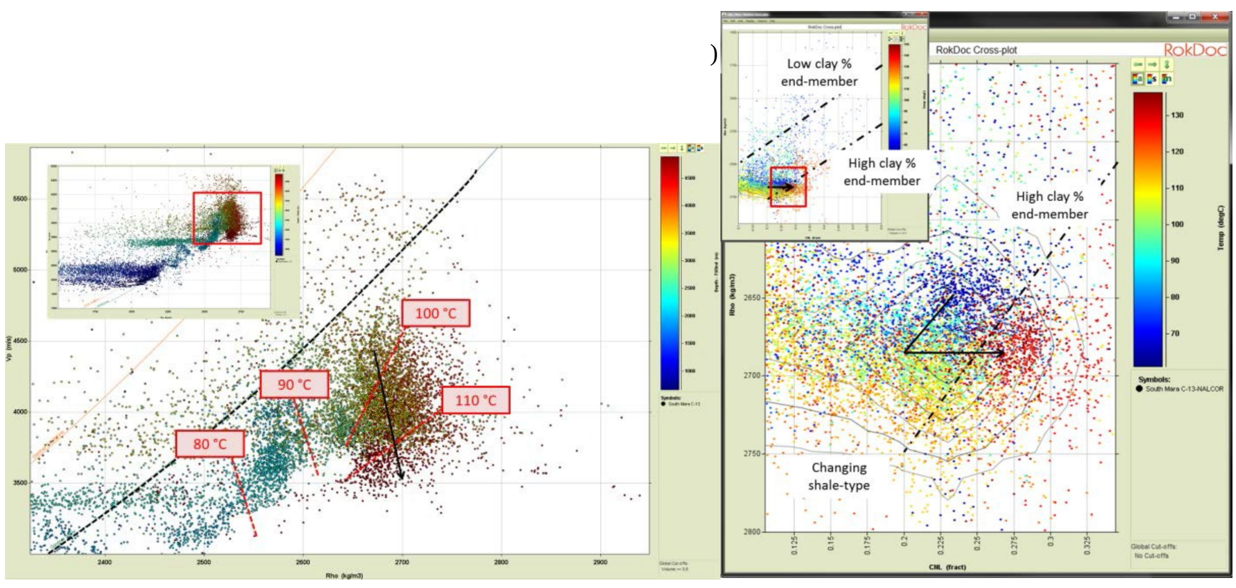

Figure 2a: Vp and Rho cross-plots of South Mara C-13 showing 'evidence' of unloading (log data courtesy of Nalcor Energy). Figure 2b: Cross-plot of CNL/Rho for all shales in South Mara C-13. Below 100°C the density remains constant (>2500 kg/cm^3) with rapid change in porosity implying that the unloading is apparent and more likely associated with a lithology, facies change in these deeper, hot, Jurassic shales.

Development of Extension over time during rifting of the Jeanne d'Arc Basin, Offshore Newfoundland

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Opening of the North Atlantic

The Jeanne d'Arc Basin formed during multiple rift events associated with the stepwise opening of the North Atlantic (Fig. 1). Seafloor spreading between Nova Scotia and Africa commenced 150 Ma and was preceded by northwest-southeast oriented extension in the Late Triassic to Early Jurassic (rift phase I). During the Late Jurassic to Early Cretaceous (rift phase II), extension was in an east-west direction and culminated in seafloor spreading between Newfoundland and Iberia around 112 Ma.

Northeast-southwest oriented extension during the Aptian-Albian (rift phase III) was possibly associated with the opening of the Labrador Sea.

Mapping using seismic and well data

2D and 3D seismic data (Figure 2) and well data were used to create time structure maps of the unconformities representing the start of each rift phase. Faults were mapped at the level of each unconformity.

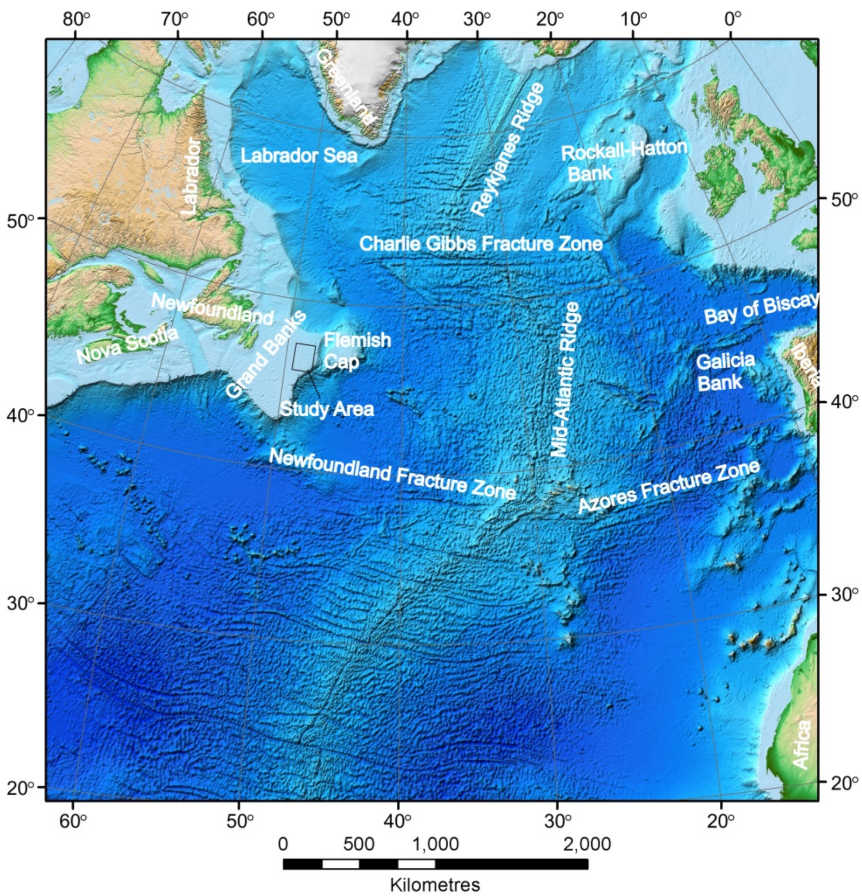

Figure 1: Bathymetric map showing the North Atlantic spreading centres.

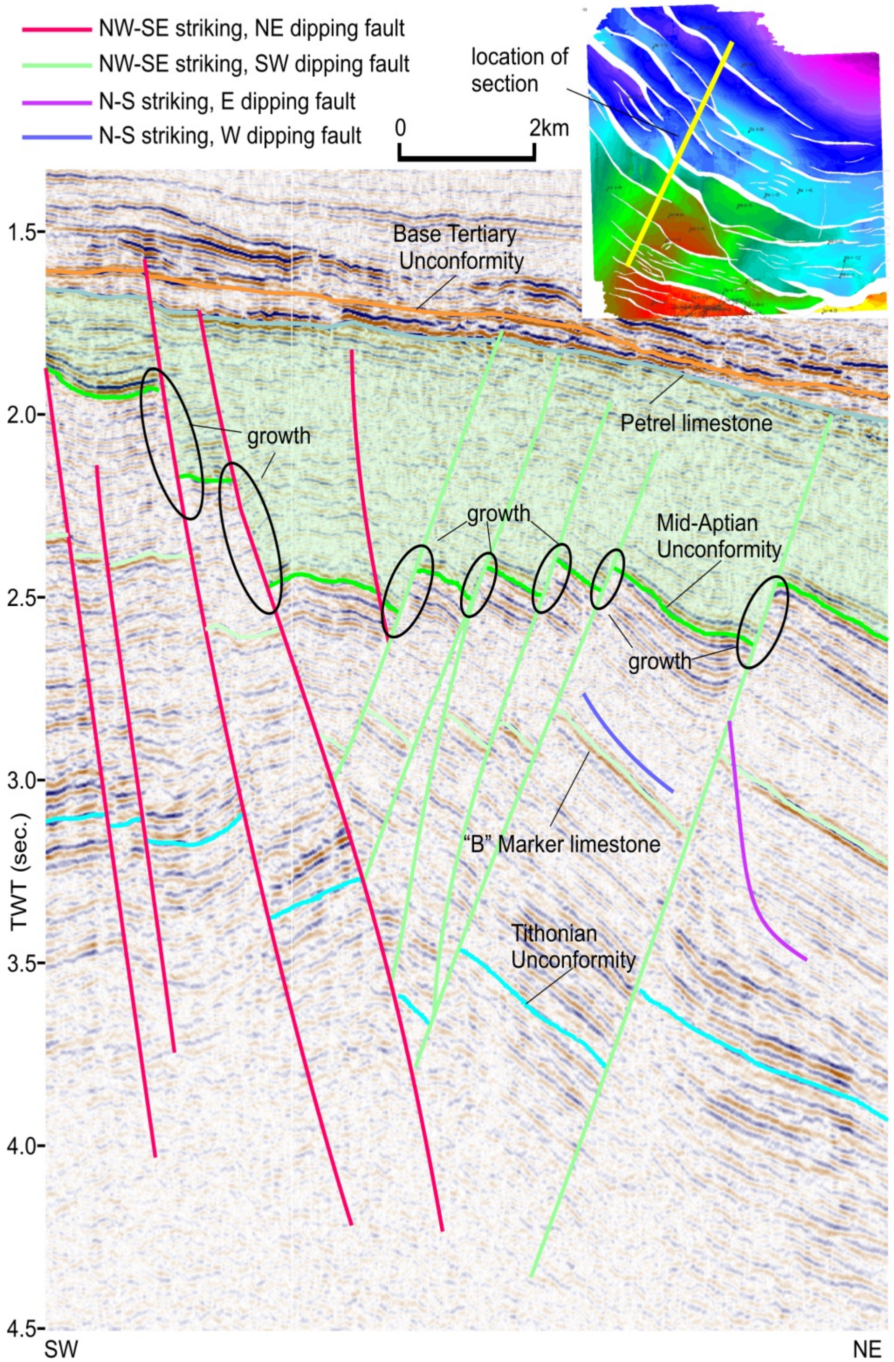

Figure 2: Interpreted northeast-southwest seismic profile across the Hebron 3D data. Data courtesy of Husky Energy. The location of the section is shown on a time structure map at the Mid-Aptian Unconformity from the Hebron area.

Measuring extension using fault heaves

Assuming dip slip motion on most of the faults, the heave was measured perpendicular to the strike of the fault. To obtain the component of heave in the analysis direction, a correction was applied to faults that are not perpendicular to the extension direction.

The extension across each fault for a given rift phase was calculated by subtracting the heave associated with the subsequent rift phase from the heave associated with that rift phase.

There are obvious limitations with assuming dip slip motion, particularly concerning fault motion associated with the Aptian-Albian rift phase. The 90° rotation of extensional stress in the Aptian-Albian is inferred to have caused oblique slip fault reactivation. Aptian-Albian extension was measured as oblique slip in a northeast-southwest direction.

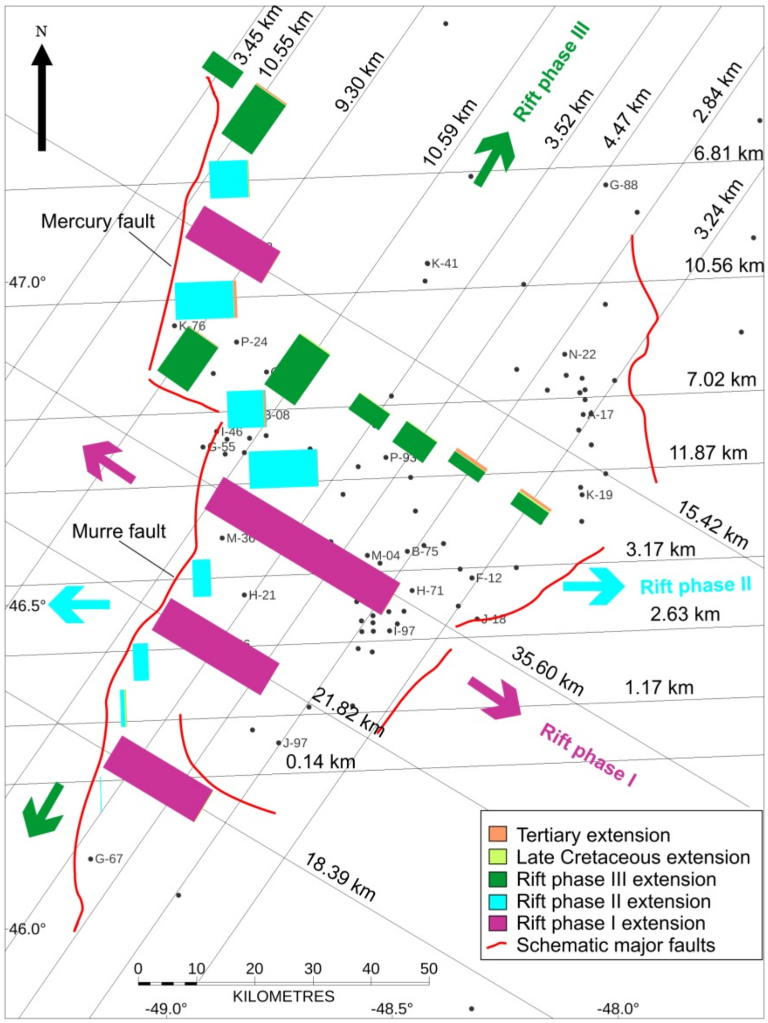

Figure 3: Summary of the temporal and spatial variation in extension across the Jeanne d'Arc Basin using the double extension estimates

Underestimation of extension

It is difficult to image completely the geometry of polyphase faulting with seismic sections. Detailed fault mapping of the Hebron area using the 3D data revealed complex fault interactions. It is observed that the extension measurements across the Hebron area using the 3D data are approximately double the measurements across the same area using the 2D data. This missing extension in the 2D data was accounted for in order to estimate the extension across the basin and to restore the time structure maps to their position before each rift phase.

Summary of extension

The extension across the basin is summarized in Figure 3 using the double extension estimates. The length of the coloured bars represents the amount of extension in that direction according to the scale at the bottom.

The coloured bars are placed along the Murre and Mercury faults on the northwest-southeast lines and the east-west lines, and across the centre of the basin on the northwest-southeast lines, however they represent extension along the entire line.

Looking at the general pattern, the extension is dominated by rift phase I (pink bars). The extension increases northwards to the centre of the basin during rift phase I (pink bars) and rift phase II (cyan bars). Further north the extension estimates from rift phase I and rift phase II decrease slightly. However, there is a lack of data from rift phase I in the north of the basin where the Top Basement Unconformity becomes deeper than the depth extent of the seismic.

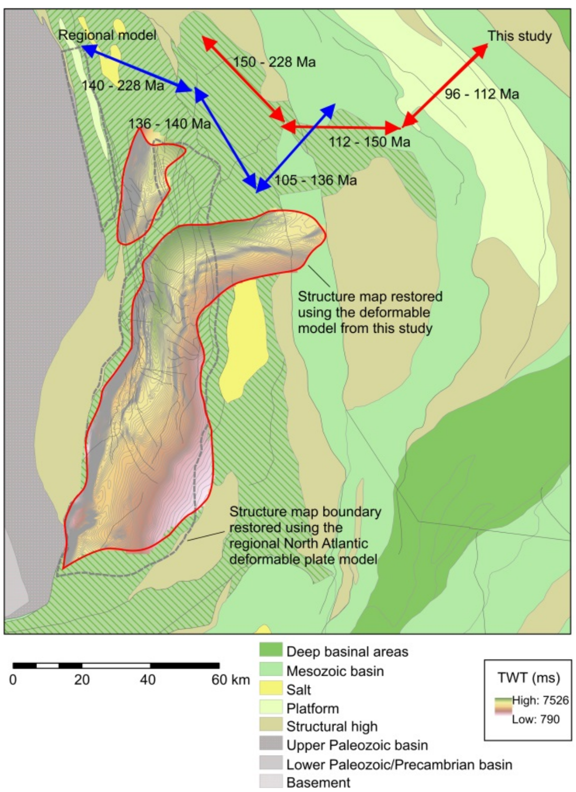

Figure 4: Top Basement Unconformity time structure map restored to before rift phase I using double extension values from this study, overlain on GeoArctic's regional tectonic elements map restored to before rift phase I using the North Atlantic deformable plate model. GeoArctic data and models are derived from a project funded jointly by ISPSG and Nalcor Energy.

On the northeast-southwest lines extension is predominantly from rift phase III (dark green bars) and is greater on the lines that cross the Murre and Mercury faults. There is insignificant extension after the Early Cretaceous as indicated by the scarcity of light green and orange bars.

Integration of the restored time structure maps with the regional North Atlantic deformable plate reconstruction

Beta grids derived from the extension estimates were used to restore the time structure maps to their position before each rift phase using GeoArctic's deformable plate modelling software. The restored maps were integrated with the regional North Atlantic deformable plate reconstruction (Fig. 4). The reduction in area of the Top Basement Unconformity map between present day and before rift phase I (228 Ma) is 46% from this study, using fault heaves to estimate extension, compared to a 40% reduction from the regional North Atlantic deformable plate model, using change in crustal thickness to estimate extension.

Conclusion

The total amount of extension measured using fault heaves in this study corresponds closely with the total amount of extension measured using change in crustal thickness in the regional North Atlantic deformable plate model. This indicates that extension is uniform with depth in this area.

Acknowledgements

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Data and models derived from a plate reconstruction study carried out by GeoArctic Ltd. and its subcontractors for the Petroleum Infrastructure Programme (PIP) were used. This project was jointly funded by the Irish Shelf Petroleum Studies Group (ISPSG) of PIP and Nalcor Energy (on behalf of the Offshore Geoscience Data Program with the Government of Newfoundland and Labrador).

Paleoenvironmental Changes During South Atlantic Rifting: New Well Data from the Pernambuco Basin.

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Introduction

The Pernambuco Basin is situated on the coast of the Northeast Brazil and was formed during the breakup of the Gondwana supercontinent. Similarly formed basins, such as the Santos, Campos and Sergipe-Alagoas basins, are widely known for their oil potential and are the focus of ongoing research. However, despite its similarities, the Pernambuco Basin still lacks the stratigraphic and structural framework necessary to evaluate the regions petroliferous potential. We analysis a new IATE stratigraphic well (1-LABIO-PE3) collected and being studied in collaboration with PETROBRAS. Drilling was undertaken at the little-explored northern of the Basin of Pernambuco, close to the Paraíba Basin (Lima Filho, 1998).

Methodology

Lithostratigraphic, geophysical and geochemical (TOC, S, pyrolysis and □^{13}C) analysis was undertaken over the 145 m core. Palynomorphs were used for age control.

Regional Geology

Sediment overburden across the Pernambuco Basin is highly heterogeneous. In 1969 a 400 m well to the north found basements rocks, whereas a 1980 well to the South failed to reach basements, even at 2980 m. The reason for this difference in sediment thickness is the subject of some debate but likely owes to the dramatically different tectonic regime to the North of the Pernambuco Shear Zone (PSZ; Figure 1).

The Pernambuco Basin is tectonically and stratigraphically different from its neighbor, the Paraíba Basin. The Paraíba Basin, between the PSZ and the Touros High, is comprised of a narrow coastal strip and sharp continental break. By contrast, of the Pernambuco Basin is stretched-out with a series of gravity faults that cause a complex internal partitioning of the basin with a graben-associated thick sedimentary cover, typical of rifted basins (Lima Filho et al., 2005). Stratigraphically the Paraíba Basin has a stratigraphic column made of Coniacian-Santonian siliciclastics, followed by Campanian sandstones and shales. The installation of a Maastrichtian carbonate platform occurs after, with carbonates linked to a regressive Paleocene-Eocene regime after (Barbosa et al. 2004). Marine sedimentation basin thus commenced in the Santonian-Campanian. Meanwhile, in the Pernambuco Basin deposition starts with the Aptian-Albian alluvial sediments (Cabo Formation) and is followed by the Cenomanian-Turonian carbonates of the Estiva Formation. Both formations are cut by the intrusive rocks of the Ipojuca Suite. A sedimentary cap is provided by the Algodoais Formation, represented by Santonian-Paleocene alluvial fan deposits (Lima Filho, 2005; Lima Filho, 1998).

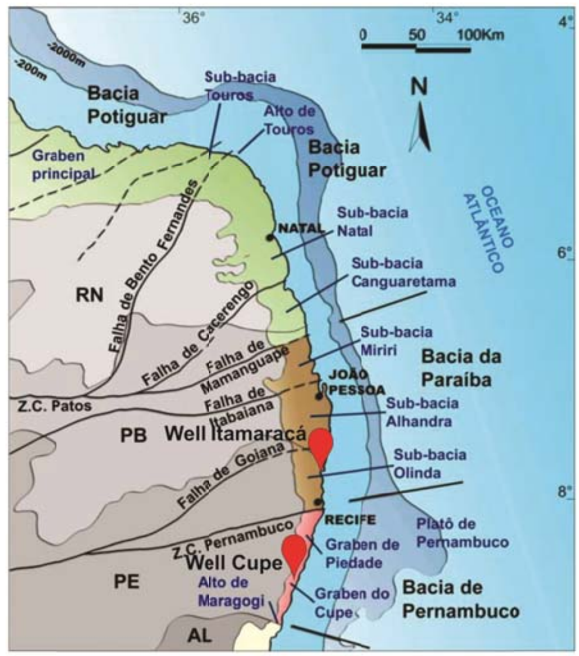

Figure 1: Location of the Pernambuco and Paraíba basins and sub-basins, with Petrobras well locations (Lima Filho & Barbosa, 2006).

Well Data

The IATE well is dominated by sandstones and siltstones capped by a reddish green shale, considered to be the Cabo Formation. The clear quartz sandstones make up more than 50 meters thick in the studied well, constituting the Suape Formaton. Above this are grey sandstones intercalated with calcareous facies. With this package are black shales, considered to the base of the Estiva Formation. Dolomnitic sandstones follow, attributed to the Gramame Formation, the only known occurrence in Paraíba Basin.

Pollen analysis was performed on two core samples derived from black shales occurring at ca. 77 meters depth. The results were compared with pyrolysis data in order to ascertain the dominant organic matter source. Value indicate.

Opaque phytoclasts and palynomorphs (pollen, spores and palinoforaminifera), indicative of predominantly continental source area. The palinoflora binding recovered consists principally of species typical of the Albian-

Cenomanian. However the joint presence of the species *Gnetaceaepollenites undulatus* and *papilioniformis Psilatricolporites* allowed us to restrict the section on biozone P. *papilioniformis*, Lower Cenomanian. Traces of marine microplankton (palinoforaminiferas) were also found, indicating a marine influence in the level. It is also worth noting the absence of gender *Classopollis*, normally abundant in Lower to medium Cretaceous sections.

Geochemistry

A clear correlation is seen between the three traces in Figure 2 with three distinctive peaks at the shallower depths corresponding to three events (marked as events 1, 2, 3 and 4). These peaks probably correspond to periods of enhanced organic carbon burial with the largest amount occurring during event 3 which sees 1.15% TOC. Assuming the majority of sulfur (S) is bound in pyrite, the similarity between the C and S curves OM accumulation was closely tied to early diagenetic changes in the sediment.

TOC values of 0.5% are considered very low potential for hydrocarbon generation, representing a siliciclastic input. Values between 0.5 and 1% are the minimum to be considered a potential source rock. The very light $\delta^{13}C$ values suggest a terrestrial source for the organic matter. In general the curve follows that of TOC and S suggesting is can be used an approximate paleoproductivity indicator.

Pyrolysis data (Figure 3) yielded zero values for S1 (no liquid hydrocarbons – curve not shown) and a single very low value for S2. The vast majority of organic matter was found within S3, supporting a predominately terrestrial source of OM.

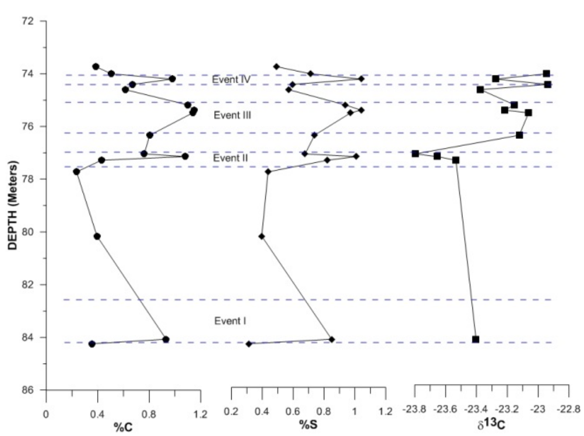

Figure 2: %C (TOC), sulfur (S) and $\delta^{13}C$ traces in the core. Dashed lines delineate events discussed in the text.

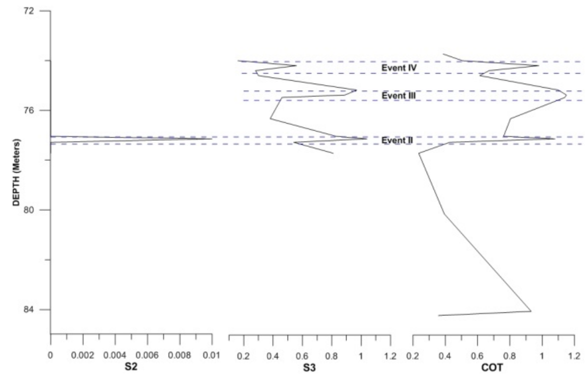

Figure 3: S2, S3 and TOC across studied core.

Stratigraphic implications

Three major unconformities were identified in the lithologies (Figure 4) each of which is associated with regressive tracts and/or lowstands. Unconformity 1 is not obvious in the core, however as the Cabo-Suape formation transition is better documented in other cores which do possess an unconformity, we infer one likely exists here too Lima Filho (1998) and Maia (2011). Unconformity 2 coincides with the sudden appearance of conglomerates with pebbles up to 5cm in diameter. The 3rd unconformity being associated with a regressive carbonate sequence of a few meters. Two, possibly 4th order, regressive cycles appear towards to the top, with unconformity 2 separating them. Smaller fluctuations were identified in gamma logs and may relate 5th order sea-level changes.

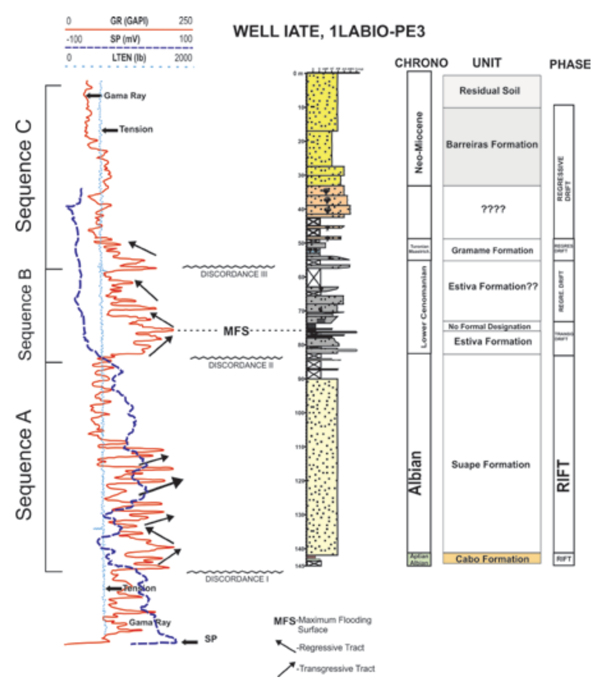

Figure 4: Correlation between lithologic and geophysical profiles with interpretations of major stratigraphic surfaces.

The occurrence of black shales, which see the highest TOC and S values, corresponds to a Maximum Flooding (or transgressive) Surface (MFS) (Holz, 2012), despite pyrolysis, stable isotopes and palynological data suggesting a continuously strong terrestrial signature. We assign a Lower Cenomanian age to the MFS.

As previously mentioned, the studied core was derived from the northern onshore portion of the Pernambuco Basin, which was shallower and thus contains a complete albeit condensed sedimentary succession through the tapering of sedimentary layers towards the basin edges. Based on this observation we combining stratigraphic surfaces and gama logs, to derive a pattern of ordered stacking that are in alignment with previous models such as Holz (2012; Figure 5).

Conclusions

The data acquired from the IATE stratigraphic well provide new lithostratigraphic, geochemical and stratigraphic information regarding the onshore portion of Pernambuco Basin. The lithological analysis of the associated Gamma Ray profile well, allowed for the identification of carbonate and siliciclastic rocks, which belong to both the Pernambuco Basin and Paraíba Basin. This shows that after the final rifting the late Turonian (Lima Filho, 1998), transgressive sedimentation belonging to the Paraíba Basin, were deposited in Pernambuco Basin.

Geochemical analysis, despite yielding a low shale oil potential, are important in their stratigraphic and paleoenvironmental implications, with the identification of fourth and fifth order transgressive / regressive cycles. We also identified the MFS that marked the initiation of the drowning of the Pernambuco Basin.

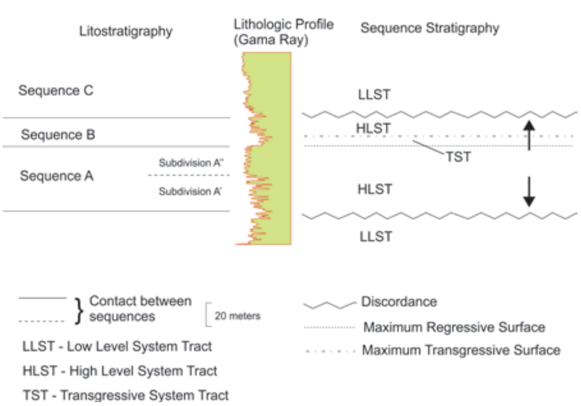

Figure 5: Interpretation of the Gamma Ray profile based on sequence stratigraphy and lithostratigraphy. Where TSNB = tract of low-level system; TST = transgressive system tract and TSNA = Tract high-level system. Modified from Holz (2012).

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POSTER ABSTRACTS

First Onshore Record of Volcanism in the Northern Portion of Sergipe-Alagoas Basin in Brazil: Conjugate Margin Implication

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Introduction

The Sergipe-Alagoas Basin is an oil and gas producing basin of Brazil. It is located on the continental margin of northeast Brazil, and its deposition is related to the opening of South Atlantic during Cretaceous. Before the opening, this basin was probably connected with Rio Muni Basin, where today the Ceiba field is located, making Equatorial Guinea one of the major oil exporting African countries (Figure 1).

Structurally, the Sergipe-Alagoas Basin is formed by an asymmetric rift, elongated in an NNE/SSW direction, and is delimited to the north with the Pernambuco Basin by the Maragogi-Barreiros High, and to the south with the Jacuípe Basin by the Vasa-Barris fault system.

Stratigraphically, the basin presents remnants of Paleozoic sediments, overlain by a well-developed package formed during the pre-rift stage in the Jurassic to Early Cretaceous, and Meso-Cenozoic syn- and post-rift sequences. Magmatic events are inferred by seismic lines shot in the offshore portion of the Alagoas-Sergipe Basin. In this paper new data about the occurrence of an explosive volcanism in the onshore northern portion of the Sergipe-Alagoas Basin are presented.

Studying this magmatic event helps us to understand how it would have affected the rocks of Pernambuco and Sergipe-Alagoas basins, as well as those located in the sedimentary basins from the West African coast, and consequently how it affected petroleum generation and its thermal maturation.

1.1. Stratigraphy of Sergipe-Alagoas Basin

This basin presents the most complete stratigraphic sequence, with four mega sequences (pre-rift, sin-rift, transitional and post-rift), each one representing a distinct phase of tectonic development (Campos Neto *et al.*, 2007).

The pre-rift megasequence (Paleozoic and Mesozoic), includes Cambrian rocks (Estância Formation), glacial deposits from Carboniferous (Batinga Formation), deposits of coastal sabkha from Permian (Aracaré Formation), and fluvial-lacustrine sediments from Neo-Jurássico/Eo-Cretáceo (Candeeiros, Bananeiras and Barra de Itiúba formations).

The sin-rift phase is characterized by siliciclastic deposits (Rio Pitanga, Penedo and Barra de Itiúba formations) from Neocomian-Barremian.

The transitional mega sequence is locally affected by a fault system, and its deposition occurred from Barremian to Aptian (Poção, CoqueiroSeco and Maceió formations). During the Aptian, the first marine incursions occurred, causing the deposition of two evaporitic sequences within the Muribeca Formation (Paripueira and Ibura members).

During Albian, a carbonate platform was installed, characterizing the post-rift mega sequence (Riachuelo Formation). After a predominantly transgressive period, an intense regression in the Campanian began, which continued until recent times (Calumbi, Mosqueira and Marituba formations, from low to high energy facies). Continental sediments of the Barreiras Formation overlay all the mega sequences cited above.

The oil's source rocks are principally lacustrine shales from Barra de Itiúba and Coqueiro Seco formations, as well as black shales, marlstones and calcilutites from Maceió Formation.

Oil migration occurred by listric and normal faults, and also along uncomformities. Its reservoirs can be found in the sandstones from Serraria, Barra de Itiúba, Coqueiro Seco and Maceíó formations, as well as in cretaceous deep-water turbidite systems (Calumbi Formation).

1.2. Volcanism correlating South America and West Africa

The main magmatic phase that occurred in West Africa, which can be correlated with the northeastern portion of South America, is the Benue Trench, in Nigeria. This structure is part of a 50-150 km wide NE-SW trending sedimentary basin, extending for 1000 km from Niger Delta to Lake Chad.

Volcanic activity in Benue was particularly important during the Cretaceous - Lower Paleogene (Anudu *et al.*, 2014) and follows several stages. The first phase is related to extensional tectonics that affected the main trench. The volcanic activity was interrupted in the northeastern part of the Trench (upper Benue) around 106 Ma, but continued into the Eocene (47 Ma).

The magmatism of the upper Benue is predominantly basaltic, although rhyolites occur locally. These basalts present tholeitic to transitional alkali composition. Magmatic actvity is located on the edge of the basement horst, associated with a trend towards the ENE-WSW, NW-SE, NS and EW faults. In contrast the lower Benue is characterized by a diverse range of igneous rocks (basalts, dolerites, lamprophyres, trachytes, syenites, phonolites) and in the form of lava flows, pyroclastic rocks, dikes, sills, domes and necks. Intrusive forms are predominant in the upper Benue.

In addition, according to recent data, the Cameroon Volcanic Line had a phase much more closely related to the volcanism of the Benue Trench, and could also be related to the opening of the Atlantic Ocean. The conjunction of $^{40}Ar/^{39}Ar$ ages, major, trace and rare earth elements geochemistry data demonstrate a magmatic phase that is significantly older and different from that of the Maastrichtian (~70 Ma), and younger than the

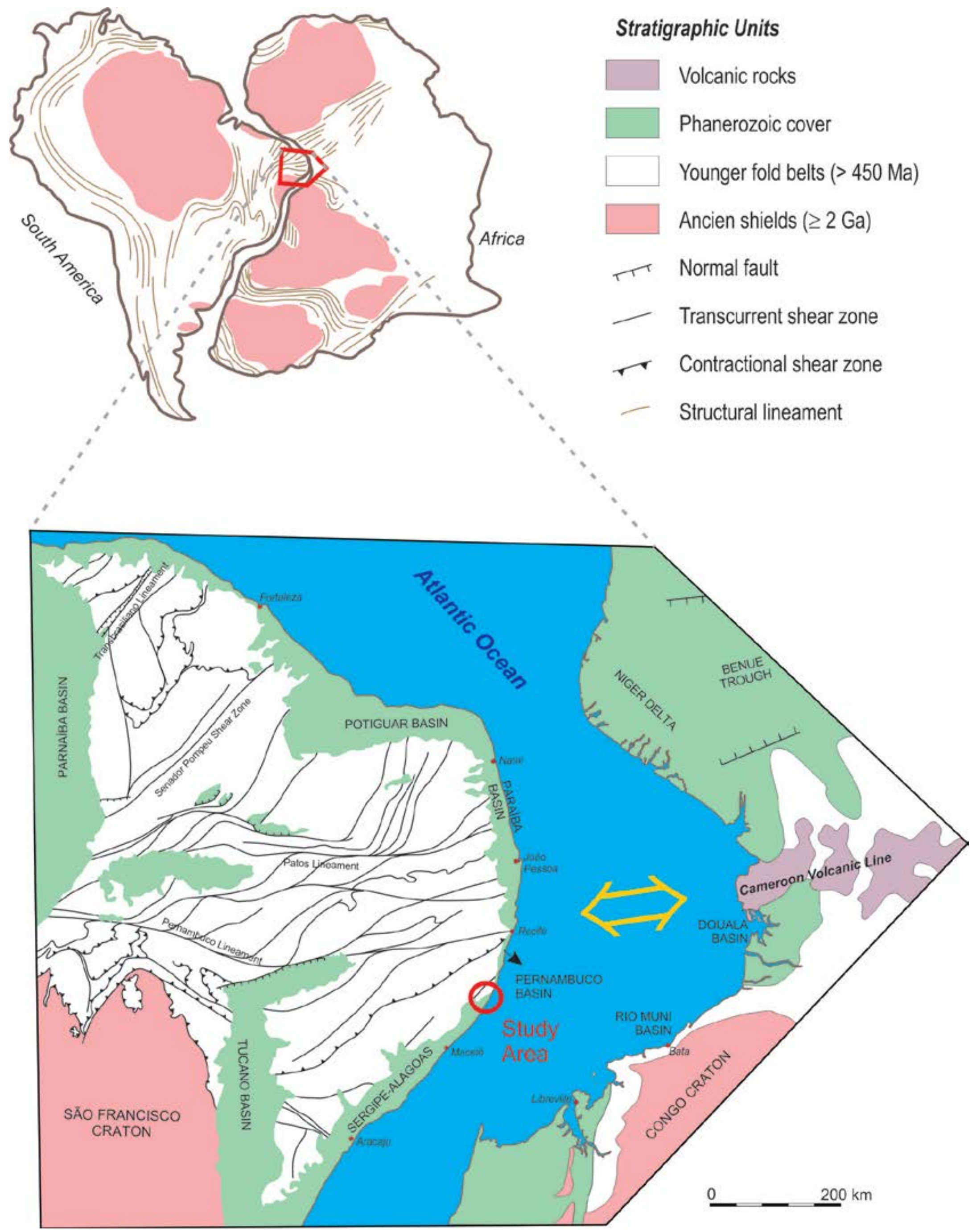

Figure 1. Geological map of the northeastern portion of Brazil and its connection with Africa. The red circle locates the study area

dominantly granitic neoproterozoic to early paleozoic magmatism in the region (Tchouankoue *et al.*, 2014).

Methodology

In a preliminary stage a circular structure was detected in the northern portion of Alagoas-Sergipe Basin by means of photointerpretation of aerial photographs (Gantois, 2008). This was interpreted to be the trace of a volcanic crater. After, during fieldwork, pyroclastic rocks were observed in the study area, and samples were collected for petrographic analysis.

Results

The samples collected during fieldwork were classified as ashes, breccias, as well as ignimbrites, i.e., rocks that were generated by pyroclastic fluxes. Some samples present a kind of banding structure, and could indicate deposition via suspension or traction, while others present a chaotic structure. The presence of fiammes shows that the volcanic material was extremely hot during deposition, and vesicles and rock fragments attest a gas-rich explosive magma (Figura 2).

Figure 2. Welded ignimbrite with banding structure and fiammes.

The study by thin sections shows that the ignimbrites are composed of sanidine, biotite, microcline, and quartz - a rhyolitic composition (Figure 3).

Conclusions

This is the first record of volcanoclastic rocks in the onshore portion of Sergipe-Alagoas Basin, and their presence shows that the sediments in the northern portion of the basin have a greater affinity with the rift section of the Pernambuco Basin, which experienced intense bimodal-like volcanism, around 102 Ma (Ipojuca Magmatic Suite) – Nascimento *et al*. (2003).

Volcanism of the same age also occurred in the African basins, principally in the Benue Trough, a major geological formation originating from the rifting of the Central West African basement, and possibly the Cameroon Volcanic Line. Thus, it is suggested that the northern part of the Sergipe-Alagoas Basin and Pernambuco Basin had been affected by the same volcanic event that occurred in West Africa.

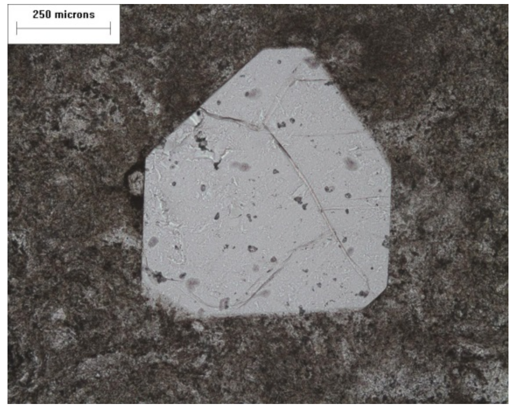

Figure 3. Thin section of welded ignimbrite showing a quartz crystal in a fine-grained matrix

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Formation of the West Greenland Volcanic Margin: Exploring alternatives to the plume hypothesis

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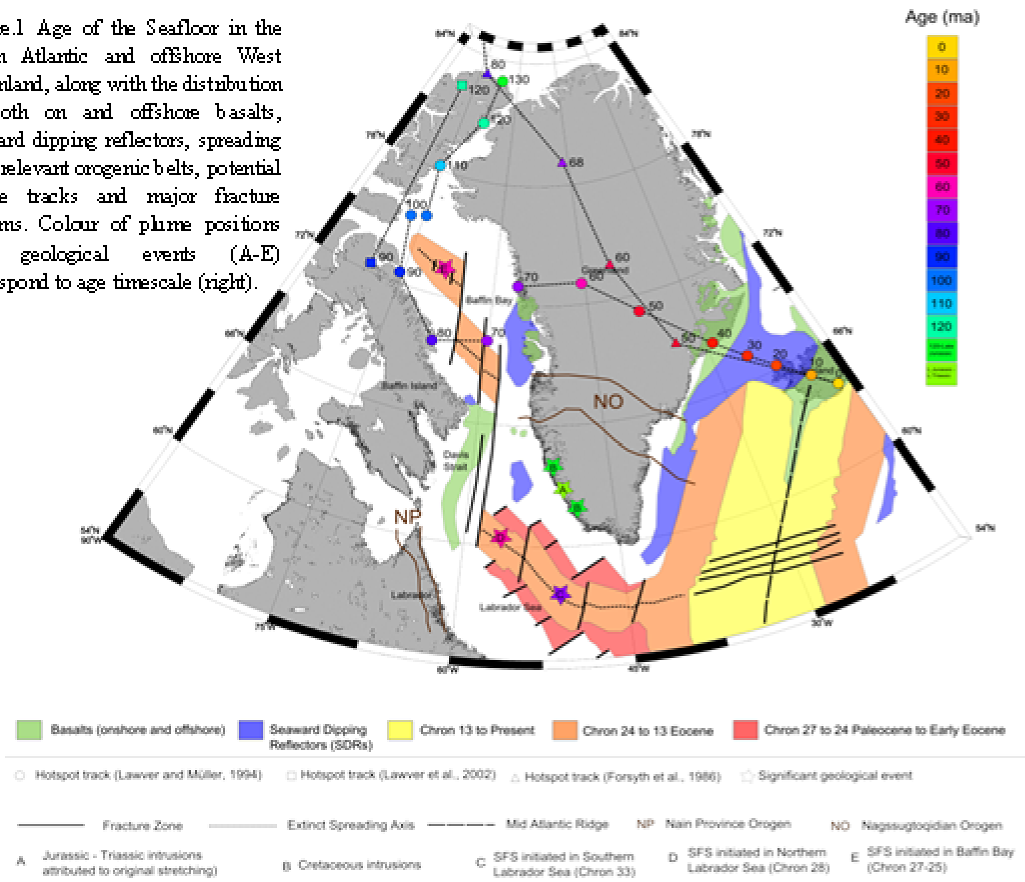
Figure.1 Age of the Seafloor in the North Atlantic and offshore West Greenland, along with the distribution of both on and offshore basalts, seaward dipping reflectors, spreading axis, relevant orogenic belts, potential plume tracks and major fracture systems. Colour of plume positions and geological events (A-E) correspond to age timescale (right).



Introduction

The abundance of igneous rocks on the West Greenland volcanic passive margin (VPM – Figure 1) has generally been attributed to a mantle plume elevating mantle temperatures resulting in the excess volcanism. Similar hypotheses have been proposed for many other VPMs worldwide.

The mantle plume hypothesis in West Greenland

Observations on the West Greenland margin that have been attributed to the passage of a hypothesised mantle plume beneath the region at 120 - 60Ma (Figure 1) include; 1) the onset of seafloor spreading in the Labrador Sea, 2) major volcanism in West Greenland and Baffin Island, 3) underplating of the Davis Strait by a high-velocity body, 4) uplift of onshore sedimentary successions, 5) seismically observable volcanics for 400km east of Baffin Island 6) high $^{3}He/^{4}He$ and low $^{187}Os/^{188}Os$ ratios in Picrites.

The presence and role of mantle plumes during the formation of VPMs nevertheless remains equivocal. On the West Greenland and North-Eastern Canadian margins, it is at odds with several large-scale features. These include; 1) timing of seafloor spreading in Baffin Bay, 2) the progressive, fan-shaped opening of the Labrador Sea from south to north, 3) the age of onshore margin-parallel dyke swarms and 4) the nature of the crust in the Davis Strait.

1. The timing of seafloor spreading in Baffin Bay is contrary to what would be predicted by the plume hypothesis. The hotspot track reconstruction of Lawver and Müller (1994) places the proto-Icelandic plume in the Baffin Bay area at ca. 120 – 70 Ma, whereas seafloor spreading did not initiate until much later at Chron 27-25 (52 – 62 Ma). This is despite the fact that it lay in close proximity to the alleged plume track for a prolonged period of time at a much earlier time. It has been recognised that there should be a delay to account for the time it would take a cold lithosphere to heat up,

on the arrival of a plume, with spreading proposed to postdate plume arrival by 10 – 40 Myrs (Hill, 1993). However, using even the uppermost limit proposed by Hill (1993), the delay in Baffin Bay is too great with a timespan of approximately 60 Myrs between first plume arrival (in Northern Baffin Bay) and seafloor spreading initiation is too great.
2. Tectonic reconstructions of the movements of Greenland relative to Canada suggest an 'unzipping' motion with progressive opening from south to north. Although there is some debate regarding the precise onset date of seafloor spreading it is accepted that it started in the southern Labrador Sea before the north. This does not fit a model whereby a plume producing voluminous magmatism initiated seafloor spreading (Gerlings et al., 2009). If a plume were present, then rifting, and subsequent seafloor spreading would be expected to start nearest to the plume and to propagate away from it.
3. It has been suggested that the prolonged location of a plume could "pin" the position of subsequent spreading, through thermal and mechanical weakening of the lithosphere, which a subsequent stress field could exploit (Hill, 1993). Onshore coast-parallel dykes have however been geochemically dated as early as the Jurassic (Figure 1). This implies that the weakness exploited by subsequent continental breakup was already in place before the proposed plume was in the vicinity.
4. In the more volcanic Davis Strait seafloor spreading was never fully initiated as it did in the Labrador Sea and Baffin Bay. Instead a 'leaky transform' system developed (Funck et al., 2007). It is not clear why a mantle plume should cause seafloor spreading in the distant Labrador Sea but not at the Davis Strait which is much closer to the alleged plume.

Reliability of 'Hotspot Tracks'

This work has primarily considers the hotspot track of Lawver and Müller (1994) (Figure 1). It is of course possible that this hotspot track is erroneous and the plume hypothesis could still provide an explanation for the formation of the West Greenland margin. This hotspot track is however based on relatively well-constrained plate tectonic reconstructions, and even significant unreliability would still be insufficient to account for the observations made on the West Greenland margin.

It should also be pointed out that the hotspot tracks considered herein are not based on observations; they were produced from absolute plate motion reconstructions. Some subsequent work has however misused them, assuming they were based on an observable hotspot track. This has led to the problems discussed herein.

Alternatives to the Mantle Plume Hypothesis

If continental breakup between Canada and Greenland occured in response to the arrival of a mantle plume, now located under Iceland, it would be expected that the earliest and most extensive seafloor spreading would have occurred closest to the plume. In fact the opposite is observed. Since the *observations* do not match the model predictions, the plume hypothesis as applied here is unlikely to be correct in its current form. Non-plume mechanisms should thus be considered to be the causal factor in the formation of the West Greenland margin. We cannot however entirely rule out that although not the causal factor behind initial rifting and seafloor spreading initiation a mantle plume may have contributed to the later volcanic evolution of the area.

Several mechanisms have been previously proposed to explain the formation of VPMs including; 1) a direct effect of rifting and 2) small scale convection. These margin formation mechanisms (along with the plume hypothesis) produce different predictions for the sedimentary and tectonic evolution of the margin which should be detectable through appropriate seismic interpretation, and subsequent reconstructions. This should allow us to contribute to understanding the likely causal mechanism(s) reasonable for the formation of this VPM.

Methodology

Access to industry well and seismic data has enabled us to elucidate the tectono-stratigraphic evolution of the various segments of this margin, in particular at the syn-rift to post-rift transition. Integration of the well and seismic reflection data has allowed us to produce isochron thickness maps of defined sediment ages, enabling us to reconstruct the syn-to-post-rift evolution of the West Greenland margin in detail and to critically test the predictions of contrasting models of margin development. Our results demonstrate that the widely-cited plume model cannot explain key observations on the West Greenland margin. A mantle plume may have contributed to the later development of the margin but is unlikely to have influenced the early stages of margin development as proposed by some previous workers.

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The International Appalachian Trail: the ancient Appalachians as ambassador of the geosciences to modern societies

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Throughout human history, the geological foundation of our landscape has determined the location of settlements, trade routes, and human migratory paths, inextricably linking our culture to geology. The International Appalachian Trail (IAT) addresses our common geoheritage across the North Atlantic conjugate margins by establishing a long-distance walking trail that extends *beyond borders* to all geographic regions once connected by the "Appalachian Mountain" range, formed more than 300 million years ago on the super-continent Pangaea. In addition to connecting people and places, the goal of the IAT is to promote natural and cultural heritage, health and fitness, environmental stewardship, fellowship and understanding, and cross-border cooperation.

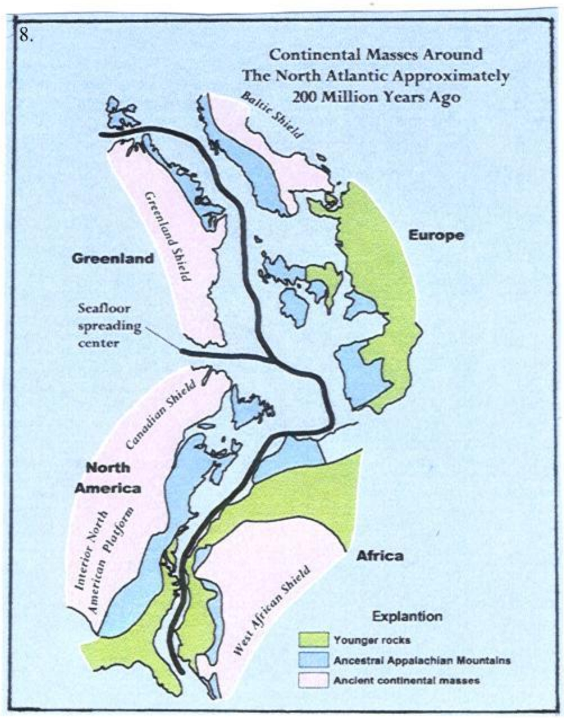

Figure 1:. Distribution of Appalachian terranes (blue) at approximately 200 Ma (modified from van Staal and others, 2009).

The IAT was founded on "Earth Day" in Maine, USA, in 1994 and currently includes 21 chapters representing an estimated 12,000 miles of trail along the ancient Appalachian terranes rimming the North Atlantic. Built on the concept of the iconic Appalachian Trail in the eastern United States, the IAT is a "connector" trail to the AT and begins at the northern terminus of the AT on Maine's Mount Katahdin. The first phase, completed in 2000, connected the highest points in the provinces of New Brunswick and Quebec, eventually extending to the northern terminus of the Gaspé Peninsula at Cap Gaspé. In the second phase completed in 2009, the trail was extended to Canada's remaining Atlantic provinces. Newfoundland was an early participant and continues to provide leadership on development and outreach. The development of IAT chapters in European nations and northern Africa began in 2010 and continues today.

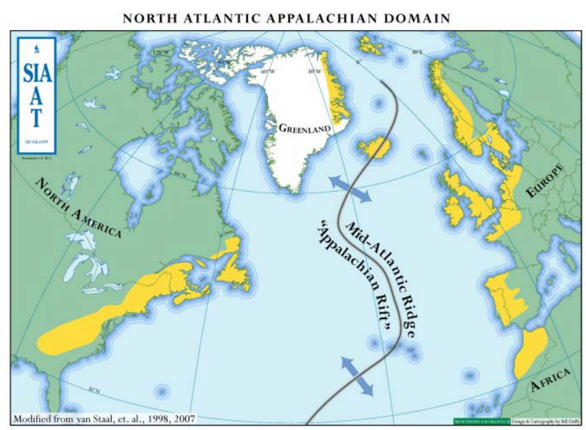

Figure 2: The distribution of Appalachian terranes today.

The IAT is a natural fit with the Geopark model, such as that in an early conceptual stage for the Bay of Islands ophiolite area of Newfoundland, the Cabox Geopark. In Europe, the IAT extends through Geoparks in Scotland, England, Wales, Spain, and Portugal. Both the IAT and Geopark concepts promote rural economic development based on natural resources.

A work in progress, the development of the IAT continues as individual Chapters: (1) construct a long-distance walking trail; (2) locate the IAT within areas that have been identified by geologists as having been part of the ancient Appalachian/Caledonian landscape; (3) locate the IAT so that it connects to bordering Chapters; (4) make available to the public map and trail descriptions of the IAT within its jurisdiction via the IAT web site; and (5) produce educational web site trail guides. The IAT provides an excellent opportunity for earth scientists to participate in this unique recreational/educational project and to engage the public in a discussion of the geological foundations of modern society.

http://www.iat-sia.org/index.php

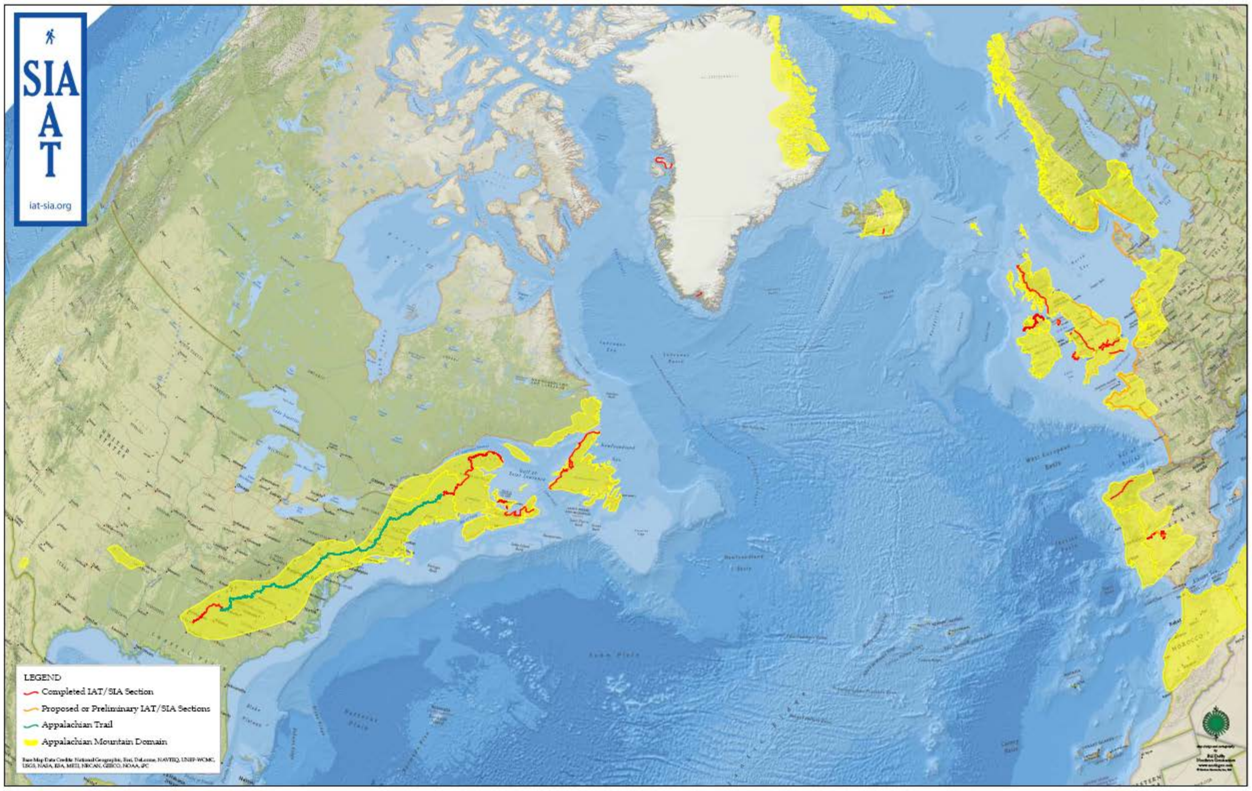

Figure 3: Current status of IAT development in Appalachian terranes. Map by Bill Duffy, Northern Geomantics. Trail key: Green – Appalachian Trail; Red – completed IAT; Orange – proposed or preliminary IAT.

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Paleobathymetry from 3-D flexural backstripping: A case-study from the Sierra Leone-Liberia basin

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Introduction

The ability to restore 3-D surfaces to their paleobathymetric position provides exploration geologists a fundamental tool for understanding the evolution of basin geometry through time. These surfaces provide information on depositional environments, paleo-geometries and paleo-slopes; all of which impact reservoir quality, source rock deposition and preservation, stratigraphic trap geometries and seal presence, and hydrocarbon migration pathways.

Methodology

We utilize the 3-D backstripping application of Lovely et al., 2014 that incorporates flexure to restore several key regional surfaces across the Sierra Leone-Liberia offshore basin. These surfaces are correlated with the onshore and offshore geology to develop an integrated 3-D structural and tectonic evolution of the basin geometry based on both rift-related and passive margin subsidence.

We have developed a 3-D backstripping application that incorporates flexural isostasy, and is implemented in a workflow modeled after Roberts, et al. (2003). The application restores the isostatic components of basin geometry and bathymetry, and may account for the effects of sediment loading (isostasy & compaction), rift related subsidence (post- and syn-rift effects of homogeneous or depth-dependent pure-shear stretching models), as well as effects of dynamic topography. Implemented as a plug-in to Gocad, the application is accessible to a broad audience of geoscientists.

We review the numerical implementation of flexural backstripping, and discuss implications, as well as limitations, of paleobathymetric maps for source rock preservation and reservoir presence in the offshore of the Sierra Leone-Liberia basin.

Application

The restoration of key surfaces across the basin including basement, the break-up unconformity and markers in the passive margin sequence provides insight on the tectonic evolution of the basin and the sedimentary systems which fill the basin through time. We discuss the implications and importance of the major controlling factors of the basins evolution, including the transform margins that bound the basin and the structural style of the rift system that impacts the basins geometry. This discussion is further extended to the hydrocarbon system where the restored paleobathymetry at key time intervals is used to interpret depositional environments, reservoir quality, trap geometries, and source rock deposition and preservation.

By implementing new 3-D software and workflows across the Sierra Leone-Liberia basin which includes flexural isostacy – it is possible to develop sequential paleobathymetric restorations that provide insights on the hydrocarbon system and basin evolution of both the rift and passive margin phases of basin development for the Equatorial Atlantic margin of West Africa.

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Integrated chemostratigraphic and biostratigraphic evaluation of the Early Cretaceous and Jurassic strata within the Porcupine Basin

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The Porcupine Basin, located offshore Western Ireland has a proven hydrocarbon system, despite this, however, well penetrations are relatively scarce, particularly in the south of the basin. A firm understanding in the correlation of sediments across the area is vital for successful exploration and, whilst seismic acquisition is generally good, the ground-truthing of this data from penetrated sections is critical. To go some way in addressing this, a combined chemostratigraphic and biostratigraphic evaluation has been proposed. The aim will be to establish a detailed, integrated correlation scheme for key well penetrations across the basin.

Chemostratigraphy involves the characterisation and correlation of sedimentary rock successions based on stratigraphic variations in their inorganic geochemical data. Using this technique, variations in mineralogy, including clay minerals, heavy minerals and lithic components can be identified, which in turn can provide information of changes in palaeoclimate, palaeoenvironment, sediment provenance and any diageneis or weathering that may have occurred. The biostratigraphic data will provide a vital chronostratigraphic framework on which the chemostratigraphy can then be tied.

The integrated chemostratigraphic and biostratigraphic datasets will also yield vital information on sequence stratigraphy and lateral variations linked to depositional environment; such information being critical to the regional sedimentological interpretation.

This study follows on from previous work carried out on the conjugate Grand Banks area (Eastern Canada) and it is hoped the results will be integrated into the overall understanding of this margin.

Understanding Hydrocarbon Generation in the Irish Atlantic Margin

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To maximise our knowledge of subsurface petroleum systems it is imperative that we have a thorough understanding of the two key components: the hydrocarbon-generating source rock and the associated hydrocarbons. However, uncertainties regarding the timing of oil generation and the source of the generated oil are common exploration problems. Understanding the chemical composition of petroleum source rocks and their associated oils provides critical information regarding the temporal and spatial controls on the formation of hydrocarbon deposits. Further, direct radiometric dating of hydrocarbons yields the timing of oil generation and so provides a robust temporal constraint on the timing of oil formation and migration within the petroleum system. Determining the age of the generated oil also has the potential to enable identification of the source rock, thus providing significant potential for oil-to-source correlation studies. In addition, identification of chemical similarities that are internally consistent between a source rock and its generated oil, also allow for oil-to-source correlation. Determining how and when oil moves from its source rock to the reservoir has the potential to provide insight into oil migration pathways, basin, reservoir and trap structure, and also the ability to highlight possible new oils. As such, oil-to-source fingerprinting is an exceptionally valuable tool in petroleum exploration.

Herein, we utilise the rhenium-osmium (Re-Os) geochronometer to achieve our key goals. Rhenium-osmium geochronology exploits the β decay of ^{187}Re to ^{187}Os (with a half-life of ~42.5 billion years). The decay of ^{187}Re to ^{187}Os provides a useful chronometer and tracer tool, as both elements are highly enriched in organic-rich sedimentary units (due to their organophilic nature), relative to upper continental crust. Further, such organic-rich sediments include shales and black shales, which are the crustal source rocks of many crude oils. This enrichment likely occurs through the sequestration of Re and Os from the water column during sedimentation and under oxygen-limited conditions (where the Re and Os become insoluble in the water column). Once enriched in hydrogenous Re and Os, the organic-rich sediment will record the Os isotope composition (^{187}Os/^{188}Os) of the water-column at the time of deposition. This can be utilised as an invaluable tracer tool. Additionally, assuming that the ^{187}Os/^{188}Os composition at the time of deposition is constant and the sample Re-Os systematics are undisturbed; the ^{187}Re/^{188}Os and ^{187}Os/^{188}Os ratios of a given section of an organic-rich sedimentary rock will positively correlate. The slope of this correlation together with the decay constant of ^{187}Re will yield the age of deposition of the sedimentary unit.

The Re-Os geochronometer can also be used to directly date hydrocarbon deposits, thus constraining the timing of oil generation. This is due to the transferral of Re and Os from the source rock to the generated oil at the time of source rock maturation. Both Re and Os are enriched in the asphaltene fraction relative to the whole oil and, importantly, both the Re and Os isotopic compositions of an asphaltene are similar to those of the oil it is separated from. Therefore it is possible to analyse the asphaltene fraction of the oil (with its enriched Re and Os concentrations) and be confident that the Re-Os isotopic compositions reflect that of whole oil. To date all published work points towards the ages produced from Re-Os analysis of asphaltene to record the timing of hydrocarbon generation and migration.

Oil to source rock correlation relies on utilising and identifying genetic parameters that are internally consistent between an oil and its source rock. For such parameters to be useful they should be relatively insensitive to the effects of biodegradation and differences in thermal maturity levels. Previous investigations have shown that the osmium isotopic composition of an oil is inherited from its source rock, thus making it an ideal candidate for oil-source correlation work. In addition, previous work has also demonstrated that thermal maturation and biodegradation do not observably disturb source rock Re-Os systematics. Oil-source correlation studies are conducted by calculation and comparison of calculated Os isotopic compositions of a suite of oils, together with their potential source units. This technique also benefits from being able to utilise drill chippings from potential source units rather than relying on core.

By applying the above we will produce a new model for oil generation across the IAM which will both constrain the timing of oil generation as well as identify the dominant source units within the petroleum system.

Influence of the basement architecture and rheology on the rifting process: example from the conjugate margins of the South Atlantic.

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Structural interpretation in conjunction with 2D gravity modelling is an important tool in understanding the crustal architecture and the rifting mechanism of passive margins. In this study we consider the influence of basement configuration and rheology on the rifting process in the Central South Atlantic. To this end a new structural map of the South Atlantic has been developed incorporating gravity, magnetic, SRTM and Landsat data. Fifteen 2D gravity models - seven on the African margin and eight on the South American margin- have been constructed in order to determine the crustal architecture. These 2D models (Figure 1) have been used to define the extent of stretched continental crust.

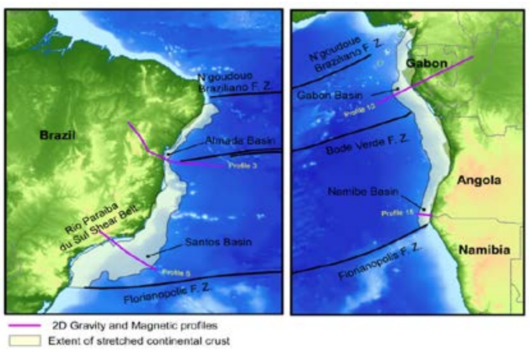

Figure 1: Location of the 2D Gravity profiles.

The stretched continental crust shows an example of wide-narrow conjugate margins where one margin has a wide area of stretched continental crust and shallow Moho slopes, whilst the other has un-stretched continental crust thinning very rapidly into the oceanic crust – with high angle Moho slopes (Figure 2).

The outcropping Precambrian basement in the wide margins shows thrusts dipping towards the ocean, suggesting that these have been reactivated during the rifting. Examples of these are seen in both the Gabonese and Brazilian margins. Correlation with seismic data shows that the high angle transpressional faults in the Rio Paraiba du Sul Shear Belt (Hebert and Hasui, 1998) translate into high angle normal faults in the Santos Basin (Figure 2) interpreted on the seismic section of Kumar et al (2012).

Comparison of outcropping basement lithologies west of the Almada Basin (mainly meta-gabbro) (Alkmim and Noce, 2006) and east of the Gabon basin (schist, quartzite and migmatites) (Kadima et al. 2011) suggests that the terranes west of the Almada Basin are stronger than those to the east of the Gabon Basin.

In the conjugate Santos and Namibe basins, the basement outcropping west of Santos is made mainly of Quartzite (Geologic map of Brazil), paragneiss and schists, whereas the basement east of the Namibe basin is formed of gneiss and migmatites (Geologic map of Angola) that form comparatively stronger material.

Given these observations, a conceptual rifting process is proposed (Figure 3) where crustal thinning migrates from the centre towards the margins of the proto-oceanic basins; as the central part is thinned, it gets stronger due to stress hardening and the extension propagates across the unstretched continental crust of the two conjugate margins where it is accommodated by pre-existing weakness zones. Once the deformation reaches a strong (e.g. cratonic) unit and there are no more weakness zones to absorb the strain, the stretching can propagate no further and rupture will occur at the junction between the weaker and stronger material. At this point, continental stretching ceases and oceanic opening commences, leaving one wide and one narrow margin. This model is inspired by the physical experiments of Karman and Duwez (1950) on iron annealed wire subject to stretching at different speeds (their figure 13). They observed that, at low impact velocities, plastic deformation occurs first in the middle then propagates to the sides of the specimen. For medium velocities the deformation occurs all along the specimen with high rates of strain on the edges of the specimen, whereas for high velocities only high strain rates are observed and are located at both ends of the specimen. The fact that the maximum stretching seen in both margins is in the middle of the basin, and that hyper-extended margins have been explained by slow rifting velocities suggests that the deformation started in the middle and propagated away from the proto-oceanic basin.

The proposed model fits the example of the Almada and Gabon Basins where weaker schists on the African side deform rather than meta-gabbro on the South American side. Further south, the weak schists underlying the Santos Basin deform rather than the stronger migmatites under the Namibe Basin.

In our model, distal grabens near the centre of the basin would be expected to be deeper and contain older sediments than the proximal grabens. In an alternative model where rifting starts over a wide zone, one would expect that the proximal grabens and half grabens will be deeper and have the same age if not older than the sediments deposited in the distal parts of the basin. This difference can be tested from the stratigraphy of the synrift sequence. In three of the studied cases, Almada, Gabon and Namibe Basins, the proximal grabens and half grabens are less deep than the distal grabens, indicating that the proximal structures have been subject to less strain. In the Santos Basin, the proximal grabens and half grabens are deeper than the distal structures located over the Sao Paulo Plateau; this can be explained as the Sao Paulo Plateau would have been part of the African margin if the rift was successful along the Abimael ridge, where one can observe the same asymmetry of the Moho slope but at a smaller scale. Hence the real proximal structure in this case is where the Late Cretaceous sediments have been deposited (Figure 2).

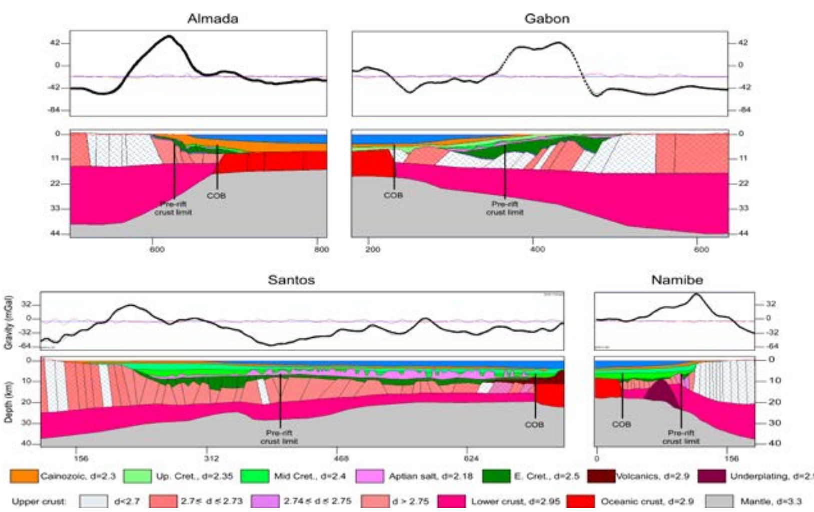

Figure 2: Pairs of conjugate 2D gravity and magnetic profile.

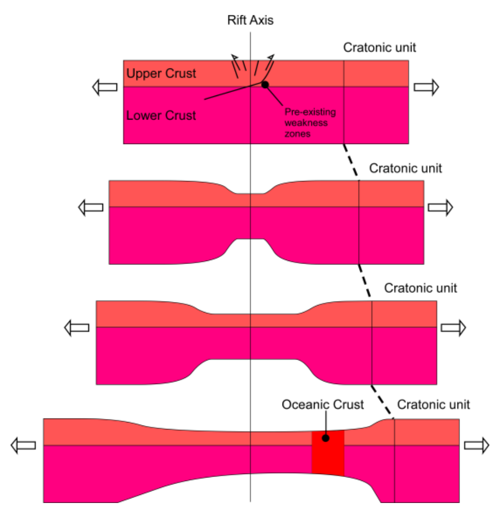

Figure 3: Model proposed for the rifting in the central South Atlantic.

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Facies of the vertebrate-bearing Scots Bay Member at Wasson Bluff, NS

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Sedimentological research on the Scots Bay Member of the McCoy Brook Formation at Wasson Bluff provides evidence of lacustrine facies that rest unconformably on the Early Jurassic North Mountain Basalt. Since the first vertebrate fossils were found at Wasson Bluff in 1976 by Paul E. Olsen, the site has been the focus of extensive paleontological research. The Scots Bay Member extends as a series of micro-basin successions for several kilometres. Although attributed to a lacustrine or playa setting, a detailed sedimentological study is needed to constrain this interpretation.

The initial 10 m of strata above the basalt were measured in a trench on the beach. The basal 1.9 m corresponds to the Scots Bay Member, which fills the uneven topography on the basalt surface. The lowermost fine- to-medium-grained red-brown sandstone is overlain in turn by red mudstone, grey-green mottled siltstone, ostracode-rich biomicrite (5 cm and 12 cm beds) and further red mudstone. The member is overlain by red fluvial sandstone with dinosaur bone fragments.

In a cliff separated from the trenched area by faults are three lithofacies not observed in the trench: vertebrate-bearing purple-grey fine-grained sandstone, green sandstone, and nodular limestone (a single bed 12 cm thick). The purple-grey sandstone, draped over basalt clasts, contains abundant, densely packed semionotid fish material. The nodular limestone has a disrupted fabric with discontinuous concave-up laminae of varied colour, sediment-filled cracks, and minor continuous red-brown laminae. This lithofacies contains abundant pale nodules of sparry calcite that increase in proportion upwards and layers with matrix-supported ostracodes. Disrupted fabrics are present also in the grey-green mottled siltstone, red mudstone, and ostracode-rich biomicrite in the trenched section. Minor fish material is present in the mottled siltstone, red mudstone, and nodular limestone facies.

The sedimentology, sequence stratigraphy, and taphonomy of the Scots Bay Member imply an extensive shallow lake that ponded on the basalt in the earliest stages of basin subsidence after the eruption. Correlation of the measured sections suggests the initial filling of an ~2.5 m depression on the basalt surface in this area. The fish-rich sandstone marks a transgressive lag, and the ostracode-rich biomicrite marks the most offshore and probably deepest conditions. Disrupted fabrics indicate periodic drying up and the topmost red mudstone may represent a regressing shoreline. The green sandstone and nodular limestone facies represent isolated playa ponds on top of the basalt that developed during second-order transgressive-regressive cycles. Dinosaur fragments in the Scots Bay Member and overlying fluvial strata imply transport of bone into the lake and deposition in a shoreline facies.

Key words: Minas Basin, lower McCoy Brook Formation, basalt, lake, sedimentology.

Reefs and Deltas at the edge – the highly unusual close association of a thick Abenaki carbonate platform and the major Sable delta, Mesozoic offshore Nova Scotia Shelf Canada

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Summary with table and figures

"Rivers, not temperature, organisms or chemistry appear to control the distribution of carbonates" (Chave 1967). This is the key thought that often introduces cool-water carbonate discussions. But it speaks to the typical absence of carbonates near deltas anywhere, especially 'classical' warm-shallow-water carbonates and particularly if oolitic. In searching for exceptions to use as analogues to this long-standing observation very very few modern or ancient examples seem to exist. The mainly Late Jurassic Abenaki platform with its shelf-edge oolites and reefs with gas at Deep Panuke and the large gas-bearing Sable delta complex that at Venture includes shelf-edge deltas is a large but lonely example of an unusual association. Indeed there is a list of unusual features of this Nova Scotia-shelf association. Specifically:

1) it is the north end of longest reef chain and platform trend with shelf margin reefs in the Phanerozoic geologic record (gigaplatform of Poag 1991, Kiessling 2001),

2) all 3 typical Late Jurassic reef/mound types are present even in one well – Demascota G-32 with sponge reef mounds, coral-stromatoporid shallow-water reefs and slope thrombolitic-microbial mud mounds (Eliuk 1978, Leinfelder et al 2002),

3) it is the youngest reef-bearing carbonate complex in Canada already well known for its Devonian reefs and hydrocarbon-bearing Paleozoic carbonates,

4) the Sable-Laurentian delta formed the largest and continental-scale delta on the North American (NA) Atlantic and Gulf of Mexico margin until the larger Mississippi delta that developed in the mid-Cretaceous, (arguably a possible example of mega "stream capture" though provenance studies by Georgina Pe-Piper, David Piper and associates make this fairly unlikely but consider the modern St. Lawrence River carries the most Canadian water to the coastal oceans, cf. Milliman and Farnsworth 2011, yet it does not have a delta but uniquely does cut the Appalachians),

5) both platform and ramp margin morphologies are present including prograding ramps associated with the Sable delta (Eliuk 1978, Wade and MacLean 1990, Kidston et al 2005, OETR 2011),

6) both Late Jurassic-earliest Cretaceous shelf margin deltas (Venture) and shelf margin reefs (Deep Panuke) are present and gas-bearing (Cummings and Arnott 2005, EnCana 2006, Weissenberger et al. 2006),

7) worldwide Jurassic carbonate reservoirs contain huge hydrocarbon volumes (eg. Saudi Arabia) but only a rare few are in reefs at shelf margins (Greenlee and Lehmann 1993),

8) it has the only commercial gas field in carbonates on NA Atlantic offshore at Deep Panuke and finally

9) it is a unique(?) occurrence of a thick carbonate platform closely adjacent to very large delta over an extended period of time (circa 15MY) (McIver 1972, Eliuk 1978). **Figure 1** illustrates the general setting and points 1 and 4. This area and the Baltimore Canyon Trough USA are the only two areas with well control on the Late Jurassic NA Atlantic carbonate margin.

The original intention of my PhD work was to study the presumed changes in Abenaki platform shelf-margin reefs and carbonate facies in a proximal-distal manner relative to the Sable delta. This led to a more significant problem; how did this unusual 'mega-scale' mixed carbonate-siliciclastic association exist at all and how did it persist for so long.

Application of general principles (Wilson 1967, Mount 1984, Leinfelder 1997) and of analogy from mixed carbonate-siliciclastic studies may give insight. Some principles, that may apply include the following: **1)** reciprocal sedimentation (alternations in time/climate/ locality/bathymetry – arid/monsoonal, delta lobe shifts, high/low relative sea-levels favouring one or the other sediment), **2)** slow sedimentation with vigorous/adaptable organisms (heterotrophs, exceptional algae & atypical corals), **3)** ocean currents of appropriate strength and direction, and perhaps most significant **4)** isolate and separate by barriers (islands/ridges/salt walls-diapirs), by isolated highs (offshore atolls, pinnacles), by deep water ('moats'/lagoons/ gulfs/basins = the classic controls), and by bypass and sediment sinks (deep-water channels and salt withdrawal). Analogies are few but some of the better ones are given in **Table 1.** A study of that table also reminds one of some other controls especially changing ocean chemistries through the Phanerozoic that might be critical.

This probably explains why sponges so important as limestone contributors in Lower Paleozoic and Jurassic reefs contribute very little Recent carbonate sediment in spite of being abundant in modern reefs. Before leaving analogies which attempted to find modern or at least Neogene analogues with limited success, it is surprising and intriguing to learn that the largest river in the world – the Amazon – may be underlain by a carbonate platform which may be the thickest Paleogene carbonate deposit in the world. Carozzi's (1981) Amapa Formation was considered by him to be "the largest coralgal-foraminiferal platform of the geological record" with a composite thickness of over 4 km. Its' being under the mouth of the world's largest river appears to make the Abenaki less unique even second rate. Subsequent studies on the Amazon drainage pattern (Latrubesse et al. 2010) and on the onset of the Amazon deep sea fan (Figueiredo et al. 2009) showed that in fact the Amazon for its early history was confined to interior drainage and the present continental scale drainage into the Atlantic only starts in mid Miocene. That is the time of the abrupt termination of Amapa carbonates. Thus the Amazon delta and thick carbonates are not contemporaneous but result from a mega-scale single event when continental-scale interior drainage broke through to the Atlantic in the Miocene and eliminated the carbonates. Such is the joy and danger of analogues.

This gives us insight to possible controls that allowed the Abenaki and Sable to co-exist. And - going back to the opening quote (Chave 1967) - sometimes, albeit rarely, *temperature* (a warmer Mesozoic perhaps), *organisms* (heterotroph sponges, microsolenid corals and microbs in turbid waters) and *chemistry* (calcitic seas allowing calcification of sponges, high carbonate saturations forming ooids) can nullify the killing effect of a big delta on carbonates. Indeed, sometimes the delta can deposit prodeltaic ramps and abandoned river-mouth bars that act as paleohighs to be 'carbonate-armoured' by oolite and reef following delta-lobe shifting. Although not easily apparent, since the delta and platform are juxtaposed on the same shore, isolation by several mechanisms was the key factor that allowed the co-existence of this unusual sediment association (**Figure 2**). That juxtaposition eventually resulted in shelf-edge delta and platform-margin reef gas fields within about 60 km of one another. Some of the isolating mechanisms include:

1) seismically-seen morphologies and isopach thicks with by-pass channels between the Penobscot area and the main carbonate bank just to the southwest,

2) sediment sinks updip of Penobscot due to salt withdrawal caused by sediment loading that also may explain the absence of correlative platform cyclicity/sequences in Abenaki J-56 that most probably was the result of being on a salt swell (later a diapir) with its own local tectonic history,

3) direction of fine sediment off the shelf through these channels to give progressive younging-southward migration of foreslope shale depositional thicks in front of the carbonate bank that provide for major basinward migration of capping carbonate ramps near the delta (shown by well control in L-30 = proximal ramp and O-76 = distal ramp) but during the Jurassic none-to-limited progradation to the south (near-forereef well J-14/A versus foreslope M-88 provide the only well control in the Panuke Trend for this). Hyperpycnal flow of sediment-laden river water below warmer ocean waters (Piper et al. 2010) may have aided this channel bypass. The thin #9 limestone in the Venture field possibly illustrates one of these channels as well as gives evidence via vertical changes in carbonate facies for a forced regression or relative-sea-level fall previously proposed by Cummings and Arnott (2005) for the Sable delta (Eliuk and Wach 2008). It may have the only major sequence break captured in a core with carbonates.

4) On a smaller field-area scale, carbonate-encased isolated-or-pinnacle reefal buildups (F-70 & D-41) occur that closer to the delta (J-14/A) may be partly shale-encased.

5) Hypothesized north-flowing paleo-Gulf Stream coupled with shallow-water wave agitation explain the presence of interbedded oolite and quartz sandstone couplets in the delta area (L-30, O-76) and as far south as G-67 and at the margin in L-35/A at the top of the Abenaki (or top limestones of MicMac-basal Missisauga formations) whereas fine siliciclastics were mainly deposited in deeper settings.

The presence of top-Abenaki sponge-rich and argillaceous limestones or shales in most wells near the Panuke Trend margin further southwest (L-97 and south) indicates a sub-regional deepening. This deepening is not obvious (and perhaps absent?) near the Sable delta. It is not evident in the Western Shelf Abenaki margin wells that continue shallow-water carbonate sedimentation into the Lower Cretaceous long after the 'Base-Cretaceous Unconformity' of OETR (2011). These sponge-rich argillaceous beds are diachronous and could be considered a prodeltaic-starved-basin subfacies of the delta or represent a drowned delta or shelf with slower deeper-water sedimentation. In some areas of the shelf interior they occur associated with red-coated ironstones ("Fe-oolites"). On the Western Shelf carbonate foreslope white and even pink to red microbial/ thrombolitic limestones occur - yet another unusual feature of the Abenaki but also seen in the European Jurassic as the Ammonitico rosso on isolated seamounts. Oolites too are white. These features, over 300km away, finally indicate little or no influence of the Sable delta on the Abenaki carbonate platform

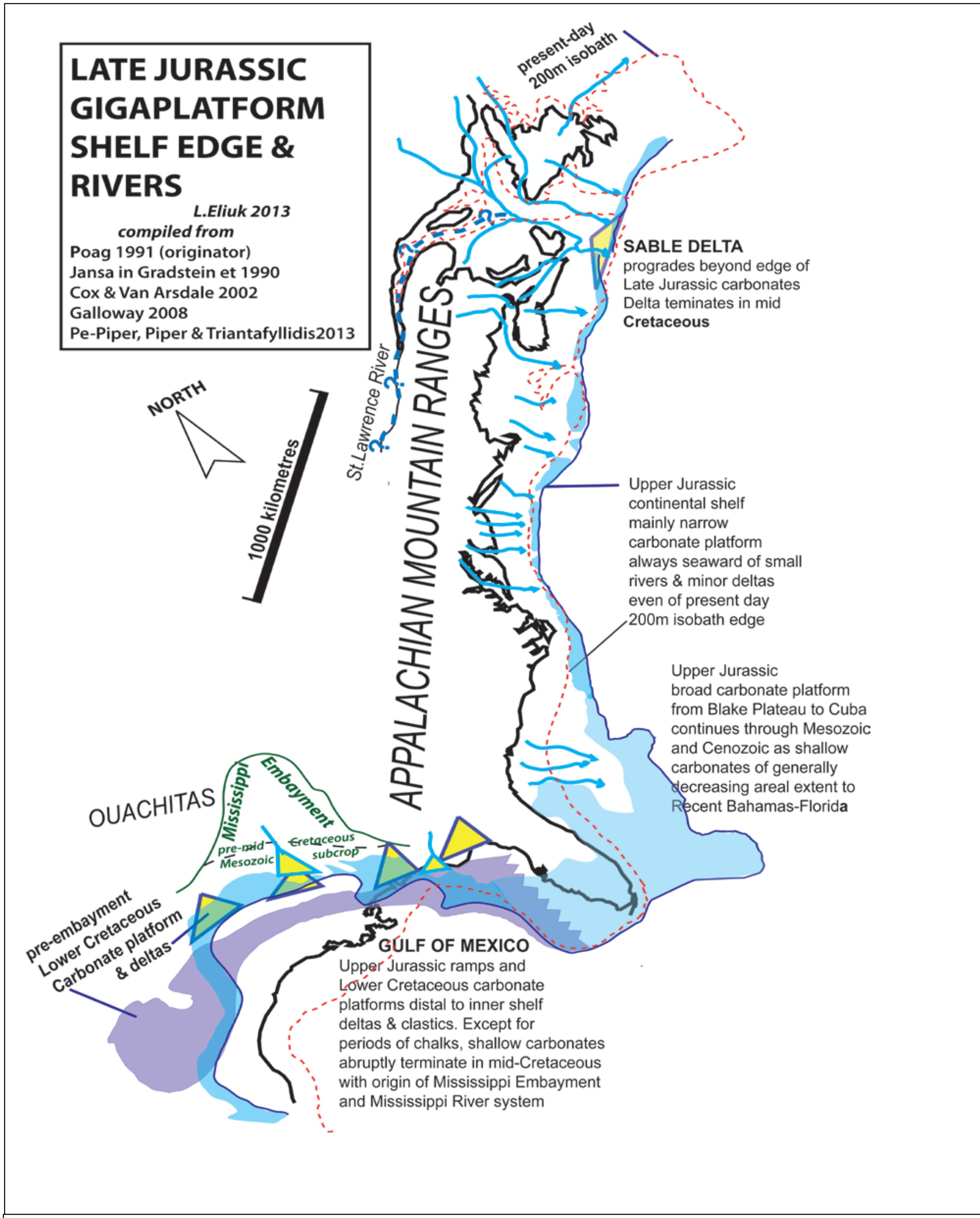

Figure 1. **Late Jurassic gigaplatform shelf edge and hypothetical rivers.** Poag (1991) first named this feature that is the largest Phanerozoic platform and coral reef trend (Kiessling 2001). Only the Sable-Laurentian delta as shown by the modern 200m isobath extends seaward of the Late Jurassic carbonate margin along the whole central Atlantic-Gulf of Mexico seaboard until the Mississippi River delta area. But prior to Late Cretaceous all Gulf deltas were small with continuous carbonate shelves seaward (Galloway 2008; Late Jurassic = blue and Early Cretaceous = mauve). In the Late Cretaceous, Gulf shallow-water carbonate shelves terminate (as does the Sable delta). Later the Mississippi delta progrades in a major degree due to breeching of the Ouachita-Appalachian barrier with the Late Cretaceous creation of the Mississippi embayment over a collapsed hot-spot according to Cox & van Arsdale (2002).

EXAMPLES / CONTROLS	**Nova Scotia Shelf (NS) ABENAKI PLATORM – SABLE DELTA Late Jurassic-early Neocomian**	**Baltimore Canyon Trough, USA (BCT) 'ABENAKI EQUIVALENT' Late Jurassic-early Neocomian**	**Borneo (Indonesia) MAHAKAN DELTA Neogene (Miocene reef outcrops) to Recent**	**Gulf of Papua FLY RIVER DELTA –N. GREAT BARRIER REEF Neogene- with Miocene platform to Recent**	**Arabia-Persian Gulf SHATT AL ARAB DELTA (Tigris-Euphrates-Karun) - KUWAIT RAMP Holocene-Recent**
LARGE DELTA SIMULTANEO USLY - siliciclastic input	**YES**–Sable paleo-delta contemporaneous then eventually buries nearby carbonates	NO – several small later deltas therefore NOT ANALOGUE BUT USEFUL COMPARISON	NO – relatively small delta but in a petroleum -rich basin WELL STUDIED MIXED EXAMPLE	**YES** -Fly River drains high Papua-New Guinea mountain chain (in Miocene Borabi carbonate shelf drowned, progrades near delta)	**YES** – complicated by anthropogenic overprint of shoreline developments **Oolite common; reefs rare.**
SUBSIDENCE	Less than BCT	Greater than NS	Greater? (glacial effect)	Greater? (glacial effect)	Greater? (glacial effect)
PLATE TECTONIC DRIFT	North out of reef sub-tropic carbonate zone	North out of reefing but further south so delayed	North into reef zone of equatorial tropics??	North into reef zone of equatorial tropics	?North but within carbonate reef zone. Arab plate colliding with Zagros mountains
REGIONAL TECTONIC SETTING	Rifted blocks – passive margin. Thick salt affect delta (possible ponding slowed sediment supply periodically)	As left (NS) - Rifted blocks but regional clastic(?) wedge under carbonate margin. Thin salt	Complex convergent margin with small basin being in-filled by active delta	Rifted blocks later collision change from passive to active margin (greater influx of sediment)	Epeiric sea (300m or less depth) in nearly enclosed Mesopotamian Foreland Basin to mountain-building in Iran
EUSTACY	Important but not great fluctuations – mainly a rising trend (Base K tectonics?)	Same as Nova Scotia and many events equivalent	Major glacially controlled global fluctuations of late Neogene	Major glacially controlled global fluctuations of late Neogene	Major glacially controlled global fluctuations of late Neogene
CLIMATE	Greenhouse time – equable subtropic humid	Greenhouse time – equable subtropic humid	Icehouse time. Humid equatorial	Icehouse time – major variations but in tropics (humid to monsoonal)	Arid, subtropical– water salinities and temperatures elevated above open marine seas
Oceanography – CHEMISTRY – SEAWATER TYPES	Calcitic seas so high saturation (oolites & biotically induced carbonate = sponges mud mounds)	Calcitic seas so high saturation	Aragonitic-hi Mg more corals (lack lithified sponges, no oolite), fresher water (brackish) input	Aragonitic-hi Mg more corals (lack lithified sponges, less oolite), fresh input. Phosphates – Early & Mid Miocene	Slightly hypersaline (to 7% in restricted lagoons, evaporite production especially in sabhkas) Oolite formation common
Oceanography – WINDS & CURRENTS	Possible paleo -Gulf Stream with north flow	Possible paleo-Gulf Stream with north flow	Indonesian Through Flow Current south flow clears north delta lobes with reefs absent from south lobes	East Australian Current with clockwise & north flow from Miocene (also cause prograded shelf?)	Shemal winds blow down axis to SE supply Aeolian quartz & carbonate. Flow counter-clock'
EFERENCES	Eliuk 1978, Wade & McLean 1990	Meyers 1989, Prather 1991, Eliuk & Prather 2005	Wilson 2005 Wilson & Lokier 2002	Davies et al. 1989, Tcherepanov 2008, Tcherepanov et al.2008,	Evans 1995, Gischler & Lomando 2005, Purser 1973 (**but**-Walkden & Williams 1998)

Table 1 Analogue comparisons: Late Jurassic Abenaki (Nova Scotia) and Baltimore Canyon Trough (Delaware, USA) compared to some modern-Neogene mixed deltaic-carbonate platform analogues – Mahakam Delta (Borneo, Indonesia), Fly River Delta-Great Barrier Reef (Papua-New Guinea). Shatt al Arab Delta-Kuwait carbonate ramp (Arabian-Persian Gulf). Prodeltaic turbid-water living coral reefs in Iraq are a relevant new find (Pohl et al. 2013) and provide additional analogues to the 1990's discovery of siliceous sponge reefs off Canada's west coast in the Fraser River prodelta (Conway et al. 2004).

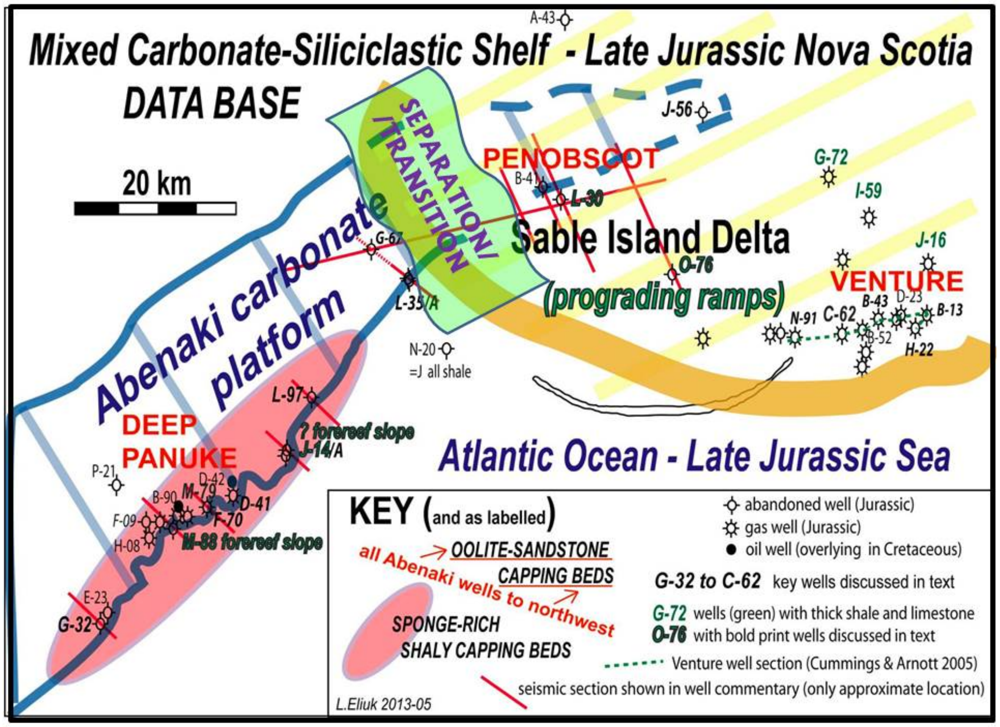

Figure 2. Abenaki platform-Sabledelta association relationship map. Except for capping shales and limestones rich in lithistid sponges southwest of L-35 and G-67, the Abenaki near its margin is thick and nearly pure carbonate. Isolation southwest of Penobscot as discussed in text is seen as the main contributing factor aided by postulated northerly paleo-currents. To the northeast and including L-35 and G-67 the upper Abenaki has mixed oolitic limestone and quartz sandstone interbeds. L-30 and O-76 are respectively proximal and distal ramp carbonates-siliciclastics with capping shallow-water limestones and coarser sandstones built on prodeltaic shales and thinner microbial-thrombolitic limestones forming slope clinoforms (G-72, I-59 and J-16 seem similar but were not studied). The Venture area is interpreted as a shelf margin delta resulting from forced regression (Cummings and Arnott 2005). The thin #9 limestone in C-62 with a complex shoaling facies sequence appears to support their interpretation particularly since off-setting thin limestones have oolite. It may coincide with OETR (2011) base-Cretaceous unconformity though dating is lacking. The near margin trend of descending slope shale interbeds from L-30 to J-14 to M-88 shows proximal-distal deeper water siliciclastic influx.

Biostratigraphy based on Calcareous Nannofossils from Upper Campanian, Sergipe-Alagoas Basin, Northeastern Brazil

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Introduction

Sergipe-Alagoas Basin has one of the largest oil and gas exploratory potential in the brazilian continental margin, being target of calcareous nannofossils biostratigraphy since the early 70s.

Moreover, Campanian in Sergipe-Alagoas Basin represents one of the most important stages of marine sedimentation of the platform: the extension of the coastal plain of the sandy platform Marituba Formation (Schaller, 1969) on the shales of the Calumbi Formation (Campbell, 1946). This was one of the main consequences of the change in the pattern of sedimentation, from trangressive to regressive.

The main studies investigating biostratigraphic and paleoecological aspects in the Basin, through calcareous nannofossils were: Quadros & Gomide (1972), Quadros (1981), Freitas (1984), Freitas *et al.* (1986), Beurlen *et al.* (1987), Beurlen *et al.* (1992) and Cunha & Koutsoukos (1998).

Therefore, this work aims to make a contribution to the biostratigraphic knowledge of the Marine Sequence of Sergipe Subbasin, in the brazilian continental margin, making use of the study of calcareous nannofossils content.

Materials and Methods

Altogether, we analyzed tem samples from the well AB01, extracted from the onshore portion of Sergipe-Alagoas Basin, comprising a section between 1,215 and 1,491 meters deep, with intervals ranging from 30 to 36 meters.

We performed the preparation of the slides for calcareous nannofossils in the Laboratory of Geology of Petrobras/Business Unit of Exploration and Production of Sergipe-Alagoas (UN-SEAL). For this, we followed the method of Antunes (1997).

We conducted the analyzes in the Laboratory of Applied Mineralogy and Gemology, Department of Geology, Federal University of Pernambuco (LABGEM / DGEO / UFPE), with a petrographic microscope, model Olympus BX51, equipped with ocular lens with 10x magnification, and objective lens with 100x magnification (total magnification = 1000x). We got the photos using the microscope’s own camera., an Olympus DP26, and processed by the Stream Essentials 1.7 program, of the same brand.

We base the taxonomy in Burnett (1998), but widely consulted Perch-Nielsen (1985) to help identification of species and biozones.

Results

The results of this research are summarized in the photographs presented in Figure 1 and in the graphic of diversity of species, as shown in Figure 2.

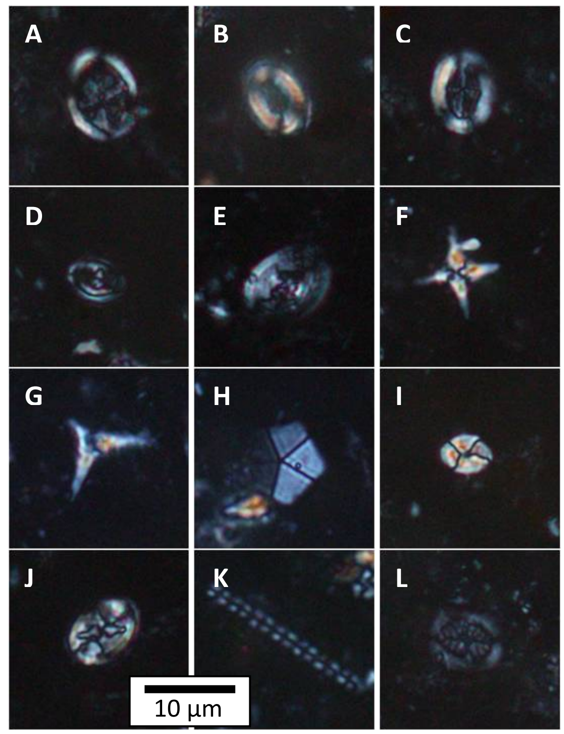

Figure 1. A) Arkhangelskiella cymbiformis; B) Broinsonia parca constricta; C) Broinsonia parca parca; D) Reinhardtites anthophorus; E) Reinhardtites levis; F) Uniplanarius sissinghii; G) Uniplanarius trifidus; H) Braarudosphaera bigelowii; I) Calculites obscurus; J) Eiffellithus gorkae; K) Microrhabdulus decoratus; L) Retecapsa surrirrela.

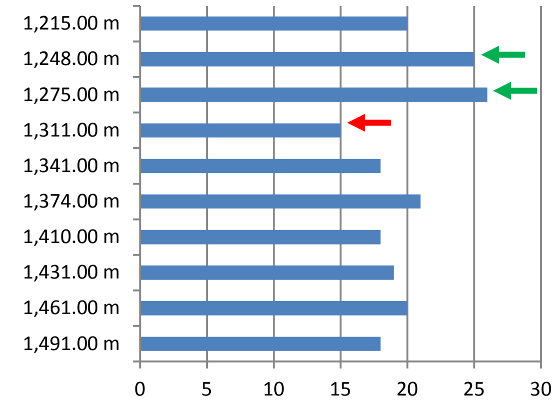

Figure 2. Graphic of diversity of species present in the analyzed samples in this study. The vertical axis represents the levels of samples; the horizontal axis represents the number of identified species. The red arrow indicates a period of loss of species; the green arrow indicates periods of high specific diversification.

Discussions

Calcareous nannofossils are considered excellent biostratigraphic tools for the Upper Cretaceous, especially for its rapid evolution, short stratigraphic distribution, wide geographical distribution and ease of sample preparation. The main global zonations using calcareous nannofossils of Cretaceous were established by Sissingh (1977), Roth (1978), Perch-Nielsen (1985) and Burnett (1998).

The sample analysis allowed identifying 37 species, 26 genera, 12 families and 6 orders. We also recorded a case of reworking with *Rhabdophidites parallelus*.

During the taxonomic study, the coexistence of an assemblage of species in all samples (or at least 70% of them) allowed to infer a Campanian age for the sequence under study. The species are: *Braarudosphaera bigelowii*, *Broinsonia parca expansa*, *Calculites obscurus*, *Eiffellithus gorkae*, *Microrhabdulus decoratus*, *Micula decussata*, *Retecapsa surrirrela*, *Tetrapodorhabdus decorus*, *Uniplanarius sissinghii*, *Uniplanarius trifidus*, *Watznaueria barnesae* and *Watznaueria biporta*.

The biostratigraphic refinement of the section was only possible, thanks to the identification of the species, whose first/last occurrence marks base or top of biozones in global frameworks. They are: *Arkhangelskiella cymbiformis*, *Broinsonia parca constricta*, *Broinsonia parca parca*, *Reinhardtites anthophorus*, *Reinhardtites levis*, *Uniplanarius sissinghii* and *Uniplanarius trifidus*.

The first occurrence of *R. levis* is in UC14d zone of Burnett (1998), of Lower Campanian age, which corresponds approximately to the boundary between the CC18 and CC19 zones of Sissingh (1977). The last occurrence of *R. anthophorus* marks the top of UC15d zone of Burnett (1998), which corresponds to the interior of the CC22 zone of Sissingh (1977). The first occurrence of *U. sissinghii* marks the base of the UC15c zone of Burnett (1998), which corresponds which is the base of the CC21a zone of Sissingh (1977). The first occurrence of *U. trifidus* marks the base of the UC15d zone of Burnett (1998), which corresponds to the top of the CC21c zone of Sissingh (1977). The first occurrence of *A. cymbiformis* marks the base of the UC13 zone of Burnett (1998), which corresponds to the CC17 zone of Sissingh (1977). The first occurrence of *B. parca parca* marks the bases of UC14a (Burnett, 1998) and CC18a (Sissingh, 1977) biozones. The first occurrence of *B. parca constricta* marks the base of the UC14d zone (Burnett, 1998), situated within the CC18a zone of Sissingh (1977). And the last occurrence of *B. parca constricta* marks the top of the UC16 (Burnett, 1998) and CC23a (Sissingh, 1977) biozones.

From these bioevents, it was possible to refine the relative age of the analyzed section, which is positioned within the UC15d biozone of Burnett (1998) and within the CC22 biozone of Sissingh (1977), which corresponds to the Upper Campanian (Figure 3).

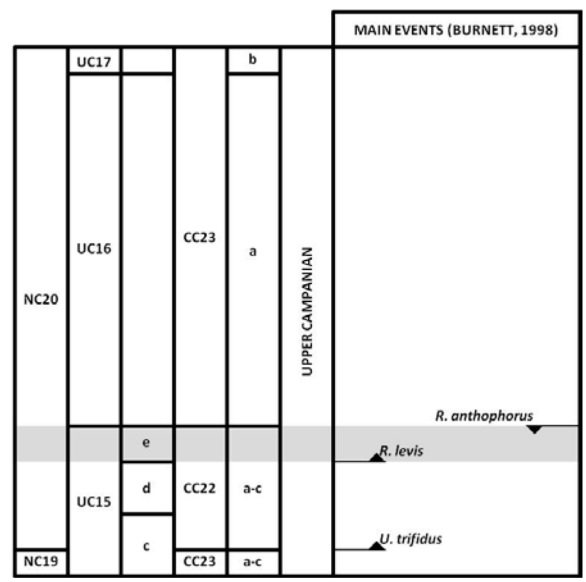

Figure 3. Correlation between the biozones of Roth (1978) (NC), Burnett (1998) (UC) and Perch-Nielsen (1985) (CC). The area in gray shows where is situated the studied interval (modified from Burnett, 1998).

Calcareous nannoplankton is extremely sensitive to environmental changes, although they have a more regional character. This is attested by numerous studies reported in the literature. Antunes (1997), however, points to a caveat: that paleoenvironmental interpretations based on this group regarding Paleogene or older sections are less substantiated, requiring, therefore, more inferences and speculations.

By analyzing the diversity of species present in all samples, we found that in the range 1,491-1,341 meters the number of species was between 18 and 21. In the sample of 1,311 m there was a considerable decrease this amount, falling to 15. In both overlapping levels (1,275 and 1,248 m), diversity increases to 25-26 species. Finally, the sample from the top of the section (1,215 m) recorded 20 species. These sharp differences were interpreted as a result of environmental changes, probably associated with changes in the pattern of sedimentation of the Basin.

Given their sensitivity, some species of nannofossils quickly disappear, creating a vacancy in numerous ecological niches. With the stabilization of new environmental parameters, some of the old desappeared species and new ones have proliferated, seeking to fill the gaps left by their predecessors. By the effect of interspecific competition, only highly suitable species survived, returning to that number previously.

This unlikely event coincides with the start of the K120 Sequence of Campos Neto *et al.* (2007), during which the coastal plain and the sandy platform of Marituba Formation widened. Moreover, Campanian of Sergipe-Alagoas Basin records various regional and local geological changes. Among them, we highlight two mutually connected: 1) the end of the transgressive sequence and the start of the regressive sequence of the Basin; and 2) the start of siliciclastic sedimentation, with deposits of Calumbi and Marituba Formations.

With this, it is possible that the paleoecological event recorded in the studied section is associated with the paleobathymetric change occurred during the Campanian. The principle of this explanation lies in one of the main functions of coccoliths, the carbonate plates covering the nannofossil: floats or depth regulators. Several authors (Aubry, 1989; Aubry, 1990; Houghton, 1991; Okada, 1992) studied the bathymetric preferences of some species.

Preliminary Conclusions

We recognize and photographed 37 species of calcareous nannofossils, classified into 6 orders, 12 families and 26 genera;

We recorded two cases of reworking: *Rhabdophidites parallelus* and *Thoracosphaera* sp.;

Through bioevents marked by first/last occurrence of the species *A. cymbiformis*, *B. parca constricta*, *B. parca parca*, *R. anthophorus*, *R. levis*, *U. sissinghii* and *U. trifidus*, we were able to position the analyzed section within the biozones CC22 of Sissingh (1977) and, more precisely, the UC15d of Burnett (1998), which corresponds to the Upper Campanian;

The studied section is in a stage of the basin characterized by profound changes in the pattern of the sedimentation, ceasing to be transgressive and passing to regressive, initiating deposition of the Marituba Formation along Calumbi Formation;

Besides the fact calcareous nannofossils are very sensitive to environmental changes, it seems to explain a possible paleoecological event recorded in the sample of 1,311 meters, where a sudden drop in species diversity occurred, followed by a rapid growth in it's number on both overlapping levels;

From the preliminary data, we intend to investigate further studies related to the Upper Campanian of Sergipe-Alagoas Basin (especially those that emphasize geochemical and biostratigraphic aspects based on other fossil groups).

Aknowledgements

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Thermal Maturity of the Carboniferous onshore basins in Ireland and its impact on carbon dioxide storage and methane recovery

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Introduction

Concerns that global climate change is linked to increased anthropogenic sourced carbon dioxide (CO_2) are driving research on different technologies to reduce atmospheric CO_2 emissions. At present, geological CO_2 sequestration options include CO_2 injection into saline aquifers, CO_2-EOR, CO_2-ECBM and many others. One option for storage and enhanced gas recovery may be by injection into organic-rich shales, in which the CO_2 is preferentially adsorbed, displacing methane. Factors that influence effective CO_2 injection and storage in the Carboniferous black shales of the Clare and Dublin basins of Ireland have been assessed.

Methodology

Previously published maturity maps were produced by analysing samples from outcrops and shallow boreholes. The maps show a progressive increase of the thermal maturity toward the south west but this trend is strongly influenced by stratigraphy. For this study, Carboniferous black shales were collected from several locations in the Clare and Dublin basins and their thermal maturity determined by vitrinite reflectance and Rock-Eval pyrolysis. Total organic carbon and CO_2 adsorption were also determined for selected samples. Three new maturity maps for the Base Carboniferous, Base Viséan and the Base Westphalian were constructed for Ireland, integrating new and existing data. These enable prediction of maturity for the selected stratigraphic levels in the subsurface

Results

Total Organic Carbon (TOC)

In terms of TOC content, some of the Carboniferous black shales from the Dublin Basin seem to have excellent source rock potential, being characterized by a TOC content ranging from 2% to 5.58% (mean 4.21%). In the Clare Basin TOC is more variable, ranging from 1.87% in Ballybunnion up to 11.48% (mean 4.69%). Therefore the quality of the source rock ranges from fair to excellent.

Thermal Maturity: Indicators and Maps

Vitrinite Reflectance was measured in the samples collected and these data were also integrated with published information and a database was created. The data were used to produce maturity maps for three ‘time slices’: Base Carboniferous, Base Viséan and Base Westphalian.

The Base Carboniferous and Base Viséan maps were also populated with extrapolated values of Vitrinite Reflectance from each other. To reduce the uncertainty in the extrapolation, thicknesses were taken from a published stratigraphic correlation of Carboniferous Rocks together with vitrinite reflectance gradients from previous University of Dublin PhD theses (Haughey 1986, Baily 1992, Fitzgerald 1994, Goodhue 1996 and Fernandes 2000). The maps also took into account the palaeogeography maps published in the Geology of Ireland (Sevastopulo & Wyse Jackson, 2009; Sevastopulo, 2009).

The vitrinite reflectance classes used are:

- 0.6-1.2 %
- 1.3-3.0 %
- 3.1-4.0%
- > 4.0% VR.

Present results showed that maturity trends for the Base Carboniferous do not seem to follow any clear structural trend. The Base Viséan shows a progressive increase in vitrinite reflectance, from N to S in Ireland. The Base Westphalian map shows the same trend as the Base Viséan, but with lower values especially in parts of Co. Wexford.

Rock-Eval Pyrolysis

Rock-Eval Pyrolysis indicates the type of organic matter preserved, the residual hydrocarbon-generating potential and the thermal maturity of the sample (McCarthy *et al*, 2011).

Preliminary results from the Rock-Eval analyses from the Clare Shale formation does not show S2 peaks and is interpreted as post mature and without any oil generating potential. The production index suggests that it is in the gas generation window. Vitrinite reflectance shows that all the samples from the borehole are post-mature..

The Rock-Eval analyses of the samples from the Dublin Basin shows marginally greater potential but they are still poor in terms of both oil potential and hydrogen index. In terms of maturity indicators, both Tmax and $R_o$ran suggest that the formation lies in the gas window.

Conclusions

Preliminary results from the Clare basin appear to confirm that the section is post-mature with regard to dry gas preservation using the conventional value of 2.5% $R_o$ran . In the Dublin Basin, the succession lies in the gas window.

Acknowledgments

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Crustal velocity structure across the Orphan Basin from new refraction/wide-angle reflection data collected as part of the SIGNAL 2009 cruise

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The SIGNAL (Seismic Investigations off Greenland, Newfoundland and Labrador) 2009 cruise was undertaken by the Geological Survey of Canada (GSC) and the Geological Survey of Denmark and Greenland (GEUS), with scientific contributions from Dalhousie University, to collect refraction/wide-angle reflection (RWAR) profiles as part of each country's continental shelf program under UNCLOS (United Nations Convention on the Law of the Sea) Article 76 (Funck et al., 2010). Of the five profiles collected, Line 1 extended from the Bonavista Platform off Newfoundland, across the Orphan Basin, to Orphan Knoll and beyond into oceanic crust. The line followed the same track as an earlier seismic refraction line from the GSC (line 84-3) from which a velocity model for Orphan Basin had been produced (Chian et al., 2001). The ocean-bottom seismometer (OBS) locations along the SIGNAL line (purple circles on Fig. 1) were chosen to complement the earlier GSC line (OBS shown as green circles on Fig. 1) and to extend the line further toward land and seaward, as well as to improve the station coverage. By combining the results from both surveys, a total of 41 OBS were used for the velocity modelling, improving the resolution of the final model.

Data acquisition and modelling

Line 1 from the SIGNAL cruise spanned 632 km and the average OBS spacing, with the combined old and new instruments, corresponded to 15 km. Independently, the original GSC and SIGNAL surveys had average OBS spacings of 23 and 26.5 km, respectively. Airgun sources of similar total capacity were used for both surveys. The average shot spacings for the old and new surveys were 150–200 m and 138 m, respectively. For the SIGNAL cruise, to overcome a relatively wide instrument spacing over a critical section of the line, the shelf break, a portion of Line 1 was reshot as Line 1A using an additional five OBS. The extra OBS were seamlessly incorporated into the data analysis and modelling.

For the data from the SIGNAL cruise, timing corrections were applied to each OBS record to account for clock drift, mechanical delay of the guns, the width of the pulse and electronic recording delay. The recorded direct wave for each OBS was picked and used to recalculate its position on the seafloor and the shot-receiver offsets were then computed relative to the corrected OBS positions. Meanwhile, the archived OBS data from the earlier GSC survey had already had all corrections applied. For all OBS, the hydrophone and vertical components were used for first break picking. A 4–10 Hz band-pass filter was applied to aid in the picking of first breaks at near offsets. For longer offsets, each OBS record was further processed with a sliding window, spatial linear coherency filter.

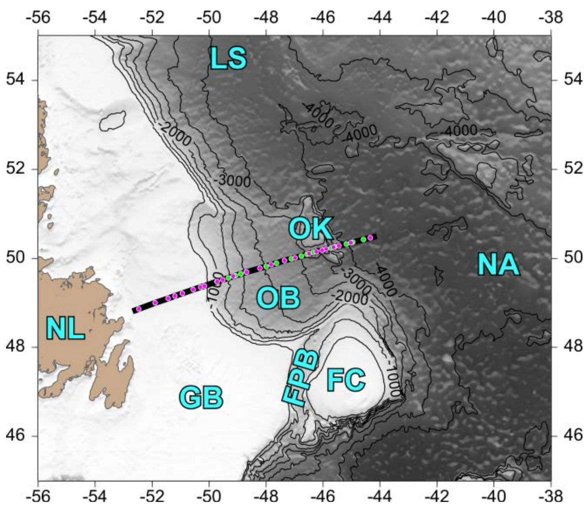

Figure 1. Bathymetric map of offshore Newfoundland and Labrador, eastern Canada. The location of Line 1 from the SIGNAL cruise is shown by the thick black line. OBS from the SIGNAL cruise are shown by the purple circles while those from an earlier GSC line (84-3) are shown as green circles. Abbreviations: FC – Flemish Cap, FPB – Flemish Pass Basin, GB – Grand Banks, LS – Labrador Sea, NA – North Atlantic, NL – Newfoundland and Labrador, OB – Orphan Basin, OK – Orphan Knoll.

The final velocity model was obtained in several steps. First, the OBS positions were projected onto a 2-D great circle and model distances for each OBS along the line were computed. Second, the clearest first break picks were used with a simple tomographic code to generate an initial velocity model (Korenaga et al., 2000; 2001). The starting model for the tomography was constructed with a water layer, accurate bathymetry and a linearly increasing velocity model for the crust. The inverted seabed velocities and velocity contours were then used to build a starting model for use with the RAYINVR ray-tracing forward modelling and inversion program from Zelt & Smith (1992). The depth-converted basement horizon interpreted from the older GSC reflection line (84-3) was also used to build the original model for use with RAYVINR. The final velocity structural model was constructed by forward modelling using a layer stripping approach from top to bottom. Reflected arrivals were modelled once most of the observed refracted arrivals could be adequately reproduced by the P-wave velocity model.

Results

The final crustal velocity model for Line 1 from the combined GSC and SIGNAL cruises reveals thinned continental crust spanning a distance of over 450 km beneath most of Orphan Basin. Thinner continental crust (less than 10 km thick) spanning a distance of 50–100 km is modelled immediately outboard of the Bonavista Platform where it had previously been suggested based on gravity modelling that was used to extend the velocity model for GSC 84-3 landward (Chian et al., 2001). This thinning was interpreted as a failed rift zone and the landward results from the SIGNAL cruise are consistent with that interpretation. Seaward of the failed rift, the velocity structure of the thinned continental crust (15 to 20 km thick) is generally uniform over 300 km toward Orphan Knoll. Immediately outboard of Orphan Knoll, the crust thins to 8 km and exhibits a velocity structure consistent with oceanic crust. Velocities resolved for the uppermost mantle are typical for unaltered mantle and range between 7.8 and 8 km/s, confirming that serpentinized mantle does not appear to be present beneath this part of the Orphan Basin.

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An igneous province near the western termination of the Charlie-Gibbs Fracture Zone, Northeast Newfoundland rifted margin

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Just north of Orphan Basin (offshore Newfoundland) where the northeast Newfoundland rifted margin was once joined to its conjugate margin off Rockall-Hatton Plateau (offshore Ireland), we have mapped an igneous province of probable mid to Late Cretaceous age (Fig. 1). Using seismic and potential field data, we identified volcanic features including sills, lava flows and volcanic highs which span a V-shaped region of over 20,000 square kilometers. This is located near the western termination of the Charlie-Gibbs Fracture Zone and thus we have named it the “Charlie-Gibbs Volcanic Province” (CGVP).

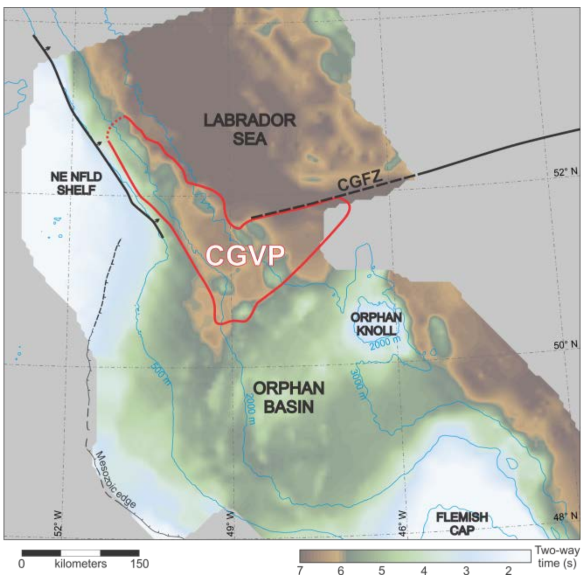

Figure. 1 Charlie-Gibbs Volcanic Province (CGVP) shown on our gridded map of the base Tertiary seismic horizon.

Large positive magnetic anomalies underlie the CGVP, particularly in association with the more than 14 volcanic highs that have been mapped seismically there. When the conjugate margins are restored to their chron 34 positions (Santonian time) a similar pattern of magnetic anomalies is also observed on the Rockall margin. These conjugate features include one of the Barra Volcanic ridges (southern Rockall Basin) which is co-linear with the eastern end of the CGVP in Late Cretaceous time. These spatial correlations suggest a common origin. After rifting ended in Early Cretaceous time within the Orphan-Rockall Basin, rifting shifted east of Orphan Basin and into the Labrador Sea at an oblique angle to the older rift. From Aptian to Santonian time, sea floor spreading propagated northward from the region east of Flemish Cap into the area underlying the CGVP. As there is no evidence of anomalously hot mantle below the region (i.e. a hotspot), magmatism probably did not occur until hot asthenosphere became available when seafloor spreading reached the region in Late Cretaceous time. As Rockall initially separated from the Newfoundland margin, the region near the rift-transform intersection probably acted as a complex leaky transform fault.

In addition, we have mapped an abrupt truncation of sedimentary and crustal-scale structures at the southern boundary of the CGVP, which forms the northern edge of Orphan Basin. These appear to be through-going, crustal-scale faults which we have traced into West Orphan Basin perhaps linking to older Paleozoic lineaments within the Appalachian basement rocks.

The results suggest that the location of the CGVP was controlled by a combination of factors:

a) the pre-existing fabric of the continental lithosphere,
b) Early Cretaceous crustal extension oblique to later seafloor spreading in the Labrador Sea,
c) rift-transform margin development in Late Cretaceous time, and
d) melt availability as seafloor spreading moved into the region.

Reference

Keen, C. E., L. T. Dafoe, and K. Dickie (2014), A volcanic province near the western termination of the Charlie-Gibbs Fracture Zone at the rifted margin, offshore northeast Newfoundland, Tectonics, 33, doi:10.1002/2014TC003547.

Results from a magnetotelluric survey across the Howley Basin, western Newfoundland

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Summary

This study aimed to develop a better understanding of the Howley Basin in western Newfoundland and its hydrocarbon potential using a magnetotelluric (MT) survey. Little is know about the Howley Basin and its structure. The Rocky Brook formation, which consists of organic rich mudstone that is known for generating hydrocarbons, is found in the adjacent Cormack Basin and is believed to also be present in the Howley Basin. An MT survey along an 18km long profile was conducted in August and September 2013, crossing from the Topsail Igneous Complex formation immediately to the southeast of the Howley Basin to the anticipated location of the boundary between the Howley and Cormack Basins in the northwest. The Howley Basin is characterized by higher electrical conductivities than the surrounding igneous basement. 2D inversions of different subsets of the data (individual TE and TM modes, joint TE and TM modes) were performed to give conductivity sections across the basin. The MT data suggest a maximum thickness of the basin of approximately 2km and that the basin is decreasing in thickness eastwards towards its eastern boundary.

Background

The Howley Basin is an onshore basin in western Newfoundland (see Figure 1). It forms a sub-basin of the Deer Lake Basin, which is divided by the Cabot Fault into the Cormack Basin on the west and the Howley Basin on the east. The Deer Lake Basin is one of several areas of Lower Carboniferous rocks in western Newfoundland belonging to the northeast margin of the Maritimes Basin (see, for example, Hamblin et al., 1997). The Deer Lake Basin is thought to have been generated by post-extensional processes after the main Acadian compressional mountain building episode. The Maritimes Basin was produced by post-orogenic extensional processes in the mid- to late-Devonian, and was further deformed along the Cabot Fault by strike-slip movement through the Carboniferous. The Deer Lake Basin contains predominantly non-marine sediments of two megasequences—the Tournaisian Anguille Group and the Visean Deer Lake Group—which were laid down in a strike slip structural setting. Later, transpressional shear created a narrow central-uplifted flower structure complex along the Cabot Fault separating the Deer Lake Basin into the Cormack and Howley lateral sub-basins.

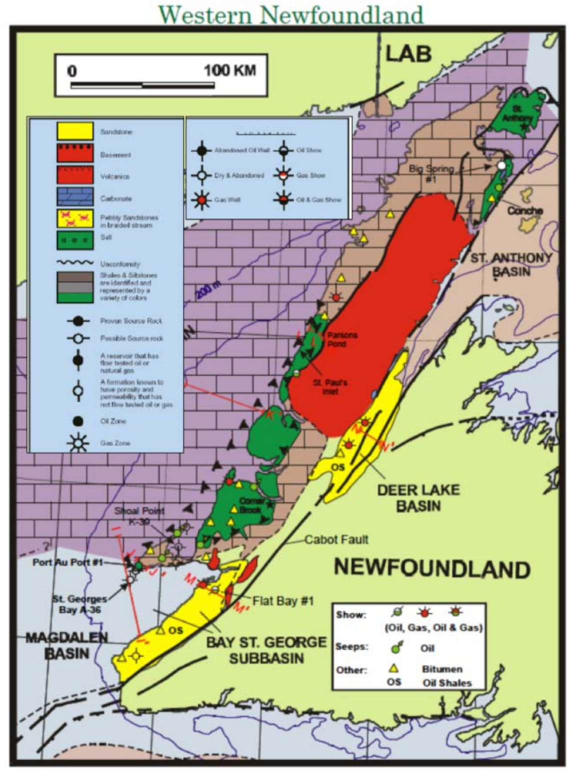

Figure 1: Geological map of western Newfoundland showing geological terranes, hydrocarbon shows, and well locations (Government of NL, 2000).

Very little is known about the Howley Basin. Outcrop is sparse and little geophysical work has been done in the area. The only geophysical data existing until recently were regional gravity and magnetic compilations and a gravity data-set acquired by Miller and Wright (1984); no seismic data had been acquired. In 2008-09 a high-resolution airborne magnetic data-set was acquired over the whole of the Deer Lake Basin. In August and September 2013 an MT survey was carried out across the Howley Basin as part of a multi-faceted field programme run by Memorial University that also includes gravity and seismic data acquisition and structural geology field mapping. It is the results of this MT survey that are presented here.

The MT method involves measuring the variation with time of the naturally occurring electric and magnetic fields on the surface of the Earth. The ratios of these electric and magnetic fields and how these ratios change with the frequency content of the signal contain information about how the electrical conductivity of the rocks varies in the subsurface beneath the survey line. This in turn provides information that can be used to construct a vertical geological section down to tens of kilometres into the subsurface, albeit a fuzzy, diffuse, non-unique section.

Results

MT data were acquired along an 18km long profile across the Howley Basin from the Topsails igneous formation in the east past the town of Howley to approximately the Cabot fault in the west (see Figure 2).

Initial analysis of the data indicated a mixture of dimensionality of the data: most stations and frequency ranges were consistent with a 2D subsurface, but a substantial number of stations and frequencies were consistent with 1D subsurface structures and some data exhibited 3D effects. The shorter period data, which are sensitive to shallower depths and hence basin structure, exhibited a geo-electric strike direction of 9°. The longer period data, which are sensitive to deep structure, preferred a geo-electric strike of 33°. This is consistent with the regional-scale strike of the Howley Basin. There were also indications in the data of a geo-electric strike of 85°.

Vertical conductivity sections were created by 2D inversion of the data. Various sub-sets of the data (TE and TM mode only inversions, joint TE and TM node inversions) and the two main strike directions (9° and 33°) were considered for the inversions. Figure 3 shows the 2D conductivity section produced for the TM-only inversion for the geo-electric strike direction of 9°.

Assuming that the sedimentary rocks of the Howley Basin have higher electrical conductivities than the igneous rocks of the basement, the MT data suggest that the maximum depth extent of the basin is at most 2km, and that the basin is decreasing in thickness eastwards from the Cabot Fault towards the Topsails igneous formation. The shape of the bottom of the basin as discerned from the MT data, and the larger structural features interpreted to exist in the middle of the basin, are consistent with the flower structure complex of the Cabot Fault extending the full width of the Howley Basin.

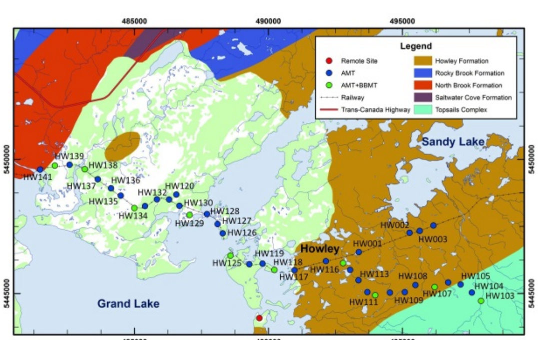

Figure 2: MT station locations: blue discs indicate shorter-period (AMT) stations, green discs indicate broad-band (BBMT) stations.

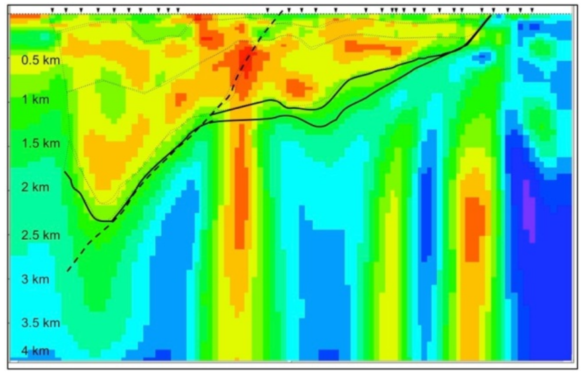

Figure 3: 2D conductivity section obtained from inverting the TM-mode data only for a geo-electric strike direction of 9°, which is more suitable for the shallower (i.e., basin) structure. The solid line indicates the interpreted base of the basin. The dashed line indicates possible faulting. (Warmer colours indicate higher electrical conductivities.)

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Post-rift hydrocarbon plays along the North Atlantic conjugate margins (Jeanne d'Arc Basin, Flemish Pass Basin, East Orphan Basin and Porcupine Basin).

Stefano Patruno, Christopher Davies and Kai Fløistad
PGS

The southern Porcupine Basin and the north-eastern ends of the offshore Newfoundland basins (Jeanne d'Arc, Flemish Pass and East Orphan basins) were connected prior to the North Atlantic break-up (Figures 1-2). The main rifting stage occurred from the late Jurassic to the earliest Cretaceous with a further possible extensional phase during the Aptian-Albian. Similarities exist in the pre-break-up section of these basins with respect to tectonic evolution, sedimentation and stratigraphic thickness. Here, we look at innovative hydrocarbon plays for these basins, following a conjugate margin exploration approach.

Upper Jurassic to middle Cretaceous fluvial, nearshore and marine sandstones deposited during syn- to early post-rift intervals are well developed on either sides of the North Atlantic, as is the highly prolific Upper Jurassic (Kimmeridgian) oil-prone marine source rock. Most of the discoveries to date within these basins were made targeting syn-rift to early post-rift upper Jurassic to basal Cretaceous reservoir sandstones within traps showing a prominent structural component, where tilted fault blocks are the classical target.

The Porcupine, Jeanne d'Arc and Flemish Pass basins have yielded several discoveries within the rift-related Upper Jurassic to Lower Cretaceous sandstone reservoirs, totalling an estimated 5,670 MMBOE recoverable reserves. Discoveries on the two conjugate sides are predominantly oil-bearing, but also include gas discoveries. In the Jeanne d'Arc Basin over 20 fields have been discovered, including Hibernia (1,395 MMBL recoverable oil reserves), Terra Nova (506 MMBL recoverable oil reserves) and White Rose (309 MMBL oil and 3.338 TCF gas of recoverable reserves). Three significant Tithonian-age discoveries were made in the Flemish Pass Basin during the 2009-2013 period, including the world's second largest oil discovery in 2013 (Bay du Nord, estimated to contain 425 MMBL oil and 450 BCF gas recoverable reserves (Figures 1-2)). The three Porcupine Basin discoveries to date (within Upper Jurassic to Lower Cretaceous sandstone reservoirs) are in comparison smaller in size and have relatively lower permeability, due to deep burial diagenesis and a partly volcanic provenance (Figures 1-2).

The Aptian-Albian deltaic to shallow marine Ben Nevis Formation is a prominent reservoir target in the Jeanne d'Arc Basin, and the nearby Springdale Field contains commercial hydrocarbons in Palaeocene shelf sandstones. Time equivalent sand-prone deltaic wedges are developed in the northern Porcupine Basin, with many hydrocarbon shows. There is scope to extrapolate these Cretaceous to Palaeogene sandstones into the coeval deep-water settings, such as the southern Porcupine Basin and East Orphan Basin, further increasing the prospectivity of the North Atlantic conjugate margins. This overlooked deep-water sag to post-rift plays rely on hydrocarbon charging from the Kimmeridgian age source rock with migration paths mostly focused along fault surfaces. A potential alternative source rock is the mid-Cretaceous Oceanic Anoxic Event ('OAE') black shales, which could be sufficiently organic-rich and deeply-buried towards the basin depocentre to have generated hydrocarbons.

The PGS and TGS seismic data library enable to define potential post-rift turbiditic to deltaic sandstones onlapping or pinching-out on the flanks of the post-rift basins, forming prominently stratigraphic trapping configurations on both flanks of the Atlantic (Figures 3-4). The library includes older 2D and 3D surveys in the Porcupine Basin and the regional 2011-2013 GeoStreamer® 2D broadband seismic data in Eastern Canada (Figures 1-2). Several Cretaceous and Palaeogene reflections, with distinctive seismic amplitude anomalies, show discrete onlap against the basin flanks. Some potential deep-water fans and draped or mounded stratal geometries have also been highlighted (Figures 3-4).

This study reveals the similarity between the Canadian and Irish offshore basins of the North Atlantic conjugate margin and their prospectivity. The numerous shallower post-rift traps, predominantly stratigraphic, that have been identified are largely undrilled, and are likely to be the driver for future hydrocarbon exploration in these areas. Higher quality Broadband seismic is often required to improve imaging resolution to better define structure, seismic amplitude anomalies and prospects ready for drilling.

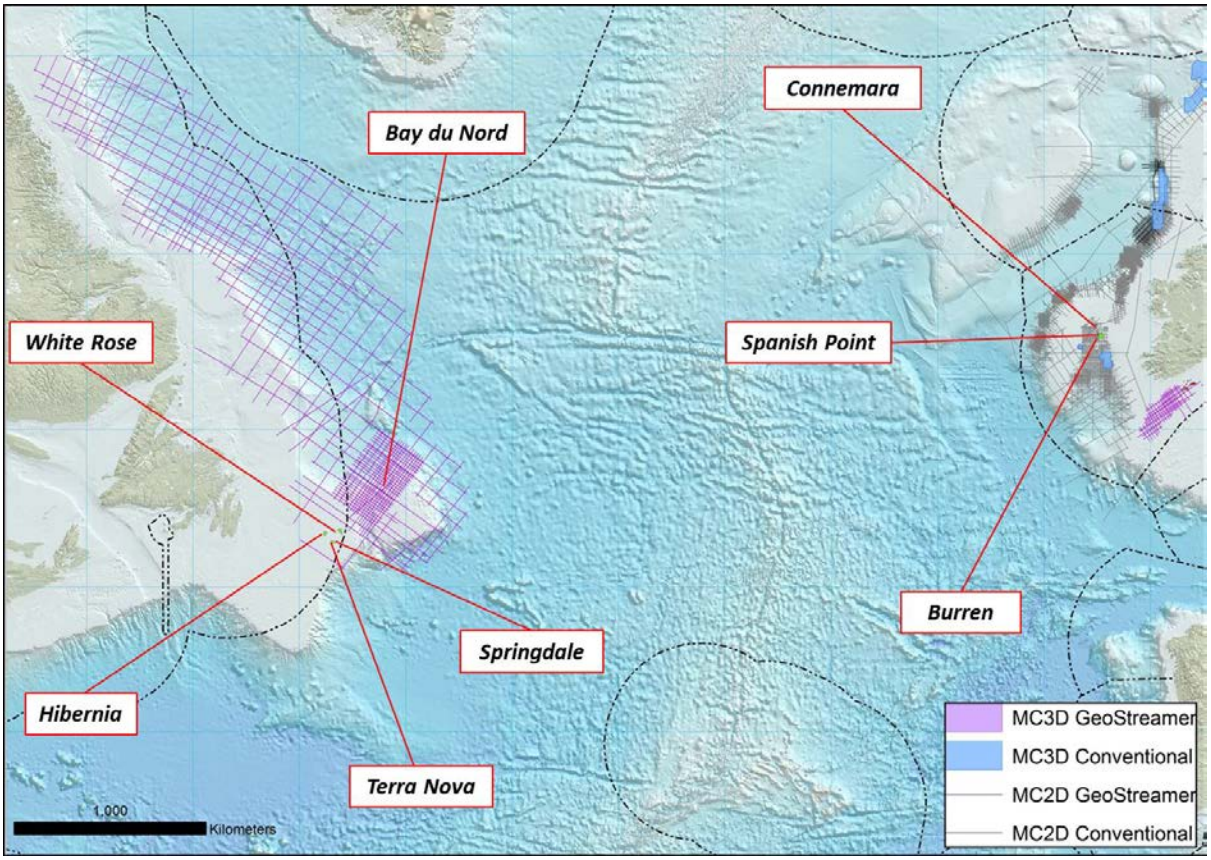

Figure 1: Study location map showing discoveries discussed in the text and PGS MultiClient library

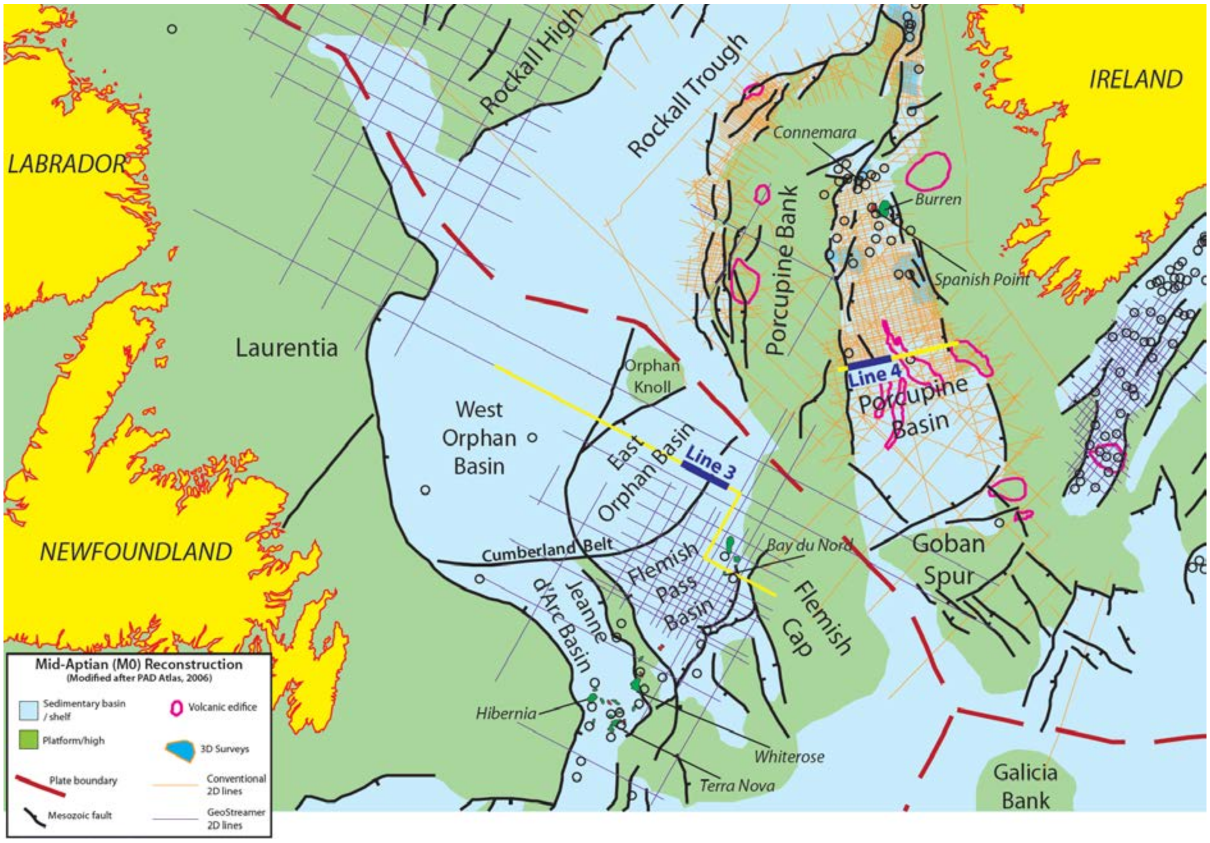

Figure 2: Middle Aptian plate reconstruction (after PAD Atlas, 2006). Main Mesozoic tectonic elements are shown, together with the hydrocarbon fields, the PGS seismic coverage and the position of the two lines shown by Figures 3 and 4.

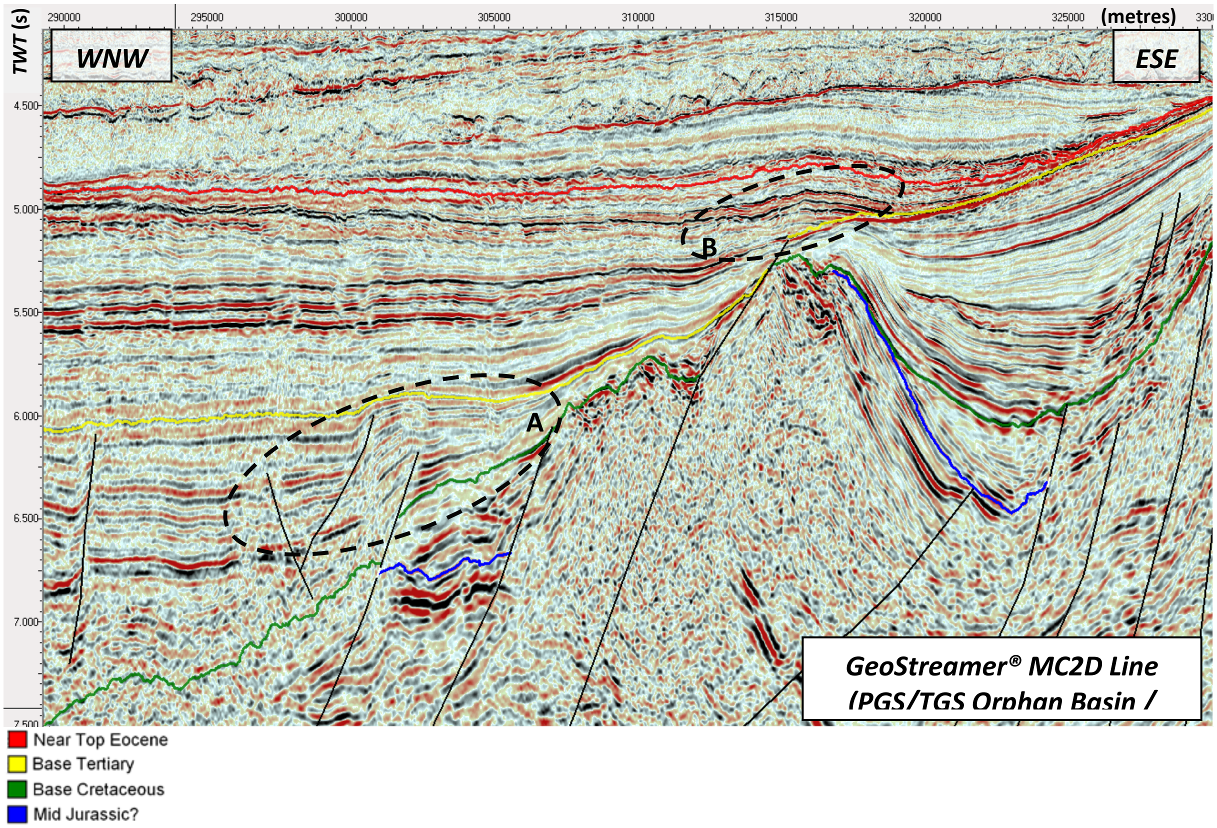

Figure 3: Post-rift play in the East Orphan Basin, Canada. See Figure 2 for line location. Potential high-amplitude reflection targets are highlighted: A) Lower Cretaceous pinch-out trap; B) Palaeogene structural-stratigraphic trap. These dominantly stratigraphic traps are located above tilted fault-blocks providing both additional reservoir targets and the Late Jurassic marine source kitchen.

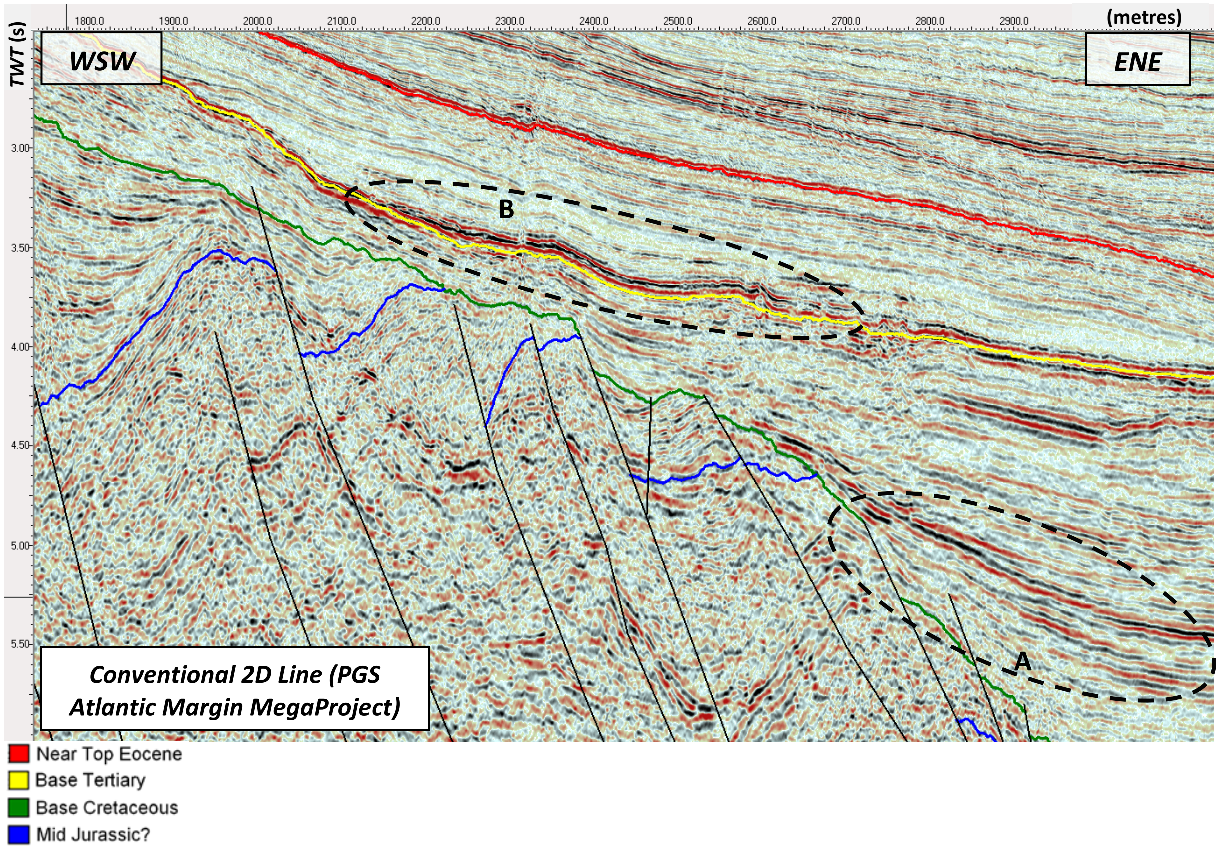

Figure 4: Post-rift play in the Porcupine Basin, West of Ireland. See Figure 2 for line location. Potential high-amplitude reflection targets are highlighted: A) Lower Cretaceous onlap trap; B) Palaeogene structural-stratigraphic trap. These dominantly stratigraphic traps are located above tilted fault-blocks providing both additional reservoir targets and the Late Jurassic marine source kitchen.

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Gravimetric framework of continental margin between the pernambuco and touros plateaus, northeast brazil

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Abstract

This work aimed to determine the main tectonic features of the continental margin between Pernambuco and Touros Plateaus, NE Brazil through combining gravity maps and digital terrain model data following the Airy-Heiskanen isostatic model to produce a comprehensive scenario of the stretched margin thickness and crustal limits. The study region corresponds to the last separation stage between South America and Africa, during the South Atlantic opening. The Free air anomaly map and digital terrain model show features of short to intermediate wavelengths related to the sedimentary basins structures and intracrustal heterogeneities. The Bouguer anomaly map shows a strong influence of long wavelength anomalies related to the crust/mantle interface. The depths of crust/mantle boundary, crustal thickness and the estimated map of crustal thinning rate allowed us to interpret how the rifting process (stretching and thinning) affected each sector of the continental crust. The results show clearly how the deformation of continental crust was mainly different between Pernambuco Basin and the basins in the northern sector (Paraíba and Natal Platform), and how the basins in the north also show differences in their characteristics. The different responses to the stretching process probably was influenced by crustal thickness/rheology of these different continental blocks, and also by the thermomechanical processes that actuated in south and north portions of study area.

Keywords: *Gravity maps, Pernambuco, Paraíba and Natal Platform basins, Crust/Mantle Boundary.*

Introduction

The continental basement adjacent to the study margin, which encompasses Pernambuco, Paraíba and Natal Platform basins (Figure 1), consists of Archean to Neoproterozoic gneissic complexes, granitic plutons, metasedimentary sequences and continental scale shear zones, forming the eastern edge of the Southern, Central and Northern Domains of the Borborema Province (Figure 1). An integrated analysis of this margin suggests that the tectonic styles developed in the Pernambuco Basin and in the Paraíba and Natal platform basins are different. This differentiation is observed in more expressive aspects such as the sedimentary cover thickness (including syn-rift and post-rift intervals) and the extension and form of the continental shelf break. Moreover, there are also clear differences in the structural control exerted by basement and by syn to post-rift magmatism. This paper presents a regional scale systematic analysis of gravity data to evaluate the structural/gravimetric behavior of crustal domains in the offshore region that make up the area, from the slightly affected zone of continental margin until the boundary with the oceanic crust **(COB)** (Figure 1). The **COB** was defined from integration of gravity, magnetic and seismic information.

Material and Methods

Free Air and Bouguer anomalies were compiled by the BGI-WGM project data, and the digital terrain model **(DTM)** was acquired from Etopo 1 project (Figures 2A, 2B and 2C, respectively). Initially the gravity data and the **DTM** were interpolated using the kriging method on a regular grid with 15 km spacing. Additionally, a map of the crust/mantle boundary depth **(CMB)** was obtained based on the isostatic compensation of topographic masses, using the Airy-Heiskanen isostasy model (Figure 2D). The map of crustal thickness **(MCT)** was obtained by removing the **DTM** from the **CMB** (Figure 3A). Using the **MCT**, we estimated the rates of crustal thinning **(RCT)**, assuming a standard thickness of 30 km for undeformed continental crust (Figure 3B). It was assumed that thicknesses less than 30 km indicate regions that suffered crustal thinning along the continental margin, until its limit at the **COB**.

Results

i) The Free Air Anomaly Map: the continental crust domain, along the continental shelf break has an important positive-negative gravimetric alignment. This shelf break shows a NNE-SSE trend in Pernambuco Basin and changes to NNW-SSE in the Paraíba and Natal Platform basins (Figure 2A). This structural vary orientation possibly is related to rheological variations of Borborema Province. Furthermore, in the Pernambuco Basin, the negative gravimetric anomalies highlights main depocenters, and the positive anomalies are related to structural highs of the basement and also magmatic intrusions. The beginning of the oceanic crust domain is marked by the presence of volcanic seamounts. Most volcanic seamounts are aligned in a E-W trend, indicating that the Precambrian structural fabric influenced the formation of transform faults and fracture zones, along which these structures has developed.

ii) The Bouguer Anomaly Map: shows an overall E-W gravity gradient roughly parallel to the continental margin, indicating an eastwards crustal thinning to the **COB** (Figure 2B). This pattern points to a strong influence of the **CMB** ascension to the regional potential field.

iii) The DTM Map: reveals a very narrow platform region at the Paraíba and Natal platform basins, and a broader extension at the Pernambuco Basin, until features related to volcanic seamounts in ocean crust (Figures 1 and 2C).

iv) MCT and RCT Maps: there is a 77% - 80% crustal thinning underneath the Pernambuco Basin closer to the **COB**, going from ca. 30 km in the undeformed regions to less than 10 km thick in the **COB** region (Figures 3A and 3B). The **COB** is positioned at approximately 140 - 150 km from the coast line in the Pernambuco Basin, corresponding to the largest extension of the thinned continental crust in the study area. In the Paraíba and Natal Platform basins the COB is located at approximately 85 km and 70 km, respectively, far from the coast line, it represents a very narrow continental margin region.

Discussion and Conclusion

The isostatic and gravity signatures of the Brazilian continental margin between the Pernambuco and Natal Platform basins indicate that this portion of the South Atlantic margin consists of two distinct regions in terms of crustal framework. Therefore, their evolution during the rifting process resulted in different continental platforms regarding to morphology and structural styles. In fact, these platforms are formed on three distinct crustal blocks, namely the Northern, Central and Southern domains. Those tectonic domains, regarding to thickness and rheology, could explain how these regions responded to the lithosferic thermomechanical processes imposed during the latter stages of rifting. The Pernambuco Basin shows a more stretched continental crust, which formed its plateau, and the Paraíba and Natal platform basins exhibit a narrow platform due a shortly stretched continental crust. The Natal platform is even narrower than Paraíba, and its shelf break is more abrupt. As a result, the potential for hydrocarbon exploration of the north and south sectors of study area are expected be different, concerning the extension of rift-related continental deposition.

Acknowledgments

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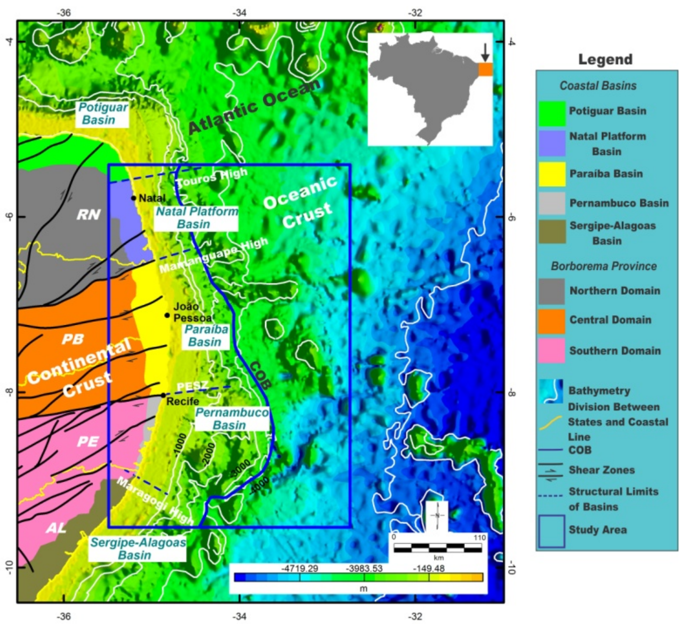

Figure 1: Tectonic framework of eastern border of the Borborema Province and adjacent continental margin. (PESZ - Pernambuco shear zone).

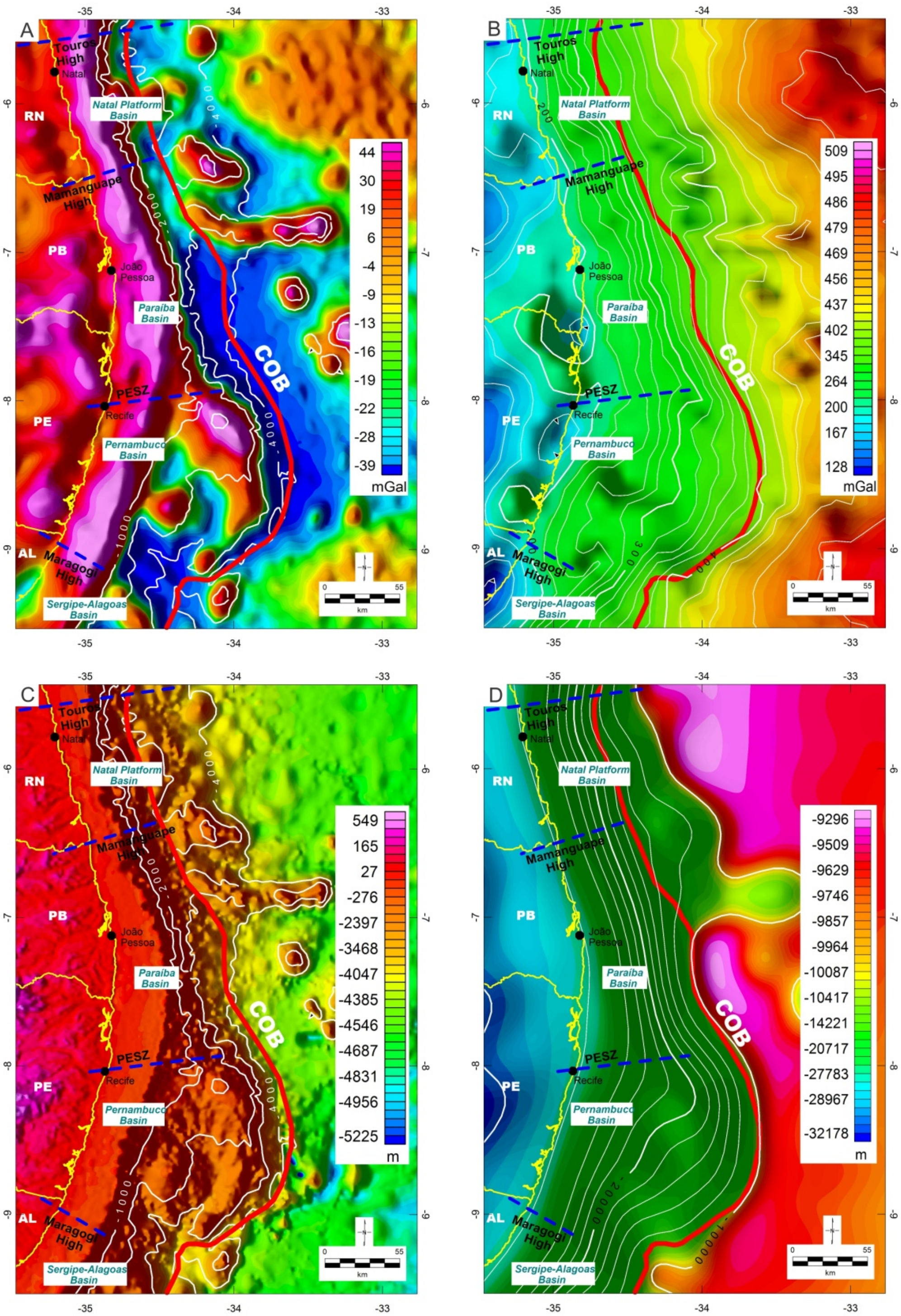

Figure 2: A) Free air anomaly map with contours of the bathymetry (contour interval: 1000 m). B) Bouguer anomaly map with contour interval of 20 mGal. C) Digital terrain model map (bathymetry with contour interval of 1000 m). D) Depth of crust/mantle limit map with 2000 m of contour interval. (Yellow line - coastal line and states limits; Dashed blue line - basins structural limits; PESZ - Pernambuco shear zone).

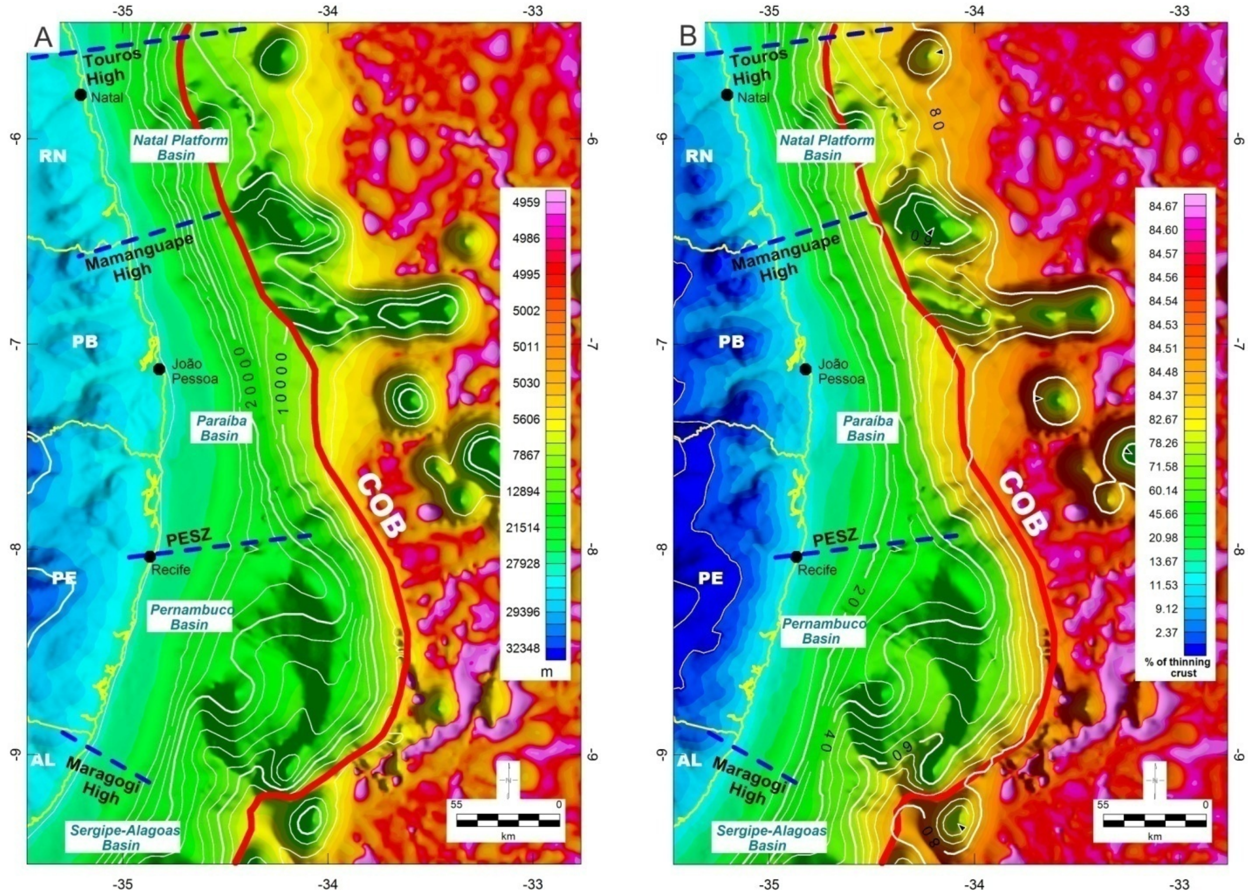

Figure 3: A) Crustal thickness map derived from the digital terrain model and crust/mantle boundary. The contour interval is of 2000 m; B) Map of estimated crustal thinning. The region with 30 km thickness was assumed as the limit of undeformed continental crust in the proximal region of coastal line. The contour interval is 5%. (Yellow line - coastal line and states limits; Dashed blue line - basins structural limits; PESZ - Pernambuco shear zone).

The Structural Framework of the Pernambuco Basin, NE Brazil.

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The Pernambuco Basin (PE Basin) located on the eastern part of the Borborema Province, Northeast Brazil. The Maragogi High bound it to the south the Pernambuco Shear Zone to the north. The basin is comprised of a narrow coastal zone and an offshore plateau above a stretched continental margin. Of the basin's 20,800 km^2 area, 98% is located offshore.

Despite several decades of research, the tectonic framework of the region and how it relates to it's conjugate margin, remains poorly understood. This study attempt to improve our understanding into the genesis and evolution of the basin by employing an integrated geophysical investigation. We use data from 2D seismic reflection lines and potential data (gravimetric and magnetic) to characterise the main structural domains as well as to give an estimation of principal depocenter depths.

Potential data allowed us to recognise several features. We see the division of the PE Basin into two portions; an internal basin separated from a larger offshore plateau by a structural high (the Maracatu High). Three lows (depocenters) were identified in the plateau, each of which are defined by surrounding highs. Regional gravimetric inversion maps were used to estimate depocenter depths. These depth were corroborated with an onshore stratigraphic well (CP-01-PE) which cuts through 2.98 km of sediment. Furthermore the depocenter depths were compared to estimations based on seismic data yielding a positive correlation. Depths of the different center ranged from 5 – 8.5 kms.

These interpretations allow us to start considering the burial and thermal histories of potential source and reservoir rocks currently being identified in sister projects and to start correlating our data with Pernambuco's conjugate margin.

Keywords: Structural Framework, Depocenters, Seismics, Potential Data.

The subduction-driven breakup of Pangaea with implication for the tectonic and thermal history of the central Atlantic basin between Nova Scotia and Morocco in the early Jurassic

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Plate tectonic principles state that a compensation relationship exists between extension zones and shortening zones at the surface of Earth through time. Cumulative amounts of extension and shortening experienced across the global network of plate boundaries must balance to zero for a non-expanding or non-contracting Earth. Here, it is reviewed how the earliest extension and rifting inferred in the central Atlantic domain was balanced by contemporaneous shortening and oceanic closure in the Paleo-Tethys and Tethys domains1,2. The Atlantic-Tethys compensation relationship has been implicit in kinematic compilations available for the past thirty years or more3, but explicit recognition of this relationship is new. In particular, acknowledgement of the Atlantic-Tethys compensation relationship departs from the widely-held misconception that closure of the Panthalassic domain acted as compensation for the rift breakup of Pangea. The tight link between the rotational kinematics of Paleo-Tethyan and Tethyan closure versus central Atlantic opening helps to explain several first-order, but heretofore enigmatic, geological observations documented for the breakup of the Pangean supercontinent. These include: (1) why rifting in the central Atlantic exploited the late Paleozoic suture zone between Laurentia and Gondwana, but (2) why reactivation of the Laurentia-Gondwana suture zone was limited to its axial extent south of the Avalon Peninsula of Newfoundland, Canada. Broadly, the trace of the Laurentia-Gondwana suture zone ran parallel to the Paleo-Tethys/Tethys subduction zone off southern Eurasia in the governing relative tectonic reference frame, and the extents of tectonic latitude spanned by the central Atlantic rift zone and closing Tethyan domains were equivalent. These tight kinematic relationships are hypothesized to diagnose the subduction-driven breakup of Pangea, as discussed in depth elsewhere2.

Results

The Jurassic stage poles governing net extension and opening between North America and Africa across the central Atlantic, on the one hand, and between net shortening and closure between southern Eurasia and Cimmeria before 180 Ma (and Africa after 180 Ma) across the Paleo-Tethys (and Tethys) domain, on the other hand, are shown to be almost coincident. Stage poles for Atlantic opening and Paleo-Tethys (Tethys) closure plot within southern European locations during the Jurassic and early Cretaceous. Critically, the poles lie in an intermediate position between the axial extents of the Atlantic and Tethyan deformation traces. Relative to the common rotation axes, the northeastern limit of the early central Atlantic rift zone is shown to correspond almost exactly to a tectonic latitude equivalent to the southwestern limit of the Paleo-Tethys and Tethys subduction zones. A tight geometric and kinematic link between the Atlantic and Tethys deformation zones is thus confirmed.

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The Porcupine Basin: an integrated geophysical and geological study

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Over the last 15 years, a new type of rifted continental margin has been identified where high degrees of crustal extension (hyperextension) occur but are not accompanied by significant magmatism (Whitmarsh *et al.* 2001). However, the crustal-scale tectonic processes that lead to hyperextension still remain poorly understood. The Porcupine Basin,part of the frontier petroleum exploration province west of Ireland, is underlain by thin to ultra-thin continental crust (O'Reilly *et al.* 2006) and is therefore an excellent natural field laboratory in which to investigate these processes. This basin may provide important insights into these processes because the degree of crustal extension is known to increase dramatically from north to south in the basin (Reston *et al*. 2004; Readman *et al*. 2005). A new research project will investigate basin structure from the Mesozoic to Cenozoic basin-fill sediments to deeper levels in the crust and upper mantle. The project will re-evaluate the crustal structure of the Porcupine Basin using wide-angle seismic data gathered in a collaboration between the Dublin Institute for Advanced Studies (DIAS) and the Helmholtz Centre for Ocean Research Kiel (GEOMAR) but not hitherto comprehensively analysed.

This will be accomplished by quantifying variations in crustal geometry and seismic properties both along the basin axis and across the basin towards mainland Ireland, using various geophysical and geological methods. The project will determine the stratigraphic response to varying amounts of tectonic extension and its potential impact on petroleum systems. An integrated crustal model for the region will be produced (including gravity, magnetic and seismic stratigraphic data from industry and government sources) as well as previous results from PIP-funded projects in this sedimentary basin, as well as other studies (Reston *et al*. 2004; Readman *et al.* 2005; O'Reilly *et al.* 2006).

The study will interrogate the formation and thermal history of the Porcupine Basin as an analogue for failed and successful rifts elsewhere. The thermal history of the lithosphere is likely to be very different to settings where a significant amount of magmatism occurs, with important implications for hydrocarbon source rock maturation. It will also help de-risk further exploration activity in the basin by providing a better understanding of how hyperextension evolves in the continental lithosphere.

The study will address a large and critically important gap in understanding of geological/geophysical processes in this region of the North Atlantic west of Ireland. The results will be of importance in understanding the interaction between the Earth's hydrosphere and lithosphere and for heat flow modelling studies for petroleum generation in other basins in hyperextended settings. On a regional North Atlantic scale the Porcupine Basin is crucial in understanding the kinematics of early Mesozoic basin development and plate tectonic linkages with conjugate eastern Canadian basins that are part of a frontier hydrocarbon province (Welford et al. 2012). The project will be an important preparatory step for future planned wide-angle seismic initiatives in the poorly understood southern Porcupine region (the Porcupine Seabight Basin (O'Reilly *et al.* 2010; O'Reilly *et al*. 2012) and also at a more regional scale, which will provide data to refine regional plate tectonic reconstructions of these North Atlantic conjugate margin basins.

The project, scheduled to begin in late 2014, is funded by the Irish Shelf Programme Study Group (ISPSG) of the Petroleum Infrastructure Programme (PIP).

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Diagenetic barite and sphalerite in middle Mesozoic sandstones, Scotian Basin, as tracers for basin hydrology

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Cementation of sandstone by minor late barite and sphalerite is widespread in the Scotian Basin at burial depths > 2 km, providing information on fluid flow in the basin. The texture and geochemistry of these minerals was analysed by scanning electron microscopy and electron microprobe on samples from conventional core. Barite and sphalerite post-date silica and carbonate cementation, occurring in veins or occupying secondary porosity. They occur with diagenetic chlorite, kaolinite, pyrite, titania minerals, kutnohorite and Mn-siderite.

This study relates barite and sphalerite to the salt-tectonic evolution of the basin, based on seismic interpretation, and to the thermal history of the basin, based on fluid inclusion studies. Barite is readily transported in basinal fluids >100 °C, yet is consistently a very late diagenetic mineral, implying that the source of Ba is due to late diagenetic breakdown of K-feldspars at 2–3 km depth, confirmed by co-variation of Ba and Rb in sandstones. Sulfur isotope data suggest that the SO_4^{2+} was derived from Argo Formation evaporites which include 1–7% anhydrite. Sphalerite is mobile only in saline formation water >140 °C and requires long-distance transport through sandstones with Zn-rich Fe-Ti oxides. Active detachment faults on salt welds provide pathways and a source of salt for migrating formation water. The particularities of source and transport of both barite and sphalerite allow the pathways of basinal fluids and their relationship to active salt tectonics to be inferred, providing indirect dating of the later stages of diagenetic paragenesis corresponding to times of hydrocarbon charge.

The provenance and petrography of Early Tertiary sandstones in the northeast Porcupine Basin

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Introduction

The Porcupine Basin, a north-south oriented deep-water basin offshore west of Ireland, is one of the largest sedimentary basins in the North Atlantic (Fig. 1). A thick succession of Cretaceous and Tertiary sediments was deposited in a general thermal subsidence setting, interrupted by periods of minor rifting and regional epeirogenic movements and overprinted by eustatic sea-level changes (Naylor and Shannon, 2011). Exploration wells in the north of the basin have encountered reservoir quality sandstones of Early Tertiary age. However, little is known about the provenance and petrography of these sandstones. Determining the source(s) of the sandstones will allow a more accurate re-construction of Tertiary palaeogeography, especially ancient drainage system scales and pathways, and will help constrain reservoir sand distribution and quality. Petrographic analyses assist with classification of the sandstones and will contribute towards identification of their potential reservoir quality.

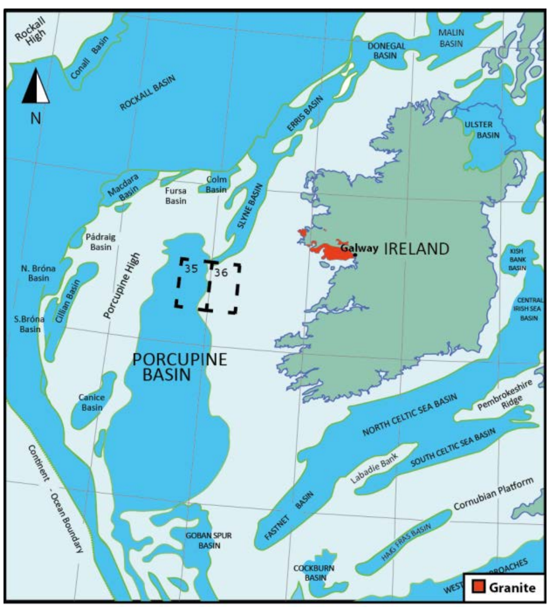

Figure 1: Map location of study area (quadrants 35, 36) in the northeast Porcupine Basin and the Galway granites, onshore Ireland (modified from Naylor and Shannon 2011).

Methods

Sampling

An initial review of proprietary composite well log data and petrophysical analysis (provided by Petrel Resources plc.) guided identification of the depths and thicknesses of target reservoir sandstones for sampling. A total of 19 sandstone cuttings samples (provided by the Petroleum Affairs Division of the Irish Department of Communications, Energy and Natural Resources) from the Early-Middle Eocene (deltaic and marine strata respectively) and Upper Paleocene intervals were analysed from five wells.

Petrography

The composition of the sandstones was analysed using standard optical petrography, scanning electron microscopy (SEM) - and energy dispersive x-ray spectroscopy (EDS). Visual estimation of the detrital constituents allowed classification of the sandstones, as well as estimates of the proportions of matrix-cement and framework grains to assess their potential reservoir quality.

Provenance: Pb in K-feldspar

The utility of the Pb isotopic composition of detrital K-feldspars as a provenance tool has been proven in a number of studies. This single-grain geochemical provenance technique was pioneered at University College Dublin (UCD), Ireland, and holds several advantages over similar provenance methods. Its application is appropriate to sandstones in the northeast Porcupine Basin due to its ability to constrain medium to-large-scale drainage systems (Tyrrell *et al* 2010; 2012). Feldspar grains are less stable in climates where chemical weathering outstrips mechanical weathering, and its presence is likely to indicate first cycle material, that can be related directly back to the source(s). Feldspars often represent a high proportion of framework grains (<25% in arkoses) and therefore source(s) can be ascribed to a significant proportion of the detrital sediment. In addition, feldspar contains Pb but insignificant uranium and thorium, hence there is negligible radiogenic growth within the crystal and Pb is largely unchanged since crystallisation of the feldspar in the source.

SEM analysis was used to identify and image detrital K-feldspar grains in the targeted sandstones. Pb isotope compositions were subsequently analysed by laser ablation multiple collector inductively coupled plasma mass spectrometry (LA-MC-ICPMS). The Pb isotopic signatures of the detrital feldspars were then compared with K-feldspar compositions from potential basement sources both onshore and offshore with a view to constraining sedimentary provenance.

Significant new Pb data from the Caledonian Galway granites on the west coast of Ireland were also collected via LA-MC-ICPMS, for comparison with detrital K-feldspar analyses. Existing data for the granites were sparse compared to other onshore sources, and systematic sampling of seven granitic plutons in the Galway area was carried out. Granite samples were analysed from the Errisbeg Townland (main), Errisbeg Townland (megacrystic), Roundstone, Carna, Shannaphaesteen, Costello Murvey (main) and Costello Murvey (porphyry) bodies. New data from these plutons helps constrain or exclude these granites as a source of detrital K-feldspar.

Results

Petrographic results

Petrographic analysis demonstrates that the Early Tertiary Porcupine sandstones are generally arkoses or lithic arenites, with greywackes at some intervals. Framework grains consist primarily of quartz (both mono- and polycrystalline varieties), feldspar (predominantly K-feldspar) and lithic (igneous and metamorphic) fragments. Fossil fragments are also common and nummulites are abundant in the Eocene marine sandstone units. Diagenetic components include pore-filling calcite cement, glauconite and pyrite. The general mineralogical composition of the sandstones is similar, but their proportions vary both laterally between the wells and with depth in stratigraphic units.

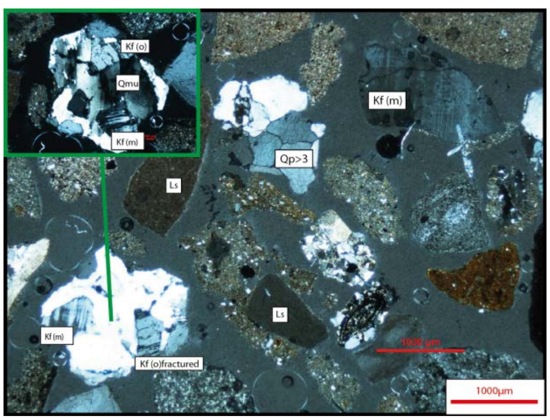

Figure 2: Photomicrograph of the Eocene marine sandstones showing Qmu (monocrystalline undulatory quartz), Qp>3 (polycrystalline quartz), Kf ((m) – microcline and (o)- orthoclase) and Ls (sedimentary lithics). Insert focuses on a sedimentary rock fragment.

In addition, the results of petrographic studies indicate the dominance of orthoclase in the majority of samples (Fig. 2), with microcline and plagioclase present at some stratigraphic levels. These trends are likely linked to the provenance of the K-feldspars and reflect the compositional nature of their source(s).

Provenance results

Pb isotopic data from detrital K-feldspars reveal five isotopic populations within the Eocene sandstones (Fig. 3). Populations 1, 2 and 3 are major, distinct populations which are consistently present in both marine and deltaic sandstone strata. Two additional sub-populations 2a and 2b occur in the Eocene deltaic sandstones. These are subordinate populations and appear to be related to Population 2.

Population 1 has a Pb composition similar to Proterozoic crystalline basement sources such as the northern part of the Porcupine High, offshore Ireland. Population 2 represents the largest proportion of K-feldspars (75%) analysed and Populations 2, 2a and 2b correspond well with new data from the volumetrically significant Caledonian Galway granites, on the west coast of Ireland. The source of Population 3 is currently uncharacterised; however the Pb signature is similar, yet isotopically distinct, from some granitic plutons in Galway. Pb signatures from Costello Murvey (main and porphyry), Roundstone and Shannaphaesteen granites overlap partly with populations 2 and 3. However, Population 3 is generally more radiogenic, and the linear trend defined by the data differs from that of the Galway granites.

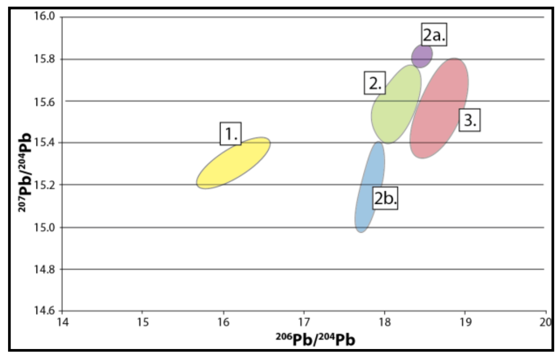

Figure 3: Detrital Pb populations from Tertiary K-feldspars in arkosic sandstones, shown on $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ scale. Several distinct populations (1, 2 and 3) and sub-populations (2a and 2b) are highlighted.

Preliminary data from Paleocene sandstones suggest that these share many of the same sources as the Eocene sandstones, indicating some continuity of sediment supply. However, Population 3 grains have so far not been identified in Paleocene sandstones, and there are indications of additional, as yet unclassified, populations at these levels.

Discussion

Several distinct K-feldspar populations are present in the Eocene sandstone samples and the relative and spatial distribution of these populations in each of the five wells suggests at least two sediment input directions. Previous studies have characterised north-south prograding fan structures in the north of the basin during the Tertiary. It is suggested that sediment generated from the Galway granites onshore in Ireland (Population 2/2a/2b grains) was transported westwards across the shelf to an entry position in the north of the basin, prior to southward dispersal down the basin axis. This dispersal pathway could also account for the presence of Population 1 grains. Interestingly, the higher proportion of Population 3 grains in wells adjacent to the east margin of the basin suggests a local source, and may be indicating derivation laterally into the basin from an as yet uncharacterised crystalline basement source on the continental shelf, east of the study area.

This work is part of an MSc research project funded by Petrel Resources plc.

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A stratigraphic study of the Labrador Sea

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TGS has conducted a sequence stratigraphic and depositional environment evaluation of the Labrador Sea. Well log data for 31 wells across the Hopedale, Saglek and St Anthony Basins was interpreted along with a regional 22,000km multi-client 2D seismic data set acquired in 2011-2012 (figure 1).

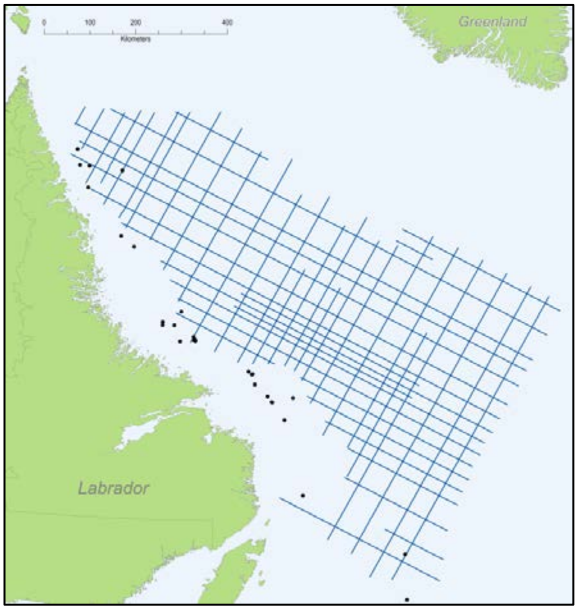

Figure 1: Study Area

The study was undertaken as part of a regional seismic facies and play fairway analysis project. The results have provided new insights into the structural and stratigraphic evolution of the area and allowed the distribution of both proven and potential petroleum elements to be mapped, both on the shelf and in the deeper basins.

Sixteen 2nd order and thirty three 3rd order sequences have been interpreted, ranging from Paleozoic to Recent in age. The sequences were defined from a petrophysically processed well data set and correlated to the seismic data.
The well log responses, lithologies and available biostratigraphic data were used to determine the depositional environments and facies for each sequence, constrained by seismic interpretation and core log descriptions where available. The distributions of these environments and facies were then interpreted across the study area.

Seismic facies analysis was used to extend the interpretation beyond well control on the shelf and identify potential reservoir, seal and source distributions in the deeper water basins. Temperature modelling was also used to determine source rock maturity and risk on hydrocarbon charge.

The study has combined all the selected relevant public data into one interpretation and is delivered in an integrated environment. Wells were standardized, sequences interpreted, and, once depositional environment and facies were allocated, multi-element maps have been drafted showing how the basin changed with time and structural evolution.

Recent drilling success in the Flemish Pass Basin has renewed interest in hydrocarbon exploration in the Labrador Sea. Understanding and mapping the variations in regional facies distributions, such as those identified in this study, can be a key exploration tool in relatively underexplored basins.

Plate Tectonics and Organofacies: Mapping Jurassic Source Rock Types and Yields in the Palaeo-Contiguous North Atlantic

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Abstract

The early stages of continental rifting and break-up of the North Atlantic between the late Triassic and Early Cretaceous resulted in the development of sedimentary basins which were episodically connected to, or remained isolated from, oceanic circulation. The source rock geochemistry can imply depositional environments and help understand whether these rift basins were connected to oxygenated oceans, or remained (at least partially) restricted, promoting anoxia and the preservation of organic matter. We use three large geochemical datasets in the Norwegian North Sea, Porcupine Basin and the Grand Banks, together with sparse information from the Morocco, West Iberia and Nova Scotia margins, to compare Jurassic source rocks and estimate potential hydrocarbon yields across North Atlantic conjugate margins in the context of kinematic reconstructions. In the Lower-Mid Jurassic, the combined analysis of kerogen quantity (TOC), type (algal Type I, bacterial-algal Type II or terrigenous plant Type III) and molecular fingerprints (biomarkers), suggests the deposition of a regional, non-marine source rock across the present day Atlantic conjugate margins, in restricted (or partially-restricted) basins in a hypersaline or stratified environment. These rocks are characterized by the presence of Gammacerane, reduced C_{28}/C_{29} steranes and distribution of C_{29}-$C_{34}\alpha\beta$ hopanes in the Porcupine Basin (Ireland), Celtic Sea (UK), Iberia & Morocco and appear to positively correlate to oil/bitumen samples from Nova Scotia and Portugal. In the Upper Jurassic, the North Sea, Jeanne d'Arc and Flemish Pass basins are judged to have remained as restricted based on organofacies, the Porcupine Basin as semi-restricted, while the Rockall Trough and associated West and East Orphan Basin rifts form a more oxygenated link between the Boreal and Central Atlantic seas. In the Jeanne d'Arc Basin, an increase in algal macerals (Type I kerogen) and TOC in the upper sections of the Upper Jurassic Rankin Fm. (Egret Mbr) may be related to a westward jump of the Orphan Basin rift axis, leading to the apparent isolation of the Jeanne d'Arc Basin. Other rifts such as the Whale Basin appear to remain connected to the Central Atlantic and hence remain oxygenated. This tectono-geochemical model allows prediction of source rock quality in the more sparsely drilled or undrilled areas of the North Atlantic.

Introduction

The analysis of conjugate margins when appraising data-deficient basins is a powerful tool for evaluating petroleum potential in prospective areas. For example, the emerging new plays offshore Brazil have been used as proxies for new exploration targets in the conjugate margin of Namibia (Mello et al., 2012). Understanding the geochemistry of source rocks in the context of plate tectonics is crucial when evaluating the exploration potential and risks in frontier basins, such as the Labrador margins and the deep offshore realms off Morocco, West Iberia and Nova Scotia, where there remains uncertainty about the quality, maturity and presence of Mesozoic source rocks.

This study aims to compare source rocks between different margin segments and across conjugate margins by quantifying the hydrocarbon potential of regional source rocks (Fig. 1) and extrapolating this information into conjugate margins in order to help utilise more statistically-significant source rock properties for future exploration.

Database

In the Grand Banks (Canada) the interpretation is based on a large geochemical database which includes publically available data from the Jeanne d'Arc, Flemish Pass, Horseshoe, Carson and Whale basins (IGI's 2014 Grand Banks Database comprising 22,105 rock & 150 oil samples). This is used together with other large geochemical databases from the Norwegian North Sea (7,558 samples) and Porcupine Basin, offshore Ireland (1,177 samples). Sparse data from the Morocco, West Iberia and Nova Scotia margins place further constraints on the regional variation across the palaeo-contiguous North Atlantic and adds credence to published kinematic reconstructions.

We further explore the Grand Banks database, which comprises data from a wide range of analytical techniques, from basic source rock screening and maturity analysis (Rock-Eval, visual kerogen, vitrinite reflectance, etc) to medium-resolution analyses such as gas chromatography and carbon-isotope analysis, to characterise the source rock types and depositional environments.

North Atlantic Kinematics

The North Atlantic margins and peripheral rift basins (e.g. Jeanne d'Arc, Porcupine, Rockall Trough, North Sea Basins) formed through a sequence of extensional pulses interspersed with periods of tectonic quiescence between the Triassic and Late Cretaceous (Ziegler and Cloetingh, 2004).

As a result of this complex tectonic history, rift basins were episodically restricted from oceanic circulation which may have resulted in anoxic conditions favoring the preservation of large amounts of organic matter and the development of regionally significant source rocks. The Rankin and Kimmeridge Clay Fms. are two extensively documented examples of Upper Jurassic deposits, dominating the source-charge in most of the petroleum fields in the Jeanne d'Arc and North Sea basins, respectively (Fowler and McAlpine, 1994; Cornford *et al*. 1998). Though isolated, the Upper Jurassic North Sea rifts were connected to the Boreal Sea to

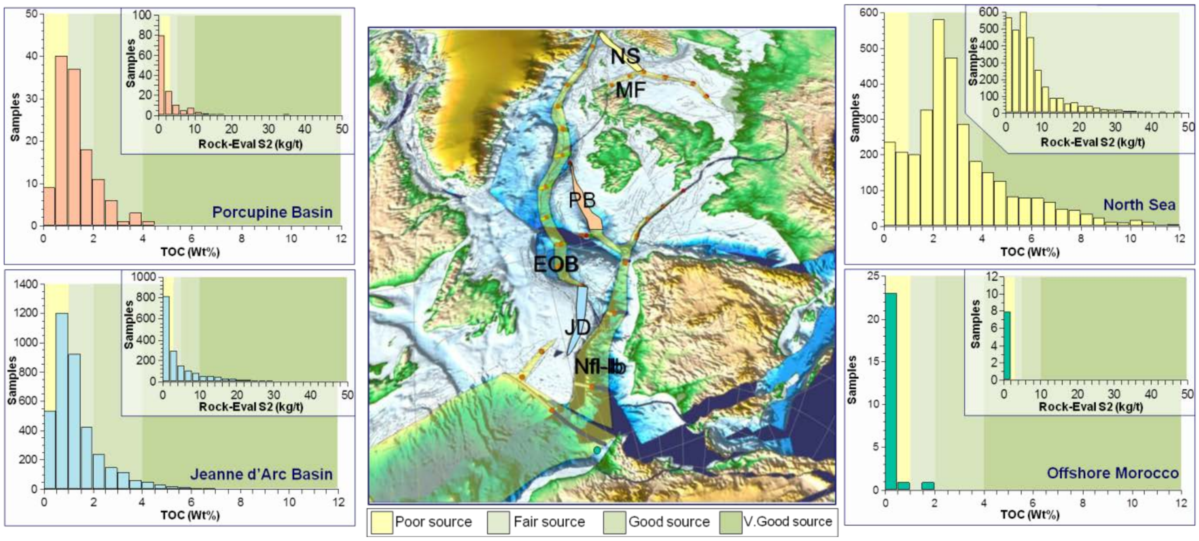

Figure 1: *Hydrocarbon richness (TOC) and yield (Rock-Eval S2) for Upper Jurassic samples in the Porcupine (top left), Jeanne d'Arc (bottom left), Norwegian North Sea (top right) and Offshore Moroccan (bottom right) basins, from IGI's multi-client databases (see References). The palaeotectonic reconstruction at 160Ma is taken from Skogseid et al. 2010: EOB – East Orphan Basin; JD – Jeanne d'Arc Basin; MF – Moray Firth; Nfl-Ib – Newfoundland – Iberia; NS – North Sea; PB – Porcupine Basin*

the north, while the Porcupine and Rockall troughs were potentially a more open seaway connecting the Boreal and Tethyan provinces (e.g. Skogseid 2010) at this time. Thus these marine grabens and troughs can be defined as 'restricted' (North Sea, Moray Firth, Jeanne d'Arc basins), or as 'connecting' (East and West Orphan Knoll Basins, Rockall Trough, Porcupine Trough and ultimately the Newfoundland-Iberia Basin).

In contrast, rifting and break-up in the central Atlantic occurred over a single extensional phase during the Late Triassic-Early Jurassic (Sahabi *et al.* 2004), resulting in an open marine, oxygenated depositional environment in the Morocco and Nova Scotia margins.

Upper Jurassic

In the Jurassic and Cretaceous seas of the proto-North Atlantic, preservation (high sedimentation rates, sea bed anoxia) rather than photic-zone bioproductivity seems to control the amount and type of kerogen accumulated (Cornford, 1998). In summary, productivity was adequate for oil-prone source rock accumulation if conditions favored preservation (e.g. anoxia). Figure 1 compares the Upper Jurassic TOC and Rock-Eval S2 yields ("pyrolysate -yield") from samples in the Jeanne d'Arc Basin, Porcupine Basin, Norwegian North Sea and Offshore Morocco using our databases.

There is a good correlation between the TOC (amount) and S2 (kerogen type) distributions in the Jeanne d'Arc and Porcupine Basins, which suggests that the Jeanne d'Arc and Porcupine Basins were partially restricted basins with mean TOC values between 3.00 to 4.75wt%. Despite these similarities, these two basins remained essentially unconnected during the Upper Jurassic, with the Jeanne J'Arc basin closed to the south and the Porcupine closed to the north (Skogseid, 2010). Analogous depositional conditions during this period in the East Orphan, Celtic Sea and Western Approaches Basins suggest that comparable Upper Jurassic organic-richness to the partially-isolated Porcupine Basin may be present here. The Norwegian North Sea has a higher mean TOC value of 5.50% which is likely to reflect the higher degree of bottom water anoxia (preserving organic matter) resulting from a restriction in water circulation associated with extreme distance to open marine waters in the north.

A large sample set of Upper Jurassic carbonaceous shales from the Rankin Fm. (and Egret Mbr) in the Jeanne d'Arc Basin has been used to characterize the quality and quantity of the source rock on the western conjugate margins. Traditionally the Rankin Fm. is described as dominated by Type II kerogen (Fowler and McAlpine, 1994).

Once corrected for maturity, the Rankin Fm. has an average TOC_i of 3.0-3.2wt%, a Rock-Eval $S2_i$ yield of 15-20kg/t, and initial Hydrogen Indices (HI_i) values between 500-550mg/gTOC in the Jeanne d'Arc Basin, indicating a highly oil-prone kerogen. These yields lie between those of partially-connected Upper Jurassic basins such as the leaner Porcupine Basin (TOC_i of 2.8-3.5wt%, $S2_i$ of 9-12kg/t and HI_i of 300-550mg/gTOC), and the richer and closed Norwegian North Sea (TOC_i of 5.0-5.5wt%, $S2_i$ of 22-28kg/t and HI_i of 450-550mg/gTOC).

In Figure 2 we compare the Upper Jurassic Rankin Fm. (Jeanne d'Arc) & Mandal Fm. (Norwegian North Sea) kerogen type using a bulk analysis, Rock-Eval (to derive HI and T_{max}) together with an a subjective visual kerogen analysis.

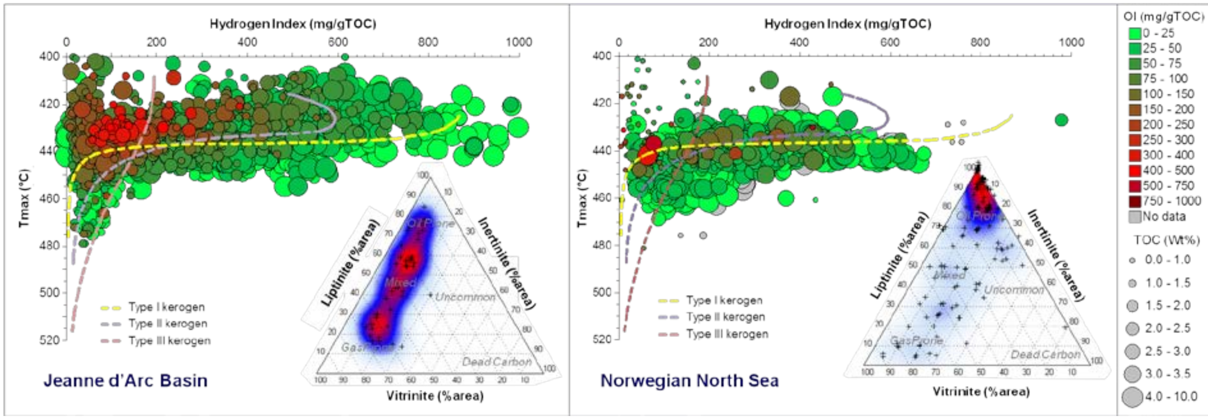

Figure 2: *Evaluation of kerogen type using Hydrogen Index (HI) and Oxygen Index (OI) as bulk-indicators of oil-proneness against Rock-Eval Tmax (maturity) and visual kerogen analysis (inset) in the Upper Jurassic Rankin Fm. (Jeanne d'Arc Basin) & Mandal Fm. (Norwegian North Sea). The visual kerogen colour represents sample density. The Rankin Fm. distribution is largely due to kerogen type while the Mandal Fm. is due to a more dominant Type II kerogen with increasing maturity. All data is sourced from IGI's 2014 Grand Banks Database (see References) & graphs from p:IGI-3© & MatLab©*

The Lower Rankin Fm. is dominated by a mixture of Type II (planktonic/algal) and Type III (higher plants) kerogen, whilst the upper Rankin Fm. becomes increasingly-rich in Type I (algal) kerogen (HI >650mg/gTOC); particularly towards the centre and north of the basin. This may indicate that during the Late Jurassic the deposition conditions changed from a marine environment (but with high terrestrial input from land plants growing on the basin margins) to an increasingly restricted marine environment where preservation of the bacterial-algal component dominated.

In the kinematic reconstruction of Skogseid (2010), this period corresponds to a westward jump in the rift axis from the West Orphan Basin to the Flemish Pass basin. This 'jump' is confirmed by the dominantly Type II/III kerogen seen in the Porcupine Basin and thus predicted for its southerly extension as the East Orphan Basin (Figure 1).

Since most analyses derive from drill cuttings samples over meter-scale intervals, HI values reflect the mean kerogen type in the composite sample. The database highlights that (and arguably connecting to the Boreal Sea), would lead to well-oxygenated, open marine conditions which are less prone to source rock deposition. The low TOC and S2 values shown from our sparse data most likely result from aerobic bacterial consumption at the sediment surface (Parrish, 1995) despite high photic zone phytoplankton productivity (Cornford, 1998). For this reason the source quality of Upper Jurassic sediments offshore Morocco (Cornford 2014) and Iberia (Spigolon *et al.* 2010) are likely to be generally poor except in isolated sub-basins.

The implications of using the incorrect kerogen type (e.g. Type II rather than a Type and Type III mix) in kinetic models can significantly affect the timing of generation and hydrocarbon quality (e.g. GOR). We suggest a careful consideration of kerogen-type is fundamental to properly appraising the source potential in North Atlantic basins.

the Rankin Fm. kerogen is dominantly composed of a bimodal Type I/II kerogen (HI of 550-900mg/gTOC) and Type III kerogen (HI <250mg/gTOC). We suggest that the average 500mg/gTOC HI value is likely to be composed of both a liptinitic and vitrinitic component (Figure 2, insets), giving a composite HI value between 300 – 700mg/gTOC. The HI *vs.* T_{max} plot (Figure 2) shows a wide variation which largely reflects kerogen type (confirmed by decreasing OI with increasing HI) and not maturity (i.e. the T_{max} axis)).

The geochemical database also highlights differences between sedimentary basins within the Grand Banks. The highest TOC samples (>2wt%) are restricted to the Jeanne d'Arc and Flemish Pass basins, inferring a greater degree of marine isolation than the Whale, Carson and Horseshoe basins which have most TOCs below <1wt% and are therefore thought to be open to marine circulation.

Extensive rifting and subsidence offshore Morocco and Iberia by the Upper Jurassic and the subsequent development of an open seaway to the Central Atlantic basin and Tethys Ocean

Lower/Middle Jurassic

Regional Lower and Middle Jurassic source rocks in the Atlantic margins have been discussed by several authors (Monnier *et al.* 2010; Spigolon *et al.* 2010; Scotchman *et al.* 2001) but are still poorly constrained with respect to quantitative source rock quality values such as TOC, S2 (hydrocarbon yield) and HI. 477 Lower Jurassic and 1,655 Middle Jurassic samples have been characterized based on TOC, Rock-Eval and visual kerogen analysis from 24 wells within the IGI's 2014 Grand Banks database across a 500,000km^2 area.

The presence and quality of regional Lower to Middle Jurassic source intervals is unclear due to poor sample availability, high maturity when sampled offshore and exploration wells terminating in younger sediments. However the presence of a Lower to Middle Jurassic source

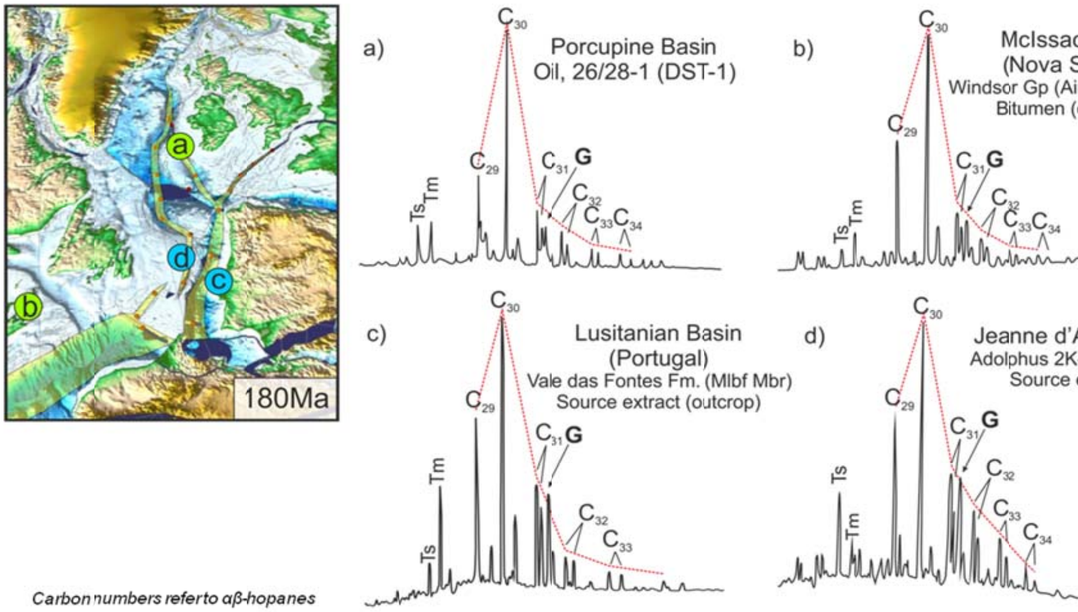

Figure 3: *m/z191 chromatograms (GC-MS) representing terpane distributions showing an excellent correlation between Lower/Middle Jurassic source extracts from the Lusitanian & Jeanne d'Arc basins (c & d) and oil/bitumen samples from the Porcupine Basin and Nova Scotia (a & b). Note the presence of gammacerane ("G") in all samples as well as the common relationship of* C_{29}-$C_{34}\alpha\beta$ *hopanes suggesting that fluids are at least partly charged from a Lower-Middle Jurassic source. GC-MS chromatograms are taken from a) Scotchman, 2001, b) Fowler et al. 1993, c) de Oliveira et al. 2006, d) NRC BASIN database. The palaeo-tectonic reconstruction from Skogseid et al (2010) at 180Ma is shown for context*

has been supported by a strong geochemical correlation between source extracts and oil/bitumen samples throughout the North Atlantic margins (Fig. 3).

Biomarkers can provide useful environmental indicators (Fig. 3), with Lower-Middle Jurassic source rock extracts characterised by the presence of gammacerane (associated with stratified and often hypersaline, restricted environments), a C_{28}/C_{29}-sterane ratio below 0.7 (Middle Jurassic and older sources) and the absence of 28,30-bisnorhopane (a compound common in Upper Jurassic source extracts). These biomarker interpretations are consistent with kinematic and palaeo-environmental reconstructions in the Jeanne d'Arc, Porcupine and Lusitanian Basins during the Lower to Middle Jurassic (e.g. Skogseid *et al.* 2010, Sibuet 2012).

The good correlation between Iberian and Nova Scotian source extracts (Fig. 3) could indicate that conditions ideal for source rock formation during this period were replicated over the North Atlantic margins, and may extend as far north as the Porcupine Basin and Slyne Trough (Scotchman, 2001) and west as far as Nova Scotia. The presence of a Lower to Middle Jurassic non-marine source rock has positive implications for future exploration in the North Atlantic, particularly in areas where an Upper Jurassic source is absent or immature.

Once Lower Jurassic samples of the Grand Banks are corrected for maturity using the method of Peters *et al* (2006) the initial TOC (TOC_i) values range from 0.2-3.2wt% with a mean initial value of c.2.5wt%, the HI_i values range between 20-250mg/gTOC and Rock-Eval $S2_i$ yields vary between 0.1-12.5kg/t with a strong vitrinite-rich (gas-prone) kerogen. The kerogen appears mixed with a strong component of non-generative Type IV (inertinite-rich) while organic-rich samples (>1% TOC) contain higher HI values, up to 300mg/gTOC. However these organic-rich samples account for only c.10% of available geochemical samples and are distributed widely across the Grand Banks.

Middle Jurassic samples have corrected TOC_i values between 0.2-5.2wt% (plus two coal samples) with an average value of c.2.0wt%. HI_i values between 0-800mg/gTOC while a mean HI value of c.300mg/gTOC indicates some mixed oil & gas proneness. The $S2_i$ values range up to 51kg/t with a mean value of ~6kg/t, this inferring good oil source rock yields within organic-rich intervals.

However, like the Lower Jurassic samples, the organic rich samples (>1% TOC) comprise only about 10% of the available geochemical samples and again appear to show this distribution across the whole Grand Banks. When combined with the very low source quality of the remaining 90% of samples (low TOC & Hydrogen Index and high Oxygen Index), the implied environmental reconstruction suggests a high sediment-input from a terrestrial source (Type III/IV kerogen) leading to TOC 'dilution'. Periodic phases of hypersaline lacustrine deposition in a syn-rift setting accounts for the sporadic presence of oil-prone Type I or Type IIS kerogen.

Discussion

A comparison of geochemical databases from the Grand Banks, Porcupine Basin and North Sea can be related to plate kinematic reconstructions of the North Atlantic rift and breakup.

Upper Jurassic sources rocks are the major producers of hydrocarbons in the Atlantic margins, with the best quality source rocks accumulating in 'restricted' basins and poorer (or non-source) rocks accumulating in 'connecting' narrow seaways. The geochemistry indicates that the North Sea Central Graben, Flemish Pass and Jeanne d'Arc basins had prolonged periods of marine isolation which promoted anoxic conditions and hence increased organic preservation which are commonly associated with the deposition of algal (Type I) and/or algal-bacterial (planktonic, Type II) precursor kerogens with high oil-generative potential. The Jeanne d'Arc and Flemish Pass basins also had significant woody terrestrial input from eroding sub-aerial continental blocks such as the Flemish Cap and Nova Scotia which resulted in a gas-prone Type III kerogen component.

The tectonic history of Lower-Mid Jurassic evaporite-hypersaline conditions followed by restricted marine Upper Jurassic (before fully open marine conditions are established) means where the Upper Jurassic sourcing is absent or immature, there is increasing evidence of an older Lower-Middle Jurassic, non-marine source below.

Partially connected basins, such as the Porcupine and Western Approaches, may have encountered periodic marine isolation events favoring the preservation of organic matter in dysoxic conditions and are commonly characterized by Type II and Type III kerogen with some oil and gas generative potential. Contrastingly, connecting basins would lead to prolonged periods of well-oxygenated marine environments, and thus poor source rock forming environments (e.g. offshore Iberia/Morocco and Rockall Trough).

The wide-spread correlation between Lower to Middle Jurassic source rock extracts and fluids across the North Atlantic indicates that a source rock deposited in a hyper-saline, restricted environment may be a regionally-significant petroleum source rock. Although in the Grand Banks the available rock data suggests that this earlier source is not as organic-rich or oil-prone as the Upper Jurassic carbonaceous shales.

However, the lateral extent, stratigraphic position and thickness of the Lower to Middle Jurassic sources may make previously disregarded petroleum plays a target for future exploration, not only in mature basins, but in developing basins too.

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East Coast Canada, Grand Banks, 2014. IGI Ltd.
Norwegian North Sea, 2014. IGI Ltd.

Development of the conjugate margins of Canada and Greenland after the opening of the Labrador Sea: implications for hydrocarbon prospectivity

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East-west symmetry across Baffin Bay: evidence for uplift after Paleogene breakup

The mountainous areas of Canada and Greenland on either side of the Davis Strait and Baffin Bay, show significant east-west symmetry (although the gentle, inland slope of the Greenland mountains is covered by the Inland Ice); cf. Figs 1, 2 (Japsen et al., 2012; Oakey and Chalmers, 2012). Mountains reach ~2 km above sea level (asl) and are characterized by elevated plateaux that dip gently away from the ocean whereas the descent towards the ocean is commonly much steeper; Fig. 3 (Bonow et al., 2006; Kleman, 2008).

Offshore of these mountains, Paleogene and older strata dip away from the coast and are truncated below late Cenozoic strata as illustrated by Figure 4 (Chalmers, 2000; Japsen and Chalmers, 2000; Kleman, 2008; MacLean et al., 1981). Paleogene volcanic and sedimentary rocks are exposed onshore on both sides of Davis Strait (Dam et al., 2009; Harrison et al., 2011). A thick Paleogene volcanic sequence that accumulated during subsidence after oceanic breakup in the Paleocene contains marine deposits at elevations up to 1.2 km asl (Oakey and Chalmers, 2012; Piasecki et al., 1992) is exposed on Nuussuaq, West Greenland. Paleogene marine sediments are also exposed on Bylot Island, eastern Canada (Miall et al., 1980), and Cretaceous–Paleogene basins and outliers crop out on the margins around Baffin Bay.

The presence of post-breakup, marine sediments on both margins shows that they subsided after continental breakup and that they were subsequently uplifted. The truncation of Paleogene strata towards the coasts on either side of Baffin Bay indicates that the uplift happened in the Neogene.

High-level plains cutting across Paleocene basalts: evidence of mountains shaped long after breakup

Bonow et al. (2006) mapped extensive, high-level planation surfaces in West Greenland that truncate Paleocene basalts and argued that the surfaces had formed by erosion to the level of the adjacent ocean long after breakup, and that they had been subsequently uplifted to their present-day elevation. Japsen et al. (2006) used apatite fission-track analysis (AFTA) to conclude that the upper of these planation surfaces formed during the Oligo–Miocene and that it was uplifted in two events, one in the late Miocene and one in the Pliocene. Consequently, the present-day mountains in West Greenland were shaped in the late Cenozoic, about 50 million years after breakup between Greenland and America.

The stratigraphic evidence on these conjugate margins indicates that Baffin Island (and perhaps Labrador) has experienced a similar style of episodic development to that documented in West Greenland. The presence of elevated plateaux on both margins is another indication of the similarity of the development of these margins after breakup.

Synchronous development of the conjugate margins? Investigation of the burial, uplift and exhumation history

To what extent the development of the conjugate margins was synchronous remains to be investigated. We have demonstrated how an integrated analysis based on three independent datasets can define the detailed history of burial, uplift and exhumation of a number of other margins (Green et al., 2013). A similar approach on the margins around Baffin Bay – with a focus on Baffin Island – would involve:

1. Stratigraphic landscape analysis based on a detailed mapping of erosion surfaces to establish a relative denudation chronology (Figure 3).
2. Acquisition of AFTA data with both regional and vertical coverage to define the magnitude and absolute timing of regional episodes of exhumation. GEUS acquired more than 200 samples of sediment and basement north of 65°N during fieldwork in 2011 and 2013 for this purpose (Figure 1).
3. Investigation of the geological record focussed on the presence of sedimentary outliers onshore and identification of unconformities offshore (which often correlate with major periods of exhumation onshore) (Figure 5).

Such a program would provide detailed definition of the development of Baffin Island, in a similar way to that already done on the conjugate West Greenland margin (cf. the review provided by Green et al. 2013).

The results of such an integrated study will be of importance in assessing the hydrocarbon prospectivity in the offshore sedimentary basins, because uplift and denudation of continental margins can have profound effects on the hydrocarbon system; e.g.

- in providing reservoir clastics to the offshore basin,
- by disrupting traps leading to breach of seals,
- by phase changes due to the resulting drop in pressure and
- by changing migration routes due to tilting of the sedimentary succession.

The results will also be of significant scientific interest, both for understanding the regional development and for providing new constraints on the forces that drive the vertical movements of elevated, passive continental margins.

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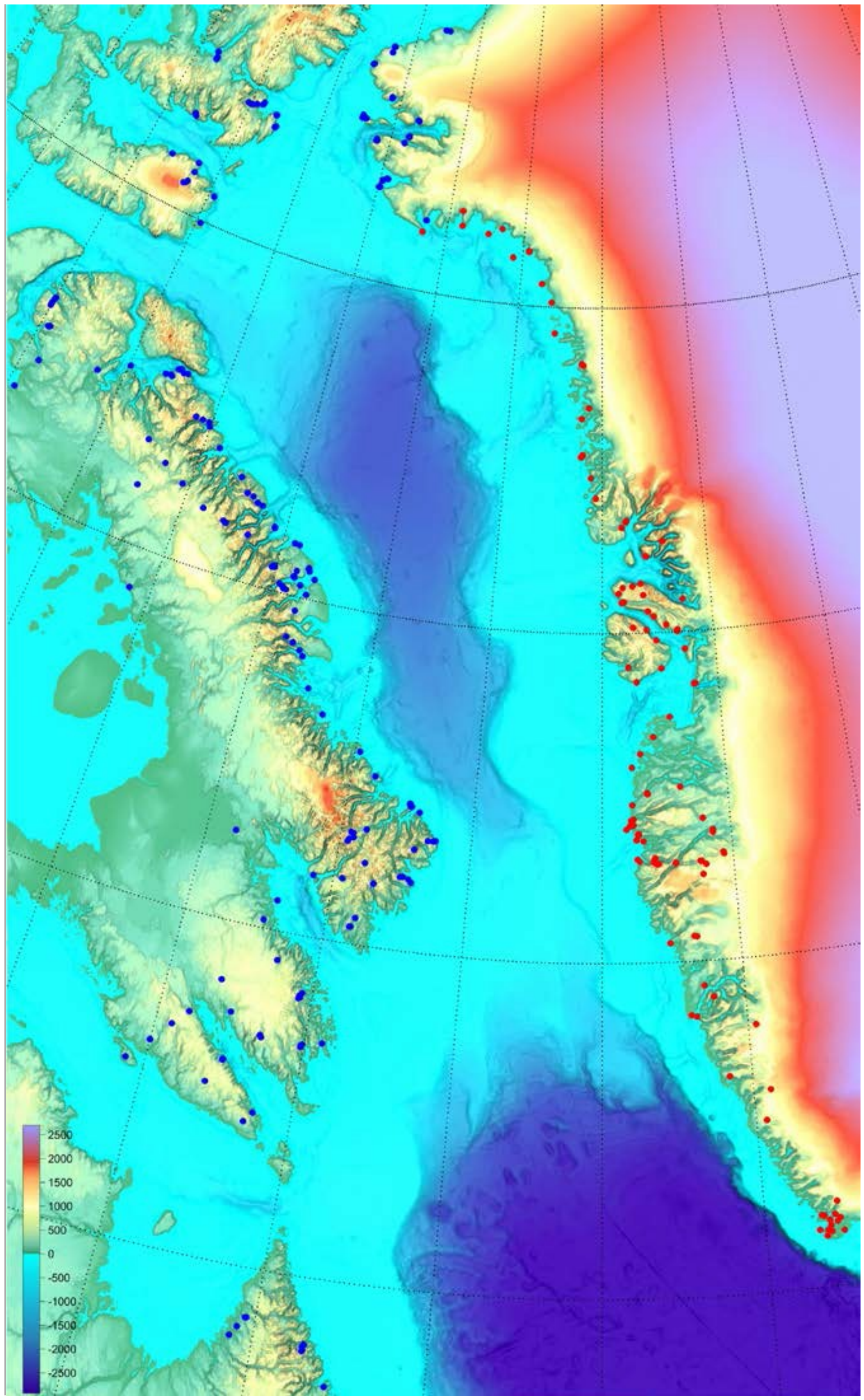

Figure 1: Symmetry across Baffin Bay between Baffin Island and West Greenland (see Fig. 2). Steep margins towards the ocean and gently dipping plains towards the interior, Hudson Bay and central Greenland (below the Inland Ice), respectively. Distribution of the rock samples for which AFTA data are available (Greenland, red dots), and the more than 200 samples that are available for AFTA studies north of 65°N (Canada and NW Greenland, blue dots).

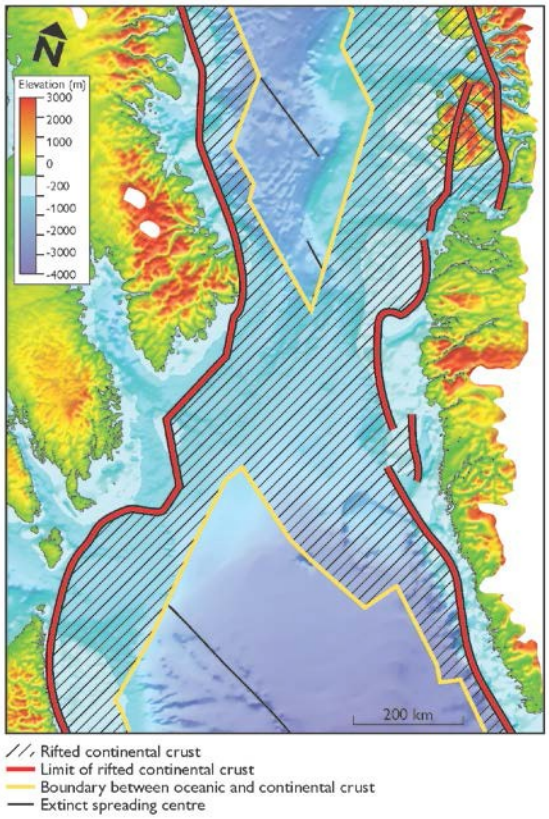

Figure 2: There is a close relation between the mountainous margins on either side of Baffin Bay and the edges of the Greenland and American cratons indicated by the limit of the rifted continental crust (thick red line; Chalmers and Pulvertaft, 2001). The West Greenland margin was formed by late Neogene uplift, c. 50 Myr after breakup west of Greenland (Japsen et al., 2006) and the east–west symmetry suggests that this was also the case with the elevated Canadian margin. The presence of Eocene marine sediments several hundred meters above sea level on the Canadian margin (MacLean and Falconer, 1979) supports this conjecture. From Japsen et al. (2012).

Figure 3: Deep glacially eroded fjords coexist side-by-side with high plains that are almost untouched by glacial erosion despite having been overridden by ice (Meta Incognita Peninsula, Baffin Island; 67ºN). From Kleman (2008).

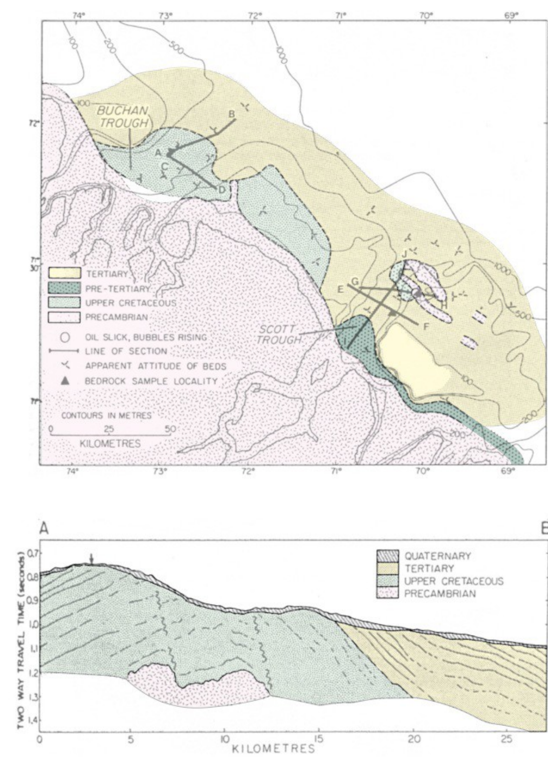

Figure 4: Truncation of Tertiary (yellow) and older strata (green) towards the coast of Baffin Island (Precambrian basement: pink). The upper part of the figure shows a geological map of the area and the lower part a geological cross section A-B along the axis of the Buchan Trough. Scott Inlet – Buchan Gulf, Baffin Island (72ºN). From MacLean et al. (1981).

Sediment Provenance Based on Heavy Minerals Assemblage Characterization of Different Sandstones from the Pernambuco Basin, Northeast Brazil.

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Introduction

The Pernambuco Sedimentary Basin is located within the Borborema Province, NE Brazil (Figure 01). The geological units of the onshore portion of this basin consist of several sedimentary formations and a magmatic suite. These can be described as follows: Cabo Formation (arkose sandstones and carbonate-bearing facies, interlayered with conglomeratic deposits, all of them Aptian in age), Suape (Meso-albian sandstones and arkose sandstones, with interlayered volcanic tuffs of around 102 Ma), and the Paraíso Formation (quartz-rich sandstones with clay-rich matrix of Eo-Albian age). The Ipojuca Magmatic Suite (rhyolites, trachytes, basalts, and ignimbrites) is 100-105 Ma. The main objective of this work is to characterize the heavy minerals assemblages in the sandstones of the Cabo, Suape and Paraíso formations, generating information on sedimentary provenance in order to establish distinctive signatures between these geological units, which were until recently assigned to a single fluvial continental stratigraphic unit, named the Cabo Formation.

Methodology

Representative samples were collected from coarse-grained sandstones, which contain a potentially greater abundance of heavy minerals than finer-grained facies. After soft disaggregation, heavy minerals were separated out via suspension. Heavy minerals were identified via stereoscope and identified according to their shape, color, transparency, and brightness, as well as other distinctive features such as twinning, striations, etc. Igneous and metamorphic mineral groups were established with the best specimens forwarded for SEM imaging and SEM- WDS qualitative chemical microanalysis.

Preliminary Results and Discussion

According to preliminary results, the analysis carried out in a sample of sandstones of the Cabo Formation revealed heavy minerals typically corresponding to an igneous assemblage as it follows: Zircon ($ZrSiO_4$; most of the grains showed elongated prismatic habit, with bi- pyramidal edges (doubled endings Figure 02a and 02b), with colors ranging from pink to dark brown; Hf, Th, and U were detected in SEM-WDS analyses(Figure 3a)) and Xenotime (YPO_4; bi-pyramidal with doubled tetragonal endings). In the sample of the Suape Formation were found igneous minerals such as Zircon ($ZrSiO_4$; light pink, transparent, prismatic elongated (Figure 02c) grains, containing Hf, Th, and U as traces elements, and Spodumene ($LiAlSi_2O_6$; fibrous appearance (Figure 02d)). Some metamorphic minerals were also found in this last sample, such as Tourmaline ($(Na, Ca)(Mg, Al, Li)_3(Al, Fe, Mn)_6(BO_3)_3(Si_6O_{18})(OH)_4$; dark green prismatic colored grains which could range from dark

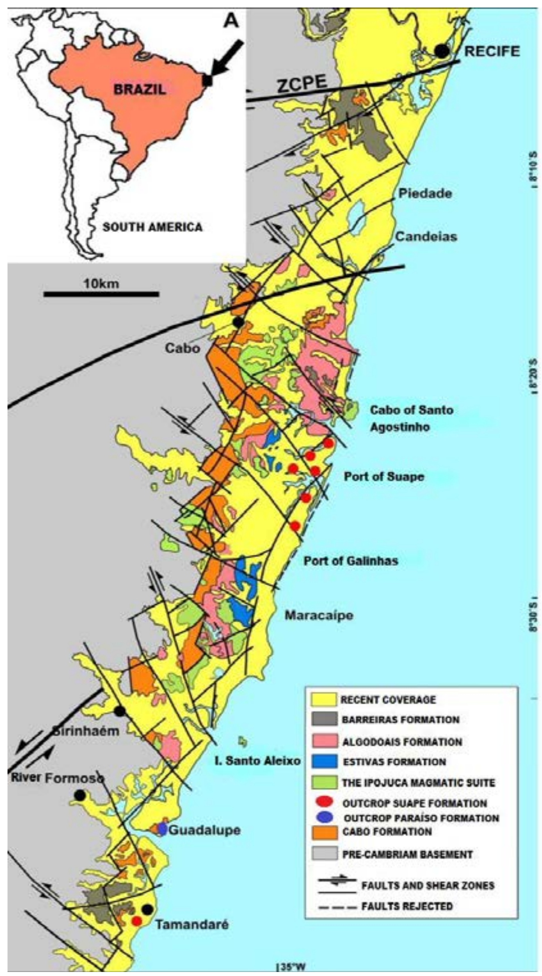

Figure 1. Location map of Pernambuco Basin and their corresponding geological units, and the main outcrops of Suape and Paraíso formations (Simplified from Maia 2012).

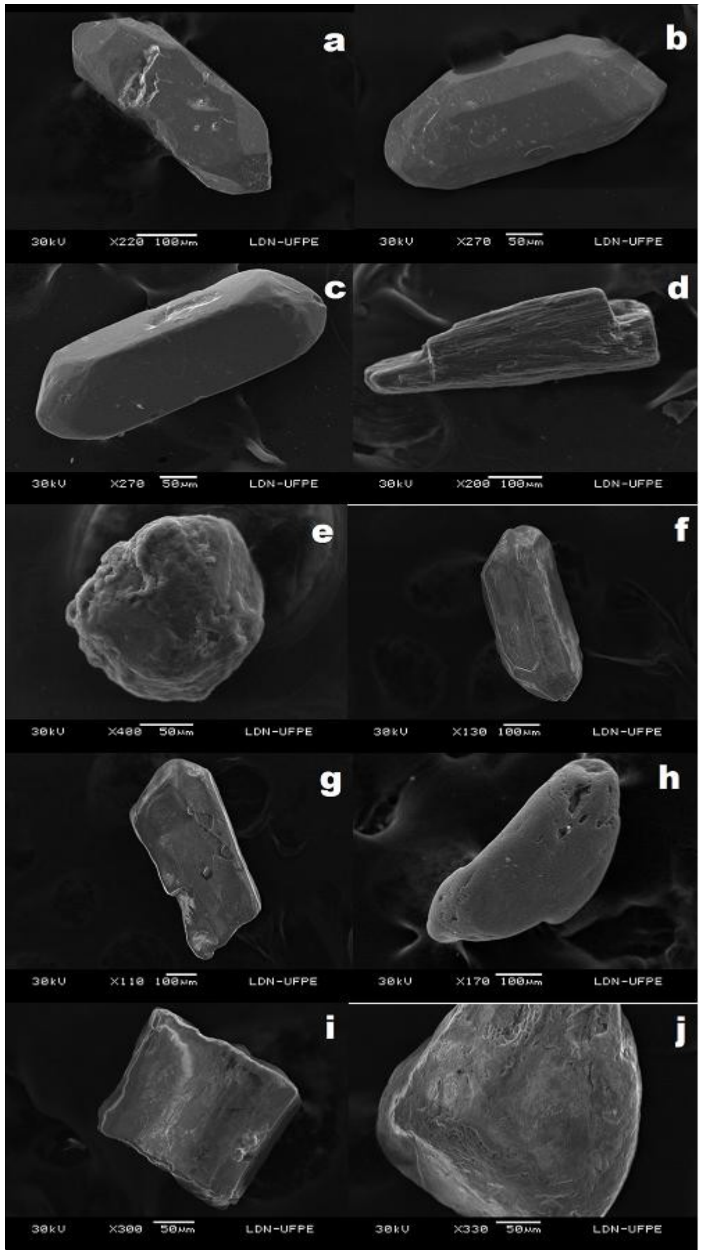

Figure 2. SEM images of representative minerals. Zircon (a) and (b), grains showed elongated prismatic shape (sample from Cabo Formation. Zircon (c), prismatic elongated (Suape Formation); Spodumene (d) fibrous appearance (Suape Formation); Garnet (e), rounded grains showing overgrowths (Suape Formation). Zincon (f) short prismatic grain (Paraíso Formation); Rutile (g) shaped prism (Paraíso Formation); Epidote (h) elongated and fractured grains (Paraíso Formation) ; Turmaline (i) short and flattened prism (Paraíso Formation); Garnet (j) grains presenting rounded edges and conchoidal fractures (Paraíso Formation).

green to dark brown color), Sillimanite (Al_2SiO_5; in acicular and fibrous slightly yellowish grain), and Garnet ($Fe_3^{2+}Al_2(SiO_4)_3$; rounded grains showing overgrowths (Figure 2e)). Sandstones of the Paraíso Formation one sample have shown igneous assemblage composed of: Zircon ($ZrSiO_4$; elongated and short prismatic grains (Figure 2f), transparent with colors ranging from pinkish to dark brown; Hf and U were detected in chemical microanalysis); Xenotime (YPO_4; bi-pyramidal doubled- ($LiAlSi_2O_6$; prismatic and flattened grains, showing prismatic faces deeply striated lengthwise, and whitish in color); Rutile (TiO_2; striated prisms (Figure 2g) with Fe and U detected (Figure 3b).

In this sample of the Paraíso Formation a more diverse metamorphic assemblage was found, containing Kyanite (Al_2SiO_5; most grains are transparent grains and showing irregular shape). This later mineral indicates relatively high pressure metamorphic rocks; Epidote ($Ca_2(Al,Fe)Al_2Si_3O_{12}(OH)$ in elongated and fractured grains (Figure 2h); Tourmaline ($(Na,Ca)(Mg,Al,Li)_3(Al,Fe,Mn)_6(BO_3)_3(Si_6O_{18})(OH)_4$; prismatic (Figure 2i) and greenish brown colored grains; Garnet ($Fe_3Al_2(SiO_4)_3$; grains presenting rounded edges and conchoidal fractures (Figure 2j).

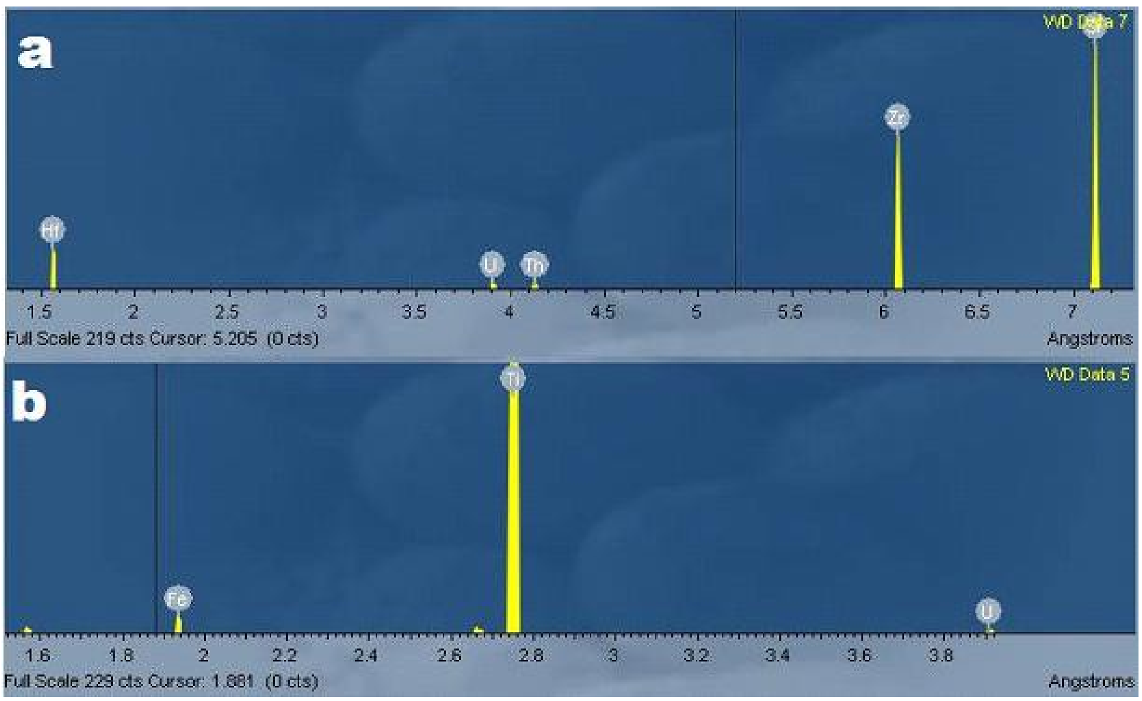

Figure 3. Representative wavelength spectra (WDS) - Zircon (a) of the Cabo Formation and Rutile (b) Paraíso Formation.

Preliminary Conclusions

Sandstones from the Cabo Formation were found to contain minerals of exclusively igneous origin such as Zircons and Xenotime, which are probably derived from the Neoproterozoic plutonic granitic rocks. In contrast, the Suape Formation contains both igneous and metamorphic mineral assemblages although the zircons present are clearer and more homogenous, and thin prismatic in shape, indicating a more recent source rock, probably of volcanic origin (ca. 100 Ma). Tourmalines, Garnets and Sillimanites in the investigated sample of the Suape Formation are must be derived from the Paleoproterozoic gneiss of the basement (Belém do São Francisco Complex) occurring to east (Figure 01). The sample from the Paraíso Formation revealed both, igneous (Zircon, Xenotime, Spodumene and Rutile) and metamorphic mineral assemblage (Kyanite, Tourmaline, Epidote, and Garnet). We could notice zircons in short prims in heterogeneous colours in sample of the Paraíso Formation. They led us to the conclusion of metamorphic sources, and it can probably coming from the Paleoproterozoic gneiss of the basement (Belém do São Francisco Complex, apart from tourmaline, kyanite, epidote, and garnet probably coming from mica schists of the basement also (Belém do São Francisco Complex). Geology and tectonic setting of the Pernambuco basin probably exerted a strong control on the production of the sedimentary content to the different sedimentary units, and consequently to the mineralogical composition of the formations. However when introduced these products into the sediment dispersal system, their original composition could be modified modified by factors such as transport, deposition, and diagenesis. from the analyses of mineral assemblages, it can be concluded that heavy minerals found in the studied samples show a relatively low mineralogical diversity in the Cabo Formation, and a relatively high mineralogical diversity in the Paraíso Formation. In terms of textural analysis, were found fractured and striated grains, as well as grains with rounded edges. Some of those minerals of the Paraíso Formation, such as the prismatic rutile occurs typically as euhedral grains and also have shown slightly rounded edges, whereas garnet can occur in fractured grains. These characteristics may indicate significant transport, either reworking of previously deposited sediments, or *in situ* deposition of high hydrodynamic energy. These characteristics can be produced by subaquatic and fluvial transport and accumulated in a transitional tidal environment. The presence of euhedral and subeuhedral zircons and tourmalines in the sample from the Suape Formation can indicate transport from different source areas. These variations are significant through the sedimentary succession studied and can reveal different provenances.

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Unravelling Basin Evolution Using Basement Terranes

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The basement of any basin provides the foundation onto which the sediments are deposited. Physical and geological models that attempt to understand how and where basins first localise deformation, often assume a competent and uniform basement. However the complexity of the inherent basement structures and basement lithological composition control how the basement will behave under extensional or compressional stress regime and therefore will control the development and subsequent evolution of the overlying basins.

By improving our knowledge of basement terranes, we can provide a good first-order understanding on basin evolution and petroleum systems elements, including basin geometry, rate of subsidence, heat flow distribution, maturation history, migration pathways and distribution of reservoir and source rocks.

We have refined basement terranes in Nova Scotia and Newfoundland, based on the interpretation of potential field datasets, including a set of enhancement filters, along with an extensive compilation of georeferenced published geological maps and cross-sections. Each basement terrane has been defined by a basement type, minimum and maximum ages, and has a short abstract that summarises the tectonic evolution and composition. All datasets, including the basement terranes geodatabase, have been compiled in an ArcGIS document for the ease of the interpretation. Combined with tectonic reconstructions, such a dataset becomes very powerful as it allows us to: 1) predict far-field state of stress and identify structures that are likely to be re-activated to accommodate the margin rifting, and 2) refine paleogeographic maps and identify the preferred locations of depocentres and the provenance of reservoirs and source rocks.

Mesozoic synrift successions associated with the breakup of Pangea and opening of the Atlantic Ocean: examples from the Fundy Basin and Scotian margin (Nova Scotia, Canada)

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Synrift successions cropping out along the margins of the Fundy Basin and the Orpheus Graben are the best successions for defining basin evolution (structural development and associated coeval sedimentary successions) offshore Nova Scotia. Synrift successions offer critical information for interpreting the structural evolution and petroleum systems of rift basins. Basin fill is influenced by displacement of the basin bounding normal faults and provides data on the architecture of the sedimentary successions and their reservoir characteristics.

The study presents an examination of the tectonically connected siliciclastic fluviatile lower Wolfville (Minas Subbasin) and Chedabucto (Orpheus Graben) formations using the principles of architectural element analysis. The basal section of the Wolfville Formation represents a multi-cycle depositional braided channel complex, completely incised (20+ m) by later fluvial events in response to a marked shift in base level on the basin margin. These changes in basin fill are captured in the architectural element analysis. New data from the Chedabucto Formation type section, marking the western margin of the Orpheus Graben, show increased amounts of conglomerate, cross bedded sandstone, and mudstone facies. New findings on the age of the Chedabucto Formation, using pollen grain identification, suggest deposition post-Norian.

The Eurydice Formation, from the Orpheus Graben Eurydice P-36 well, shows a noticeable decrease in grain size dominated by fine-grained sandstone and mudstone facies and displaying possible spring-neap tidal bundles. Although the Fundy and Orpheus synrift successions are tectonically linked, the results from core and outcrop suggest different patterns of basin fill in the eastern rift successions (Orpheus Graben), perhaps exhibiting early brackish to marine influence, when compared to the western rift successions (Fundy Basin)

Field data (spectral gamma-ray and permeability) and petrography (porosity and provenance) studies are used to investigate reservoir characteristics of these discrete synrift successions. Porosity, permeability, and spectral gamma-ray data, collected from outcrop and field grab samples, are currently being processed and incorporated into a geocellular flow model for the Wolfville Formation braided channel complex. The results of this flow model can be applied to the subsurface Triassic deposits where core and seismic data are limited; keeping in mind that individual basins can have discrete patterns of basin fill.

Paleoceanographic constrains on organic matter preservation in the Lusitanian Basin during the Late Pliensbachian

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The Pliensbachian (Lower Jurassic) hemipelagic carbonate series of the Lusitanian Basin (Portugal) are of major importance as they materialize a hinge zone between the Tethyan and Boreal realms. One of the most conspicuous features of the Lusitanian Basin is the organic-rich nature of most of the Margaritatus Chronozone hemipelagic series, with the occurrence of several well defined regional black shale occurrences. The Pliensbachian organic-rich deposition (observed in several locations around the world) is coeval with a positive $\delta^{13}C$ excursion recorded in carbonates and organic substrates.

The analysis of selected redox sensitive elements (V, Cr, Co, Ni, Mo, and U) from the Lusitanian Basin worldwide reference section of Peniche indicate that most of the organic-rich facies of Ibex–Margaritatus chronozones were deposited under an oxic–disoxic regime, while the rare centimetre well-defined black shales where deposited and preserved under suboxic–anoxic(?), intermittently euxinic conditions. Evidences suggest that these basinwide black shales events were driven by extreme climate warming coupled with high oceanic productivity and intermittently stratified (thermally?) epeiric areas, promoting widespread mucilage and microbial outbreaks preserved as the black shales. Regionally, these "hot snaps" also allowed the rapid but short-lived expansion of Tethyan ammonites into Boreal domains or lead to decrease benthic diversity. Ensuing cooling during the Margaritatus Chronozone was accompanied by southwards influx of northwards ammonite fauna or radiation of cyst forming dinoflagellates.

It is recognized today that the "greenhouse" Mesozoic Era includes several short-lived icehouse episodes. One occurred during the Spinatum Chronozone (Late Pliensbachian), which immediately preceded a 2nd-order extinction event and a major carbon cycle perturbation associated to the Early Toarcian Oceanic Anoxic Event. Worldwide preservation of organic matter during the Late Pliensbachian resulted in decreased atmospheric CO_2 levels, triggering and/or amplifying the Spinatum Chronozone icehouse event, which led to permafrost and/or methane gas hydrates in locations easily disturbed by the subsequent Early Toarcian warming, or/and increased volcanic activity driven by deglaciation.

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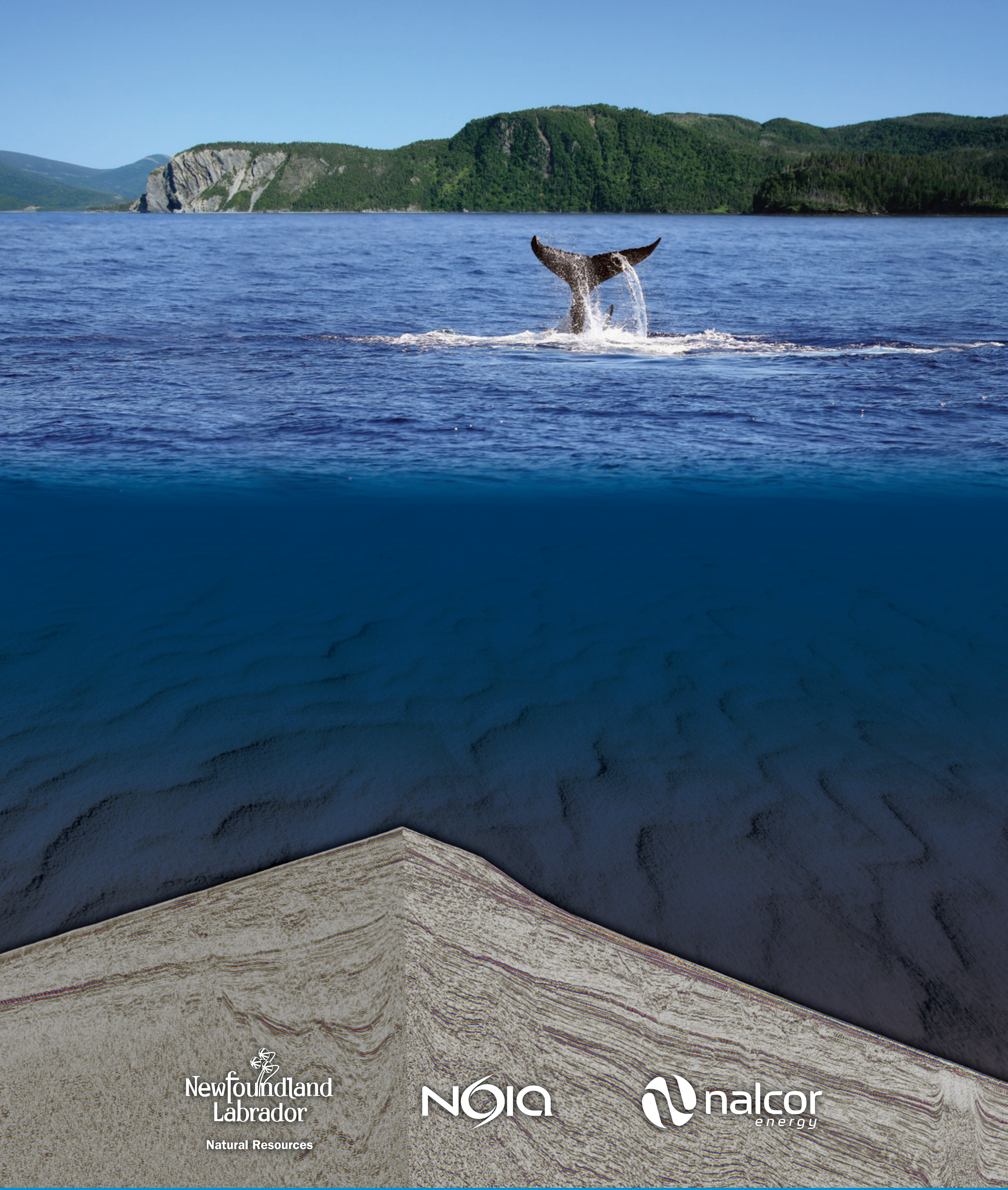

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