CENTRAL & NORTH ATLANTIC

CONJUGATE MARGINS CONFERENCE
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# THIRD CONJUGATE MARGINS CONFERENCE 2012

## ABSTRACTS VOLUME

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# CONTENTS

# Keynote Speakers

## A NEW KINEMATIC PLATE RECONSTRUCTION OF THE NORTH ATLANTIC BETWEEN IRELAND AND CANADA

**Bridget Ady[1] & Richard C. Whittaker[1]**

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A critical re-examination of the rifting history of the Ireland-Newfoundland conjugate margins in a regional and global context and development of a new kinematic plate reconstruction is fundamental for an evaluation of the prospectivity of the offshore basins. A two-year government-sponsored research project to develop *A New Kinematic Plate Reconstruction of the North Atlantic between Ireland and Canada* is nearing completion by a team of researchers from academia, government, and industry on both sides of the Atlantic. The new kinematic model project takes into account the wide range of geological processes responsible for basin development by incorporating interpretations of recently acquired industry seismic data and older seismic data (Whittaker *et al.,* this conference; Štolfová *et al.,* this conference) with analytical techniques that include 2D and 3D gravity inversion, flexural backstripping, fault restoration and forward modelling (Kusznir *et al.,* this conference), detailed local studies around the margin and deformable plate reconstruction analyses.

The deformable plate analysis provides techniques to extract Beta stretching factors (β) from total β derived from gravity inversion and other methods for time intervals associated with tectonic events. Major tectonostratigraphic sequences and tectonic events have been defined for the project and the amount of crustal extension is sub-divided into individual tectonic events or time intervals and converted to a stack of β grids (ßeta-Stack). These β grids are constrained both by the plate kinematic model and by all available onshore and offshore geological data. The ßeta-Stack forms the key component of the deformable plate model and can be fully integrated with the plate kinematic model. Deformable plate reconstruction analysis provides a means by which to quantify the amount of thinning from depth-dependent stretching and sub-seismic faulting.

The deformable plates analysis carried out as part of the new plate kinematic study shows that there has been over 200 km of Late Jurassic to Early Cretaceous extension in the East Orphan and West Orphan basins, offshore Newfoundland. The extension in both the East and West Orphan basins is related to the well-documented breakup of Newfoundland and Iberia which was initiated in the Tithonian and finally separated the Flemish Cap from the Galicia Bank in the Barremian. The significant extension that must have occurred on the margin at this time corresponds closely with extension determined from crustal thinning in the area. Simple fault extension modelling carried out for this project along regional seismic profiles in the Orphan Basin gives β values much lower than our kinematic plate modelling indicates, and we propose that a more complex multi-phase faulting mechanism must have occurred. An approximation of the amount of depth-dependent thinning in this area may also be quantified by application of deformable plate reconstruction analysis.

The good quality modern seismic data in the central part of the East Orphan Basin clearly shows that most extension in the basin had taken place by the end of the Valanginian (Whittaker *et al.,* this conference). However, the deformable plate model predicts that there was significant extension in this part of the margin from late Valanginian to Barremian, which means that much of this extension is likely to have occurred in the West Orphan Basin. This major extension in the West Orphan basin is supported by high extension factors present in the gravity inversion data from the area. The differential extension between the more highly extended East and West Orphan Basins and the Jeanne d'Arc Basin and Flemish Pass Basins also provides a mechanism to explain the clockwise rotation of the Flemish Cap away from North America. By analogy with the Newfoundland margin, it is proposed that the Rockall Basin shared a similar structural evolution to the West Orphan Basin and the

Porcupine Basin to the East Orphan Basin, and that major Tithonian to Barremian extension also took place in these basins resulting in the high β values observed in these basins.

Following the separation of the Flemish Cap from Iberia the breakup of Eurasia and North America turned northeast along the Newfoundland-Ireland margins. Rifting along this trend was initiated in the early Hauterivian, corresponding to the formation of major rift basins and volcanism in the Labrador Sea. The Newfoundland margin was therefore likely to have been subjected to extension in a NE and NW direction during Hauterivian to Barremian times. Deformable plates analysis of the NW-propagating seafloor spreading during this period supports interpretations that there is a zone of highly extended continental crust rather than seafloor spreading along the eastern Labrador Sea margins at least until the Santonian.

Extension derived from gravity inversion on the Greenland-Eurasian margin north of the Hatton Basin corresponds closely to β calculated from the plate model. However, at the Hatton Basin margin there is a substantial β remaining after the extraction of β for the Paleocene tectonic events. Further application of the deformable plates analysis, constrained by the kinematic model, reveals evidence of considerable Cretaceous extension in two distinct sub-basins within the Hatton Basin. This supports the interpretation of Cretaceous extension from the seismic data observed in windows beneath the pervasive Hatton Basin Tertiary volcanics (Štolfová *et al.,* this conference). The presence of an extensive Mesozoic section within the Hatton Basin, with indications that clastics in the area were derived from Greenland, may have implications for reservoir distribution along the western margin of Ireland, and even on the conjugate West Orphan margin prior to breakup in the Santonian. Previously it has been unclear how much Mesozoic extension had affected the Hatton Basin.

The new kinematic model has provided new insights into the evolution of the major Mesozoic and Cenozoic basins around the margin. Fully understanding the kinematic plate model is vital for the analysis of basin development in this area. The interpretation of regional seismic data from the margins of Newfoundland and Ireland has enabled a comparison of both margins and has also resulted in an improved understanding of the evolution of the conjugate passive margins of Canada and NW Europe in general.

### References

Kusznir, N., Roberts, A., Alvey, A., Whittaker, R.C. & Štolfová, K. 2012. Crustal Structure, Subsidence History and Stretching within the Ocean-Continent-Transition of the Conjugate Ireland and Newfoundland North Atlantic Margins. *Abstract, Central Atlantic Conjugate Margins Conference, Dublin, 2012*.

Štolfová, K., Whittaker, R.C. & Shannon, P.M. 2012. New insights into regional Mesozoic and Cenozoic evolution of the Irish offshore continental margin. *Abstract, Central Atlantic Conjugate Margins Conference Dublin*, 2012.

Whittaker, R.C. 2012. Geological Constraints for a New Plate Reconstruction of the Newfoundland Continental Margin. *Abstract, Central Atlantic Conjugate Margins Conference Dublin*, 2012.

### Acknowledgements

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## HYPEREXTENSION, WEAKENING AND CRUSTAL FOLDING IN THE NORTH ATLANTIC DOMAIN

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Using regional data from the Norwegian Sea and adjacent margins (Figure 1), we demonstrate how Early Cretaceous hyperextension on the proto-North Atlantic margin influenced the subsequent deformation history and structural style of the area. A combination of low-strength, stretched crust with a beta factor of 3-4 or more, underlain by similarly weak, partially serpentinised mantle resulted in a lithosphere that was prone to compressive deformation under relatively low stress levels. Triggering events for this deformation may include the far-field effects of plate reorganization, significant build-up of body forces from development of the Iceland volcanic edifice, and others.

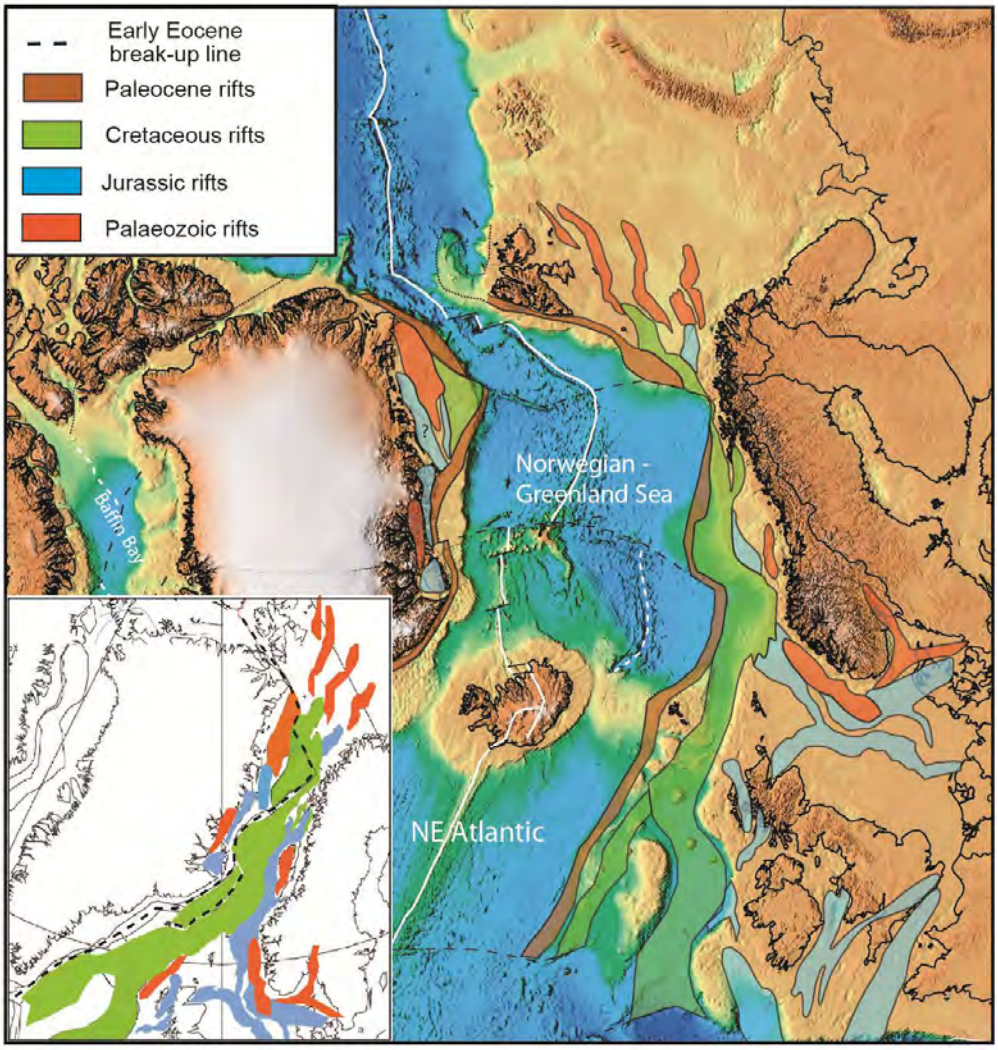


***Figure 1:*** *Map showing progressive rifting leading to Early Eocene* breakup *in the NE Atlantic. The early Cretaceous basins shown in green are characterised by highly stretched crust and are underlain by candidate bodies for upper mantle partial exhumation and serpentinisation.*

In the Late Cretaceous, perhaps beginning as early as the Cenomanian, this deformation was manifested in the development of regionally extensive, long-wavelength regional folds in the Vøring Basin such as the Vigrid and Någrind Synclines (Brekke, 2000; Lundin & Doré, 2011)

(Figures 2 & 3). The largest of these features, the Vigrid Syncline, has a half-wavelength of about 80 km, suggesting that it is a lithospheric-scale fold of the type described by Cloetingh and Burov (2010) and supporting the idea of a weak and deformable lithosphere.

The compressive regime may have existed for much of the late Cretaceous, since synclinal development affected sedimentation patterns in the Cenomanian-Turonian (onlap to the flanks of the syncline) and Campanian (axial distribution of turbidite sands). The regime was probably also episodic. A late inversion phase of Maastrichtian age is identified in the region of the Nyk High, northern Vøring Basin, where backstripping shows significant evidence of doming, now overprinted by later extensional faulting.

The bounding anticlines, e.g. the Utgard High, Gjallar Ridge, and particularly the Nyk High, formed a locus for the NE-SW and E-W extensional faulting, mainly Paleocene in age, that preceded breakup in the NE Atlantic (Figures 2 & 3). This structural architecture – lightly faulted or unfaulted Cretaceous synclines bounded by highly faulted "collapsed" anticlines – is a distinctive feature of the northern Vøring Basin. We suggest that this geometry represents inherent instability in anticlinal folds cored by weak, serpentinised mantle, which were thus preferentially exploited by pre-breakup Paleocene extension.

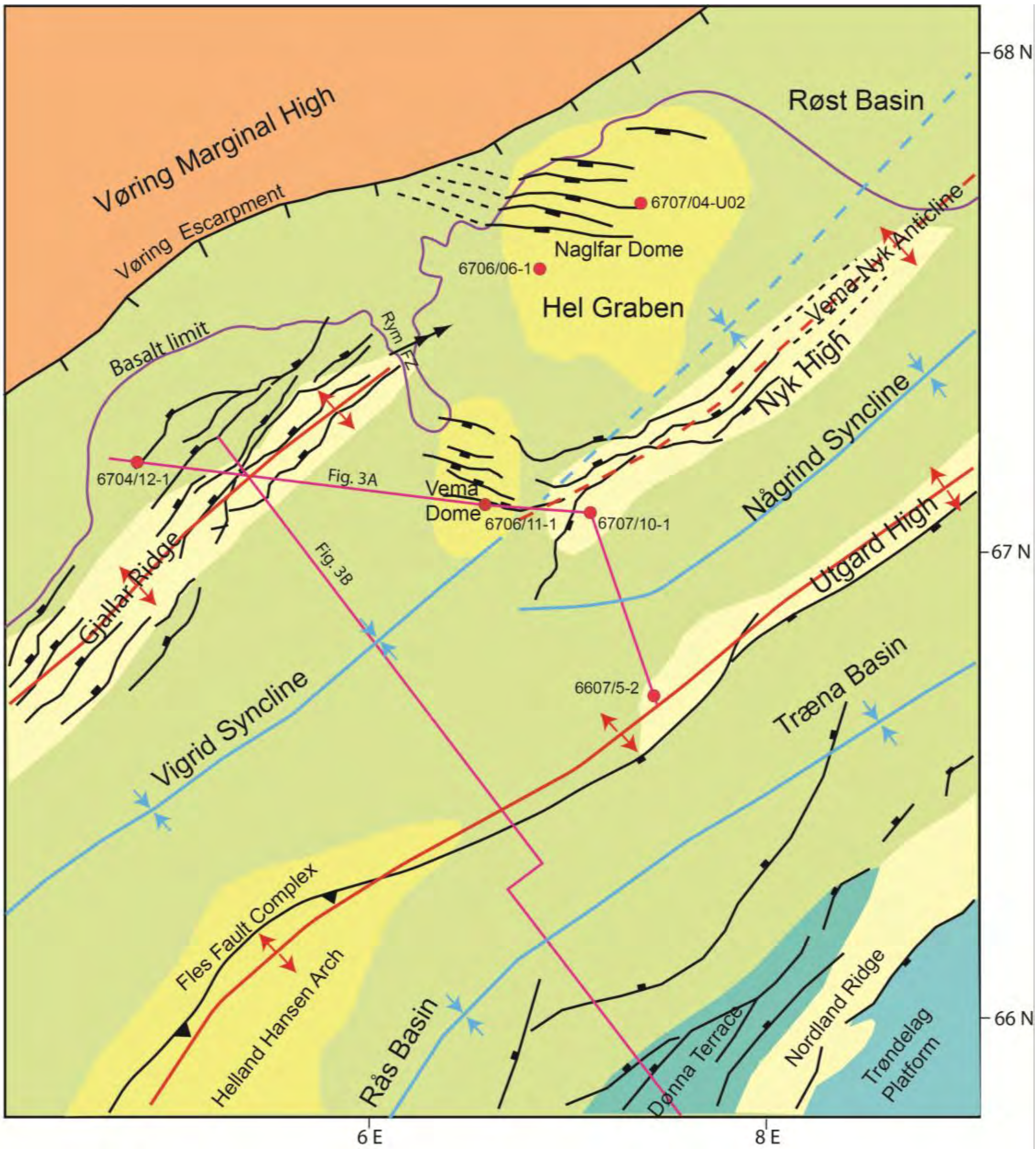


***Figure 2:*** *Tectonic features map of the northern Vøring Basin showing location of sections in Figure 3.*

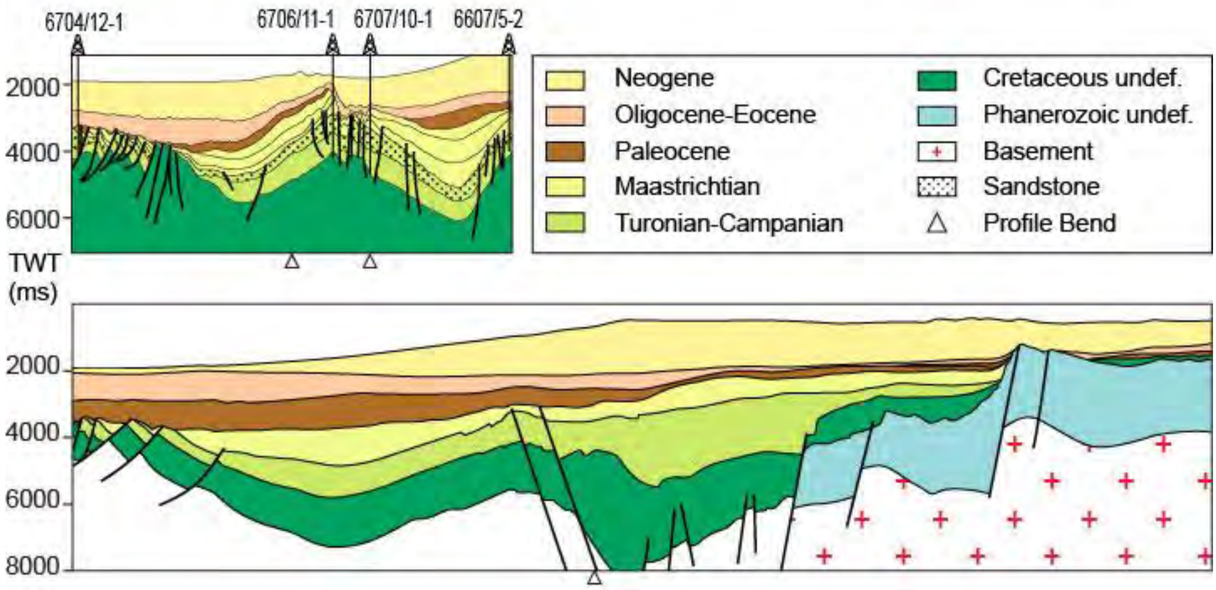


***Figure 3:*** *Geoseismic sections over the Gjallar Ridge, Vigrid Syncline, Nyk High and Någrind Syncline (upper section), Gjallar Ridge, Vigrid Syncline, Utgard High and Rås Basin (lower section). Note the characteristic axial collapse geometry of the anticlines.*

Following breakup, the area was overprinted by the better-known Cenozoic compressive deformation that can be traced along the hyperextended basin chain between the Vøring Basin and the northern Rockall Basin. Locally, this suite of structures is represented by, for example, the northern Helland Hansen Arch, the Vema Dome and the Naglfar Dome (Figure 2). These structures appear to have reached an acme of compressive deformation in the Middle Miocene. The combined duration of compressive deformation in the northern Vøring Basin was 80 million years or more, spanning continental breakup at about 54 Ma. We postulate therefore that the weak, deformable substrate of hyperextended basins can persist for significant geological time, in contrast to the rapid increase in lithospheric strength normally expected for extended lithosphere (e.g. Close *et al.,* 2009). These general ideas can be tested as petroleum exploration and geological evaluation proceed on other probable hyperextended margins such as the Labrador Sea, Baffin Bay and the Canadian Beaufort Sea.

## References

Brekke, H. 2000. The tectonic evolution of the Norwegian Sea continental margin with emphasis on the Vøring and Møre Basins. *In:* Nøttvedt, A. *et al.* (eds) *Dynamics of the Norwegian Margin.* Geological Society London, Special Publications, **167**, 327-378.

Cloetingh, S. & Burov, E. 2010. Lithospheric folding and sedimentary basin evolution: a review and analysis of formation mechanism. *Basin Research,* **23**, 257-290.

Close, D.I., Watts, A.B. & Stagg, H.M.J. 2009. A marine geophysical study of the Wilkes Land rifted continental margin, Antarctica. *Geophysical Journal International*, **177**, 430-450.

Lundin, E.R. & Doré, A.G. 2011. Hyperextension, serpentinisation, and weakening: A new paradigm for rifted margin compressional deformation. *Geology*, **39**, 347–350.

# DEPOSITIONAL ENVIRONMENTS AND SOURCE DISTRIBUTION ACROSS HYPER-EXTENDED RIFTED MARGINS OF THE NORTH ATLANTIC: INSIGHTS FROM THE IBERIA-NEWFOUNDLAND MARGIN

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Passive margins develop by extension and rupture of continental lithosphere. The processes that govern margin formation are responsible for a remarkable diversity in basin architecture and magmatic construction. In general, the structure of a passive margin depends on a number of fundamental parameters, including the inherited rheology, rheological evolution during extension, magmatism, relative plate motions and the thermal properties of the continental crust and mantle before, during, and after rifting. These parameters determine the style, distribution and rate of extension, as well as the amount of syn- and post-rift accommodation and magmatism. The importance of each of these parameters for the evolution of passive margins can vary considerably as evidenced by the large variations in passive margin architecture observed around the world. A detailed knowledge of the crustal structure and stratigraphy of a continental margin may yield crucial information about margin-forming processes, their interactions, and their role in the development of passive margin systems. In this presentation, we intend to discuss the following: 1) What are the palaeo-water depths developed during hyper-extension of the Iberian margin? 2) What is the timing of crustal thinning across the Iberian margin? 3) What are the implications for the timing, existence, and preservation of source rocks across the Iberia-Newfoundland hyper-extended rift system?

Many passive continental margins are characterised by large regional subsidence with only minor accompanying brittle deformation, for example, the Exmouth Plateau of northwest Australia; the Brazilian and West African conjugate margins, and the South China Sea. While the geological details and sedimentary facies and packaging differ between various margins, the style of deformation and the regional distribution of accommodation are broadly similar. This relationship between large regional subsidence and apparently minor concomitant brittle deformation may be explained in terms of: 1) the existence of low-angle fault structures that thin the brittle upper crust and the lower crust/upper mantle, which is difficult to recognize, and 2) depth-dependent extension across a zone of decoupling that separates a relatively non-deforming upper crust (i.e., the upper plate) from a significantly deforming lower crust and lithospheric mantle. The recognition of low-angle fault structures in seismic sections is particularly difficult; these structural features are often mistaken for exposed basement and/or unconformities. Thus, while high-angle faults are easily observed and interpreted in seismic sections, low-angle fault structures are not.

Studies from the Iberia-Newfoundland margin and the Tethyan margin in the Swiss Alps have helped to define the possible role of low-angle normal faulting of continental crust during the formation of passive margins. The European lithosphere can be characterised rheologically as a brittle upper crust, a ductile or weak middle crust, and a strong and brittle lower crust and uppermost lithospheric mantle, strengthened by a Permian underplate of the entire region following the Variscan Orogeny. Lavier & Manatschal (2006) have suggested that crustal extension can be described by a predictable sequence of deformation modes. This sequence initiates with a broadly distributed, brittle deformation (high-angle faults; stretching phase). Faulting is limited to the upper crust and brittle lower crust or upper mantle – at this stage, upper crustal faults cannot penetrate the weak middle crust. The relatively small amount of extension of the upper and lower crust can be approximated by depth-independent models (i.e. McKenzie, 1978). The stretching phase is followed by progressive strain localisation and crustal thinning along upper and lower crustal brittle shear zones that are decoupled across a zone of ductile middle crust (thinning phase). The final or exhumation phase is characterised by large crustal-scale faults that are: 1) downward-concave, a geometric consequence of large extension across faults that are deformed by the flexural rebound of the unloaded hangingwall block and low flexural rigidities; and 2) formed when the middle crust has been sheared out and the remaining upper and lower crust couple such that new faults can transect the remaining brittle crust. Typically the crust is 5-10 km thick when this occurs. If this deformation sequence is applicable at other margins, it implies that the earlier, but regionally distributed, high-angle faulting is replaced by low-angle upper and lower crustal fault systems. However, in many situations, identifying these low angle fault systems is difficult. Top-basement (exhumed) detachments are often overprinted by later high-angle normal faults that result in impressive structuring of the upper crust, but make recognition on seismic data more difficult. This later structuring tends to dominate what is seen in seismic sections and obscures the geometry and "true" identity and role of the earlier low-angle detachment systems. Often, exhumed fault surfaces may appear as unconformities rather than kinematic surfaces.

Figure 1 summarizes the structural complexity and architecture of a hyper-extended margin in terms of the poly-phase deformation of the margin (Péron-Pinvidic *et al.,* 2007; Péron-Pinvidic & Manatschal, 2009). Discrete high-angle faulting restricted to the upper crust (blue faults) produces a series of localised rift basins that are characterised by block rotations and depositional wedges. As extension continues, the upper crust is thinned by top-basement detachments (green and red faults) while shear zones thin the lower crust (green faults). In turn, mantle shear zones may thin the lithospheric mantle, thereby advecting heat into the extended region and offsetting the subsidence induced by thinning of the crust.

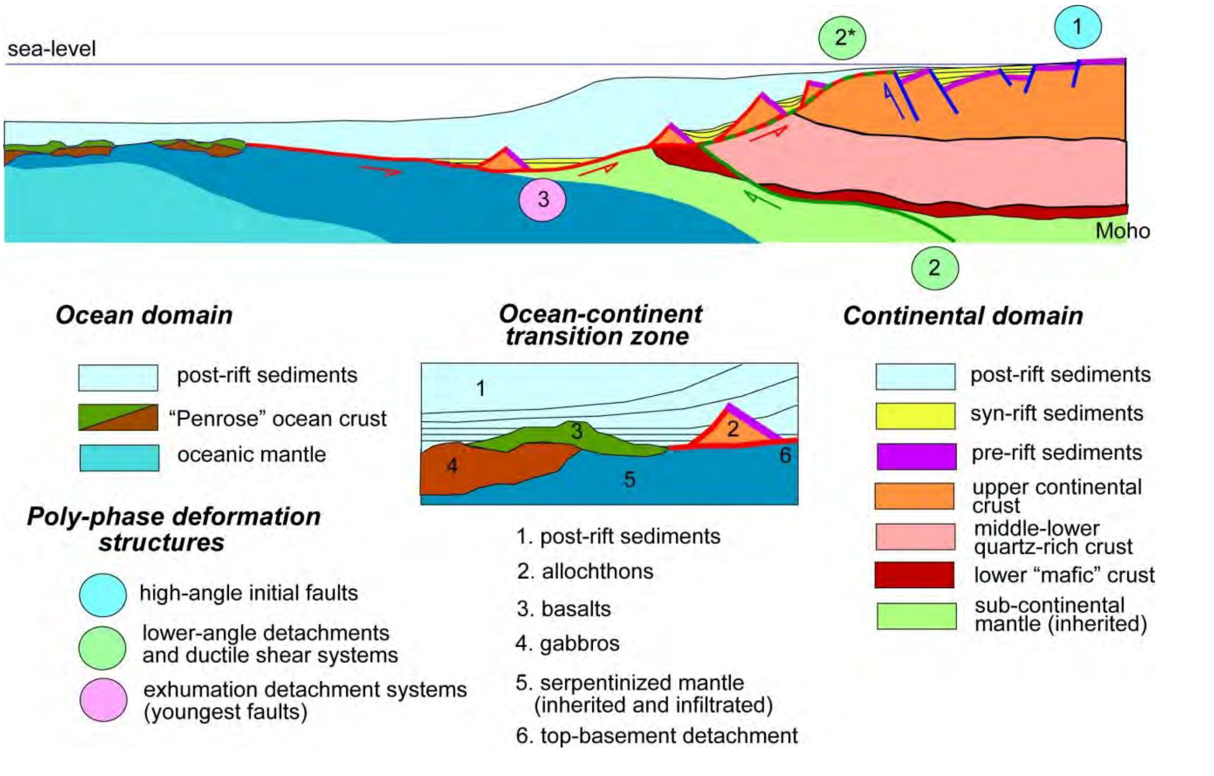


***Figure 1:*** *Architecture of hyper-extended margin produced by poly-phase deformation of a rheologically layered continental lithosphere that eventually resulted in mantle exhumation along top-basement and lower crustal detachment faults. The upper crustal detachment system allows the formation of continental allochthons. Continental and oceanic crust is separated by a zone of exhumed continental mantle. Purple surface: original top basement (modified from Péron-Pinvidic et al., 2009).*

In Figure 1, the top-basement detachment is responsible for completely necking the upper crust while truncating the lower crust. The colour scheme indicates that this same fault system may initiate during the thinning phase (green faults) but may be reactivated during the exhumation phase (red faults). Since this scheme was based on the Iberia margin, note that concave-down faults, necessary to exhume the continental mantle in the Lavier and

Manatschal (2006) model, do not exist on this figure – if fact, it appears that these faults characterise the final stages of extension and exhumation of the conjugate Newfoundland margin implying that the exposed continental mantle (Unit 5, Figure 1) was pulled out from beneath the Grand Banks.

The depth-range of brittle faulting allows a definition of hyper-extension, being the location along the margin marked by the transition from decoupled to coupled upper and lower crustal extension (Sutra & Manatschal, 2012). In turn, this is recognised by faults that start from a surface break-away zone and can be traced through the crust where they offset Moho (Figure 2; red faults). Decoupled deformation is when faults independently deform the upper crust and lower crust (Figure 2; green faults) and merge into a ductile shear zone in the middle crust.

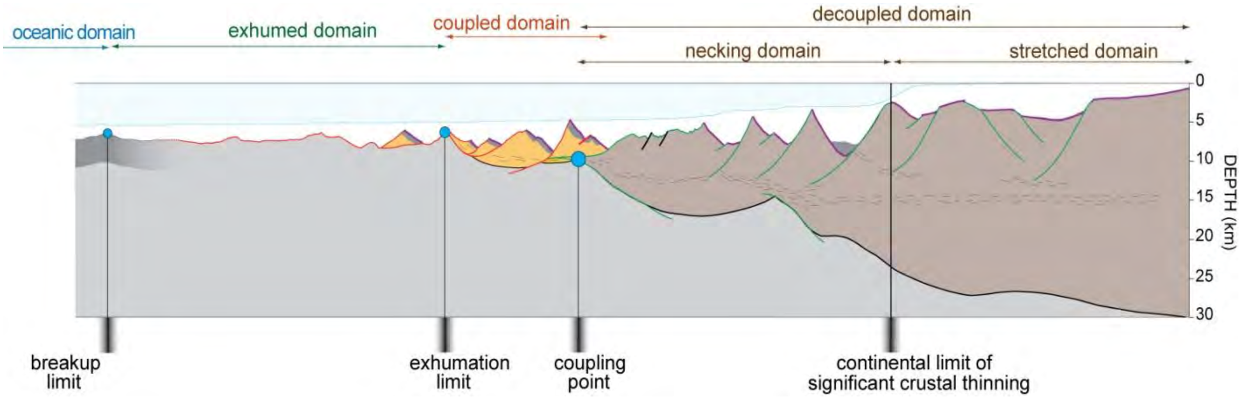


***Figure 2:*** *Structural architecture of a generic hyper-extended margin: Hyper-extension is shown on the margin, marked by the transition to coupled upper and lower crust. Coupling is recognised by faults that start from a surface break-away zone and can be followed with depth where they offset Moho. Decoupled deformation is when faults independently deform both the upper crust and lower crust and presumably merge into a ductile shear zone in the middle crust (Sutra & Manatschal, 2012).*

Insights from seismic reflection and refraction data and ODP drilling of the Iberian margin can be used to describe how continental crust can be thinned from pre-extension thicknesses of 30-40 km to values of 5-10 km immediately prior to brittle failure of the crust and mantle exhumation. In particular, the Galicia Bank is characterised by a relatively sharp boundary that separates a region of crustal coupling from a region of crustal decoupling (e.g. Sutra & Manatschal, 2012) between a wide continent-ocean transition zone (COTZ) at the western edge of a broad plateau.

As with many margins, the Iberian margin was affected by poly-phase extension. During the final extension phase that led to breakup, the crust becomes completely dismembered by a series of late-stage faults. If the extension on any one fault is significant, then it will be flexurally deformed into a concave-downward listric fault that can efficiently thin the remaining crust leading to mantle exhumation. An extensional strain balance is maintained via mantle exhumation, producing 100's km of exposed and serpentinised continental mantle containing organised magnetic anomalies. However, these magnetic anomalies, rather than being part of the seafloor spreading process, are likely a consequence of mantle exhumation and serpentinisation rather than mid-ocean ridge basalt production at the spreading centre, a review of which was recently published by Sibuet *et al.* (2007).

**Iberia-Newfoundland margin: Continuing controversies**

The crustal configuration of the Iberian margin has been approximated by a crustal reconstruction reported by Manatschal *et al.* (2007). The Manatschal *et al.* (2007) reconstruction of the hyper-extended Iberian margin is fundamental because it demonstrates that the region characterised by extreme brittle deformation and crustal thinning (i.e. the S-reflector of the Iberian margin; e.g. Reston *et al.,* 2007) and the zone of eventual continental mantle exhumation is spatially restricted and may not be most important in terms of lithospheric thinning; rather, this extreme brittle zone of deformation is the relatively rapid, terminal extension phase immediately prior to breakup and responsible for thinning the crust from ?? to zero (i.e. the exhumation phase). However and most importantly, this phase of exhumation was necessarily preceded by a phase of bulk thinning of the crust and continental lithospheric mantle that involved the Galicia Bank, the Iberian margin to the south of the Galicia Bank, and the conjugate margin of Newfoundland to the west: the thinning phase. This extension was responsible for thinning the crust from its initial ~32-34 km thickness to 15 km for the Galicia Bank (Reston & Pérez-Gussinyé, 2007) and significantly less than 10 km for the western region over a very broard zone. During this thinning phase, maximum water depths were ~1500 m as documented by nannofossil chalks drilled at Site 1069 (on a basement high; Urquhart, 2001).

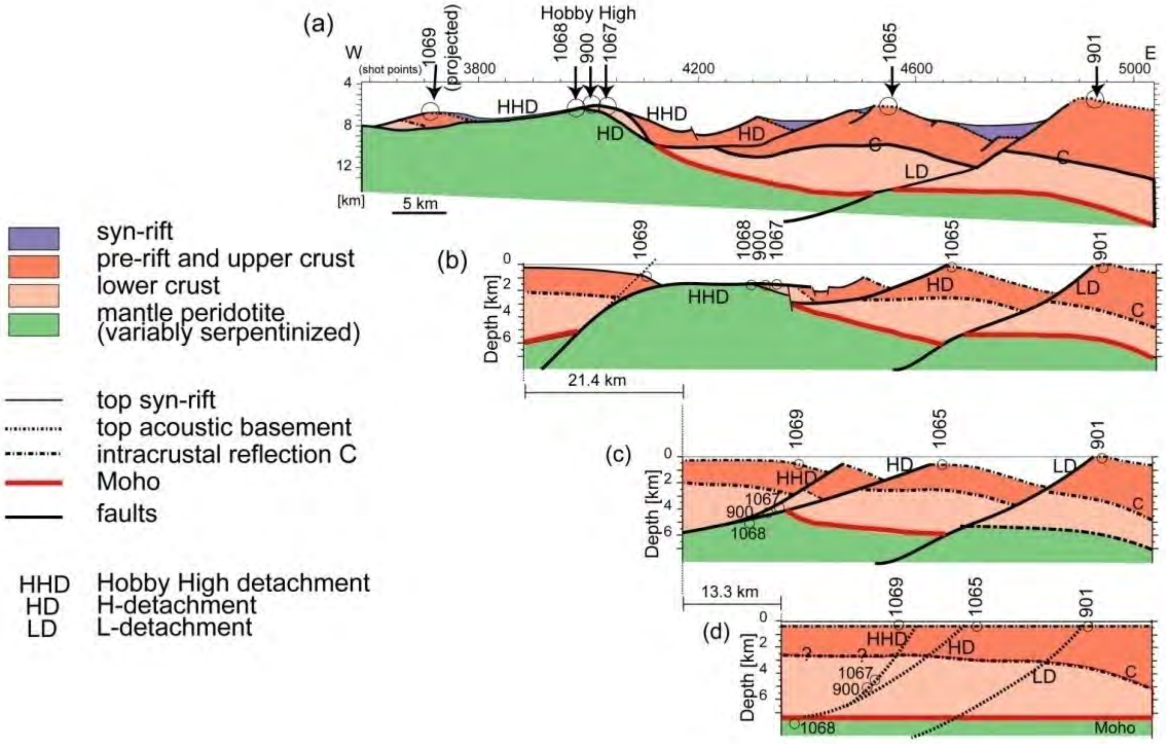


*__Figure 3:__ Structural restoration of the hyper-extended Iberian margin (modified from Manatschal et al., 2001; Péron-Pinvidic et al., 2007). a) Geological interpretation of the depth-migrated Lusigal 12 profile showing the distribution of upper and lower crustal rocks, exhumed sub-continental mantle and reflections interpreted as detachment faults. ODP sites are shown. b)–d) Evolution of faulting as determined from kinematic inversion of the interpreted Lusigal 12 profile. b) Mantle exhumation along downwards-concave fault HHD, the bathymetry being a constraint for this stage (less than 1500 m); c) Crustal extension accommodated by upwards concave faults LD, HD and HHD; and d) Initial reconstructed crustal configuration prior to extension along faults LD, HD and HHD.*

The Manatschal *et al.* (2007) reconstruction of the hyper-extended Iberia margin highlights a significant enigma in that the thinned continental crust (6-8 km) appears to be capped by shallow water Tithonian carbonates. Although shipboard micro-palaeontologists (ODP Legs 149 and 173 drilling results and Wilson *et al.* 2001) assigned these sediments to shelf and outer shelf conditions (i.e., bathymetries of ~800 m), Manatschal *et al.* (2007) used the existence of carbonates to suggest that the starting elevation of their structural reconstructions were at sea-level. However, for reasonable crustal and mantle densities, this is extremely difficult to achieve isostatically. The fact that the present-day crustal thickness and water depth are consistent implies that it is the mantle densities that were significantly different in the past, likely related to the addition of heat to the base of the lithosphere during extension. For example, if we allow differential extension to remove completely the continental lithospheric mantle and adiabatically replace it with asthenosphere, we would predict a bathymetry of ~2307 m (assuming a pre-extension crustal and lithosphere thickness of 34 and 125 km, respectively, and an ocean crustal thickness of 8 km). For a crustal thickness of 10 km, the bathymetry at the end of extension would be ~1962 m. However, if we increase the bulk crustal density from 2.8 g/cm$^3$ to 2.95 g/cm$^3$, then the predicted palaeobathymetry would be ~600 m, approaching the water depth values predicted by Peron-Pinvidic & Manatschal (2009). There is no evidence from ODP drilling for high-density Iberian crust. Thus, it is extremely difficult to have shallow water carbonates or even the 800 m water depth determined by ODP Legs 149 and 173 palaeontologists.

Likewise, geodynamic modelling analyses fail to predict an uplift of the necking and coupled domains (Figure 2) from deep to shallow water depths. While the advective rise of asthenospheric mantle heat can indeed induce uplift, thinning of the crust induces subsidence and tends to be dominant. Dismembering this necking domain can transfer portions of the domain from the hanging wall to the footwall block, thus helping to uplift specific sections of the domain. However, these processes cannot cause the necking and coupled domains to be transformed from deep water to shallow water environments. Recent modelling by Huismans & Beaumont (2011) offers a possible solution. They suggest that when cratonic lithosphere is adjacent to the zone of extension, the depleted, low density, sub-continental craton mantle tends to underplate the zone of extension, thereby helping to uplift the necking and coupled domains. While this is a tantalizing concept, the problem now becomes how to remove this material or significantly increase its density during the post-rift subsidence so that these domains can subside to depths consistent with their crustal thickness, as is the case today. All of these observations and analyses challenge the assertion that the thinning phase is pre-Cretaceous in age and synchronous along the margin.

Perhaps the prudent way to address this apparent isostatic contradiction is to review the evidence for shallow water carbonates comprising the pre-extension stratigraphy of the Iberian margin. Quoting from the initial report for Site 901 (Leg 149), “In the absence of any diagnostic structures or facies sequences, no precise interpretation of the depositional environment of the [early Tithonian claystones, calcareous sandstones and dolomites] can be given. The presence of black, presumably organic-rich claystones, the common occurrence of plant debris, the apparent lack of bioturbation, and the abundance of calcareous nannofossils in some intervals indicate that deposition took place in a relatively deep marine basin with anoxic bottom conditions and that was fringed by well-vegetated areas” (Shipboard Scientific Party 1994). Similarly, for Site 1069 (Shipboard Scientific Party 1998), Tithonian limestones show clear evidence for the re-deposition of debris from older or contemporaneous deposits of boundstones, rudstones, and grainstones. Variscan metasedimentary basement clasts were also transported together with the carbonate debris, suggesting that this unit represents the deposition of turbiditic intervals. Some 300 km to the north of Site 901, Site 639, immediately adjacent to the Galicia Bank, drilled a 95 m section of *in-situ* Tithonian carbonates that were part of a rotated footwall block (Shipboard Scientific Party 1987). However, the Manatschal *et al.* (2001) reconstruction is for the deep-water Iberian Abyssal Plain south of Galicia Bank rather than the Galicia Bank itself. We necessarily conclude that there is no evidence for a Tithonian, shallow water depositional environment for Sites 901 and 1069.

So, if the Tithonian is characteristic of deep-water depositional environments, what impact does this have on the tripartite deformational sequence outlined by Lavier & Manatschal (2006)? Deep-water conditions at the end of Jurassic time imply that significant continental extension was already well underway south of the Galicia Bank, controlling the change in crustal thickness from ~32-34 km to 5-10 km across the region. If on the other hand the Tithonian sediments are indeed shallow water, then extreme strain partitioning between the crust and lithospheric mantle is required. But as we have already shown, even if we were to remove the lithospheric mantle completely with crustal thicknesses of 5-10 km, it is not possible to produce a shallow water environment. To help address this problem, we have re-examined the evidence for shallow water sediments by re-sampling the black shales from 1069A (Leg 173 1069A16R3 127-130), the depositional unit responsible for the Tithonian shallow water interpretation from ODP Leg 173. There are an adequate number of benthic forams in the sample for dating and depositional environment determinations. Quoting from Yow-Yuh Chen and Chengjie Liu (pers. comm.), "The in-situ species are *Conoglobigerina cf. caucasica*, which range from the Late Tithonian to upper Berriasian. Benthic forams are:

*Hoeglundina sp., Lenticulina sp., Vulvelineria sp., Trochammina sp*., and a few other foram ghosts. Based on the presence of these forms, lithology and the fact of dissolution/leaching, the environment of deposition is consistent with a slope setting, definitely not restricted shallow marine. The large organic content within the sample is dominated by woody and coaly particles; they are so abundant that the whole slide is overwhelmed and completely covered by this debris". This sample is interpreted to be part of a debris flow rapidly deposited from the shallow, adjacent Galicia Bank into deep water of 500-1000 m to the south. So if the evidence for shallow water Tithonian sediments is not correct, then the isostatic dilemma of thin crust and shallow water environments of deposition is no longer a problem. What remains a problem are the original structural reconstructions of Manatschal *et al.* (2001).

**Quantitative basin modelling: Galicia Bank (northern section) and Iberian margin (southern section)**

We apply the Quantitative Basin Analysis (QBA) approach of Driscoll and Karner (1998) and Karner and Driscoll (1999), and integrate seismic stratigraphic interpretations of two representative sections across the northern and southern Iberian margin and Newfoundland margin (Sutra and Manatschal 2012), with forward kinematic basin modelling to simulate the tectonic development and generation of accommodation as a function of space and time and thus the time-line stratigraphy across the evolving Iberian-Newfoundland margin. One transect corresponds to seismic lines SCREECH 1 – ISE 1 (Figure 4; transect A-B; Henning *et al.* 2004 and Zelt *et al.* 2003) and the second south of the Galicia Bank corresponds to seismic lines SCREECH 2 – TGS/LG12 (Figure 4; transect C-D; Shillington *et al.* 2006 and Hopper *et al.* 2006). ODP leg 103 was drilled on the northern transect (Figure 1; Boillot *et al.* 1987) while ODP legs 149 and 173 were drilled on the southern transect. Seismic reflection seismic refraction and the ODP wells are the observational constraints for the geological development of the Iberian-Newfoundland margin. A successful match between the observed and predicted time-line stratigraphic geometries implies accurate prediction of crustal extension and lithospheric mantle thinning, crustal structure and hence Moho topography, palaeo-water depth history, denudation history, and heat flow history. In particular, we can reverse the modelling to show the time development of the margin.

The following events were part of the modelling scheme. A late Permian lithospheric event accompanied by major underplating resulted in significant denudation that set the boundary conditions for subsequent extension events. Following the Permian event, a series of relatively minor but broadly distributed rifting events occurred in late Triassic and early Liassic times. This was followed by Jurassic rifting that increasingly became localised and depth dependent in the early Cretaceous, and eventually led to break up. For the southern transect, these events are Oxfordian – early Tithonian (161-149 Ma), late Tithonian – early Berriasian (148-140 Ma), and late Berriasian – Aptian/Albian (139-111 Ma). In contrast, for the northern transect, these events are late Tithonian – early Berriasian (150-140 Ma), late Berriasian – Hauterivian episode (139-130 Ma), and Barremian – Aptian/Albian (129-111 Ma). In terms of the Lavier-Manatschal tripartite faulting sequence, the Triassic-Jurassic events are the stretching phase, the Berriasian-Hauterivian the thinning phase, and the Aptian-Albian, the exhumation phase. It is clear from Figures 5a and 5b that extension focuses oceanward during time, and propagates from south to north. Oxfordian – early Tithonian extension engendered water depths of 1000-1200 m across the southern transect while the northern transect had yet to be extended significantly and thus was characterised by shallow water carbonates. It is the debris from these carbonate systems and shallow rift blocks on the Galicia Bank that is the source of the siliciclastic turbidites and debris flows with shallow-water carbonate clasts drilled at ODP Sites 398 and 1069.

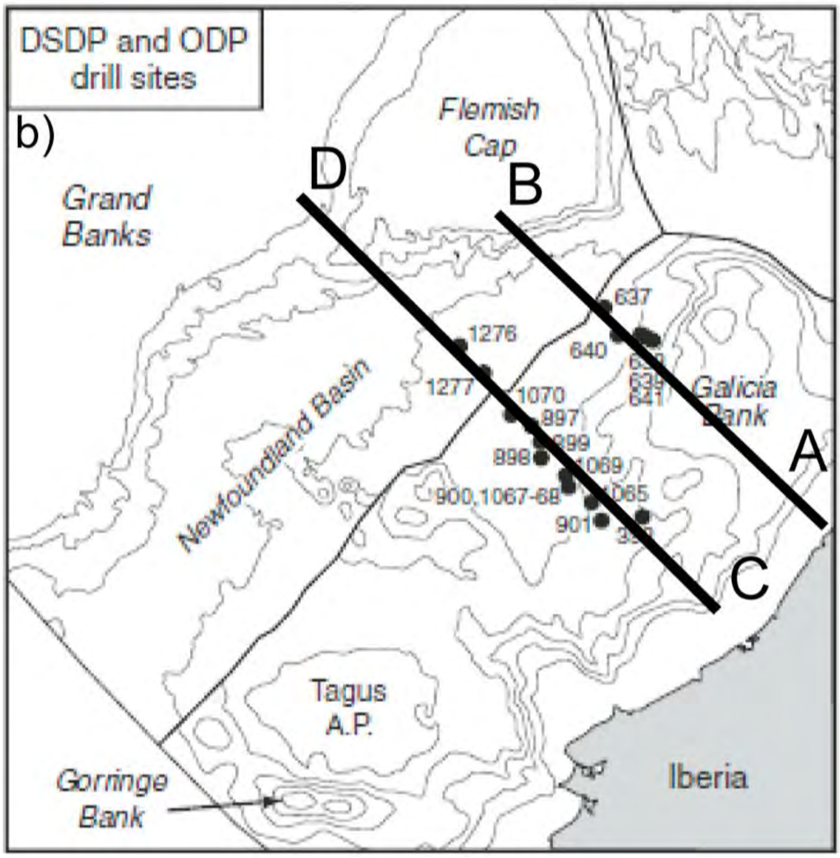


*Figure 4: Reconstructed bathymetric map of the conjugate Iberia-Newfoundland rift system at anomaly M0 time showing the location the seismic sections used for the QBA modelling (modified from Hopper et al., 2006).*

While it is clear that shallow water Tithonian carbonates are part of the rotated footwall blocks on the Galicia bank, indicating their pre-rift setting, the carbonates of the Iberian margin to the south of the Galicia Bank appear to be deep water. On both transects, significant water depths (3000-4000 m) are predicted to develop by the Valanginian.

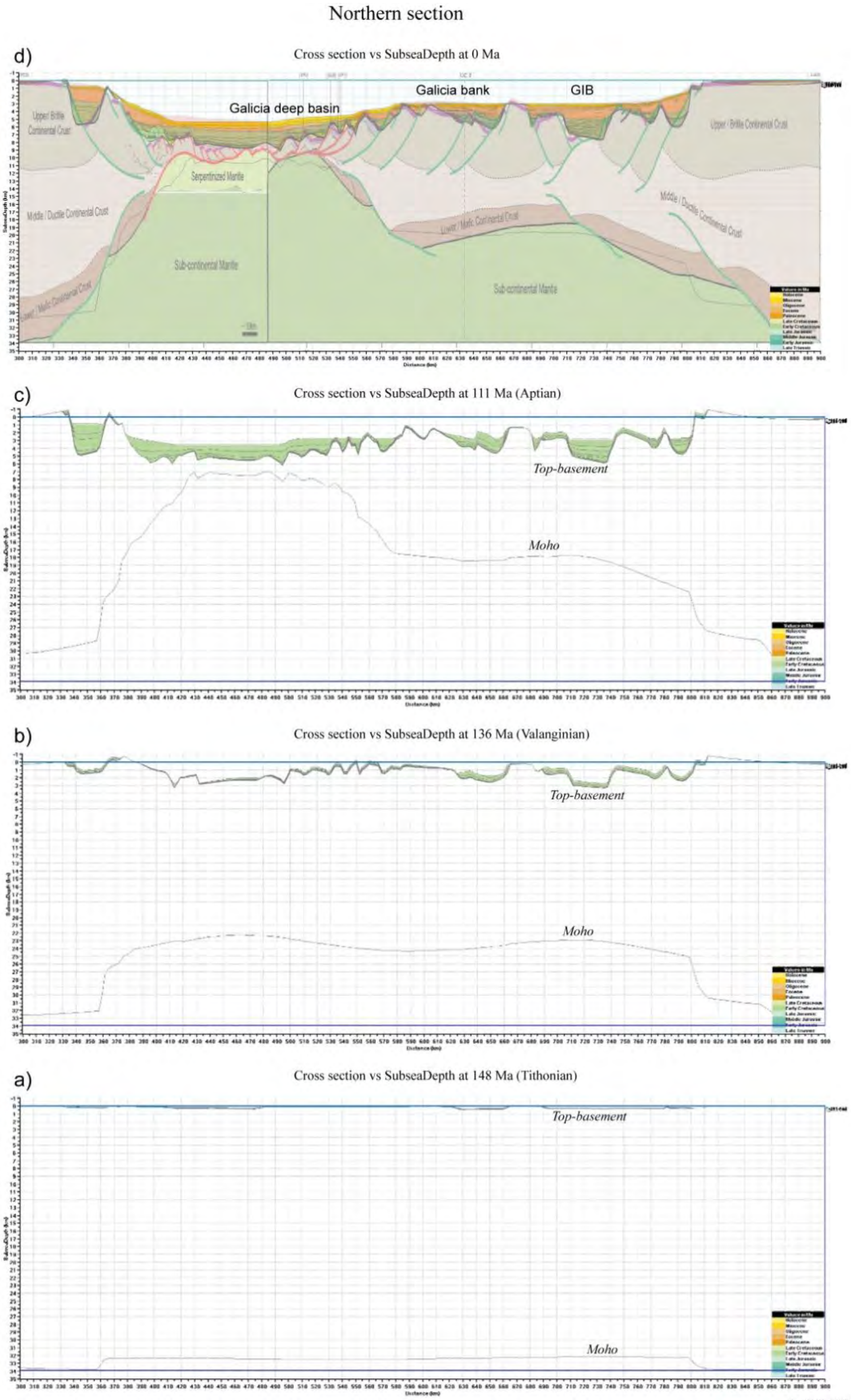


***Figure 5a:*** *Geological transect of the northern conjugate Iberia-Newfoundland rift reconstructed at anomaly M0 time showing the implications of Tithonian to Aptian extension as a function of time in terms of the subsidence history and block distribution (a-c). Part d) shows the present-day modelled and observed stratigraphy and crustal structure.*

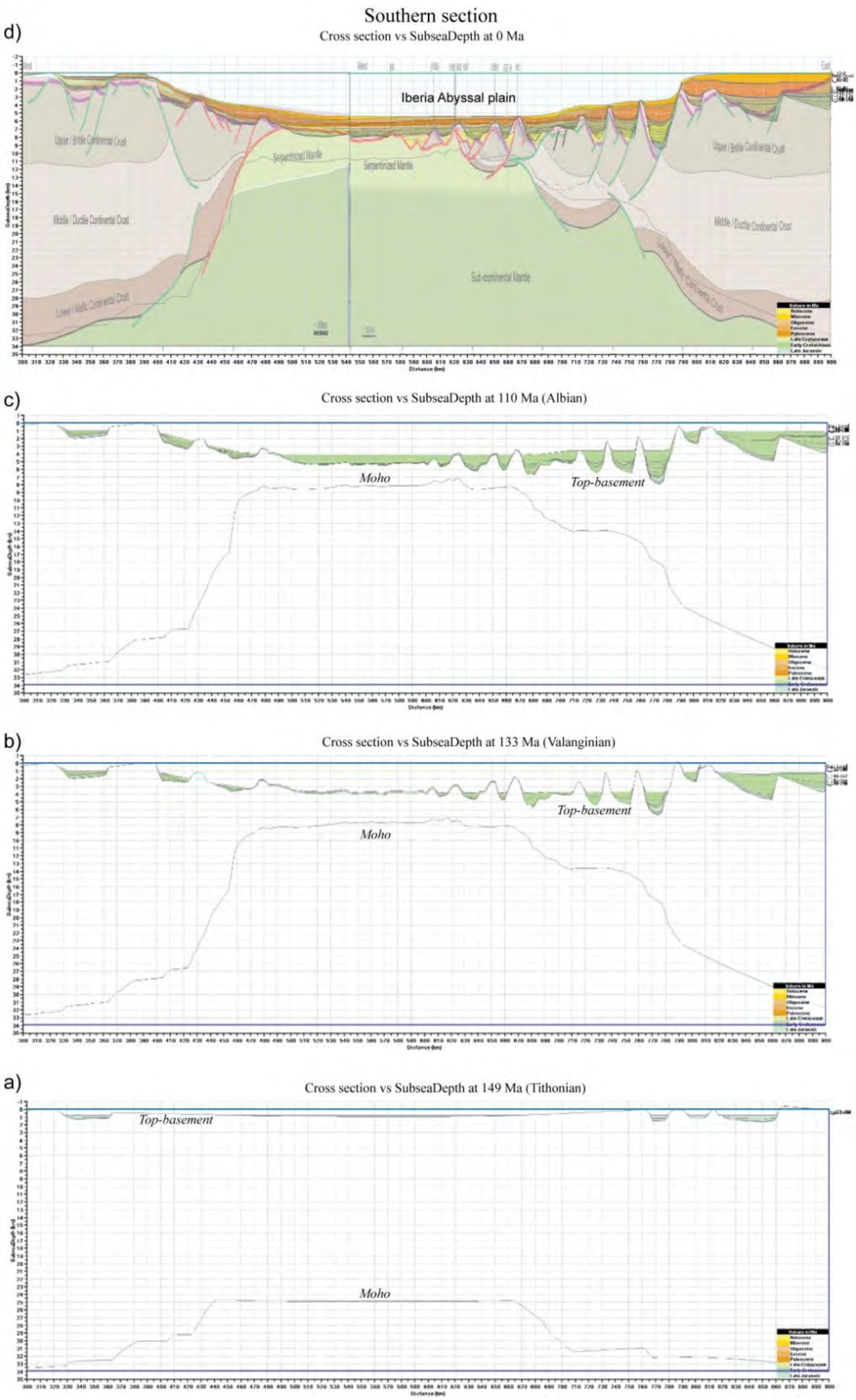


***Figure 5b:*** *Geological transect of the southern conjugate Iberia-Newfoundland rift reconstructed at anomaly M0 time showing the implications of Oxfordian to Aptian extension as a function of time in terms of the subsidence history and block distribution (a-c). Part d) shows the present-day modelled and observed stratigraphy and crustal structure.*

As reported by Arnaboldi & Meyers (2006), during ODP Leg 210, a greatly expanded sedimentary sequence of continuous Cretaceous black shales was recovered from the ultra deepwater Newfoundland margin. The cored sequence extends from the lowermost Albian, or possibly uppermost Aptian, to the Cenomanian/Turonian boundary and is characterised by several sedimentary intervals with high total organic carbon (TOC) content. These source rocks, showing TOCs ranging from 1-3%, have a vitrinite reflectance today of 0.5-1.0%Ro. Similar Hauterivian-Albian-aged source rocks were drilled during Legs 103 and 149 on the Iberian margin, as were Cenomanian-Turonian source rocks with TOCs of 9-11% (Meyers, 1996; Stein *et al.,* 1988). Where organic material is deposited on exhumed mantle, the sediment does not show evidence of any contact metamorphism. The implications are clear: during mantle exhumation, the mantle surface basically approximates the temperature of the bottom water. Even though heat flows may be extreme, these late syn-extension condensed sections do not develop significant sediment temperatures and so tend to be preserved.

**References**

Arnaboldi, M. & Meyers, P.A. 2006. Data report: multiproxy geochemical characterization of OAE-related black shales at Site 1276, Newfoundland Basin. *In:* Tucholke, B.E. Sibuet, J.-C. & Klaus A. (eds). *Proceedings of the Ocean Drilling Program, Scientific Results*, **210**: College Station, Texas (Ocean Drilling Program), 1–16. doi:10.2973/ odp.proc.sr.210.102.2006

Boillot, G., Winterer, E.L. Meyer, A.W. et al. 1987. *Proceedings of the Ocean Drilling Program, Initial Reports*, **103**, Ocean Drilling Program, College Station, Texas.

Driscoll, N.W., & Karner, G.D. 1998. Lower crustal extension across the northern Carnarvon basin, Australia: Evidence for an eastward dipping detachment. *Journal of Geophysical Research,* **103**, 4975-4992.

Hopper, J.R., Funck, T., Tucholke, B.E., Louden, K.E., Holbrook W.S. & Larsen, H.C. 2006. A deep seismic investigation of the Flemish Cap margin: implications for the origin of deep reflectivity and evidence for asymmetric breakup between Newfoundland and Iberia. *Geophysical Journal International*, **164**, 501-515.

Huismans, R.S. & Beaumont, C. 2011. Depth-dependent extension, two-stage breakup and cratonic underplating at rifted margins: *Nature,* **473**, 74-78.

Karner, G.D. & Driscoll, N.W. 1999. Style, timing, and distribution of tectonic deformation across the Exmouth Plateau, northwest Australia, determined from stratal architecture and quantitative basin modelling. *In:* "*Continental Tectonics*", Mac Niocaill, C., and Ryan P.D. (eds), Geological Society London, Special Publications, **164**, 271-311.

Lavier, L. & Manatschal, G. 2006. A mechanism to thin the continental lithosphere at magma-poor margins, *Nature*, **440**, 324-328.

McKenzie, D.P. 1978. Some remarks on the development of sedimentary basins. *Earth and Planetary Science Letters*, **40**, 25-32.

Manatschal, G., Müntener, O., Lavier, L.L., Minshull T.A. & Péron-Pinvidic, G. 2007. Observations from the Alpine Tethys and Iberia–Newfoundland margins pertinent to the interpretation of continental breakup. *In:* Karner, G.D., Manatschal, G. & Pinheiro, L.M. (eds). *Imaging, Mapping and Modelling Continental Lithosphere Extension and Breakup*. Geological Society London, Special Publications, **282**, 291–324.

Meyers, P.A. 1996. Geochemical comparisons of organic matter in Cretaceous black shales from Site 897, Iberia Abyssal Plain, Sites 638 & 641, Galicia margin and Site 398, Vigo Seamount. *In:* Whitmarsh, R.B., Sawyer, D.S., Klaus, A. & Masson, D.G. (eds). *Proceedings of the Ocean Drilling Program, Scientific Results*, College Station, Texas (Ocean Drilling Program), **149**

Péron-Pinvidic, G., Manatschal, G., Minshull, T.A. & Sawyer, D.S. 2007. Tectono-sedimentary evolution of the deep Iberia-Newfoundland margins: Evidence for a complex breakup history. *Tectonics*, **26**, TC2011, doi:10.1029/2006TC001970,

Peron-Pinvidic, G. & Manatschal, G. 2009. The final rifting evolution at deep magma-poor passive margins from Iberia-Newfoundland: a new point of view. *International Journal of Earth Sciences,* **98**, 1581-1597.

Reston, T.J., Leythaeuser, T., Booth-Rea, G., Sawyer, D., Klaeschen D. & Long, C. 2007. Movement along a low-angle normal fault: The S reflector west of Spain, *Geochemistry Geophysics Geosystems*, **8**, Q06002, doi:10.1029/2006GC001437.

Reston, T. & Pérez-Gussinyé, M. 2007. Lithospheric extension from rifting to continental breakup at magma-poor margins: rheology, serpentinisation and symmetry. *International Journal of Earth Sciences*, **96**, 6, 1033-1046. doi: 10.1007/s00531-006-0161-z

Shillington, D.J., Holbrook, W.S., Van Avendonk, H.J.A., Tucholke, B.E., Hopper, J.R., Louden, K.E., Larsen H.C. & Nunes, G.T. 2006. Evidence for asymmetric non-volcanic rifting and slow incipient oceanic accretion from seismic reflection data on the Newfoundland margin. *Journal of Geophysical Research*, **111**, B09402, doi:10.1029/2005JB003981

Shipboard Scientific Party, 1998. Site 1069. *In:* Whitmarsh, R.B., Beslier, M.-O., Wallace, P.J. *et al.* (eds). *Proceedings of the Ocean Drilling Program, Initial Reports*, **173**. Ocean Drilling Program, College Station, Texas, 219-263. doi:10.2973/odp.proc.ir.173.107.1998

Shipboard Scientific Party, 1994. Site 901. In Sawyer, D.S., Whitmarsh, R.B., Klaus, A., et al. (eds). *Proceedings of the Ocean Drilling Program, Initial Reports*, **149**: College Station, Texas (Ocean Drilling Program), 263–268. doi:10.2973/odp.proc.ir.149.109.1994

Shipboard Scientific Party, 1987. Site 639. In Boillot, G., Winterer, E.L., Meyer, A.W. et al. (eds). *Proceedings of the Ocean Drilling Program, Initial Reports*, **103**: College Station, Texas (Ocean Drilling Program), 221-407. doi: 10.2973/odp.proc.ir.103.110.1987

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

Stein, R., Rullkotter, J., Littke, R., Schaefer R.G. & Welte, D.H. 1988. Organofacies reconstruction and lipid geochemistry of sediments from the Galicia Margin, Northeast Atlantic (ODP Leg 103). *In:* Boillot, G., Winterer, E. L., et al. (eds). *Proceedings of the Ocean Drilling Program, Scientific Results,* College Station, Texas (Ocean Drilling Program), **103**.

Sutra, E. & Manatschal, G. 2012. How does the continental crust thin in a hyperextended rifted margin? Insights from the Iberia margin. *Geology*, **40**, 139-142, doi:10.1130/G32786.1

Sutra, E., Manatschal, G., Mohn G. & Unternehr, P. submitted. Quantification and restoration of extensional deformation in the Western Iberia and Newfoundland rifted margins. *Geochemistry Geophysics Geosystems* (G3)

Urquhart, E. 2001. Depositional Environment of Syn-rift Sediments on the Iberia Margin. *American Geophysical Union, Fall Meeting 2001*, abstract #PP42B-0505

## DRAINAGE EVOLUTION IN MESOZOIC NE ATLANTIC MARGIN BASINS: SAND SOURCING, SCALES AND SEDIMENT PATHWAYS

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The supply of sand into sedimentary basins is controlled by the complex interaction of a number of key factors including climate, palaeogeography and topography, and the nature of the source rocks. Provenance studies aim towards developing an understanding of these underlying controls and can provide fundamental constraints on the scale, routing and evolution of ancient drainage systems. As a consequence, these types of studies have implications for the nature and distribution of reservoir sandstones. However, some commonly applied provenance tools can produce equivocal results as potential source areas may be inadequately characterised. Furthermore, certain approaches can fail to identify and/or quantify mixing of multiple sources or incorporation of polycyclic sand grains. Provenance signals stored in specific mineral grains can be modified pre- or post-deposition. Each of these factors has the potential to obscure information that could be used to better constrain palaeodrainage.

A technique that uses the Pb isotopic composition of detrital K-feldspar grains can overcome some of the shortcomings inherent in conventional provenance approaches. K-feldspar is a common and likely first-cycle framework grain in sandstones; hence, in contrast to techniques which utilise robust mineral grains such as zircon, constraining its source can provide direct information on the palaeo-transport system. Rapid, *in situ* Pb isotopic analysis of single sand grains of K-feldspar by laser-ablation multiple-collector inductively coupled plasma mass spectrometry (LA-MC-ICPMS) provides a provenance signal that has been shown to survive weathering, transport and diagenesis. Moreover, broad regional-scale variations in Pb isotopic composition in basement terranes mean that potential source areas can be readily characterised.

This approach has been applied to Mesozoic sedimentary basins on the NW European margin in order to 1) better understand the controls on sand delivery to these basins; 2) investigate how sediment dispersal patterns have evolved over geological timescales; and 3) develop an understanding of how these factors influenced the nature and distribution of potential reservoir sandstones. Targets for study include sandstone intervals in the Porcupine, Slyne, Erris, Rockall and Faroe-Shetland basins offshore north and west of Ireland. These basins share tectono-stratigraphic similarities with those on the Canadian conjugate margin and record a complex history of rifting, thermal subsidence and, locally, inversion, prior to and during the opening of the North Atlantic. Although they contain a number of proven hydrocarbon accumulations in sandstone reservoirs, the basins are relatively underexplored.

Pb isotopic analysis of K-feldspars from Triassic, Jurassic and Cretaceous sandstones in these basins highlight important sand input points and indicate the location of significant drainage divides. The data demonstrate that East Greenland was an important source of sand during the Triassic (Figure 1) to Middle Jurassic, but its influence waned later in the Mesozoic. Offshore basement blocks (e.g. the Porcupine High, the Rockall Bank), comprising crust of Archaean and Proterozoic affinity, also played an important role in both supplying and controlling the dispersal of sediment.

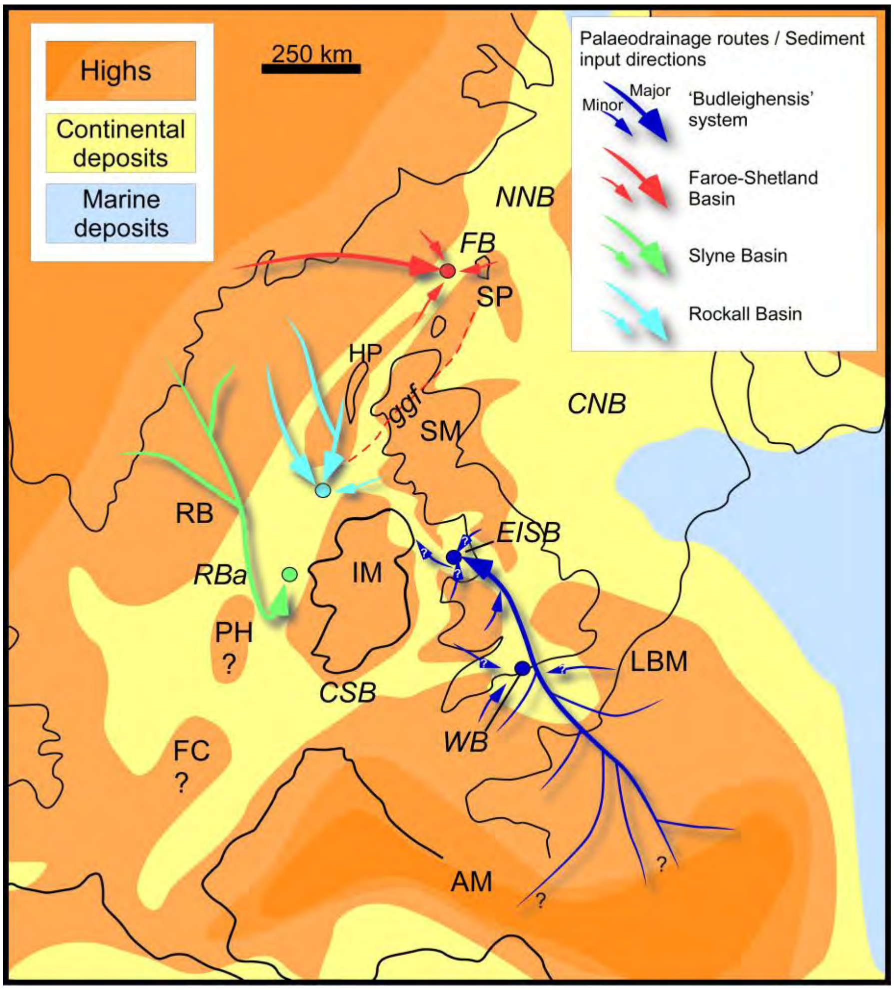


*__Figure 1:__ Schematic palaeogeographic reconstruction of the Middle Triassic showing drainage patterns as suggested detrital K-feldspar provenance data, after Tyrrell et al., 2012. AM = Armorican Massif; CNB = Central North Sea Basin; CSB = Celtic Sea Basins; EISB = East Irish Sea Basin; FB = Faroe-Shetland Basin; FC = Flemish Cap; ggf = Great Glen Fault; HP = Hebridean Platform; IM = Irish Massif; LBM = London Brabant Massif; NNB = Northern North Sea Basin; PH = Porcupine High; RB = Rockall Bank; RBa = Rockall Basin; SP = Shetland Basin; SM = Scottish Massif; WB = Wessex Basin.*

On a regional scale, the data reveal periods of major drainage reorganisation, likely associated with the rifting that eventually culminated in the breakup of Pangaea and the opening of the North Atlantic. On the scale of individual basins and sub-basins, results show that the provenance signal often changes with stratigraphy and can indicate the emergence of certain blocks. These stratigraphic variations could also be due to changes in the loci of hinterland uplift which induced periodic rejuvenation of specific tributary systems. Other data suggest the interaction of physiographic and climatic factors controlled the supply of sand and impacted directly on the nature of the resulting sandstone.

### Reference

Tyrrell, S., Haughton, P.D.W., Souders, A.K., Daly, J.S. & Shannon, P.M. 2012. Large-scale, linked drainage systems in the NW European Triassic: insights from the Pb isotopic composition of detrital K-feldspar. *Journal of the Geological Society of London*, **169**, 279-295.

## EXPLORING THE EQUATORIAL ATLANTIC

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Exploration successes for Tullow Oil and others, on both sides of the Equatorial Atlantic, came at a time when most of the focus of the oil industry was elsewhere. Those successes can be attributed to a number of factors: a) developments in seismic and drilling technologies, b) a recognition that the key elements for the occurrence of material oil accumulations were in place, and c) the willingness of key decision-makers to buy-in to the exploration concept in what was an unfashionable area at that time and to move quickly to secure opportunities. The petroleum geology of the Equatorial Atlantic is not completely unique, but, being a Transform Margin, it does have several characteristics that differentiate it from neighbouring areas.

Tullow's involvement in the Equatorial Margin of Africa began in 1996, but exploration on both sides of the ocean started much earlier. In the shallow waters offshore Ivory Coast and Ghana, Esso was foremost of a number of companies who were drilling during the 1970s but the first notable oil discoveries were made by Phillips Petroleum: Espoir (1981) in Cote D'Ivoire and North Tano (1980) in Ghana. This proof of a working petroleum system was underlined by subsequent discoveries in both countries, although many of these were small and complex and few became commercial developments. As a result of the limited number of successful developments, along with low oil prices around the turn of the millennium, oil exploration on this part of the West African margin was at a low ebb by 2000.

As in West Africa, exploration had largely stalled on the western side of the Equatorial Atlantic by the turn of the century. Aggressive exploration by Petrobras along the Brazilian margin during the 1970s and early 1980s had yielded limited success, again mostly in syn-rift structural traps, although they and Marathon did find small amounts of oil in younger reservoirs on the northern margins of the Amazon Cone. In neighbouring French Guiana, exploration was confined to sporadic drilling by Elf and Esso, again in the 1970s.

Although the discovery of the large deepwater Baobab field in Ivory Coast in 2001 clearly demonstrated the hydrocarbon potential of the margin, enthusiasm for the region was slow to reignite. Tullow had farmed into the nearby Espoir Field four years previously. This field, containing both oil and gas, was reservoired in syn-rift, Albian, shallow marine sands and trapped in a structural closure created by a tilted-fault block. The Baobab discovery was also in an Albian-age tilted fault-block but its location outboard of a major regional high undermined some existing paradigms on the origin of the hydrocarbons and their migration pathway and opened the entire deepwater realm up to exploration.

Prompted by the Baobab discovery, Tullow's team began a study of the wider African Equatorial margin. Since the occurrence of hydrocarbons appeared to be concentrated both above and immediately below the end-Albian breakup unconformity which marked the initial separation of the African and South American plates, the importance of comparing and contrasting the syn-rift/early-drift sequences on both sides of the Equatorial Atlantic was recognised at an early stage.

It was noted that the Equatorial Atlantic was bracketed by large accumulations (Dome Flore, in southern Senegal, Tambaredjo in Surinam as well as Baobab), so the potential for significant finds was clear. It was also evident that exploration to date (with the exception of the area in and around the Amazon Cone) was exclusively on the shelf - Baobab was the first discovery beyond the 200m isobath - which meant that the continental slopes were essentially unexplored. At the same time, drilling technology had advanced dramatically since the 1980s heyday of activity in the region so the deepwater realm was now accessible.

A key challenge to moves in that direction was whether or not coarse clastic reservoirs would be developed that far from sediment sources. The discovery of major oil fields in deepwater turbidite reservoirs on both sides of the South Atlantic during the 1990s demonstrated a proof of concept – but it has not yet been tested in equatorial regions. In addition, Tullow's involvement (through the acquisition of Energy Africa) in the Ceiba Field in Equatorial Guinea, had whetted the company's appetite for challenging turbidite plays.

As a result, our focus was on areas where major submarine canyon development had occurred, providing an entry point for coarse-grained shallow-water sands onto the continental slope and basin floor. In western Ghana, the major Assinie Canyon attracted keenest attention, since, as well as transferring sands from the shelf to the slope, it also provided access to a very prolific source kitchen in the deep offshore as evidenced by the abundance of oil discoveries on the shelf and seeps along the shore.

Upon these basic principles, Tullow, with strong executive support, positioned itself in a number of areas of both sides of the Equatorial Atlantic where it could test the play (Figure 1).

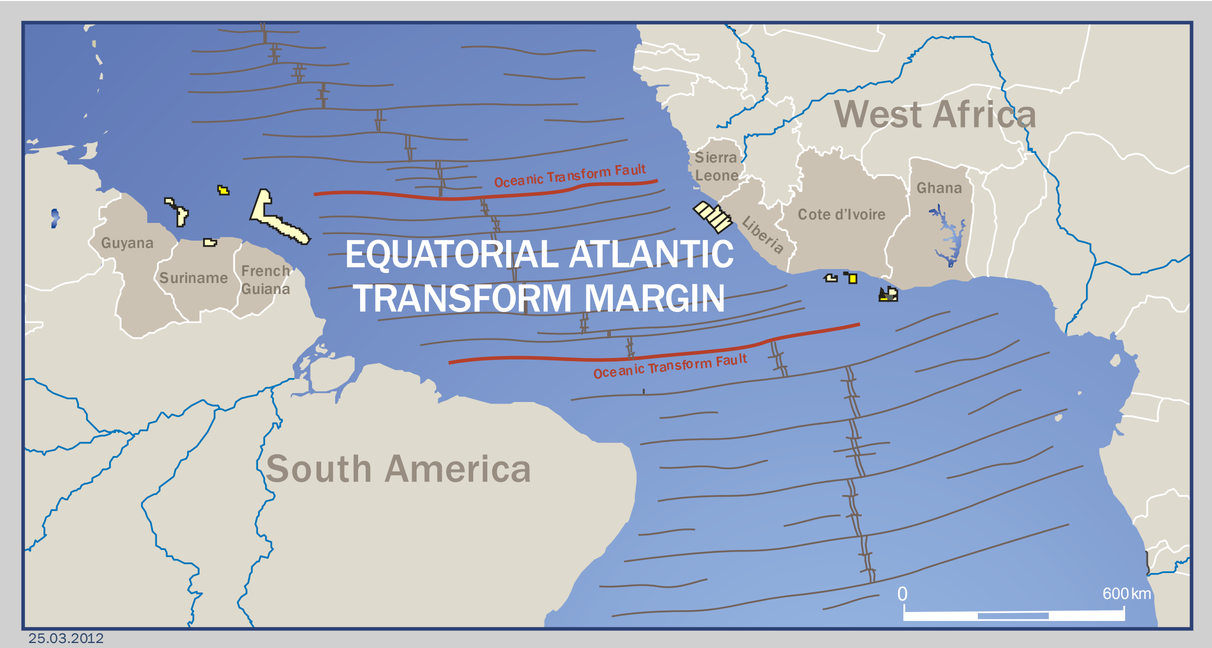


***Figure 1:** Tullow Acreage on the Equatorial Margins.*

The Equatorial Atlantic is a transform margin created by oblique separation of the continents and has therefore had a geological evolution that is distinct from the southern and northern Atlantic. So whilst the successful petroleum systems of the Equatorial Margin share many elements in common with those of the South Atlantic, they exhibit a number of distinctive characteristics, the impact of which on the hydrocarbon prospectivity of the region remains the subject of considerable debate (Figure 2).

Unlike those in the South Atlantic, oilfields discovered along the equatorial margin to date are believed to have originated almost exclusively from drift-phase marine sources of Cenomanian-Turonian age (Xareu in the Ceara Basin being a possible exception). Biomarker analysis of the oil from Jubilee Field has confirmed a strong correlation with the 93.5Ma OAE2 event. However, not many penetrations of this prolific, but elusive source interval exist in exploration wells from the region, although a thin organic-rich layer is sometimes developed immediately above the near-end Albian "breakup unconformity". Syn-rift lacustrine source rocks are commonly developed in this area, such as the Aptian Mundau Formation in the Ceara Basin and the so-called "B" Shale of the Tano Basin and recent geochemical analysis of some oils suggest that they may be a minor contributor to some accumulations, but their role seems to be limited, probably due to an excess of burial, particularly in the outer shelf and slope settings. These source intervals may have been the origin of at least some of the gas and condensate which are common components to accumulations on the West

African margin. In addition, in many cases they are surrounded and "plumbed into" syn-rift, fluvio-deltaic clastics rather than carbonate reservoirs (as in Brazil) and these sandstone often have very poor reservoir quality (e.g. North Tano). Thin and sporadic, syn-rift deltaic source rocks have also been recognised and they too could be responsible for the gas and gas-condensate discoveries common to the margin, something which has tended to discourage rather than stimulate exploration.

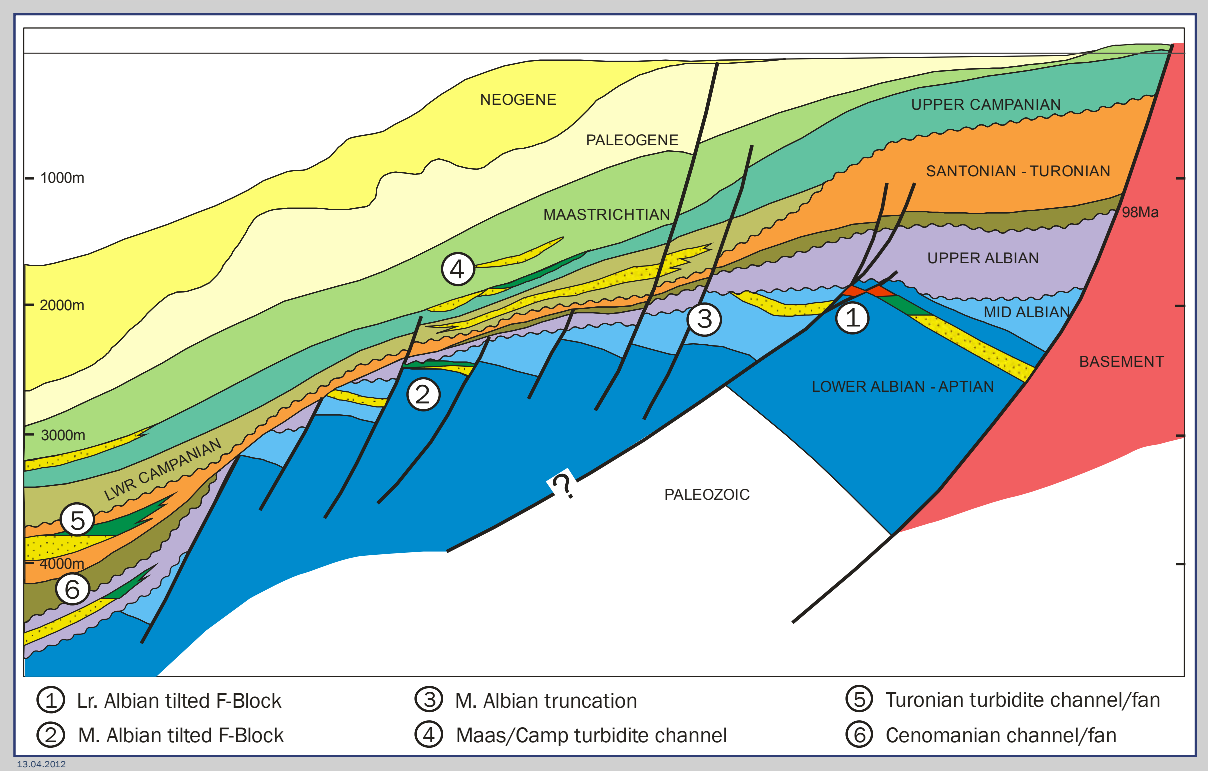


***Figure 2:*** *Equatorial Atlantic – Cretaceous Plays.*

Despite a lack of major through-going faults, migration from syn-rift and early-drift sources into younger reservoirs – right up to the Maastrichtian - seems to have been quite effective. It may be that this is the result of the abundance of carrier beds in the areas where Tullow is exploring and may not be a universal phenomenon.

It is noted above that syn-rift reservoirs are frequently low-quality, but this is not always the case – they are the main producing level in Baobab, Espoir, Atum and Curima Fields and are a viable reservoir in the South Tano accumulation. However, the main exploration target in equatorial regions is very much turbidite sandstone reservoirs that vary in age from Cenomanian to Maastrichtian. These deposits are found in a range of confined and unconfined settings depending on the gradient of the slope and the geometry of the depocentre into which they flowed. Major advancements in the quality of seismic datasets and their derivatives have greatly enhanced the ability of interpreters to recognise different depositional elements in turbidite sequences and to map out reservoir sweetspots which is, of course, critical to the successful development of deepwater oilfields (Figure 3).

The modern Equatorial Atlantic margins are home to very powerful longshore currents and this is likely to have been a feature of the region in the geological past as well. The currents would have been very effective transporters of sediment along and across continental shelves. This may be one reason why it has proven difficult to directly link the larger submarine canyons to major palaeo-river systems; perhaps the currents promoted sediment build-up and slope instability away from the main river mouths.

As one might expect, a distinctive feature of this margin is that the main structural trends tend to be oblique, or even perpendicular to, the coastline but sub-parallel to the main sediment transport direction, in contrast to the extensional margins to the south where the primary structural lineaments are parallel to the coast and perpendicular to deepwater sediment flows. As a control on the direction of sediment flows and the development of potential trapping geometries, this is a key factor in prospectivity. The fact that some, or much, of the movement on faults will have been strike-slip rather than dip-slip could also play a role in the generation of hydrocarbon traps although exploration is generally at too early a stage in the Equatorial Atlantic to be able to say much about the challenging issue of trapping.

The lack of salt, (except locally, e.g. in the Ceara Basin), is another crucial tectonic difference which has influenced the pace and focus of exploration.

Exploration efforts in this region have targeted hydrocarbon traps which combine elements of structure with stratigraphic boundaries. This has been particularly successful in the Turonian-Cenomanian section below the distinctive “Lower Senonian” unconformity although there have been some discoveries above this level, (Belier in Cote D’Ivoire, West Tano in Ghana). This relative lack of success in the Campanian-Maastrichtian seems to be more a function of lack of updip seal rather than access to charge or reservoir issues. Transform margins tend to be steeper than their counterparts in extensional settings and that can have a big impact on accumulation size where it is limited by lateral seal capacity.

In summary, Tullow’s successful exploration of the Equatorial Atlantic has been based on the recognition that prolific source rocks and high-quality reservoirs are developed on both sides of the ocean, if one looks in the right places, and by exploiting the latest geophysical techniques and drilling technologies to find and exploit hydrocarbons. As the level of exploration becomes more intense on both sides of the Equatorial Atlantic, the limits to what can be discovered, and what can be developed, will no doubt continue to be stretched.

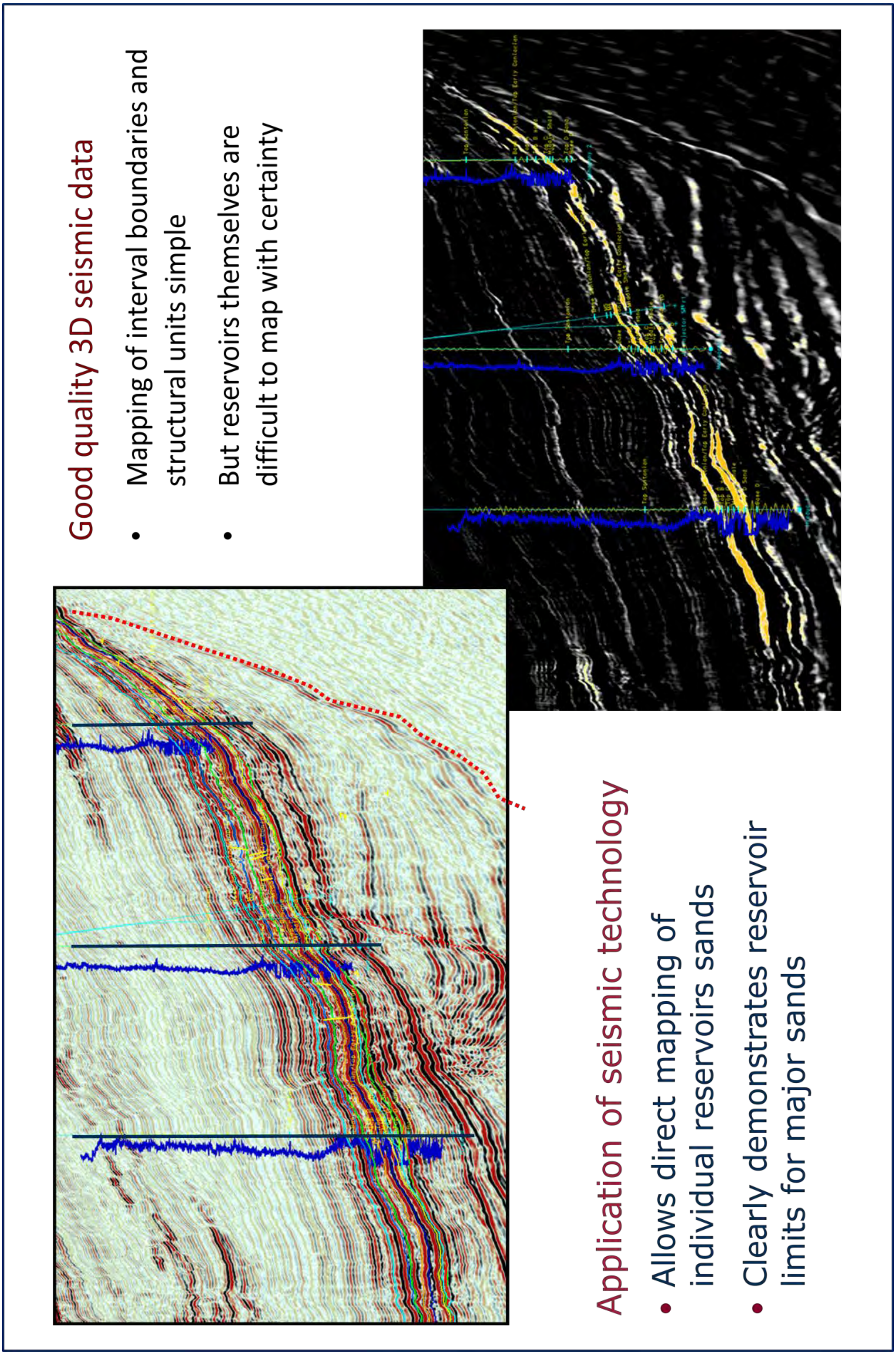


***Figure 3:*** *Turbidite Reservoirs on Seismic Data.*

# Oral Presentations

## POST-RIFT VERTICAL MOVEMENTS IN NW AFRICA: SEARCHING A MODEL FOR EXCESSIVE SUBSIDENCE AND EXHUMATION

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Sometime during the Middle Jurassic (the exact age being debated), oceanic crust appeared in the Central Atlantic domain associated with lithospheric separation between N America and NW Africa. Compatible with general models of passive margin development, normal faulting ended on both sides of the ocean. Vertical movements, on the contrary, display a pattern in contradiction with such classical models calling for a revision of i) the regional geological evolution of the two continental margins and ii) general models of passive margin development. Our contribution focuses on NW Africa. In recent years, low-temperature geochronology studies have documented km-scale exhumation along a roughly N-S trending stripe from Rabat to the High Atlas. New data show a continuation of the area of exhumation through the Anti-Atlas and, possibly, also in the Reguibate area. In the same direction, the magnitude of vertical movements seems to decrease and the age to become slightly younger. Further to the south, no information is available from Mauritania and Senegal, but our multi-technique thermochronological studies in Sierra Leone show that the Late Triassic Central Atlantic Freetown Layered Intrusive Complex underwent, after emplacement, slow cooling down to ambient temperatures of about 300°C followed by rapid cooling to <40°C in Early to Mid Cretaceous times which we interpret as associated with tectonic exhumation.

Anomalous upward vertical movements in NW Africa were associated with more-than-expected subsidence along a stripe running roughly in N-S direction at least from Northern Morocco to the Tarfaya Basin in Central Morocco. In these domains, quantitative subsidence analysis along transects across the passive margin shows that subsidence rates did not decrease significantly during the post-rift and that, on the contrary, acceleration of downward movements occurred in places such as the Agadir-Essaouira basin. Two-dimensional thermal-kinematic numeric models, taking into account lateral thermal dissipation, non-zero effective elastic thickness of the lithosphere, finite duration of rifting and lithospheric necking, reasonably exclude the possibility that such downward movements can be associated with syn-rift crustal and/or subcrustal thinning and subsequent thermal relaxation.

In the absence of theoretical models able to explain the observed patterns of vertical movements, inspiration can be gained from structural and tectonic data from our own work and from the literature. These suggest that Middle Jurassic to Lower Cretaceous deformation is ubiquitous in coeval sediments of Morocco and that contraction was the dominant strain regime.

## POST-RIFT KM-SCALE UPLIFT OF PASSIVE CONTINENTAL MARGINS CAN BE CAUSED BY COMPRESSIVE STRESSES

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Many passive continental margins are flanked by a mountain range up to more than 2 km high (Elevated Passive Continental Margins; EPCMs), e.g. Norway, east and west Greenland, east Australia and Brazil, among others. There is now good evidence (Japsen *et al.,* in press and references therein) that EPCMs have been uplifted long after continental breakup. Explanations for these uplifted margins have hitherto been *ad hoc* and there has been no explanation that accounts for their presence at both volcanic and non-volcanic margins and in both polar and tropical climatic environments.

Rifting of continental crust to create new oceanic crust happens during conditions of extensional stress. The rift margins uplift initially by flexure but they subside flexurally during post-rift development due to a combination of cooling and loading by sedimentation within the rift. The margins remain permanently uplifted only if the rifting is by simple shear where the mantle under the rift margin does not extend. In that case, there is no post-rift cooling of the mantle under the rift margin and, consequently, no subsidence. However, the innumerable successful applications of McKenzie's (1978) theory to model the subsidence at single drill holes in continental margin basins show that the assumption of simple-shear extension is unjustified.

The World Stress Map (www.world-stress-mp.org) shows that many passive margins are under compressive stress today. It is common to attribute this stress to ridge-push, which alone is totally insufficient to cause significant deformation of a passive margin. Compressional forces can, however, originate elsewhere in a continent, even from its opposite side. Formation of an orogeny requires stresses greater than the failure strength of the lithosphere and those stresses can readily be transmitted into the surrounding lithosphere. Cloetingh & Burov (2011) showed that lithosphere-scale folding in continental crust can be due to buckling of the lithosphere, but did not extend their analysis to passive margins.

Buckling of the crust (or lithosphere) requires that the compressive stress on the crust (or lithosphere) is close to that causing it to fail elastically. Current theory suggests that lower continental crust consists of two layers; an upper quartz-rich layer and a lower, more basic (dioritic) layer. The combination of increasing pressure with depth causes quartz-rich rock to increase in strength to depths of around 10 km below which increasing temperatures cause it to become increasingly weak with depth. Dioritic rock increases in strength to a depth of around 25 km below which depth it, too, becomes increasingly weak. Olivine-rich mantle is strong to depths of >100 km and oceanic crust is also strong, with no low-strength layers above ca. 100 km depth. For all likely compositions of continental crust more than 25 km thick (ca. 10 km if the entire crust is quartz-rich), there are, therefore, weak layers that separate strong upper and lower crust and strong lower crust and strong mantle, the so-called jelly sandwich. Under suitable conditions of compressive stress, flow can develop in these weak layers (see e.g. Cloetingh & Burov, 2011).

Extension and thinning of continental crust leading to sea-floor spreading causes the continental crust to thin across the zone of rifting from small amounts in the proximal rift to perhaps a factor of 5-10 in the distal rift adjacent to oceanic crust, resulting in continental crust only a few km thick. Once extension is complete and the rift has cooled to some extent, those parts of the rift that have extended to thicknesses less than about 25 km (if the lower crust is dioritic, 10 km if it is quartz-rich) are insufficiently thick for there to be a weak layer in the lower crust and the strong layers of continental crust become effectively welded to one another and to the underlying strong mantle.

Consider a passive margin some tens of millions of years after continental breakup. Sufficient compression causes flow in the weak layers, particularly that in the lower crust. Material flowing towards the rift margin from the continental side cannot continue indefinitely towards the ocean because the distal part of the rift is effectively welded. Material therefore accumulates in the lower crust on the 'upstream' side of the 'weld', thickening the crust and lifting it by isostatic response to the thickening. Flow and uplift can continue until either the rift 'upstream' of the weld is restored to its pre-rift thickness or until there is a reduction in imposed far-field compressive stress. Reduced stress causes a consequent large reduction in inflow, 'freezing' the thickened crust in place.

Compressive stresses just below the maximum strength of the crust cause buckle folds to develop, whose wavelengths are proportional to the thickness of the crust. The proximal rift and rift margin can be uplifted by the combination of lower crustal flow and buckling to form a km-scale bulge at the surface. The sediment in the proximal rift is uplifted by the formation of the bulge, tilting and eroding it. The flow into the lower crust also causes the oceanward slope of the uplifted area to be steeper than the slope towards the continent. Isostatic response to fluvial or glacial erosion in valleys of the thickened and uplifted crust will cause the material between the valleys to be uplifted even more, but, as the valleys merge, erosion will reduce the bulge back towards sea level, eventually resulting in a peneplain. The material at the eroded surface will be warmer than material near the surface at the time of rifting, resulting in apatite fission track ages that are also younger than the time of rifting.

Margins that have not been subjected to renewed compression will remain low, but many margins appear to have been subjected to several episodes of uplift (and therefore compression) (Japsen *et al.,* 2012). The renewed far-field compression forms a new marginal bulge and the peneplain formed in an earlier episode is uplifted to far above sea level (see Japsen *et al.,* 2012).

**References**

Cloetingh, S. & Burov, E.B. 2011. Lithospheric folding and sedimentary basin evolution: a review and analysis of formation mechanisms. *Basin Research,* **23**(3). doi: 10.1111/j.1365-2117.2010.00490.x

Japsen, P., Chalmers, J.A., Green, P.F. & Bonow, J.M. 2012, Elevated, passive continental margins: Not rift shoulders, but expressions of episodic, post-rift burial and exhumation. *Global and Planetary Change*: (www.sciencedirect.com/science/article/pii/S092181811100066X).

McKenzie, D. 1978. Some remarks on the development of sedimentary basins. *Earth & Planetary Science Letters* **40**, 25-32.

## OVERPRESSURE REGIMES OF THE ATLANTIC PASSIVE MARGIN AND PORE PRESSURE PREDICTION

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Overpressures can be generated by a number of different mechanisms that either increase the volume of fluids in the subsurface or reduce the available pore volume. Overpressure generation mechanisms include: disequilibrium compaction; hydrocarbon generation, aquathermal expansion and diagenesis (These mechanisms are summarised by Osborne & Swarbrick, 1997).

The contribution of each overpressure mechanism is strongly dependent on the geological environment. Disequilibrium compaction (or undercompaction) is a significant cause of overpressure in passive margins where high sedimentation rates are often prevalent. During burial, fresh sedimentation causes an increase in load on deeper sediments causing them to compact and de-water. In deltaic and associated depositional environments sedimentation rates are very high and low permeability shales are common. Here, the high sedimentation rate coupled to the low permeability of shales means that sediments cannot de-water and compact fast enough to keep up with the addition of more overburden load. The weight of any fresh overburden is then borne by the pore fluids rather than the grain structure of the under-compacted rock. This leads to increased pore pressure in shales and in sands that are surrounded by low permeability shales.

Regardless of the cause of overpressure, the observed magnitude and distribution of overpressures will be greatly controlled by the distribution of sands and shales in the subsurface. Sands have high permeabilities and will act as fluid flow pathways and a connected sand system will always have a constant overpressure (in the water phase). Shales have low permeabilities and can act as barriers to fluid flow and support pressure gradients. In order to accurately predict pore pressures therefore, a good understanding of the overpressure distribution and generation within the shales is essential, along with the extent and internal plumbing of sandstones and other permeable units within the overpressured shales. Only by understanding the geological aspects of the overpressure system can we hope to accurately predict pore pressure in wells, seismic velocity based pore pressure prediction cannot be relied on in isolation, it simply does not currently have the resolution or context.

Overpressure generation mechanisms in most passive margin environments are dominated by disequilibrium compaction. Other generation mechanisms such as hydrocarbon maturation can contribute to the magnitude of overpressure, but the overriding mechanism is that of undercompaction. This is invariably driven by an event with accelerated rates of deposition that significantly increases the loading on the shales below. Such loading events can be caused by several mechanisms, but usually they are linked to large deltas, and/or their associated sedimentary systems. Identifying the significant loading event, or the fluid retention depth (Swarbrick *et al.,* 2002), will enable identification of the surface that marks the top of overpressure. The onset of overpressure is therefore determined by lithology, not stratigraphy and will vary in depth depending on the nature of the load event. (N.B.: There are numerous examples where the lithological controls on overpressure are also major stratigraphic surfaces, but that is not to be confused with concluding the overpressure is stratigraphically controlled. Diachronous overpressure systems in deltas, for example, prove this).

By understanding and mapping overpressure systems in mature petroleum provinces, it is possible to fully ascertain the nature and character of these regimes in terms of generation, magnitude and distribution. It is therefore essential when working in less well explored basins to apply the known characteristics of these analogue basins as a first principle, and use other methods such as velocity analysis in conjunction with this knowledge to calculate probable onset of overpressure (fluid retention depth) and potential magnitude within the shales. Identifying the loading event driving fluid retention will provide a sound platform of understanding from which the finer characteristics of an overpressure regime can be defined.

With this model and approach in mind, Tullow Oil have managed to generate predictive shale overpressure models for Mauritania, Ghana and the transform margin as a whole, with great success. This understanding is now being applied to the frontier basins of French Guiana and Suriname.

A combination of direct pressure data (MDT, kick and DST) and log analysis to calculate the pressure within the shales (using Eaton and equivalent depth methods) across the entire offshore margin of Mauritania demonstrates that there is a straight line relationship between overpressure magnitude and depth of burial. The fluid retention depth is at around 1500m below mudline. Interestingly there is no demonstrable discrete loading event driving overpressure generation as there are in other systems. Sedimentation rates have clearly been high enough throughout the Cretaceous and Tertiary to prevent the shales dewatering normally and thereby generating a fluid retention depth close to 1500 m of burial. The straight line relationship between depth of burial and overpressure is striking, with little in the way of scatter, despite the variety of data, methods and regional extent of the well coverage. Calculation of the shale pressures from the log data means that the other direct pressure measurements can be put into the regional overpressure context and laterally drained sands can subsequently be identified. The use of this methodology, in conjunction with mapping the main sand fairways on seismic has provided a very powerful predictive model for overpressure at any given well location along the entire margin.

This methodology has subsequently been applied to offshore Ghana, where numerous wells are being drilled. There is a similar overpressure relationship in Ghana, except that here overpressure is caused by a significant loading event in the Mid-Upper Campanian, where a series of large basin floor fans have been deposited across the entire Ghanaian offshore margin in a compensationally stacked pattern. Beneath this event surface (sequence boundary) the shales demonstrate a similar overpressure straight line relationship with continued burial. The laterally extensive reservoirs within these overpressured shales are largely drained to a greater or lesser extent, relative to the shale pressures. It is the small, sub-seismic isolated sands that are drilling hazards, and indeed have provided several kicks. The higher net to gross in Ghana, when compared to Mauritania, means that there is more scatter on the burial vs. overpressure relationship, and consequently the drillers are provided with a P50-P10 range of overpressures. The drilling difficulty in Ghana is not high overpressures or narrow margin drilling, but overpressured shales within which are under-pressured and hydrostatically pressured reservoirs of varying magnitude, along with isolated fully overpressured sandstones. To date, the real time rig-site pore pressure prediction has verified the P50 pre-drill prediction on wells drilled after the development of the pore pressure model, thus demonstrating the veracity of the model and methodology of using a shale-based geological approach.

In frontier basins, such as French Guiana, there is almost no well data. Consequently pore pressure prediction in these provinces relies heavily on basin modelling and seismic velocity analysis. In these circumstances, it is important not to forget the known geological characteristics of analogue overpressure systems from better understood more mature regions. Post well shale pressure analysis from logs in French Guiana has greatly refined the pre-drill seismic pore pressure prediction, in particular it has identified the main loading event beneath which overpressure builds. This was not identified during the pre-drill prediction, which was purely seismic derived. Despite the paucity of well data, going forward in the region, a combination of shale pressure modelling and seismic velocity analysis should enable an accurate prediction of the magnitude and onset of overpressure for future wells on this margin.

**References**

Osborne, M.J. & Swarbrick, R.E., 1997. Mechanisms for generating overpressure in sedimentary basins: A re-evaluation. *American Association of Petroleum Geologists Bulletin,* **81**, 1023-1041

Swarbrick, R.E., Osborne, M.J. & Yardley, G.S. 2002. Comparison of overpressure magnitude resulting from the main generating mechanisms. In Huffman, M.J. & Bowers, G.I. (eds), *American Association of Petroleum Geologists Memoir* **76**,1-12

## BASEMENT INFLUENCE WITHIN THE LUSITANIAN BASIN

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The Lusitanian basin lies within the Western Iberia Margin on the coast of Portugal, and forms part of the conjugate margin to Newfoundland and the Grand Banks region. The main extensional phase occurred during the Triassic and Early Jurassic breakup of Pangaea, followed by thermal relaxation. The Portuguese margin is relatively underexplored so a new approach was needed to better understand the structural history of the region, the structural controls on the shape and depth of the Lusitanian basin and perhaps most importantly the nature and age of the underlying basement. Mohave decided to fly an aeromagnetic survey over much of the basin and, with FrOG Tech, to combine the magnetic data with existing satellite gravity and other non-seismic and seismic data to better understand the geology of the basement (terranes, composition, tectonothermal history), the depth to basement and plate reconstructions.

The basement to the Lusitanian basin comprises a set of elongate, NE-trending terranes within the broad Variscan Orogenic belt that formed between Gondwana and Laurentia during amalgamation of Pangaea. These basement terranes lie to the west of the Rheic suture and are therefore likely to form part of the Greater Avalonian terrane (or to have formed within the Rheic Ocean to the west of Iberia).

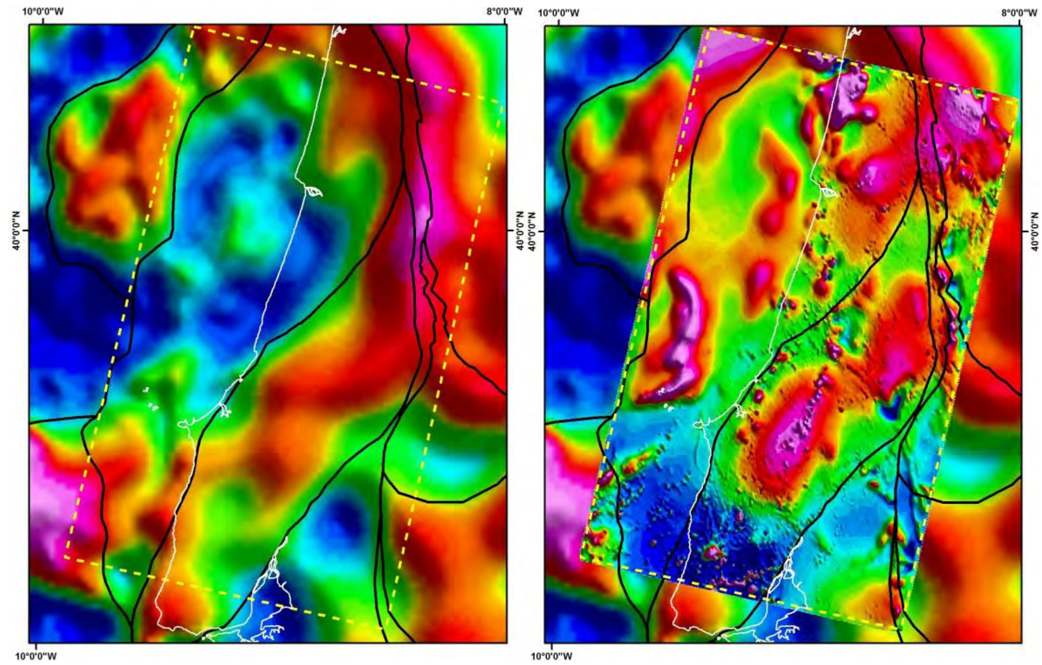
The composition of the basement terranes was interpreted from magnetic and gravity data, calibrated against the mapped terranes to the east. The basement rocks include units dominated by meta-mafic to ultramafic sequences and units dominated by metasediments. Intrusion of several large late to post-tectonic granitoids in the south resulted in a competent basement block that has not been significantly extended during rifting. In contrast, the terranes dominated by metasediments or mafic to ultramafic units localised the extension and in part, the later inversion. Interpretation of the basement composition was also used to estimate basement heat flow across the Lusitanian basin.

Intense deformation, metamorphism, and widespread magmatic intrusions are related to several stages of the Variscan Orogeny from Early Devonian to Earliest Permian. This deformation affected all terranes but is most intense along the major boundaries (suture zones and terrane boundaries). The more competent basement blocks, the Central Iberian and Ossa-Morena terranes to the east of the Rheic suture, protected Early Palaeozoic sediments such that they have undergone only weak deformation and very low grade metamorphism except along terrane boundaries and major structures. In general, the elongate NE trending terranes beneath the Lusitanian basin have deformed more readily than those to the east, however, it is possible that Early to Late Palaeozoic sequences were also "protected" within these terranes in areas away from major tectonic boundaries. In fact, localised outcrops of weakly deformed, very low metamorphic grade Late Devonian to Mississippian age sediments (including black shales) have been mapped along the Porto-Tomar-Ferreira do Alentejo Shear Zone (PTFASZ; Chaminé *et al.,* 2003 ; Machado *et al.,* 2011). These units occur within thrust slices along the eastern margin of the Lusitanian basin. Given the degree of deformation, it is surprising that Palaeozoic source rocks have been preserved within this setting.

Oil typing at the Aljubarrota-1 well shows that Early Palaeozoic source rocks may still be viable beneath the Lusitanian basin although these data are from oil stains (Uphoff *et al.* 2000) and the age control is very limited. It is perhaps more likely that Late Palaeozoic source rocks are the prime candidates for the generation of hydrocarbons in the basin beneath the Dagorda Evaporite. Interpretation of basement terrane movements highlights the regions where some terranes have been less deformed during the Variscan. In addition, understanding of regional plate/terrane movements and fault kinematics for each major tectonic event allows us to predict the likely depocentres for Late Palaeozoic units in transtensional basins during Variscan events. Significant depocentres could have developed and been preserved beneath the Lusitanian basin during the Devonian and Carboniferous. In general, the Late Palaeozoic syn-orogenic units are likely to be better preserved than the Early Palaeozoic sequences which have experienced the entire Variscan cycle.

Another key result from interpretation of the magnetic data is the identification of 200 Ma volcanics of the Central Atlantic Magmatic Province in a number of sub-basins for the first time. In addition, potential controls on the distribution of the Dagorda Evaporite which is broadly coeval with the volcanics have been interpreted.

This integrated interpretation of the Lusitanian basin has focused on understanding the basement by using gravity and magnetic data as the core datasets. It has resulted in new insights into the region. Sampling and analysis of basement rocks (geochemistry and geochronology) and Triassic Silves Formation (detrital zircon populations) from the deep petroleum wells, will help to better constrain the interpretation of the basement terranes and possible analogs for the Early to Late Palaeozoic stratigraphy beneath the Lusitanian basin.




***Figures 1 & 2:*** *Basement terrane boundaries overlain on satellite gravity (high pass 200km filter; left) and overlain on magnetic data (reduced to pole) with satellite gravity in background (right).*

**References:**

Chaminé H.I., Gama Pereira L.C., Fonseca P.E., Moço L.P., Fernandes J.P., Rocha F.T., Flores D., Pinto de Jesus A., Gomes C., Soares de Andrade A.A. & Araújo A. 2003. Tectonostratigraphy of Middle and Upper Palaeozoic black shales from the Porto-Tomar-Ferreira do Alentejo shear zone (W Portugal): new perspectives on the Iberian Massif. *Geobios* **36**, 649-663.

Machado G., Franců E., Vavrdova M., Flores D., Fonseca P.E., Rocha F., Gama Pereira L.C., Gomes A., Fonseca M. & Chaminé H.I., 2011. Stratigraphy, palynology and organic geochemistry of the Devonian-Mississippian metasedimentary Albergaria-a-Velha Unit (Porto–Tomar shear zone). *Geological Quarterly,* **55**, 139-164.

Uphoff, T.L. 2000. Subsalt (pre-Jurassic) exploration play in the northern Lusitanian basin of Portugal. *American Association of Petroleum Geologists Bulletin,* **89**, 699–714.

## DETERMINING THE COB LOCATION ALONG THE GALICIA BANK AND IBERIAN MARGIN FROM GRAVITY INVERSION, RESIDUAL DEPTH ANOMALY AND SUBSIDENCE ANALYSIS.

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Knowledge and understanding of continent-ocean boundary structure and location, the distribution of thinned continental crust and lithosphere, its distal extent and the start of unequivocal oceanic crust are of critical importance in evaluating petroleum systems in deep-water frontier oil and gas exploration at rifted continental margins. The mapping of crustal thickness, ocean-continent transition structure and continent-ocean boundary location at rifted continental margins is therefore a generic global problem.

In order to determine the ocean-continent transition structure (OCT) and continent-ocean boundary (COB) location along the Galicia bank and Iberian margin, we use a combination of gravity inversion, residual depth anomaly (RDA) and subsidence analysis. Gravity inversion had been used to determine Moho depth, crustal basement thickness and continental lithosphere thinning; subsidence analysis has been used to determine the distribution of continental lithosphere thinning; and RDAs have been used to investigate the OCT bathymetric anomalies with respect to expected oceanic bathymetries at rifted margins. Both localised 2D and regional 3D analyses have been carried out (Figure 1). The 2D studies focus on published seismic reflection lines.

Data used in the gravity inversion are bathymetry, satellite derived free-air gravity, 2D sediment thickness from seismic reflection data, and ocean age isochrons. The gravity inversion method, which is carried out in the 3D spectral domain, incorporates a lithosphere thermal gravity anomaly correction due to the elevated geothermal gradient within oceanic and rifted continental margin lithosphere (Greenhalgh & Kusznir, 2007; Chappell & Kusznir, 2008). The gravity inversion also includes a correction for volcanic addition due to decompression melting, based on White & McKenzie (1989). Sensitivities to volcanic addition have been examined. Gravity inversion results are dependent on the age of continental breakup; the lithosphere thermal gravity anomaly correction is dependent on the lithosphere thermal re-equilibration time. Gravity inversion Moho depths have been calibrated against Moho depth estimates from seismic reflection profiles. Calibration suggests that a reference Moho depth of 37.5 km is required in order to predict crustal thicknesses consistent with those seen in the seismic reflection data.

RDAs have been calculated by comparing observed and age predicted oceanic bathymetries, using the thermal plate model predictions from Crosby and McKenzie (2009). Localised RDAs have been computed along profiles (Figure 1 (b)) and have been corrected for sediment loading using flexural back-stripping and decompaction. In addition, gravity inversion crustal basement thicknesses together with Airy isostasy have been used to predict a synthetic RDA (Figure 1 (b)). The RDA results show a change in RDA signature and may be used to estimate the distal extent of continental crust and where unequivocal oceanic crust begins.

Continental lithosphere thinning (Figure 1 (c)) has been determined using flexural back-stripping and subsidence analysis assuming the classical rift model of McKenzie (1978) with a correction for volcanic addition due to decompression melting based on White & McKenzie (1989). Sensitivities to volcanic addition, in particular magma poor versus normal volcanic addition have been examined. Thinning factors determined from gravity inversion and subsidence analysis have been used to further constrain COB location along the profile lines.

Gravity inversion, RDA and subsidence analysis results have been used together to determine ocean-continent transition structure and continent-ocean boundary location. Continental lithosphere thinning factors determined from gravity inversion and subsidence analysis are in good agreement (Figure 1 (c)); whilst both are dependent on the volcanic addition correction, we prefer the magma poor margin results. The sediment corrected RDA and the synthetic RDA (Figure 1 (b)) determined outboard of the COB both show a negative RDA, of approximately -1000 m. Non-zero RDA results may be due to mantle dynamic topography (or subsidence), departure from the average oceanic crustal thickness or the presence of thinned continental crust in the oceanic domain. Our preferred interpretation of the negative RDA from the sediment corrected and synthetic RDAs is that it is a result of thinner than average oceanic crust in the oceanic domain and that mantle dynamic subsidence is negligible at this margin.

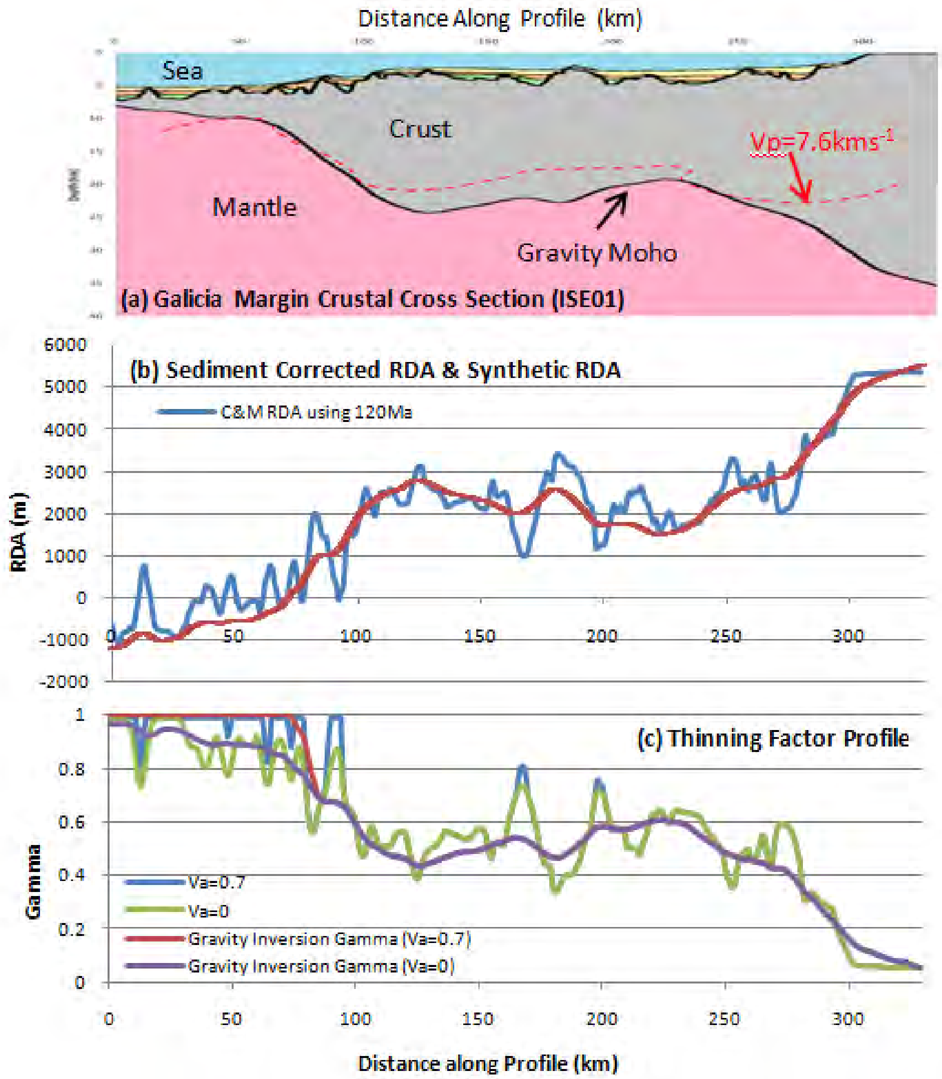


*__Figure 1__ (a) Crustal cross section for Galicia margin (ISE01) showing gravity inversion Moho compared to Vp=7.6kms$^{-1}$ derived tomographically (Zelt & Smith, 1992). (b) Corresponding sediment corrected and synthetic gravity derived RDA. (c) Thinning factor from subsidence analysis and gravity inversion for a normal and magma poor volcanic addition.*

**References**

Crosby, A. G. & McKenzie, D. P. 2009. An analysis of young ocean depth, gravity and global residual topography. *Geophysical Journal International*, **178**(3).
White, R. & McKenzie, D. 1989. Magmatism at rift zones: The generation of volcanic continental margins and flood basalts. *Journal of Geophysical Research*, **94**, 7685– 7729.
Greenhalgh, E.E. & Kusznir, N.J. 2007. Evidence for thin oceanic crust on the extinct Aegir Ridge, Norwegian Basin, N.E. Atlantic derived from satellite gravity inversion. *Geophysical Research Letters,* **34**, L06305, doi:10.1029/2007GL029440.
Chappell, A.R. & Kusznir, N.J. 2008. An algorithm to calculate the gravity anomaly of sedimentary basins with exponential density-depth relationships. *Geophysical Prospecting,* **56**, 249–258.
McKenzie, D.P. 1978. Some remarks on the development of sedimentary basins. *Earth and Planetary Science Letters,* **40**, 25–32.

## KEY STRATIGRAPHIC ELEMENTS WITHIN ORPHAN BASIN, OFFSHORE NEWFOUNDLAND, CANADA

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Early exploration in the Orphan Basin (Figure 1) focused primarily along its western margin and typically penetrated basement, revealing little about the economic potential of the area. Recently, however, renewed interest in this frontier basin has arisen from its proximity to the petroleum-rich Jeanne d'Arc Basin and potential for correlation with source rocks in neighbouring basins. Our aim is to develop a stratigraphic framework to explain the succession of depositional events linked to rifting and development of the North Atlantic Ocean. Our approach incorporates analyses of well logs, cores, cuttings, biostratigraphy, seismic data, and subsidence histories to understand key stratigraphic elements within Orphan Basin and the adjacent Flemish Pass and northern Jeanne d'Arc basins.

The effects of progressive northward rifting are recorded in two major transgressive-regressive packages driven by tectonic forces. The first package begins with the onset of relatively rapid subsidence in the Middle to Late Jurassic in the Jeanne d'Arc and Flemish Pass basins. During this time, 100s of metres of nearshore restricted marine deposits accumulated during a lowstand or stillstand when sedimentation rates outpaced the rate of relative sea-level rise during initial rifting. The ragged gamma-ray profiles that characterise this depositional phase may correlate to those seen at depth in Great Barasway F-66 (this hypothesis is currently being tested with biostratigraphic analyses). The brackish, restricted nature of Jurassic deposits may represent limited marine circulation within a stagnant arm of the Tethys Ocean prior to the development of a connection to the nascent North Atlantic.

Following accumulation of thick, nearshore, restricted marine strata, the stratal patterns in the Upper Jurassic become fining upward, signifying a transgression (T1) demarcated by a transgressive flooding surface (TSE1) and capped by a maximum flooding surface (MFS1). The thin transgressive package can include green, pyrite-bearing shales and the influx of marine fossils such as ammonites in Baccalieu I-78. This transgression also marks a transition from restricted- to open-marine conditions and possibly reflects a joining of the North Atlantic and Tethys oceans, thus influencing oceanic circulation.

Above MFS1, the Upper Jurassic through Cretaceous succession is characterised by a regressive phase (R1). Upper Jurassic and Lower Cretaceous strata are predominantly aggradational with weakly progradational shelf to distal shoreface packages. In the northern Jeanne d'Arc and Flemish Pass basins, the Lower Cretaceous Avalon unconformity appears to reflect uplift and erosion (Sinclair, 1995) of the uppermost Lower Cretaceous and much of the Upper Cretaceous succession. Major unconformities in Orphan Basin, however, tend to reflect missing time in the mid to late Cretaceous succession that may record uplift of basement blocks or non-deposition in more distal marine settings. Thick Upper Cretaceous strata preserved along the western margin of Orphan Basin record continued regression with short-lived, rapid progradation of shelf to shoreface successions suggestive of a decrease in the rate of relative sea-level rise. The overall regressive package (R1) can be explained by a decrease in the rate of subsidence (as seen on basement subsidence curves) during which sedimentation rates outpaced the ongoing rate of subsidence.

At the end of the Late Cretaceous (Maastrichtian) and into the Paleocene, the end of regression is marked by a fining-upward sequence signifying renewed transgression (T2). Wells along the western margin of Orphan Basin show transgressive ravinement (TSE2) and abrupt truncation of progradational shoreface strata. The fining-upward transgressive package is typically thin and capped by a Paleocene maximum flooding surface (MFS2) marked by: a prominent gamma ray spike; associated abundance of glauconite; presence of chalks; and/or development of green shales. This MFS2 reflects a condensed marine interval in which sediment bypass took place (like that described by Deptuck *et al.* 2003 for the Jeanne d'Arc Basin) in which associated unique sedimentological properties are likely linked with strong reflections seen in seismic data and the prominent gamma-ray spike seen in some wells. A combination of the TSE2 (where present), MFS2, and (in some wells) Cretaceous unconformities have likely been previously used to identify the "Base Tertiary Unconformity." It appears, however, that much of the missing succession can be attributed to Cretaceous unconformities, while the MFS2 is correlative with the onset of major subsidence across the study area that began around 60 Ma (middle Paleocene). The overlying Tertiary succession is characterised by a gradual decrease in the rise of relative sea level as the continental shelf built seaward during a second regressive phase (R2). Our preliminary results above and our planned integrated studies should provide a more comprehensive understanding of the evolution and petroleum potential of Orphan Basin and associated basins of the conjugate margin.

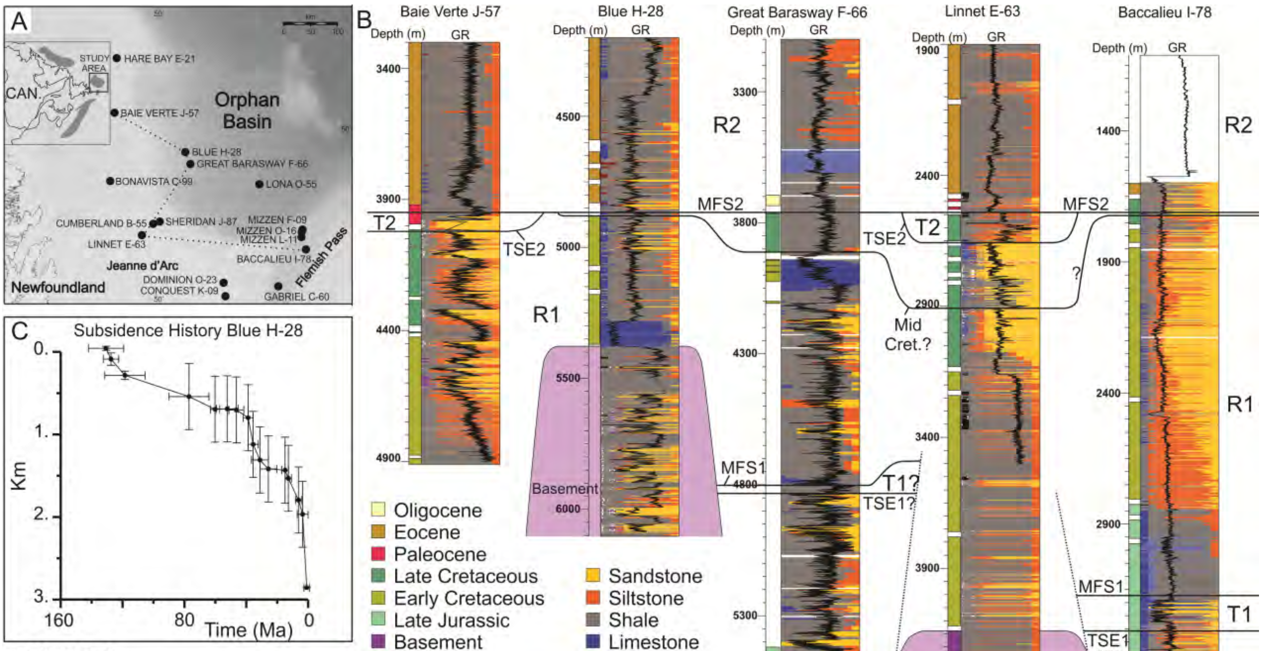


FIGURE 1

**References**

Deptuck, M.E., MacRae, R.A., Shimeld, J.W., Williams, G.L. & Fensome, R.A. 2003. Revised Upper Cretaceous and lower Paleogene lithostratigraphy and depositional history of the Jeanne d'Arc Basin, offshore Newfoundland, Canada. *American Association of Petroleum Geologists Bulletin,* **87***,* 1459-1483.

Sinclair, I.K. 1995. Sequence stratigraphic response to Aptian-Albian rifting in conjugate margin basins: a comparison of the Jeanne d'Arc Basin, offshore Newfoundland, and the Porcupine Basin, offshore Ireland. *In:* Scrutton, R.A., Stoker, M.S., Shimmield, G.B. & Tudhope, A.W. (eds). *The Tectonics, Sedimentation and Palaeoceanography of the North Atlantic Region,* Geological Society London, Special Publications, **90**, 29-49.

## CONJUGATE MARGINS OF THE EQUATORIAL ATLANTIC: SIMILARITIES AND DIFFERENCES

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The Equatorial margins of Africa and South America have become a prolific exploration area in the last decade, with significant discoveries in Sierra Leone, Cote D'Ivoire and Ghana, and French Guiana. The Equatorial margin began major rifting in early Aptian times when pull-apart basins formed between the major St. Paul's and Romanche Fracture Zones. Good quality Aptian marine saline source rocks were developed along the eastern segment in Ceara and Potiguar at this time, but these have not been proven yet on the African margins (conjugate Togo and Benin pull-apart). Rifting continued into the Late Albian and deep marine conditions were developed with potential source rocks deposited.

Plate movement vectors changed in the latest Albian to early Cenomanian (ca. 95 Ma) and the dextral strike-slip-pull-apart transform plate boundary underwent a transpressive phase (NNW-ESE directed compression). Large WSW-ENE trending en-echelon folds developed in Barreirinhas, Brazil and the conjugate Ghana-Togo margin. Fold crests were eroded on the shelf and better quality upper Albian reservoirs removed. Hence, wells drilled on the crests of the anticlines may miss the best reservoirs, and more subtle folds with less erosion are the preferred targets.

Cenomanian-Turonian shales source oil into slightly younger reservoirs in Guyana, Suriname, French Guiana, Ghana and Sierra Leone. The fold belts produced along the St Paul's and Romanche Fracture zones produced topographic barriers, so that Late Cretaceous channels were diverted to the eastern and western ends of the fold belts. The tectonic 'corners' at the ends of the fold belts are considered more prospective for reservoir development (Figure 1). The successful plays and source rock development, up until the Late Cretaceous, are similar on both margins, with Albian and Cenomanian-Turonian source rocks and Late Cretaceous reservoirs trapped in structural/stratigraphic traps. However, this play has hardly been tested along the South American margin. The first well to test the Late Cretaceous stratigraphic trap play was the successful Zaydeus-1 well in French Guiana and many similar untested prospects may exist along the South American margin.

The final split of the Equatorial margin was highly asymmetric with an abrupt narrow margin developed along the Para-Maranhão and Barreirinhas segment of the Brazilian margin and a broader margin developed in Ghana. The steep Brazilian margin resulted in gravitational instability and a large deepwater compressive-toe fold belt developed in late Cretaceous to Early Tertiary times. Compression still occurs to the present day. There is no known equivalent to this fold belt in Africa. The fold belt has been tested by a few wells with one small gas discovery recorded in an anticline in Barreirinhas, but the late Cretaceous stratigraphic play below the fold belt remains to be tested.

The NE Brazilian shallow shelf was then covered by a thick (up to 5 km) carbonate platform that grew from Eocene times to Recent; again there is no known equivalent on the African margin where clastic sedimentation dominated the Cenozoic. A high risk late Cretaceous stratigraphic pinch-out play may be present below the Tertiary carbonate platform.

Conjugate Equatorial margin studies remain relevant to exploration in rocks of Early Aptian to Campanian ages, but the petroleum systems that developed subsequently are very different and conjugate comparisons are no longer valid or useful.

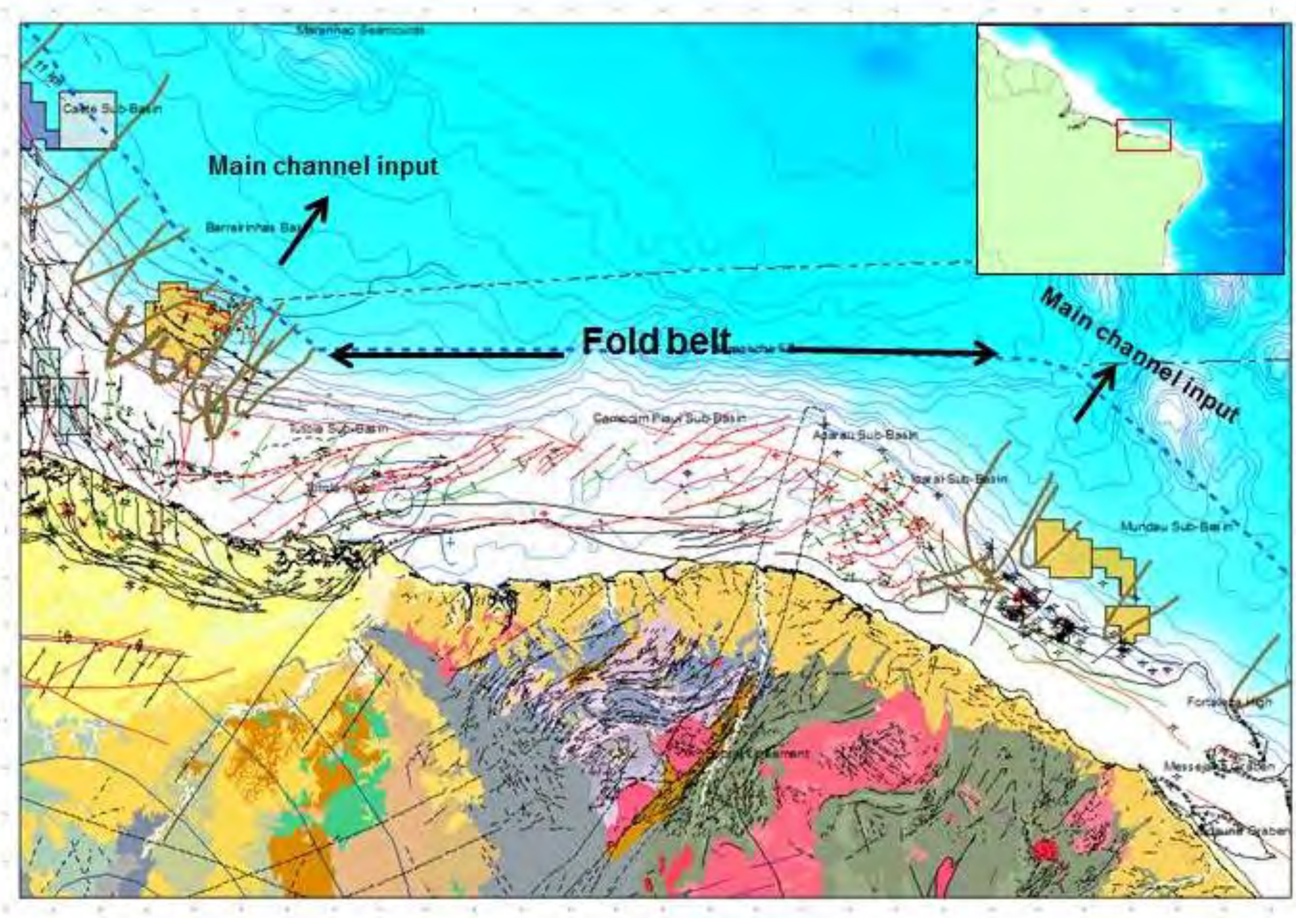


***Figure 1:*** *Map showing the central part of the Brazilian Equatorial margin highlighting the en-echelon fold belt and the main channel input points at either end detected by mapping incision channels on regional seismic sections.*

## Early Cretaceous Volcanism in the Porcupine Basin, Atlantic Margin of Ireland: Key Seismic Traverses yield new Insights into the Origin of the Porcupine Median Volcanic Ridge

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New long offset 2-D pre-stack-depth-migrated (PSDM) seismic reflection data, gravity and velocity models have been used to assess the nature and origin of a prominent, buried ridge, the Porcupine Median Volcanic Ridge (PMVR) within the Porcupine Basin, offshore south Ireland (Figure 1). Over the past 30 years the debate on the origin of the PMVR has followed the evolution of the concept of continental margin genesis.

In this presentation the origin of the ridge is assessed and evaluated on the basis of its internal geometry and the velocity structure as revealed by the seismic reflection data. Implications of the presence of these types of ridges in hyper- extensional rifted margins are reviewed and compared with other similarly structured margins. This analysis indicates that the ridge is an extrusive volcanic ridge, probably tholeiitic in composition, and constructed by stacked hyaloclastite 'deltas' and topped by carbonate platforms. These results invalidate previously proposed models involving highly rotated fault blocks and serpentinite mud volcanism.

Interpretation of the seismic data, combined with the extension magnitude analysis, suggests a highly stretched crustal structural setting where limited mantle serpentinisation may have occurred, yet the architecture and velocity model of the PMVR demonstrates that it is composed of lower velocity materials than serpentinite. During the opening of the North Atlantic the PMVR is thought to represent the northern time-equivalent magmatic event as is expressed along the Newfoundland and the Iberia-Galicia margins, recorded by the 'J'-anomaly during the early Cretaceous period.

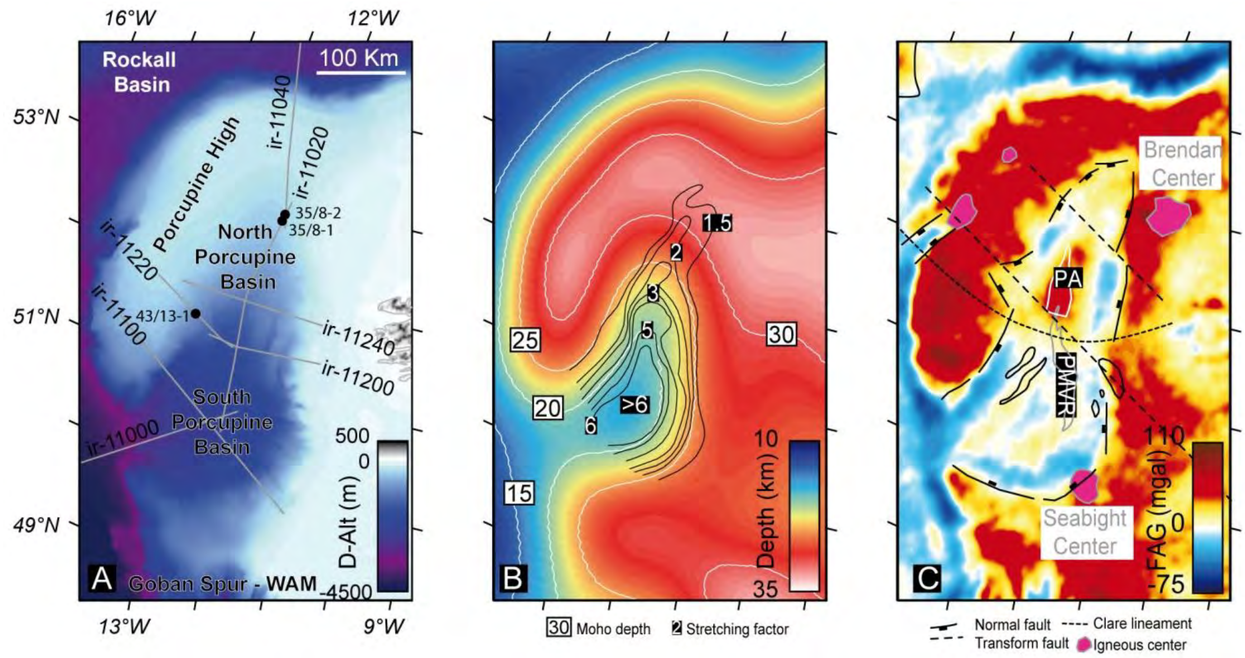


***Figure 1:*** *Setting of the Porcupine Basin (North and South Porcupine). A: Seafloor bathymetry from GEBCO compilation (www.bode.ac.uk/data/online-delivery/gebco/; British Oceanographic Data Centre, 2003). Pre-stack depth migration (PSDM) seismic reflection survey in light grey (NE AtlanticSPAN™, ION-GeoVentures), boreholes are indicated by the filled black circles. B: Average Moho depth map from the European Seismological Division – Working Group "Crustal Structural Maps of Europe" (www.seismo.helsinki.fi.mohomap/). Beta factor estimates are overlain as black contours. C: Free-air gravity anomaly map of the area (V18, http//topex.ucsd.edu/cgi-bin/hget_data.cgi) and the main structural elements, including the PMVR and two smaller ridges to the west of the PMVR. The normal faults and igneous centres from the Petroleum Affairs Divisions, DCENR and Government of Ireland (http://gis.dcenr.gov.ie/imf.jsp?site=PAD_Seismic); transform fault from Readman et al. (2005), and Clare Lineament from Bentley and Scrutton (1987). PA: Porcupine Arch; PMVR: Porcupine Median Volcanic Ridge.*

## References

Bentley, P.A.D. & Scrutton, R.A. 1987. Seismic investigation into the structure of the southern Rockall Trough: In Brooks, J. & Glennie K.W. (eds). *Petroleum Geology of North West Europe*, Graham and Trotman, London, 67-75.

Readman, P.W., O'Reilly, B.M., Shannon P.M. & Naylor D. 2005. The deep structure of the Porcupine Basin, offshore Ireland, from gravity and magnetic studies. *In:* Doré, A.G. & Vining, B.A. (eds) *Petroleum Geology: North-West Europe & Global Perspectives – Proceedings of the 6th Petroleum Geology Conference*, Geological Society, London, 1047-1056.

## SEISMIC IMAGING OF SEDIMENTARY FEATURES RELATIVE TO A BURIED PALAEO-VOLCANO, OFFSHORE MOROCCO

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Detailed mapping of a large, 1,064 km$^2$, high-resolution, 3D seismic dataset acquired in the Safi Haute Mer seismic block of offshore Morocco's Atlantic margin revealed the existence of five distinct salt diapirs situated above Palaeozoic-rifted basement (Dunlap *et al.,* 2010). Triassic-age salt mobilising from basement north-south-trending half-grabens produced a range of salt morphologies. These diapirs are expressed in the form of deep-seated tongues, canopies, and shallow salt sheets exhibiting evidence of periodic movement during the Cretaceous through to the Modern. A sixth conical feature was identified and was initially thought to be produced from two converging salt pillows. Further examination determined this feature to be a buried palaeo-volcano having 1,800 ms (~2,200 m) of vertical relief and lateral dimensions of 3,000 × 2,800 m at its base (Figure 1). The possibility of a salt core could not be fully discounted because the cone's upper boundary displayed a similar seismic response to the local diapiric top of salt and magnetic and gravity surveys proved inconclusive.

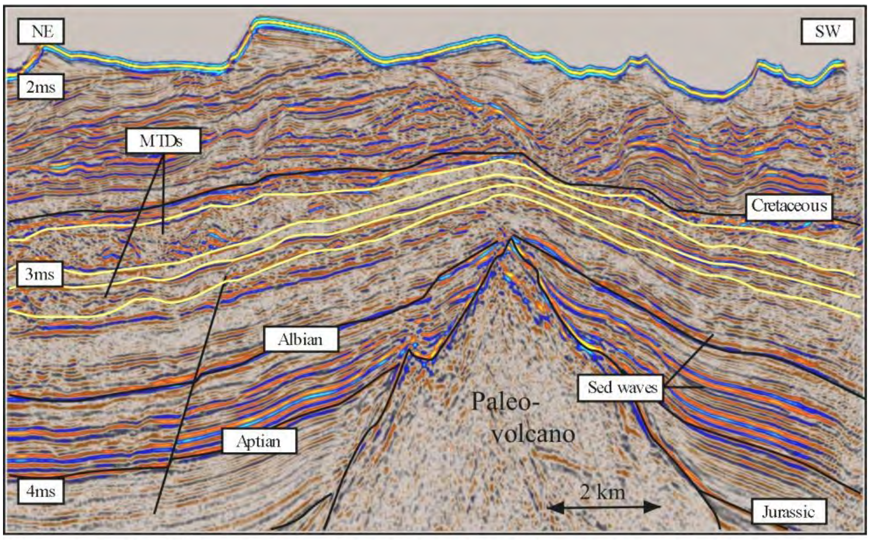


Figure 1. NE-SW seismic section over the Safi Haute Mer paleo-volcano. Note the (1) lack of internal reflections, (2) onlapping Jurassic to Upper-K terminations, (3) differential compaction, and (4) thinning of MTD deposits above feature.

The seismic distinction between buried palaeo-volcanoes and salt diapirs has broad implications for prospectivity, hydrocarbon potential, trapping styles and mechanisms, and proximity to source rock. Attributes such as internal character, proximal debris flows, adjacent stratal character, and structural mechanics were evaluated. The conical feature was determined to be a palaeo-volcano from evidence such as (1) the lack of a basal reflector, (2) a slightly rectangular base uncharacteristic of those in mobile salt, (3) uniformly stacked onlapping reflectors from base Jurassic through its peak in the Lower Cretaceous, and (4) the lack of structural and stratigraphic deformation indicative of salt tectonics.

The presence of seismic reflectors onlapping the volcanic structure from the Late Jurassic to near the end of the Early Cretaceous denotes that the feature had a persistent and stable positive seafloor expression for much of the Mesozoic, in contrast to the salt diapirs, which had been periodically mobile from the Triassic to the present. Much of the Mesozoic stratigraphy has not been preserved owing to this later salt mobilization, whereas sediments near the palaeo-volcano are relatively undeformed near its peak. This palaeotopographic obstruction greatly affected the geomorphologic character of deposits in the study area. Large-scale sediment wave fields are imaged throughout the seismic survey area. Near the cone, observed changes in the orientation of the wave axis are due to the modification of currents and subsequent wave-migration pathways around the feature (Figure 2). Individual

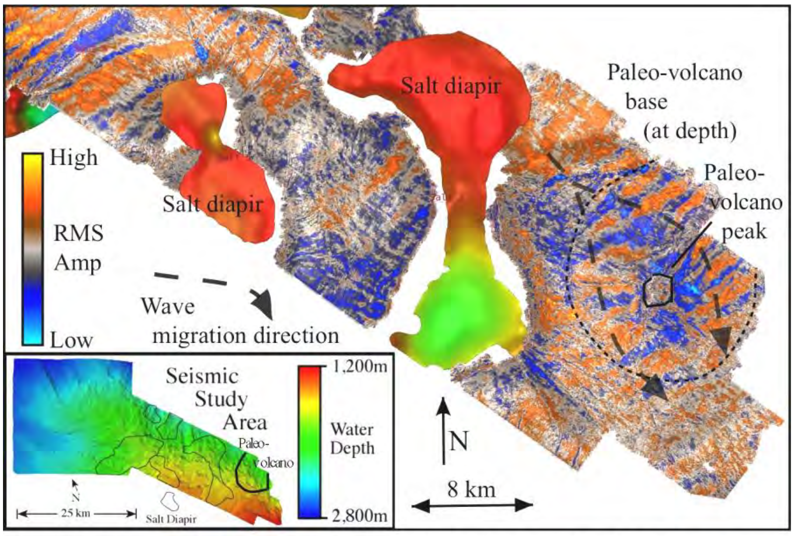


Figure 2. Root-mean-square attribute map above Top Albian (Lwr-K) horizon showing the distribution of sediment waves relative to the Safi Haute Mer paleo-volcano.

sediment waves having a length of between 10 and 15 km and wavelengths of 1 to 2 km appear to be latest Albian to early Cenomanian in age. The waves have a similar seismic character and shelf orientation to those of waves documented in other basins for alongshore, bottom-current-produced sediment waves showing upslope migration (Hohbeim and Cartwright, 2006). Sediment-wave densities increase and scale diminishes in the cone's current shadow.

In the Late Cretaceous salt mobilisation increases, and sediment-wave production decreases. Mass-transport deposits (MTDs) become common, with four individual survey-wide flows deposited above the palaeo-volcano below the Upper Cretaceous boundary. Although the palaeo-volcano is covered by the basal MTD, a mapable thinning occurs at the peak. The MTD thickens downdip to more than 500 ms in Two-way travel time (TWT) with large-scale megablocks (>3 km$^3$), whereas above the structure, only 50 ms (TWT) of the MTD is preserved. Furthermore, the mass-transport flow forms a deep (>300 ms), dip-oriented incision where the path of the resultant erosive scour suggests the existence of a deflection near the volcano location before its head came to rest downdip, beyond the salt diapiric province.

Multiple high-amplitude seismic anomalies are observed emanating from the base of the feature and are interpreted as volcanic sills. These sills upwardly crosscut Jurassic stratigraphy in several directions away from the volcano's base. Triassic sills are documented updip of the study area interfingering with Triassic salt (Hafid *et al.,* 2000). Rifting of the early Atlantic continued to influence sedimentation patterns long after the conclusion of tectonic activity. The location and placement of the Safi Haute Mer volcano dictated Mesozoic and Cenozoic salt mobilisation and minibasin formation, pathways of sediment-wave migration, and distribution and seal potential of MTDs.

**Acknowledgement**

Data access provided by ONHYM - Moroccan Office of Hydrocarbons and Minerals.

**References**

Dunlap, D.B., Wood, L.J., Weisenberger, C. & Jabour, H. 2010. Seismic geomorphology of offshore Morocco's east margin, Safi Haute Mer area. *American Association of Petroleum Geologists Bulletin,* **94**, 615-642.

Hafid, M., Salem, A.A. & Bally, A.W. 2000. The western termination of the Jebilet-High Atlas system (offshore Essaouira Basin, Morocco). *Marine and Petroleum Geology,* **17**, 431-443.

Hohbein, M. & Cartwright, J. 2006. 3-D seismic analysis of the west Shetland drift system: Implications for the late Neogene palaeoceanography of the NE Atlantic. *Marine Geology*, **230**, 1-20.

## 2012 EXPLORATION AND PRODUCTION UPDATE ON THE MESOZOIC BASINS, NEWFOUNDLAND AND LABRADOR ATLANTIC CONTINENTAL MARGIN

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With substantial undiscovered resources totalling six billion barrels of oil and 60 trillion cubic feet of natural gas, Newfoundland and Labrador (NL) Atlantic Continental Margin holds great potential for more petroleum discoveries.

The Newfoundland and Labrador Atlantic Margin has four basins with significant hydrocarbon discoveries:

1. Jeanne d'Arc Basin, the only current offshore East Coast North America oil producing region;
2. Flemish Pass Basin containing the newest N. Atlantic oil discovery;
3. Hopedale Basin, in Labrador Sea where several gas fields were found, and
4. Saglek Basin containing the Hekja gas field in the Canadian waters of Davis Strait.

### Production

During 2011, a total of 97.3 MMbbls of oil was produced from the Jeanne d'Arc Basin, offshore Newfoundland. The production from Hibernia, Terra Nova and White Rose fields and several satellites averaged 266,494 bopd. Lately, the satellite field developments have helped boost production rate to 300,000 bopd and maintain it above 250,000 bopd. Over 1.3 billion barrels were produced to date from the area.

### Development

The next major project offshore Newfoundland is the Hebron field with development scheduled to start in 2012, following project sanction. Hebron's first oil is planned for 2017 and its peak production is estimated to be 150,000 to 170,000 bopd. Development also continues at Hibernia and White Rose satellites, some of which are already contributing to production in these fields.

### Exploration

Peak production from NL offshore oil fields came in May 2007. A low level of exploration has characterised the past decade of exploration in Atlantic Canada. Numerous other NL continental margin basins remain lightly explored or unexplored, even though they are situated on the Late Jurassic source rock super-highway (e.g. Laurentian Basin and North Jeanne d'Arc Basin). The offshore Newfoundland drilling activity has been characterised by a couple of wells per year over the past decade. Many basins and sub-basins have not seen drilling since the early eighties (e.g. Carson and Hopedale basins), others were just sporadically drilled (e.g. Orphan and Laurentian basins).

In the northern Jeanne d'Arc Basin, three medium deep wells, Ballicatters M-96 and M-96Z and Glenwood H-69 were recently abandoned or suspended. While Suncor has indicated that hydrocarbons were discovered at Ballicatters, no discovery volumes have been released to date. Only one well, Fiddlehead D-83, has been drilled in the south part of the basin. In spite of a successful licensing round in 2008 in the Hopedale Basin, no drilling plans have been implemented in the Labrador Sea. Without new discoveries, the NL Atlantic Margin petroleum industry is facing a decline characterised by mature fields, shrinking reserves and many remaining undrilled prospects.

However the Mizzen O-16 oil discovery brings renewed optimism and focus to a new intermediate to deepwater exploration area in the North Flemish Pass-Southeast Orphan Basin. The Mizzen O-16 significant discovery has also triggered two successful exploration licensing rounds in the adjacent area. Over one million hectares were licensed for exploration in the recent years in the area surrounding the Mizzen discovery. The blocks contain large faulted anticlines of the type successfully drilled in Jeanne d'Arc Basin and are located in an area where source rocks were penetrated (e.g. Mizzen L-11).

**2012 Call for Bids**

This year, Canada-Newfoundland and Labrador Petroleum Board has issued Call for Bids in two offshore Newfoundland basins. Six large parcels totalling 1,589,738 hectares are offered at Call for Bids NL12-01 in intermediate to deep water of the Laurentian Basin, where large extensional and salt tectonics related prospects and leads were identified. Parcel size ranges from 143,588 hectares to 296,530 hectares. One large parcel offered at the NL Call for Bids NL12-02, totalling 208,899 hectares is located in the Flemish Pass Basin southwest of the Mizzen O-16 discovery.

**Research**

On the Newfoundland and Labrador margin, geoscience initiatives under the Offshore Geoscience Data Program, a collaboration between the Provincial Government and Nalcor Energy - Oil and Gas resulted in acquisition of modern high quality regional seismic data coupled with satellite based sea slicks studies and geochemistry analysis of shallow cores. The data and studies will be made available for licensing to the Industry.

Newfoundland and Labrador is located close to the world's largest petroleum markets, has competitive fiscal terms, open and transparent bidding system typically based on work commitments and low political risk. Minimizing the geological risk is essential to increase exploration activity and to lead to drilling success on the Canadian Atlantic Margin.

## TRACING DEEP LITHOSPHERIC STRUCTURES ALONG THE PASSIVE MARGIN OF NORWAY, ITS GREENLAND CONJUGATE, AND POSSIBLE IMPLICATIONS FOR RIFTING

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In oceanic domains and in the transition to the continental shelves, the lithosphere thickness is to a first-order thermally controlled. In the North Atlantic region this is clearly reflected in the long-wavelength gravity field and even more clearly in the geoid undulations. These thermal effects of rifting can also be observed in tomographic models, e.g. in the S-wave velocity structure at the Barents Sea margin. Further south, towards the Norwegian mainland, the situation becomes more complex, additional compositional and rheological effects play an important role.

Recent seismological, magnetotelluric and integrated modelling studies reveal major lateral changes in the deep lithospheric structures under southern Norway and southern Sweden. Differences in seismic mantle velocities can be explained by major variations in lithosphere thickness and in composition. These changes as well as changes in the lower crustal architecture correlate with the boundary between the Sveconorwegian (Neo-Proterozoic) and Svecofennian (Palaeoproterozoic) domain. They can be traced northward along the edge of the Svecofennian domain using regional gravity and isostatic studies. In northern Norway, this lithospheric boundary coincides with the high topography of the northern Scandinavian Mountain Chain (the northern Scandes) and in large parts also with the edge of the rifted margin. These variations of today's lithospheric configuration, topography and geological boundaries indicate that the old Proterozoic structures most likely affected the rifting processes, and presumably even earlier tectonic events like the Caledonian orogeny.

In ongoing studies, new geophysical data for central and northern Norway and Sweden are collected in order to better map the deep lithospheric structures. Here, we present first results from regional gravity and isostasy studies, aiming to trace key lithospheric structures of Fennoscandia along the continental margin and where possible across the Atlantic. For a proper comparison of the structures to the Greenland side, the ice-effects have been removed from the gravity and geoid data sets and are respectively considered in the isostatic calculations. The lithospheric structures investigated in this study are (1) the Sveconorwegian domain of southern Norway (high topography, thin lithosphere), (2) the edge of the Svecofennian domain (gravity low, deepening Moho and LAB, high topography along northern Norwegian Margin) and (3) local geoid anomalies. The latter are sensitive to deep structures and hence are well suited to study lithosphere characteristics.

In northern Norway, the edge of the Svecofennian domain served as a location for the Caledonian orogeny and subsequent rifting and Atlantic breakup. This was not the case in southern Norway, where it was on the other hand utilised in the Permian extension that created the Oslo Rift. Although extension thus seems to localize along pre-existing structures, which constitute weakness zones, this is not necessarily everywhere the case.

We emphasize that deep lithospheric structures, such as changes in tectonothermal age, thickness and composition, can have a large effect on the rifting process, in particular its location. Furthermore, they may control associated magmatism and the extent of the passive margin.

## EXHUMATION FOLLOWING POST-BREAKUP SUBSIDENCE IS A COMMON FEATURE OF "PASSIVE" MARGINS

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The traditional view of the development of passive margins involves onshore highs representing uplifted rift flanks which have remained elevated and undergone progressive denudation since breakup or earlier, while offshore basinal regions undergo progressive thermal subsidence, with sedimentary units being progressively buried.

However, application of palaeo-thermal and palaeo-burial indicators to the passive margins of the North Atlantic region has provided extensive evidence of multiple post-breakup episodes of km-scale exhumation (Japsen *et al.,* 2010). These episodes, identified in areas including the Norwegian-Danish basin, Norwegian North Sea, Onshore UK, Mid-Norway, West and East Greenland and the Barents Sea, correlate with regional unconformities identified along the North Atlantic Margin from Porcupine to Lofoten (STRATAGEM project, Stoker *et al.,* 2005). This evidence of synchronous episodes of uplift and erosion, which appear to also be broadly synchronous with compressional deformation on a more local scale (e.g. Doré *et al.,* 2008) strongly suggests that the driving forces act on a regional scale, and we favour an origin in terms of transmission of forces from plate boundaries, although also accepting the conclusion of Doré *et al.* (2008) that multiple causes may be acting.

Clear evidence of tectonic control on present-day mountain topography comes from the West Greenland margin. The presence of marine horizons within the post-breakup volcanic sequence, now at >1 km above sea level, provides unequivocal evidence of post-breakup subsidence followed by later uplift. Integration of landscape evidence with AFTA and vitrinite reflectance data demonstrates that subsidence terminated at ~35 Ma, with subsequent uplift and denudation leading to development of a regional planation surface which was in turn uplifted and dissected from ~10 Ma to form the present-day mountains. AFTA data from East Greenland, which show major cooling events at similar times, combined with landscapes of similar character, strongly suggest that a similar history is also appropriate on that margin. In addition, the thick Cretaceous–Eocene sedimentary and volcanic succession on the east coast of Greenland, documents a period of short-lived uplift prior to breakup followed by km-scale subsidence during the eruption of basalts and following breakup. The margin therefore continued to subside following breakup and the present-day high mountains (up to 3.7 km asl) of Paleogene basalt must therefore have been uplifted long after breakup.

Following the traditional concept of passive margin development, the elevated continental margins of the North Atlantic region, and in particular the mountains of Norway and East Greenland, have been interpreted by some simply as rejuvenated remnants of Caledonian fold mountains, with the development of these mountains understood simply in terms of the response to isostasy, climatic variation and erosion, in a manner particular to the local setting, without any tectonic input. However, in the light of the evidence reviewed above, in particular that the highest peak in the North Atlantic domain demonstrably formed after breakup, we believe a tectonic control must be involved.

On many margins, exhumation episodes identified onshore are broadly synchronous with unconformities in the adjacent offshore basins. This is again typified by results from West Greenland, where exhumation onshore which began at ~35 Ma and led to development of a regional planation surface correlates closely with a major unconformity offshore which we regard as sharing a common origin with the planation surface onshore. Exhumation episodes affecting the (now) offshore section are often recognised over areas of truly regional extent, which accounts for the low angle of the resulting unconformities (similar to those identified by

Stoker *et al.,* 2005). The significance of such unconformities is often not appreciated from seismic evidence, which may only be assessed at the scale of an exploration block. Since AFTA and VR data commonly show that considerable thicknesses of sediment were deposited and subsequently eroded during these intervals, lack of recognition can lead to serious underestimation of maturity levels below such unconformities.

While these events identified around the North Atlantic margins are clearly at odds with the traditional notion of continental margin evolution, similar histories, involving post-breakup subsidence and burial followed by uplift and erosion, have been identified on many other margins. The landscapes of the North Atlantic margin share many characteristics with other rifted margins around the World, with extensive regions of low relief at elevations greater than 1 kilometre above sea level, separated from adjacent coastal plains by areas of steep topography, often referred to as a “Great Escarpment” (although we believe this term is misleading). We refer to such regions as Elevated Passive Continental margins (EPCMs). Application of palaeo-thermal and palaeo-burial techniques shows that many EPCMs have undergone major post-breakup subsidence and burial, followed by later uplift and denudation, in similar fashion to the events identified around the North Atlantic. For example, on the Atlantic margin of Brazil significant denudation began in the Campanian, subsequent to Albian-Aptian breakup, and up to 2 km of post-breakup sediment must have been deposited and then removed following the onset of exhumation around 80 Ma. Similar histories have been identified on the southern and west coasts of Africa, the SE margin of Australia and other margins.

The development of North Atlantic margins envisaged by Japsen *et al.* (2010), involving multiple episodes of post-breakup uplift movements, therefore appears to be a characteristic feature of EPCMs around the world. This conclusion is strengthened by the common occurrence of truncated dipping sedimentary sequences offshore of many EPCMS, indicating post-breakup uplift and erosion. These, together with areas of low relief (planation surfaces) now at > 1 km above sea level, suggests that at least two major uplift events are required to produce typical EPCM topography (Figure 1); a first uplift episode and accompanying erosion leads to formation of the planation surface, which may be preserved below a blanket of sedimentary cover after later subsidence, prior to a second phase of uplift leading to stripping of the cover and incision of valleys to produce the present-day topography. In conclusion, many EPCMs do not represent long-term highs, but have undergone post-breakup burial followed by more recent uplift and dissection, often in multiple episodes, affecting both onshore and offshore regions. The tectonic processes responsible for the present-day elevated margins of the North Atlantic are therefore not restricted to that region, but appear to be typical of EPCMs in many parts of the world.

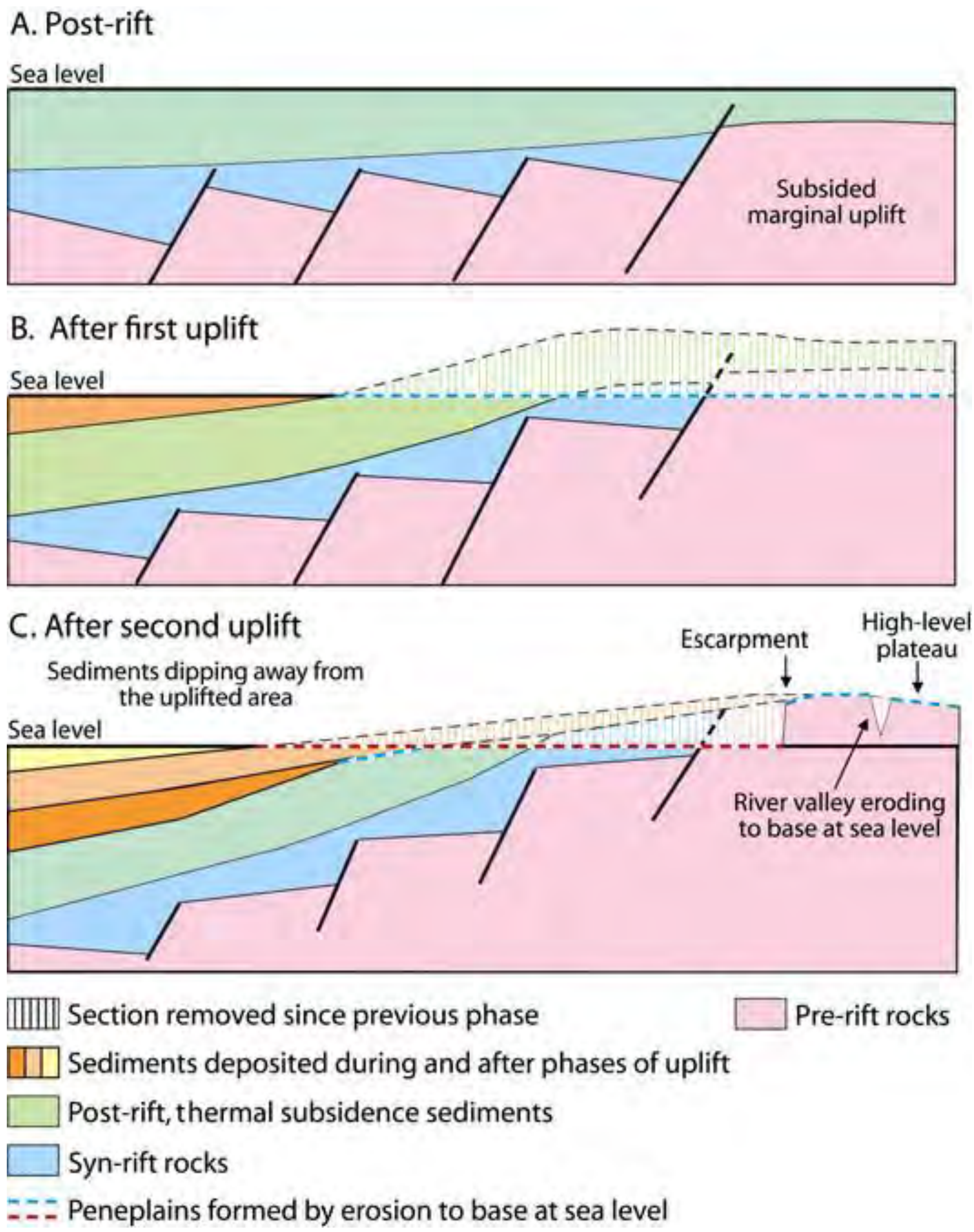


***Figure 1**: Development of EPCMs, explaining both elevated plateaux onshore and the common occurrence of truncated, dipping post-rift sediments offshore. At least two separate phases of uplift and erosion are required; one to form a regional planation surface and another to lift it to the present elevation to form a plateau, which is subsequently dissected.*

## References

Doré, A.G., Lundin, E.R., Kusznir N.J. & Pascal, C. 2008. Potential mechanisms for the genesis of Cenozoic domal structures on the NE Atlantic margin: pros, cons and some new ideas. *In:* Johnson, H., Doré, A.G., Gatliff, R.W., Holdsworth, R., Lundin, E.R. & Ritchie, J.D. (eds). *The Nature and Origin of Compression in Passive Margins.* Geological Society London, Special Publications, **306**, 1-26.

Japsen, P., Green, P.F., Bonow, J.M., Rasmussen, E.S., Chalmers, J.A. & Kjennerud, T. 2010. Episodic uplift and exhumation along North Atlantic passive margins: implications for hydrocarbon prospectivity. *In:* Vining, B.A. & Pickering, S.C. (eds). *Petroleum Geology: From Mature Basins to New Frontiers – Proceedings of the 7th Petroleum Geology Conference.* Geological Society, London, 979-1004.

Stoker, M.S., Praeg, D., Shannon, P.M., Hjelstuen, B.O., Laberg, J.S., Nielsen, T., Van Weering, T.C.E., Sejrup H.P. & Evans, D. 2005. Neogene evolution of the Atlantic continental margin of NW Europe (Lofoten Islands to SW Ireland): anything but passive. *In:* Doré, A.G. & Vining, B.A. (eds). *Petroleum Geology: North-West Europe and Global Perspectives - Proceedings of the 6th Petroleum Geology Conference*, Geological Society, London 1057–1076.

# THE PALAEOGEOGRAPHIC AND PALAEO-CLIMATIC HISTORY OF THE CENTRAL & NORTH ATLANTIC CONJUGATE MARGIN BASINS: THE PREDICTIVE MAPPING OF SOURCE AND RESERVOIR FACIES

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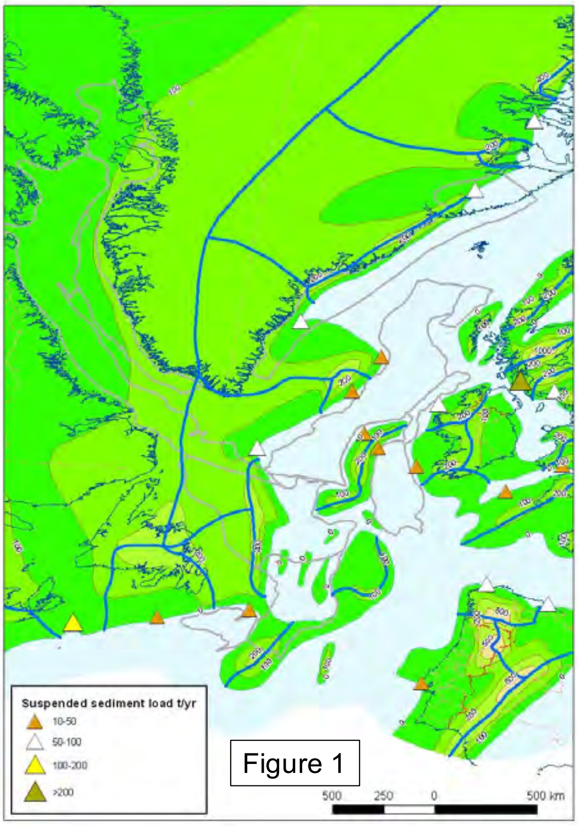
For frontier basins, the development of petroleum play concepts and the construction of play fairway maps are difficult and in particular, the presence and potential extent of source rocks and reservoirs represent some of the main uncertainties for exploration. To construct predictive tools designed to address these problems, global Plate Wizard™ reconstructions were used as the basis for palaeogeographic mapping. The palaeogeographies are underpinned by data and were coupled with state-of-the-art palaeo-Earth systems models (HadCM3 palaeoclimate model). Detailed palaeotectonics and palaeoenvironments maps were prepared and a new method relating topography and bathymetry to plate tectonic environments was used as the basis for palaeo digital elevation models (DEMs). These were gridded in GIS and used to provide the topographic and bathymetric boundary conditions for coupled ocean-atmosphere general circulation models (GCMs) and a barotropic model to simulate palaeotides. The compilation of the base maps was based on a global database of palaeoenvironmental and lithofacies data, the legacy of over 30 years of petroleum geological studies and an equally extensive source rocks database. These data include climate proxies that were used to test the veracity of the modelling results. This work is used to provide an understanding of drainage basin evolution and a regional palaeogeographic and palaeoclimatic geohistory.

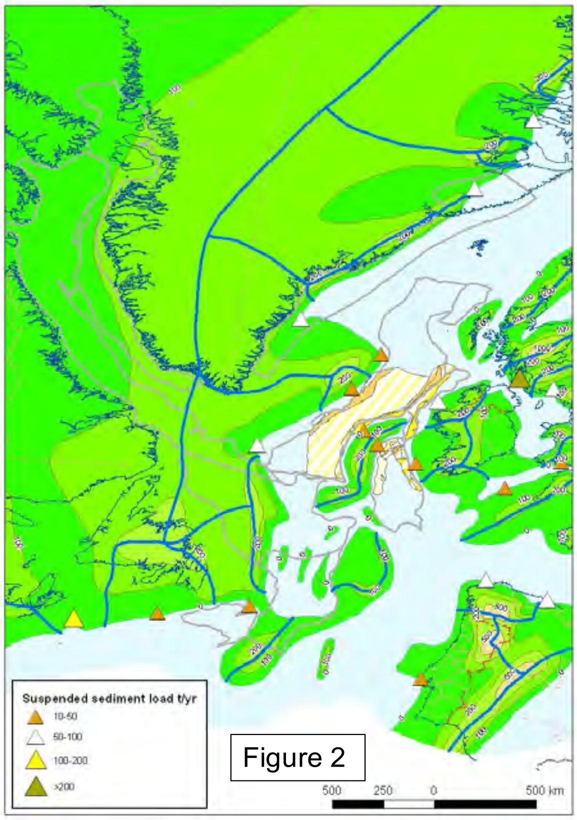
Coupled with the palaeo-Earth systems and palaeotide models the palaeogeographies were used to create a predictive methodology to define source facies depositional space. Source facies predictions are based on productivity, dilution and preservation parameters and are used here to provide key petroleum play concepts for key time slices. This innovative approach is also used to assess exploration risk and to produce improved play fairway maps, illustrated by clastic reservoir mapping for North Atlantic margin basins (Figures 1, 2 and 3).

As the first step in the prediction of clastic reservoir facies distribution, a simple method based on the Hovius (1998) multicomponent statistical analysis was adopted. This is in an attempt to quantify sediment flux to the coast and provides results in tonnes per year. It includes drainage basin area, maximum drainage basin elevation, mean daily runoff per unit area, mean annual temperature and mean annual temperature range as the top five controls for each catchment. These elements are all derived from a combination of palaeogeographic mapping and palaeo-Earth systems modelling and provide an approximation that was used to guide the mapping of clastic reservoir potential. For the North Atlantic margin basins, well data in the Northern Porcupine Basin demonstrates the veracity of the model results and for the Late Jurassic indicates the best reservoir potential in the north and east of the basin. A major clastic sediment input point is modelled at the eastern margin of the data poor Slyne-Erris Basin. Some sediment bypass into the Rockall Basin is interpreted from this input point. Modelled input points from the Porcupine High and Hatton Bank areas probably provided the marginal Rockall Basin with good reservoir potential sandstones. Potential also exists in the deeper marine facies to the north where turbidites may be prospective.

**Reference**

Hovius, N. 1998. Controls on sediment supply by large rivers. *In:* Shanley, K.W. & McCabe, P.J. (eds). Relative Role of Eustasy, Climate and Tectonics in Continental Rocks. *SEPM Special Publication,* **59**, 3-16.



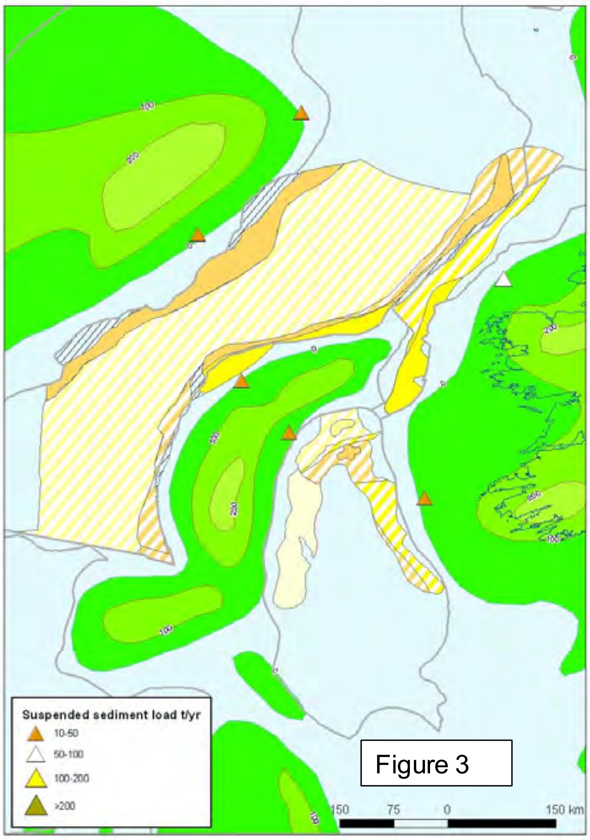




***Figure 1:***

*Late Jurassic suspended clastic sediment flux estimated for the Atlantic Margin basins west of Ireland*

***Figure 2:***

*Late Jurassic reservoir facies mapped using estimated clastic sediment flux to the coast.*

***Figure 3:***

*Details of Late Jurassic reservoir facies mapped in the Porcupine, Slyne-Erris and Rockall basins*

## MIZZEN – AN OVERVIEW OF THE FIRST OIL DISCOVERY IN THE FLEMISH PASS BASIN, EAST COAST OFFSHORE NEWFOUNDLAND

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The Mizzen field is the first significant oil discovery in the underexplored Flemish Pass Basin. The field is located at the apex of a north-south striking, extensionally faulted, oblique-slip, doubly-plunging horst block, approximately 15 km in strike length, and up to 6 km in width. The main structure is defined by two wells (Mizzen O-16 and Mizzen F-09), and the original "discovery" well (Mizzen L-11) represents a small oil accumulation in an isolated tilted fault block. A regional top seal over the entire structure is provided by marine shales of Lower Cretaceous Berriasian age.

The main reservoir at Mizzen is a very fine to medium-grained sublitharenite of Tithonian age. This unit is informally referred to as the Ti-3 sandstone, with a gross thickness that ranges from 25 to 55 m, and a N:G ratio of 51% to 64%. Core analyses of these sands establish porosities up to 32% (average 21%) and permeability measurements up to 15 Darcies (average 1.2 Darcies). A 63 m, full-diameter core was obtained from the entire Ti-3 reservoir and the underlying shales at Mizzen F-09. The reservoir in the lower half of this core consists of rounded conglomerate clasts, within a matrix of coarse to medium-grained quartz sublitharenites that are calcite-cemented in part. These rocks gradually fine upwards into fine-grained sandstones and siltstones that display planar and cross-bedding, and minor ripples in the uppermost 20 metres. The entire core has a noticeable absence of trace fossils. The Ti-3 sandstone is the uppermost unit of a series of at least 4 distinct coarse clastic cycles, which represent syn-kinematic fill as distinct channel belts into an active extensional basin. The depositional model at Mizzen is that of a braided fluvial system episodically deposited into elongate extensional troughs that were periodically flooded by shallow marine incursions.

Producible oil from the Ti-3 sandstone has been flowed to surface in the Mizzen O-16 and Mizzen L-11 wells. After encountering an oil-down-to in the O-16 well, an extended drill stem test flowed 21° API medium gravity oil at a rate of 3,800 bbls/day. The Mizzen F-09 well was subsequently drilled in 2011 on the north flank of the structure, and encountered water and residual oil. This limits the hydrocarbon column height to approximately 220-250 m, which indicates that the main reservoir in the Mizzen structure is approximately half-filled.

## INTERPRETATION OF TECTONICS OF PASSIVE MARGIN OF NE GREENLAND FROM NEW SEISMIC REFLECTION DATA AND GEOLOGICAL - GEOPHYSICAL CONSTRAINTS

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Three phases of deep 2D seismic acquisition and PSDM processing over the past 4 years provide regional coverage of the NE Greenland Atlantic passive margin that remains undrilled. The passive margin (see Poster by Dinkelman *et al.,* this meeting for tectonic base map) is divided into three segments: Thetis, Loon and Westwind. 1. The principal Mesozoic-Cenozoic tectonic elements of the Thetis margin, south of the Greenland Fracture Zone (GFZ), from shoreline to deep sea, are: a) the Danmarkshavn Basin (DB), b) the Danmarkshavn Ridge (DR), c) the Thetis Basin (TB), d) an outer high and, e) seaward-dipping reflectors (SDR's) and oceanic crust (Figure 1). 2. The Loon margin lies between the GFZ and the Hovgaard FZ and is distinctive in its DR-TB transition into salt-related structural elements and presence of the transpressional Paleogene Wandel Sea Mobile Belt (WSMB). 3. The Westwind margin in the far north has orientation and stratigraphy controlled by the WSMB and Neogene opening of the Wandel Sea. Hence all segments of the passive margin display distinctive orientations and tectonostratigraphy reflecting the inheritance of extensional events from mid-Devonian (?) through Cretaceous, the localised effects of transpression and volcanism related to the northward propagation of the opening of the Greenland Sea, and the corresponding contrasts in passive subsidence histories.

In the Danmarkshavn (DB) Basin, the post-Caledonian Palaeozoic rift-sag basin is overlain by a maximum Mesozoic sediment fill of 7 km in a sag-style morphology. Strata generally are layer-cake with peak subsidence rates in the Cretaceous except where disturbed by diapirs of Permian salt (Figures 1, 2). The growth of the basin is marked by broad structures including a landward hingeline, and a faulted shoulder seaward against the Cretaceous-Paleocene horst of the Danmarkshavn Ridge that has 2 km or so of Mesozoic cover and displays a basal LCB on the east. The depth to the Moho is 25 to 30+ km and Tertiary sediments are thin to absent across both the Danmarkshavn Basin and Ridge.

In the Thetis Basin, the maximum Mesozoic and Tertiary sediment thicknesses are 7 km and 5 km respectively. The west flank of the Thetis Basin is a faulted buttress unconformity against the DM Ridge, and the growth of the basin in Jurassic to Early Cretaceous is marked by abundant normal faults and related structures. The eastern flank is an outer high composed of Caledonian (?) basement and cover overlain by Paleogene volcanic strata. The Early Cretaceous section is thinner with discontinuous apparent fluvial facies; it is more faulted, contains intruded sills, and is more difficult to map than in the DB. However, the section beneath the base Cretaceous unconformity in the TB is sufficiently thick to include rich oil-prone Jurassic source rocks such as found in its conjugates along the Vøring and Møre basins offshore northern Norway. The Caledonian basement appears to be shallower than in the DB, as constrained by gravity modelling. Regionally, the depth to Moho is 15-20 km, but high-velocity LCBs (Lower Crustal Bodies) occur beneath the eastern Thetis Basin.

The Loon segment is transitional between the Thetis and Westwind, expressing the changing orientation of the Palaeozoic rifted foundation, termination of the DR, transpression of the WSMB, and strike change of the Thetis and Westwind passive margin prisms (Figures 2, 4, 5). The Loon High is a large salt-cored structure developed at the northern termination of the

DR. The east limit of salt deposition controls the Paleocene transpressive folding of the southwestern front of the WSMB along the extension of the Greenland Fracture Zone.

The Westwind segment (Figure 6) represents the late-stage transtensional opening between NE Greenland and the Barents Sea in early Miocene time. The Neogene prism builds out on the transpressional foundation of the WSMB (Figure 2) that has a post-Paleocene cover of rifted Eocene-Oligocene strata. The orientation of this segment seems to be controlled by the deep structure of the late Devonian to Cretaceous Wandel Sea Basin, a repeatedly rifted and wrenched basin that trends NNW into outcrops on Kronprins Christians Land peninsula.

The petroleum prospectivity of the Mesozoic and Cenozoic of the three segments of the margin are considered good by analogy with geology of established petroleum provinces of the Norwegian conjugate margins. Very large structures and stratigraphic fairways are prominent along the flanks of all basinal elements. However, the interpretations made have high risk due to lack of well control.

The Continent-Ocean Transition (COT) in the three segments, and across offsets of fracture zones, is dominated by volcanic-rich geometries. Commonly an outer high of Mesozoic rocks gives way to volcanic cover of the shelf edge and a volcanic ridge (Figure 1) and/or SDR's (Figure 7) under the continental slope. The thick volcanic/magmatic pile separates clear continental vs. oceanic reflectors on either side, but obscures their terminations, yet frequently is the site of the seaward edge of related LCBs. The top of oceanic crust and SDRs appear to be effectively in a facies-style relationship.

The NE Greenland margin is a Tertiary volcanic-rich passive margin developed upon a Caledonian orogenic crust and its cover. A foundation of Late Palaeozoic successor basins, Mesozoic extensional basins, and earliest Tertiary transpressional zones are characterised by complexity now inherited in the segmentation and geometry of the passive margin prism. The array of basins and their deep architecture suggests a west to east, chronological progression of pre-rift, sag and oceanic rift basins in the NE Greenland shelf and slope.

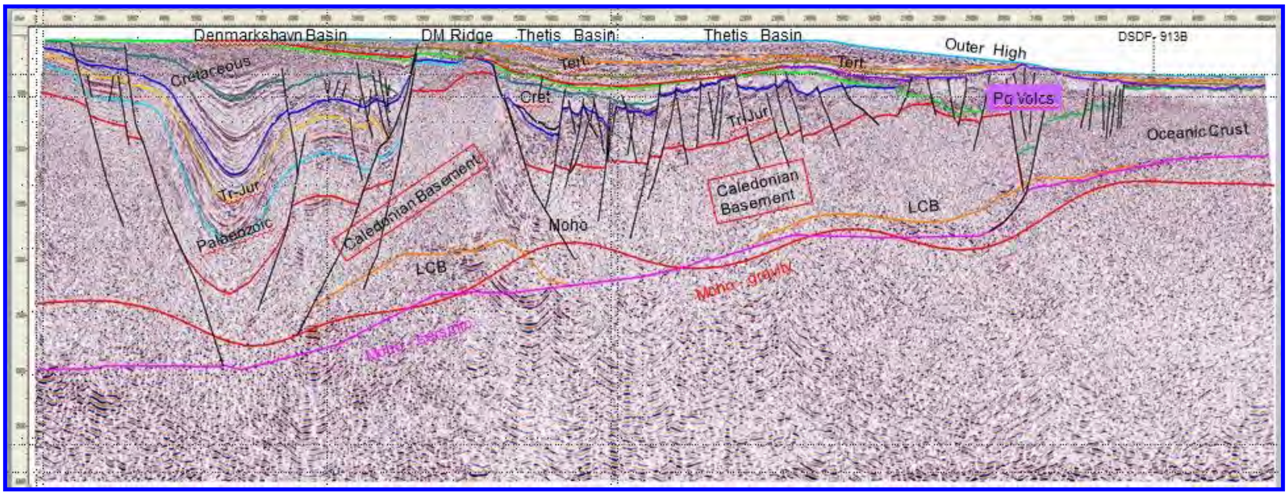


*__Figure 1:__ PSDM Profile 1800, 380 km long, 40 km deep. Note both seismic and gravity interpretation of Moho. Vertical exaggeration 2.5. Location shown below.*

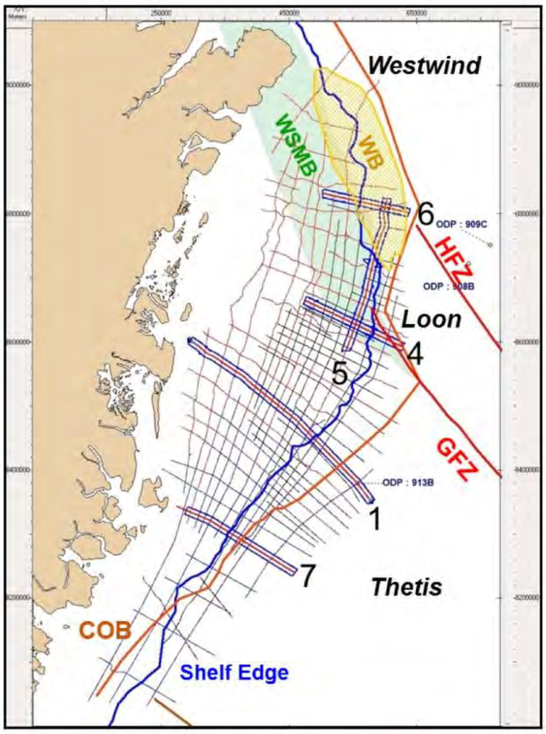


***Figure 2:*** *Location map for profiles showing Thetis, Loon and Westwind segments.*
*WB: Westwind Basin. WSMB: Wandel Sea Mobile Belt. GFZ & HFZ: Greenland and Hovgaard Fracture Zones.*

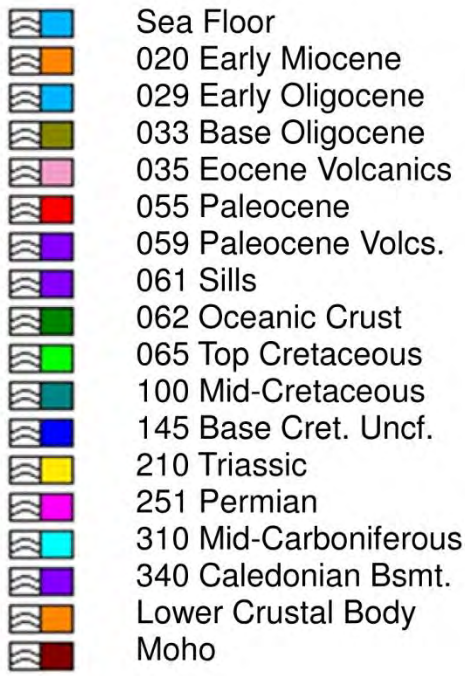


***Figure 3:*** *Horizon key for profiles.*

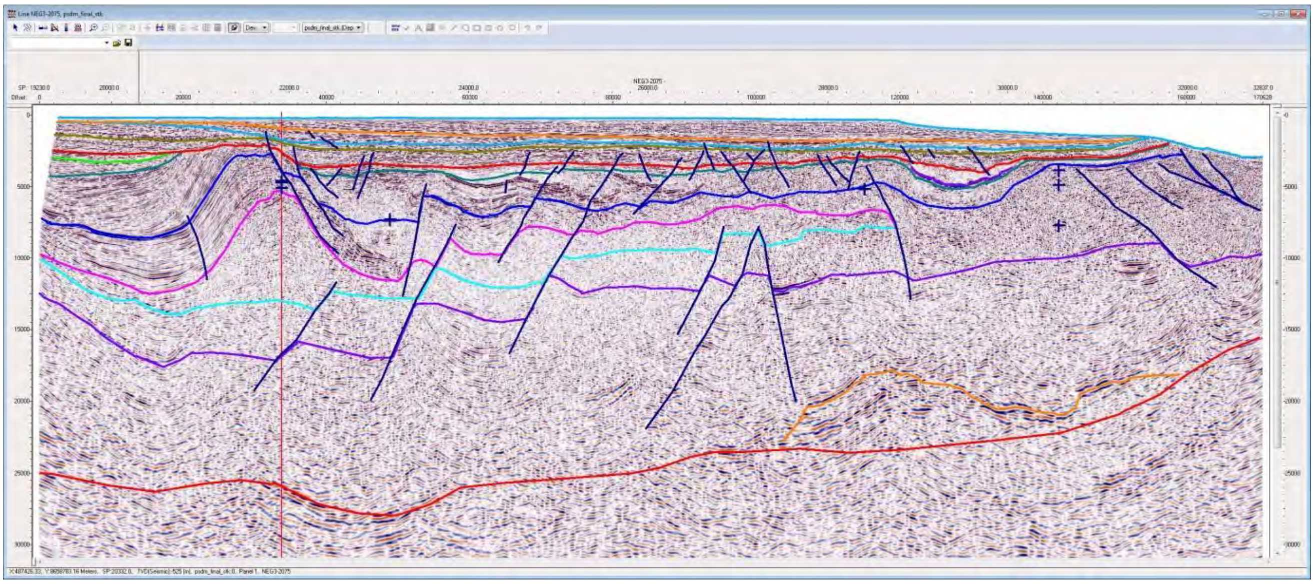

***Figure 4:*** *PSDM Profile 2075, 170 km long, 35 km deep. Loon segment and Loon High.*

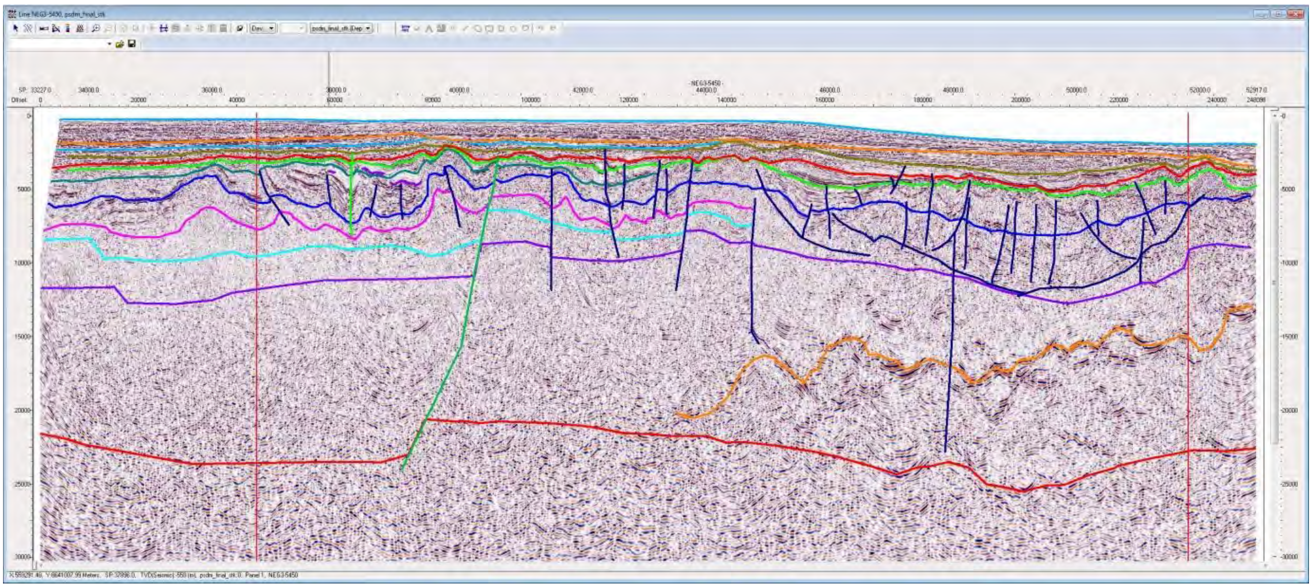

***Figure 5:*** *PSDM Profile 5450, 248 km long, 40 km deep. Loon Segment with WSMB zone of inversion and detached folding involving Permo-Carboniferous salt. WB and LCBs to North.*

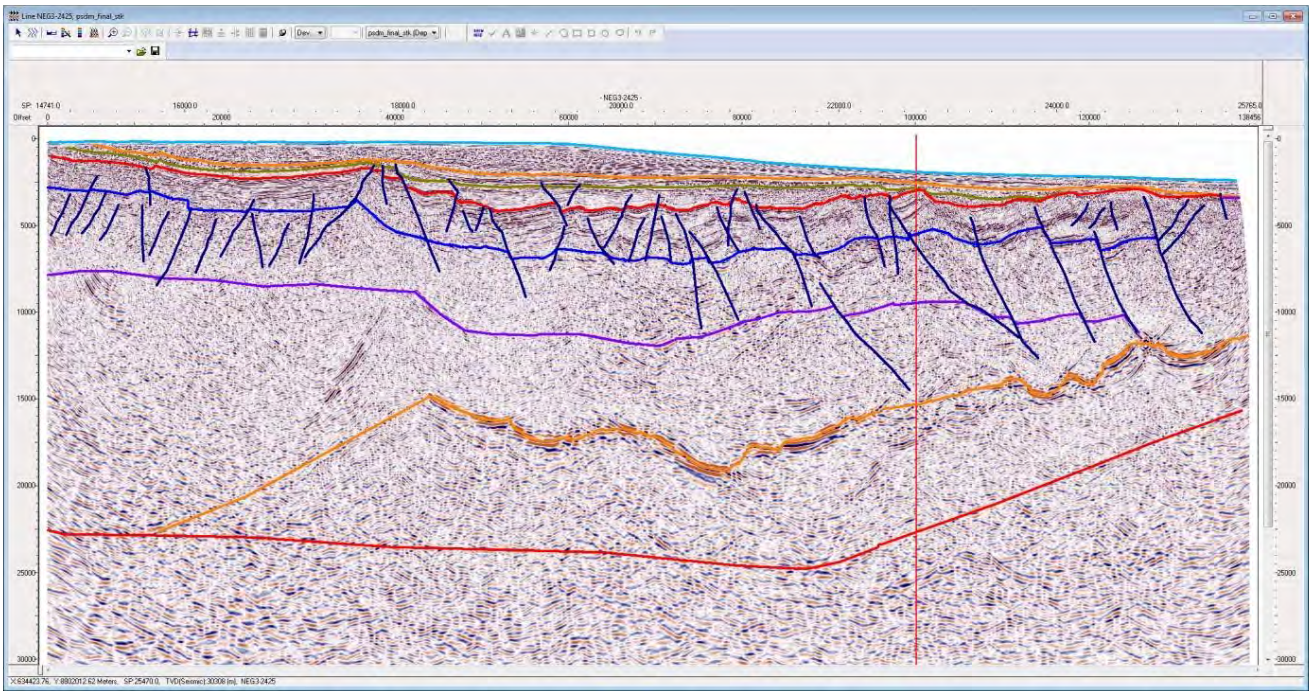

***Figure 6:*** *PSDM Profile 2425, 138 km long, 30 km deep. Westwind Basin shows inversion, transtension, and prominent LCB.*

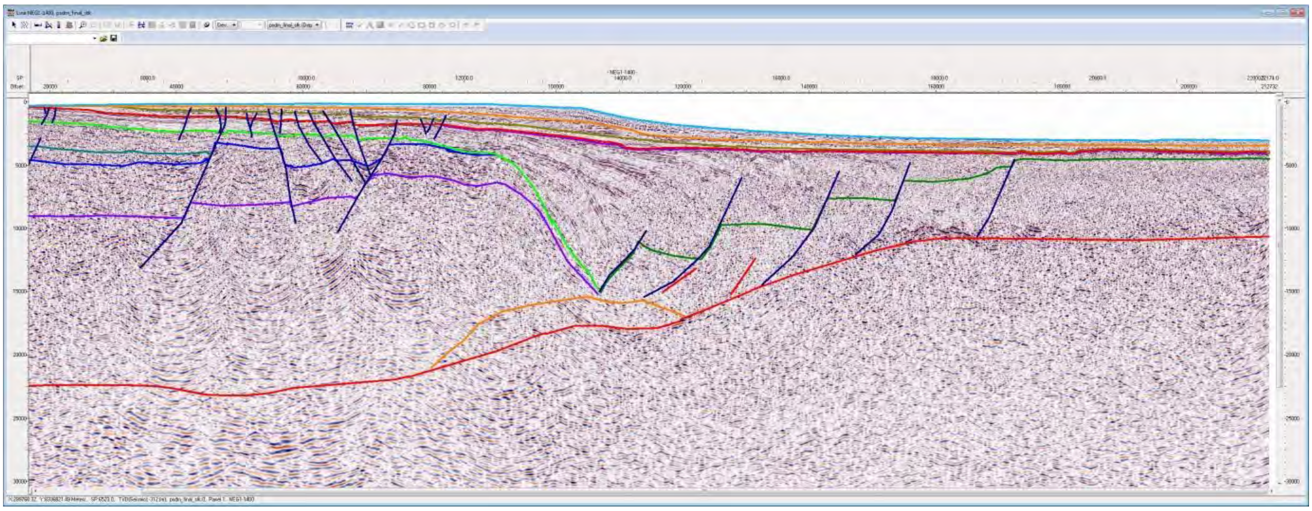

***Figure 7:*** *PSDM Profile 1400, 194 km long, 35 km deep. Interpretation of relationship between downfaulted continental and oceanic crust and massive pile of volcanic SDRs.*

## THE INFLUENCE OF COMPACTION ON THE DEVELOPMENT OF ROLLOVER ANTICLINES: AN EXAMPLE FROM THE WESTERN NIGER DELTA

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Rollover anticlines are syn-sedimentary extensional structures that are well known from deltaic regions; their geometry is classically interpreted as the direct consequence of layer bending during hanging-wall displacement above a listric normal fault that continuously transforms a steep displacement vector at the surface to a nearly horizontal one at depth. In this study, three-dimensional seismic-reflection and wire-line log data of the western Niger Delta were interpreted to document and analyse the sedimentary and structural development of a kilometre-scale rollover anticline that is characterised by a pronounced growth stratigraphy on both anticline flanks. Within the growth section, six seismic horizons were mapped and used as a reference level for incremental decompaction and sedimentary backstripping. Decompaction was applied from top (young) to bottom (old) using a Sclater and Christie (1980) approach including an Airy isostatic correction, with the lithological constraints for each sedimentary unit interpreted from wireline-log data. Measurement of the horizon dip on each stratigraphic surface before and after each decompaction and isostatic correction workstep provided data on the influence of differential sedimentary loading and compaction on the geometric development of the rollover. A key result of this study is that it can be documented in a quantitative way that the horizon bending within the studied deltaic rollover was primarily controlled by differential sediment accumulation in the overburden, which exceeded in impact at all times the tectonic displacement along the bounding fault. However, within the studied interval the loading-driven component of horizon bending decreases from top to bottom, indicating a higher relative importance of faulting during the early times of rollover development.

### References

Sclater, J.G. & Christie, P.A.F. 1980. Continental stretching: an explanation of the post-Mid-Cretaceous subsidence of the Central North Sea Basin. *Journal of Geophysical Research*, **85**, B7, 3711-3739.

# CRUSTAL STRUCTURE, SUBSIDENCE HISTORY AND STRETCHING WITHIN THE OCEAN-CONTINENT-TRANSITION OF THE CONJUGATE IRELAND AND NEWFOUNDLAND NORTH ATLANTIC MARGINS

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As part of the North Atlantic plate reconstruction project (*Ady et al., this conference*) we have investigated the crustal structure of the ocean-continent-transition and constituent major basins which comprise the conjugate margins of Ireland and Newfoundland. We have done this via three independent analyses of available 2D and 3D data:

1. 3D gravity inversion, using public-domain gravity and sediment-thickness information, has produced maps of (i) depth to Moho, (ii) crustal thickness (Figure 1) and (iii) stretching/thinning factor across both margins.
2. Gravity inversion as above, but using public-domain gravity data combined with new proprietary 2D sediment-thickness information, has produced a series of cross-sections (Figure 2) which show (i) depth to Moho, (ii) crustal thickness and (iii) stretching/thinning factor across both margins
3. Geodynamic modelling, comprising 2D backstripping and forward modelling, has been used to produce (i) estimates of stretching/thinning factor, (ii) whole-crustal cross-sections (Figure 3) and (iii) predictions of palaeobathymetry through time along a series of project-specific transects.

The 2D gravity inversion and the geodynamic modelling have both used a new set of 17 depth-transects (10 for Ireland, 1 for Galicia and 6 for Newfoundland) produced during the seismic-interpretation phase of the North Atlantic project (*Whittaker et al., this conference*). The 2D gravity inversion uses the interpreted sediment thickness from seabed to top-basement as a primary input, the geodynamic modelling uses the full horizon-by-horizon stratigraphy.

Key to both the gravity inversion and the geodynamic modelling is an ability to allow for the contributory density effects of new volcanic addition (leading to new ocean-crust formation) when estimating stretching/thinning factors. This makes a significant difference to stretching/thinning predictions across the outer margin areas. In addition, both the 2D and 3D gravity inversion methods include a lithosphere thermal gravity-anomaly correction in their calculations, allowing for the elevated geotherm in both oceanic and stretched-continental domains which results from the rifting/breakup process.

Our combined analysis, which is internally consistent across the different techniques applied, shows stretching/thinning across the basins of the conjugate margins to be markedly heterogeneous. Areas of relatively shallow present-day bathymetry, e.g. Hatton Bank, Porcupine Bank, Goban Spur (Ireland); Jeanne D'Arc and Whale/Horseshoe Basins (Newfoundland), are unsurprisingly characterised by low-to-moderate thinning factors, for which the observed upper-crustal faulting can explain the observed subsidence. Areas of deep present-day bathymetry, e.g. Rockall Trough, Porcupine Seabight (Ireland), East and West Orphan Basins (Newfoundland), are characterised by high thinning-factors, typical of continental margins. In these areas it is difficult to reconcile the observed magnitude of upper-crustal faulting with the observed subsidence.

In areas where there is an apparent discrepancy between the interpreted upper-crustal faulting and the predicted amount of crustal thinning, we believe that the lithosphere-scale process of Depth-Dependent-Thinning (DDT) may have operated, where whole-lithosphere thinning has been greater than the corresponding upper-crustal extension. DDT is believed to be characteristic of the breakup process at rifted margins worldwide but is a difficult process to corroborate by independent analysis. The plate-scale reconstructions which follow from our geodynamic analysis will provide just such an independent test.

Our analysis suggests that the conjugate, paired, deep-water basins of Rockall – West Orphan and Porcupine – East Orphan each represent a failed attempt at breakup prior to the eventual Ireland/Newfoundland separation which cut across these previously-formed failed-breakup basins.

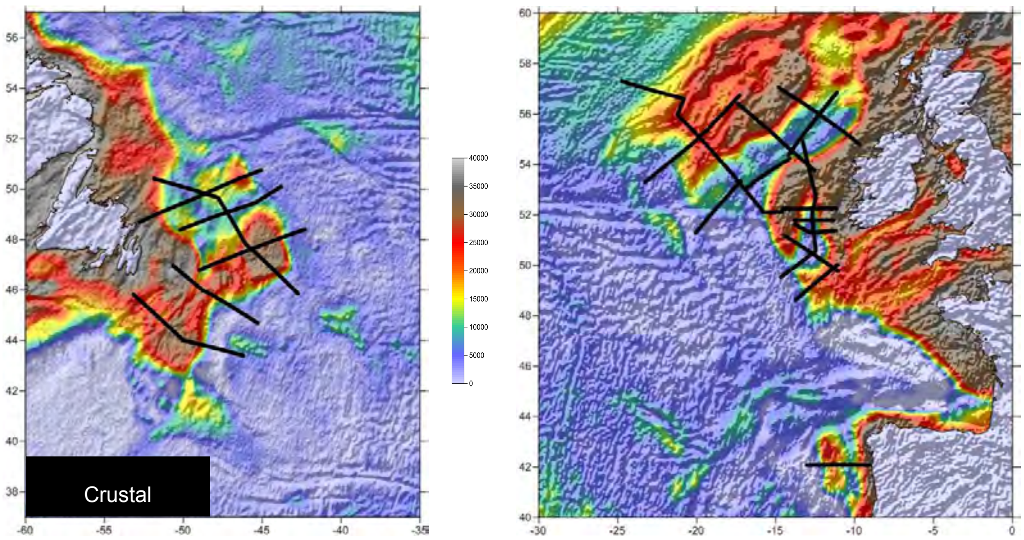


***Figure 1:*** *Crustal basement thickness determined from 3D gravity inversion using public domain free air gravity anomaly, bathymetry and sediment thickness data for the conjugate Atlantic Newfoundland – Ireland margins. The location of 17 depth transects produced by this study are also shown.*

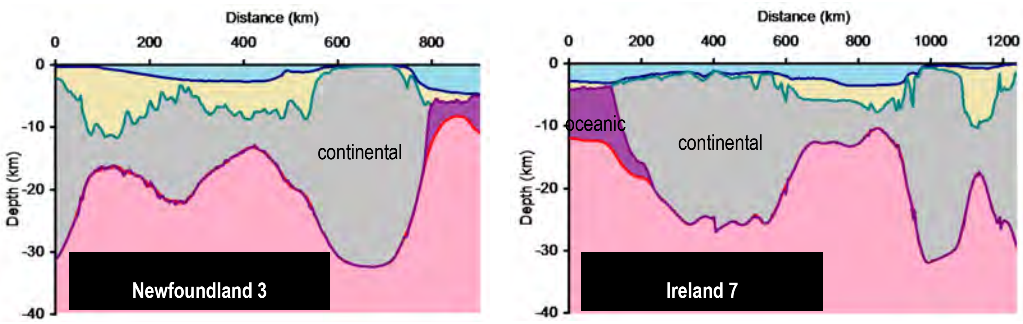


***Figure 2:*** *Example 2D crustal cross-sections from the Newfoundland and Ireland conjugate Atlantic margins with Moho depth and magmatic addition predicted by gravity inversion using sediment thickness from the 2D transects.*

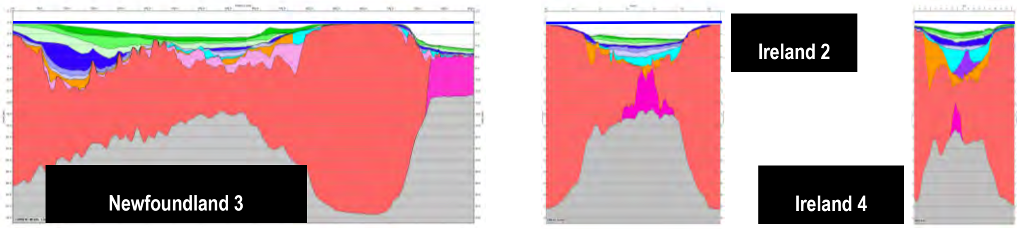


***Figure 3:*** *Example 2D crustal cross-sections from the Newfoundland and Ireland conjugate Atlantic margins showing interpreted stratigraphy from the 2D transects and Moho depth predicted by subsidence analysis.*

## SEQUENCE STRATIGRAPHY AS A TOOL IN PREDICTING PETROLEUM SYSTEMS OF THE IRISH MARGIN AND THEIR CONTEXT IN THE PALAEOGEOGRAPHIC EVOLUTION OF THE NORTH ATLANTIC CONJUGATE MARGIN

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Exploration in frontier areas is constrained by the knowledge of the petroleum systems that may be present. Risks can be reduced by analysing frontier areas, such as the Irish offshore, in the context of their conjugate margins. We have developed a proprietary, biostratigraphically constrained, global sequence stratigraphic model, which permits plate- and basin-scale stratigraphic correlation. This is a powerful tool for predicting key petroleum play elements and provides a framework on which to constrain maximum flooding surface (MFS) and lowstand (LST) gross depositional environment (GDE) maps. These GDE maps can be used in conjunction with a spatially enabled geochemical database and a global geodynamic model to help predict source rock distribution and to enhance understanding of the provenance of reservoir sands and their distribution in frontier basins.

The Canadian and Irish margins shared a common geological history prior to rifting in the Paleocene. The prospectivity of the Irish Mesozoic depositional systems will be discussed with reference to analogues from the Canadian margin and in the context of the general evolution of the North Atlantic. The potential for Late Jurassic source rocks on the Irish margin, analogous to proven source rocks of the Rankin Formation in the Jeanne d'Arc Basin will be discussed. The possibility of Cretaceous source rocks in the Porcupine Basin and elsewhere in the Irish offshore, analogous to those in Norway and Iberia, and associated with the Aptian Oceanic Anoxic Event will also be explored. Reservoir potential resulting from Early Cretaceous uplift and erosion as witnessed on the Canadian margin, and in lowstand clastics associated with a major global regression in the Middle Cretaceous will also be reviewed. Palinspastic maps will be used to demonstrate the strong links between petroleum systems of the Irish margin and the Canadian conjugate.

## NEW WIDE-ANGLE SEISMIC CONSTRAINTS ACROSS A MAGMA-STARVED, HYPER-EXTENDED NORTH ATLANTIC RIFT BASIN – ORPHAN BASIN

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### Introduction

The Orphan Basin is a large, deep water basin located north of the Grand Banks and northwest of Flemish Cap (Figure 1). It is one of the largest rift basins to have undergone hyper-extension without continental breakup and seafloor spreading. Such a setting allows detailed imaging of a cross section of a complete continental crustal extension system along a single profile. Several industry boreholes exist within the deep-water basin and the extensional structures also connect to wells within Flemish Pass and the petroleum prolific Jeanne d'Arc Basin to the south.

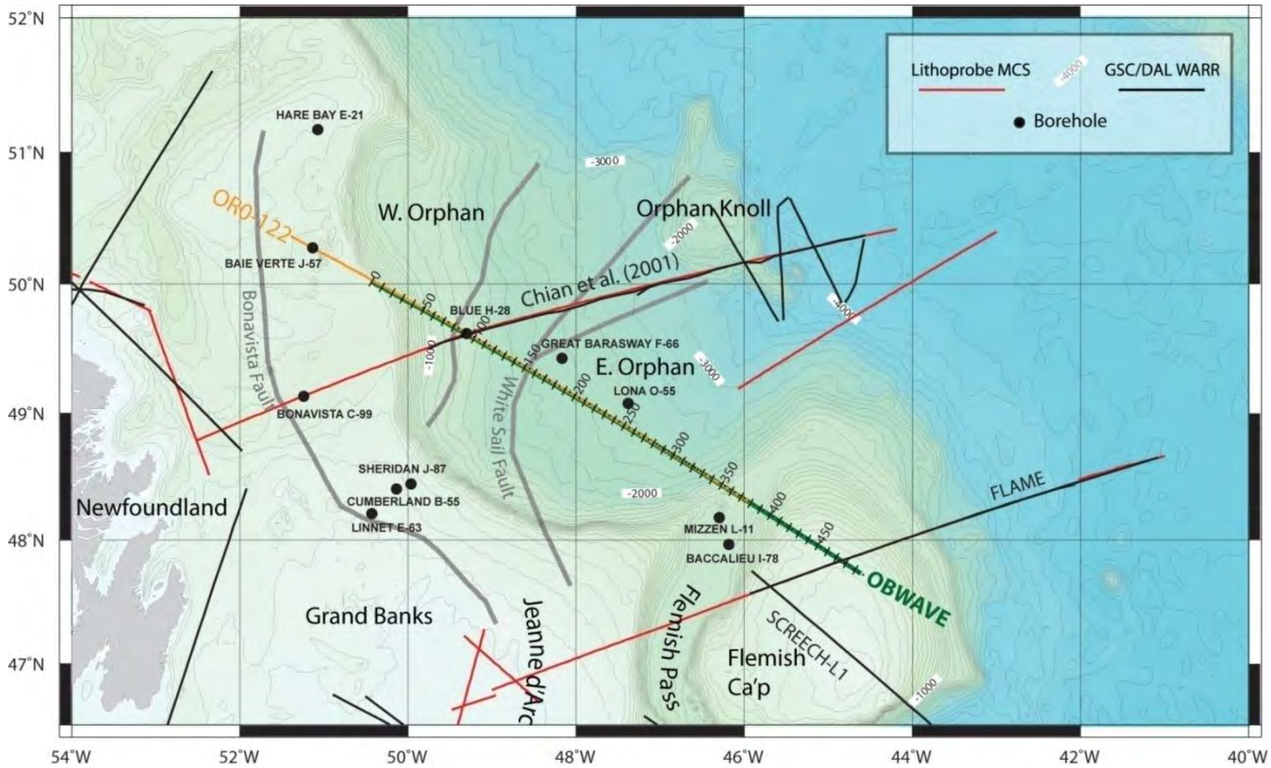


*Figure 1: Location map of selected reflection and refraction profiles across Orphan Basin and major wells. Tick marks are for velocity model distance in kilometres. Grey lines are major faults (Enachescu et al., 2005)*

Previous studies show that Orphan Basin is divided into eastern and western sub-basins by a series of faults and high relief basement ridges (Figure 1). Within each sub-basin, there are series of smaller ridges and troughs trending N-S in the west to NE-SW in the east, which formed during Mesozoic rifting between N. America and Africa/Europe and the rotation of Flemish Cap (FC) to the southeast (Enachescu *et al.,* 2005). An older Lithoprobe MCS profile and a more recent grid of extensive industrial MCS profiles have provided detailed images of these structures. However, the link between basement structures with underlying crustal layers and Moho depths remains uncertain. The only basin-wide, wide-angle seismic profile (Figure 1; Chian *et al.,* 2001), used to constrain deeper crustal structure, crossed the basement structures at an oblique angle and had wide spacing (~10-50 km) between the ocean bottom seismometers (OBS) that limited the resolution of the velocity model.

**Method**

In order to improve imaging of crustal structures, high resolution wide-angle data were acquired in 2010 during the OBWAVE (Orphan Basin Wide Angle Velocity Experiment) project. The refraction line (Figure 1) stretches along a NW-SE profile from Flemish Cap across the eastern sub-basin and into the western sub-basin. The profile is coincident with MCS profile OR0-122, previously acquired by GSI. Usable 4-component OBS data were collected at 89 receiver stations with 3-5 km spacing along a 500-km-long profile. An airgun array, consisting of 3 clusters of 3 G-guns (total volume of 4,680 $in^3$), was fired every 60 secs for an average shot spacing of 140 m. The western half of the profile was double-shot to increase fold. First arrivals and wide-angle Moho reflections (PmP) were picked from common receiver gathers. Tomographic inversion for the first arrival picks and PmP arrivals used the Tomo2D algorithm (Korenaga *et al.,* 2000) with optimisation of parameters (e.g. smoothness).

## Results

In this paper, we present our final Tomo2D P-wave velocity model with the Moho depths and their comparison with the coincident MCS profile. Although velocity variations in this grid-based model are smooth, we can divide the crust into upper, middle and lower zones with average velocities of 6.0 km/s, 6.5 km/s and 7.0 km/s, respectively. The whole crust thins gradually from ~30-32 km under FC to ~14-km-thick at model distance 320 km beneath a series of tilted fault blocks. Immediately westward, the crust thins abruptly to ~5-km-thick over a 67-km-wide zone, with partition of thinning mainly within both upper and lower zones. The maximum thinning in the upper crust is offset 13 km to the west of maximum thinning in the lower crust, indicating an asymmetric mode of extension. The shallow Moho correlates well with a system of strong reflections topping a region of fuzziness in the MCS data.

The crust thickens to 15-km-thick at the western end (255 km distance) of the abrupt thinning. Farther north-westward, the crust thins again to ~9-km-thick near the edge of the west basin (180 km distance). The connection of Moho variation with the deep crustal continuation of the White Sail Fault suggests that the thinning may be fault controlled. A velocity of 7-7.3 km/s is observed beneath the Moho in a region of strong reflectivity, suggesting a complex crust-mantle boundary.

Three major basement fault blocks are observed between 70-160 km distance, where the crust thickens to 17 km. Major faults that flank both sides of the blocks extend into the deep crust; while faults within the blocks sole within the middle crust, suggesting a complex brittle-ductile transition. Within the west basin (<70 km distance), the crust thins to 12 km thick. In conclusion, our model shows detailed crustal deformation that could not have been interpreted with confidence based solely on MCS data. The multiple zones of thinning imply complexity in subsidence history, which would impact the deposition of syn-rift sediment and its petroleum potential.

**References**

Chian, D., Reid, I. & Jackson, H. 2001. Crustal structure beneath Orphan Basin and implications for non-volcanic continental rifting. *Journal of Geophysical Research,* **106**(B6), 10923-10940

Korenaga, J., *et al.* 2000. Crustal structure of the southeast Greenland margin from joint refraction and reflection seismic tomography. *Journal of Geophysical Research,* **105**(B9), 21591-21614.

Enachescu, M., *et al.* 2005. Evolution and petroleum potential of Orphan Basin, offshore Newfoundland, and its relation to the movement and rotation of Flemish Cap based on plate kinematics of the North Atlantic. *In: Post P.J. et al. (eds). Petroleum Systems of Divergent Continental Margin Basins, GCSSEPM 25th Annual Bob F. Perkins Research Conference,* 75-131, CD-ROM, ISSN 1544-2462.

## THE HYPEREXTENDED MID-NORWEGIAN MARGIN - IMPLICATIONS FOR EXPLORATION

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Slow and extreme extension of continents may lead to the development of magma-poor rifted margins, e.g. the well-known Iberian – Newfoundland conjugate margins. Although the mid-Norwegian margin is considered a type locality for magma-rich margins, it had a pre-history as a magma-poor hyperextended basin, being an element of a hyperextended basin chain that reached from the Orphan Basin to the SW Barents Sea (map below).

Implications of the hyperextension process include a significant reduction of the strength of the lithosphere by: a) crustal thinning, and b) associated upper mantle hydration (partial serpentinisation). A new geophysical method (ASEP+E) demonstrates that the effect of serpentinisation leads to a strength reduction of the entire crustal plate.

We illustrate this with three cases (Figure below): a) a reference case, b) serpentinised mantle, and c) intruded lower crust (magmatic underplating). Case A, the reference model, is a 10 km thick plate with the stiffness described by a constant Young's modulus of 100 GPa. Case B has a 5km thick lower crustal body (LCB) with a lower Young's modulus (E = 30 GPa), and case C has a 5 km thick LCB with a higher Young's modulus (E= 160 GPa).

The effective Young's modulus (explained in detail in Wienecke *et al.,* 2008; Wienecke, 2009) is calculated in vertical direction for case B by:

$$E_{eff} = \frac{1}{\frac{5km}{10km}\cdot\frac{1}{100GPa} + \frac{5km}{10km}\cdot\frac{1}{30GPa}}$$

$$E_{eff} = \frac{1}{\frac{1}{2}\cdot\left(\frac{3+10}{300GPa}\right)} = \frac{2\cdot 300}{13}GPa = 46.2GPa$$

and for case C by:

$$E_{eff} = \frac{1}{\frac{5km}{10km}\cdot\frac{1}{100GPa} + \frac{5km}{10km}\cdot\frac{1}{160GPa}}$$

$$E_{eff} = \frac{1}{\frac{1}{2}\cdot\left(\frac{16+10}{1600GPa}\right)} = \frac{2\cdot 1600}{26}GPa = 123.1GPa$$

The geological analogy of case B is hyperextended crust underlain by serpentinised mantle with E = 30 GPa, which reduces the stiffness of the total crustal plate by ~ 60%; the effective Young's modulus is reduced to $E_{eff}$ = 42.2 GPa for a 5 km LCB, compared to the reference model with E =100 GPa. Case C illustrates the influence of a LCB consisting of metagabbro (lower crustal intrusions – so-called underplate) and reveals a stiffness increase by ~ 25% to $E_{eff}$ = 123.1 GPa. Notably, the strengths of these two cases differ by ~ 300%.

The resulting weakness, related to hyperextension and partial serpentinisation of the mantle, acts as a stress-guide, making such margins and basins prone to compressional deformation.

A number of Cenozoic compressional folds along the NE Atlantic margins formed within the hyperextended basin chain, and they have been drilled with varying results. In the case of the NE Atlantic, hyperextension was of Early Cretaceous age, hence post-dating the Upper Jurassic source rock. This resulted in fragmentation, deep burial and early maturation of the source rock, often well before reservoirs and traps were in place. The mentioned compressional folds are of mainly Neogene in age, and thus, the timing of structuring was late with respect to charge.

We argue that the mid-Norwegian margin also was subjected to Late Cretaceous compressional deformation, which started already in latest Turonian time, or possibly already in the Cenomanian. Broad simple folds, with wavelengths up to c 80 km, formed traps for deep-water sands. In the northern Vøring Basin such a palaeo-syncline, containing close to 1 km of very clean sand, was inverted and breached by erosion in Maastrichtian-Early Paleocene time. This anticline collapsed in Late Paleocene and was re-inverted in Middle Miocene time. Thus, the northern mid-Norwegian margin reveals a series of pronounced vertical motions that have affected the petroleum system. Our interpretation of Late Cretaceous compressional folding implies that, lithospheric weakening after hyperextension is more long-lived than the literature suggests.

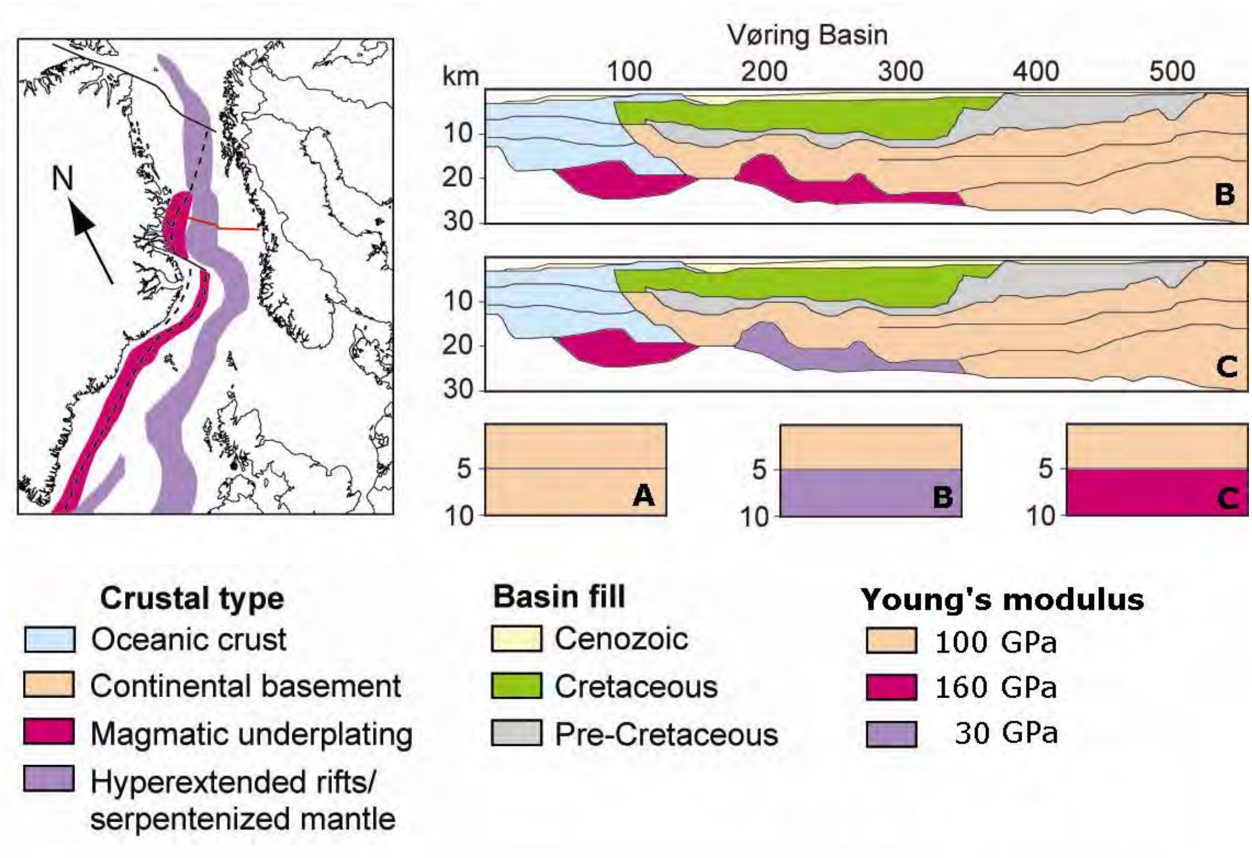


***Figure 1:*** *Early-Mid Cretaceous hyperextended basin chain of NE Atlantic, and superseding Early Cenozoic magma-rich breakup axis. The breakup axis split the hyperextended basin chain obliquely. Sections on right hand marked on map with red line. Case B (top section) assumes a magmatic underplating LCB. Case C (lower section) hyperextended rift is underlain by partially serpentinised mantle LCB and a narrow zone of magmatic underplating along margin edge.*

## TECTONIC CONTROL ON SEDIMENT SUPPLY AND RESERVOIR SUPPLY TO CONJUGATE ATLANTIC MARGINS

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Many authors have noted that similarities in topography, uplift history, stratigraphy and play systems persist across the various conjugate margins of the Atlantic well after the initiation of continental drift. In order to improve this understanding and investigate causes, porosity-removed sedimentation rate profiles have been compiled for 150 points across all Atlantic margins, mainly using published cross-sections and seismic lines, through a methodology presented fully in Macgregor (2012).

South Atlantic margins show pulses of high sedimentation rate in the Late Cretaceous and Neogene, with an extension of the former into the Palaeocene on the SE Brazilian margin only (Macgregor, 2012). These can be readily correlated with interpreted uplift phases of epeirogenic highs in the hinterlands, including elongate uplifts along the continental margins that persist to Recent times. There is also a clear correlation of high rates to periods of reservoir input into deepwater, including those holding the majority of the hydrocarbon reserves in the drift succession. Climatic variations also play a strong control with sediment supply remaining low in arid regions even where significant topography is developed.

Central Atlantic conjugate margins perhaps show the strongest stratigraphic correlations that are here related to coeval periods of high clastic reservoir supply in the Early Cretaceous and Neogene. On the American side, this pattern can be linked with the documented post-orogenic uplift history of the Appalachians. The African margin is complicated by the Alpine Atlas orogenesis, but other areas such as the Meseta and Reguibat may have experienced uplift at the same time as the Appalachians.

The European margin of the relatively young Northern Atlantic is perhaps the best understood in terms of the relationship of epeirogenic marginal uplifts to sedimentation rate and turbidite reservoir supply, typified by the well known effects of Palaeocene uplift of Scotland. The Palaeocene-Eocene sediment surge in this region contrasts with the phase of lowest sedimentation rates elsewhere in the Atlantic, associated with a period (Brazil excepted) of low topography, high sea level and relatively constant warm climates. The peak of North Atlantic sedimentation rates are however seen in the Plio-Pleistocene, associated with Norwegian and Greenland margin uplifts and glaciations.

In each sector of the Atlantic, breakup seems to be followed by a sag phase with low sedimentation rates, and may include the widespread deposition of carbonates where climatic conditions are favourable. Episodic and often correlative continental margin uplift seems to be initiated 15-40Ma after breakup, is least common in the Palaeogene and most common in the Neogene. Of all the Atlantic margins, only the Argentinian margin has escaped the effects of such uplift and is truly ‘passive’. A long term climatic-eustatic overprint is also evident on sedimentation rates across the region, with a general increase evident from Oligocene onwards.

The results of this study are summarised in the attached figure, which highlights the age of periods of high drift phase clastic sediment supply (>40m/Ma) and their relationship to uplifts and proven hydrocarbon bearing turbidite reservoirs. While the occurrence of the latter is clearly linked to high rates, it should be noted that periods of source rock deposition are linked to periods of abnormally low sedimentation rate. There are thus many aspects of the petroleum system that are better understood through the mapping of sediment supply.

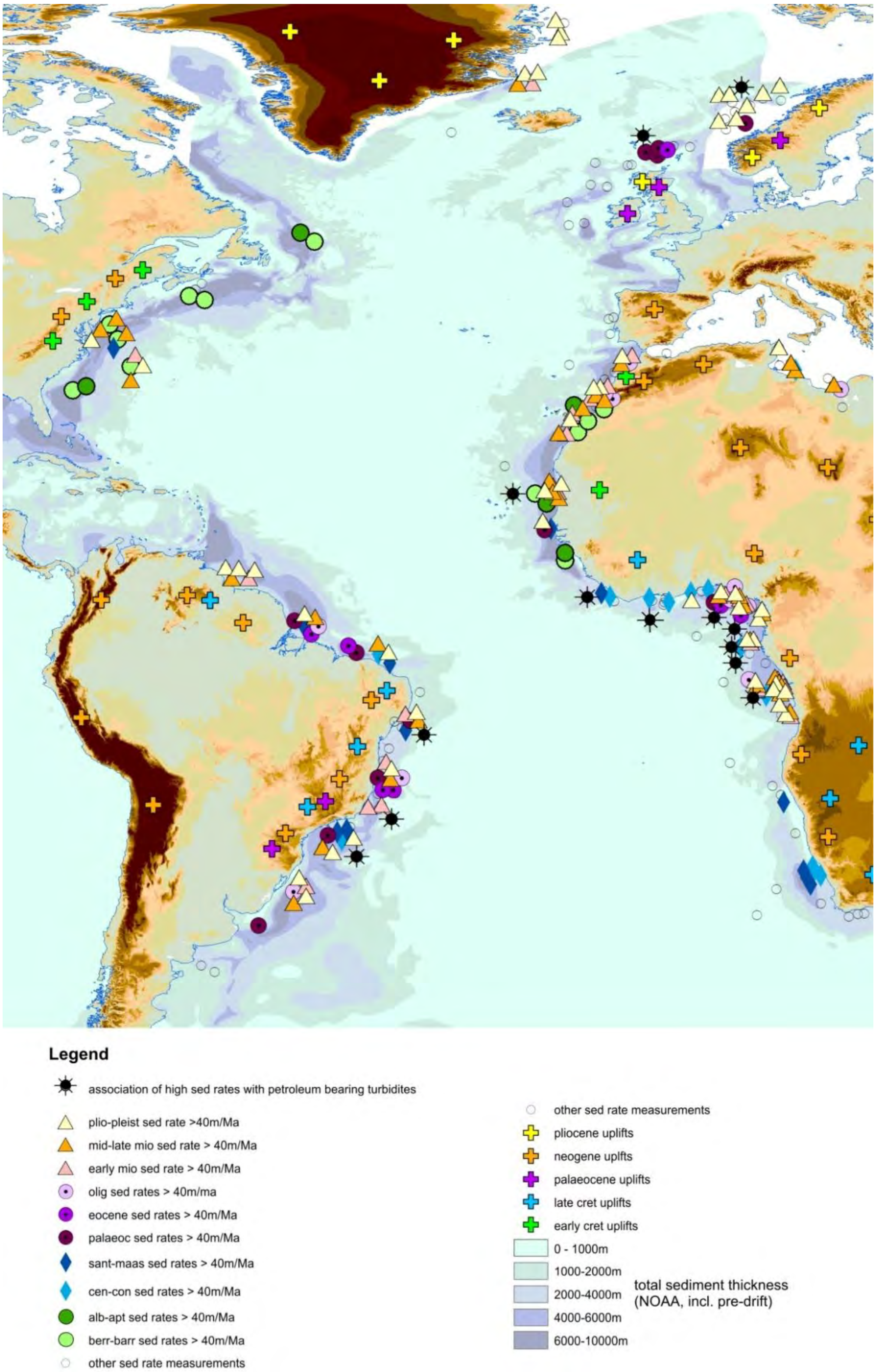


***Figure 1:*** *Sedimentation rate measurements, fully compacted, over 40m/Ma and ages, correlated to periods of continental uplift and turbidite reservoir development. sant-maas=Santonian-Maastrichtian, cen-con=Cenomanian to Coniacian, alb-apt=Aptian to Albian, berr-barr=Berriasian to Barremian. Sediment thickness and topography from NOAA website.*

**Reference**

Macgregor, D.S. 2012. Sediment and Turbidite Sand Supply to South Atlantic Margins. *In:* Mohriak, W.U. *et al.* (eds). *Conjugate Divergent Margins,* Geological Society London, Special Publications, **369**, *published online March 19 as doi:10.1144/SP 369.7*

## DEEP PENOBSCOT, AN ANALOGUE TO DEEP PANUKE – ARE MORE JURASSIC REEFS LURKING OFFSHORE NOVA SCOTIA?

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The Deep Panuke Jurassic reef discovery offshore Nova Scotia Canada is due to begin production in mid-2012. This discovery is the first production from late Jurassic reefs in North America outside of the Gulf of Mexico. Reprocessing old seismic data clearly defined the extension of the Abenaki platform to the northeast and identified a potentially hydrocarbon-charged reef near the Penobscot L-30 well (Figure 1). This Penobscot reef to the north of the Deep Panuke discovery is a second potential producing reef built on the Jurassic carbonate bank that extends along the eastern continental margin of North America from the Bahamas to Nova Scotia (Figure 3).

Biostratigraphic and seismic correlations of the Abenaki Carbonate Platform between Penobscot and the Encana Deep Panuke Field indicate that in the Penobscot L-30 area the Baccaro Reef was overwhelmed by the prograding Missisauga Delta in the early Middle Tithonian (Late Jurassic), but the Baccaro Reef continued to build into the Late Tithonian at Deep Panuke. This interpretation indicates that the gas reservoir at Deep Panuke is Middle to Late Kimmeridgian age. Seismic interpretation highlights amplitude anomalies in the Baccaro Reef north of the Penobscot L-30 well. These amplitude anomalies are confirmed by spectral anomalies which suggest that porosity in the Penobscot Reef is probably in carbonates of Kimmeridgian or Oxfordian age (Figure 2).

Both areas are marked by faults near the front of the reef that extend from the Jurassic into the overlying Missisauga, providing migration pathways for the light oil accumulation at Panuke Field, and the light oil tested in the Penobscot L-30 well. Reef porosity in both areas is likely dominated by hydrothermal dolomitisation, which means that lithology and faulting rather than age equivalency are the critical elements for reservoir development. It is thought that the oil and gas likely originated from an early Jurassic source rock, which has also been hypothesised in the recently published Nova Scotia Play Fairway Analysis. The identification of potential reservoir anomalies in the Abenaki near Penobscot and the production at Deep Panuke suggests that the application of modern seismic techniques will likely result in the discovery of additional reefs in the Jurassic carbonate play fairway along the eastern Atlantic continental margin of North America.

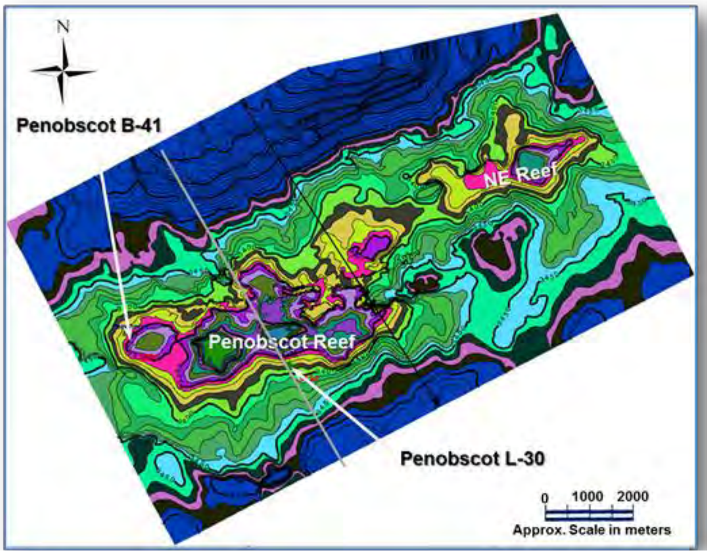


***Figure 1:** Seismic depth map of the top of the Abenaki Carbonate in the Penobscot 3D seismic volume*

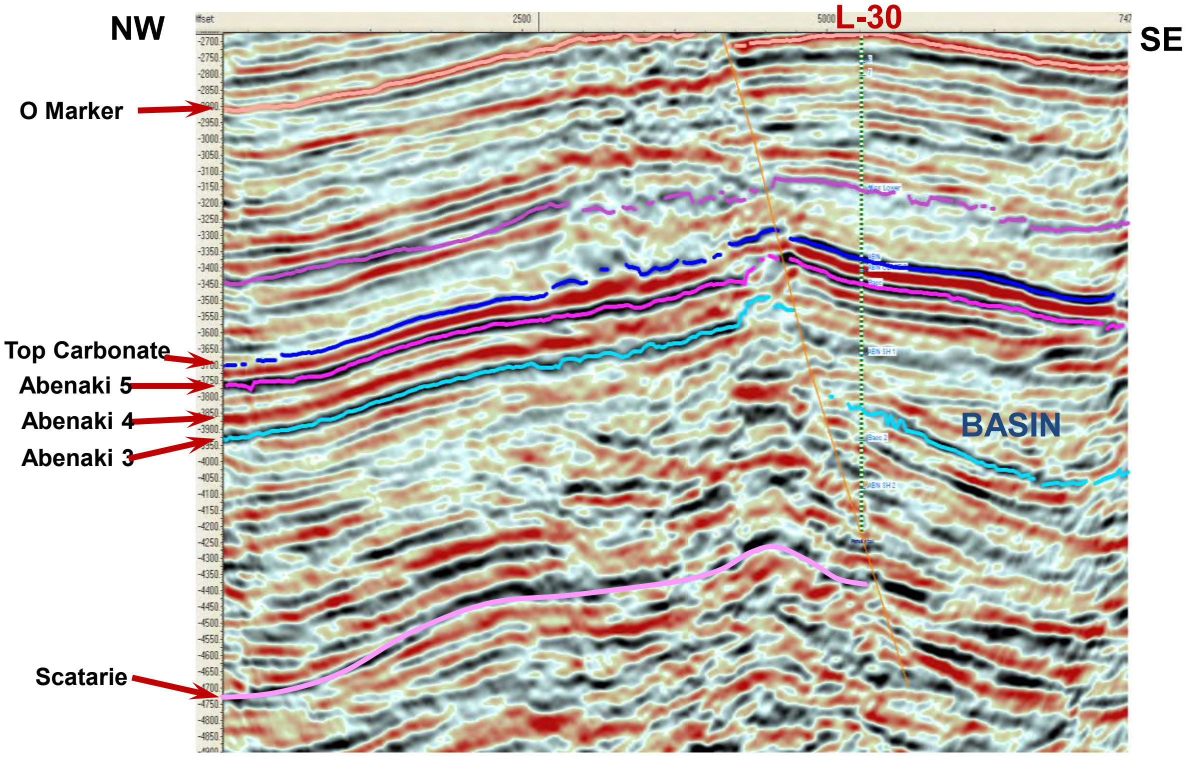


***Figure 2:*** *NW – SE PSDM seismic line across the Penobscot reef showing the forereef position of the Shell Penobscot L-30 well*

***Figure 3:*** *Mid to Late Jurassic reconstruction showing the location of the Jurassic reef trend from Penobscot to the Bahamas. Red stars indicate production, blue stars indicate where the reef has been penetrated but non-commercial. (Adapted from Blakely, R.@jan.ucc.nau.edu)*

# THE PALINSPASTIC AND SEQUENCE STRATIGRAPHIC CONTEXT OF THE CONJUGATE MARGIN OF NORTH AMERICA AND NORTH WEST AFRICA

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It is understood that the biggest contributor to play risk on the U.S. Atlantic margin is the likelihood of source rock occurrence, and whilst the U.S. portion of the Atlantic is under a drilling moratorium, the Canadian continuation of Georges Bank; the Scotian Basin of Nova Scotia, is open for bidding rounds in 2012, making the question of source rock presence a pertinent one. The application of our biostratigraphically calibrated, global, 3rd-order sequence stratigraphic Earth Model to the conjugate North Atlantic margin allows us to accurately correlate systems tracts across the Atlantic Ocean, comparing periods of organic-enrichment or sediment input. When our sequence stratigraphic Earth Model is combined with our palinspastic plate model, the conjugate margin of North America and North West Africa can be assessed in terms of their local, regional and global context.

The shared geological histories of Georges Bank and the Baltimore Canyon Trough on the U.S. Atlantic margin, with those of the Aaiun-Tarfaya, Western Saharan Marginal and Mauritanian basins on the North West African Atlantic margin, permits a number of important insights. For example syn-rift salt development in Georges Bank and the Baltimore Canyon Trough has been used to infer salt formation in the Western Saharan Marginal Basin. Furthermore the presence of Early Jurassic lagoonal shales and bituminous carbonates which source the Cap Juby discovery in the Aaiun-Tarfaya Basin, suggest that Early Jurassic to earliest Middle Jurassic organic rich facies could be a viable source rock in Georges Bank. The development of the Bahama-Grand Banks gigaplatform along the U.S. Atlantic margin in the Middle and Late Jurassic is paralleled along the North West African coastline. On both sides of the Atlantic the Early Cretaceous is marked by the cessation of carbonate development and the progradation of siliciclastics, with large shelf deltas and submarine fans developing offshore Cape Boudjour, Western Sahara and offshore Delaware, U.S. Atlantic margin.

The late Early to Late Cretaceous period is known for Ocean Anoxic Events (OAEs), which influenced the development of black shales globally. The Aptian-Albian OAE 1b is recorded in the Aaiun-Tarfaya Basin and in DSDP site 1049 on Blakes Nose (U.S. Atlantic margin) and there is potential for the extension of organic-enrichment along the U.S. Atlantic seaboard at this time. The Cenomanian-Turonian OAE 2 is also recorded synchronously in the Aaiun-Tarfaya Basin, Mauritanian Basin and Baltimore Canyon Trough, where biofacies data from wells record the continuation of anoxia through the subsequent sea level lowstand. The OAEs are an exemplary use of our palinspastic plate model in determining causality mechanisms for organic enrichment including ocean circulation patterns and the scale of freshwater nutrient input. The geographic and temporal distributions of all the facies discussed above are best understood in their palinspastic context on regional Gross Depositional Environment Maps.

## EXPLORATION UPDATE FROM ATLANTIC IRELAND

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Ireland is currently experiencing an increase in exploration interest and this is attributed to positive signals from drilling, a growing recognition of Ireland's prospectivity and recent innovative licensing initiatives. While drilling levels have been disappointing, several significant discoveries have been made over the past four decades and encouraging results are currently being achieved from reassessing and appraising older discoveries.

Working petroleum systems are demonstrated in virtually all of the major Irish basins – North Celtic Sea, Porcupine, Slyne and Rockall – but many areas still suffer from sparse well control and seismic data gaps. These shortcomings, together with the severe water depths, remoteness from shore and lack of infrastructure in the case of frontier basins, have resulted in large areas of the Irish Shelf receiving little or no attention. In order to address some of these concerns, the Department is actively sponsoring regional petroleum research, new data acquisition and other data initiatives. This new work is designed principally to reduce exploration risk by providing the means to perform more precise hydrocarbon resource assessments.

An overview of regional exploration activity on the Irish Shelf will be presented and will include:

- offshore E&P authorisation status
- development and production forecasts
- drilling results and future plans
- geophysical data acquisition
- time lines for regional technical work integration

While the level of exploration activity, drilling in particular, has been far from satisfactory, there have been a number of recent encouraging signs. These include record numbers of authorisation applications received, the rate of companies entering Ireland for the first time and the expected near term increase in drilling levels; wells planned for 2013 are set to focus on high profile targets of international interest.

Although substantial oil and gas resource potential has been indicated for Ireland's offshore basins, this potential can only be realised if the industry is prepared to commit the high level of investment required for exploration drilling over a period of several years. Significant exploration challenges lie ahead, but Ireland remains committed to maximising the potential from its natural resources.

## SEISMIC STRATIGRAPHIC ANALYSIS OF THE CENOZOIC SEDIMENTS IN NW FAROE-SHETLAND BASIN – IMPLICATIONS FOR INHERITED STRUCTURAL CONTROL OF SEDIMENT DISTRIBUTION

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In this study the post-rift strata in the Faroese area have been investigated based on interpretation of 2D and 3D reflection seismic data. The post-basalt package is divided into 5 units which have led to the construction of 6 structural maps and 5 thickness maps (Figures. 1 and 2). Major progradational systems dominate along the contemporaneous basin margins in Unit 1 (Lower Eocene) and Unit 5 (Pliocene).

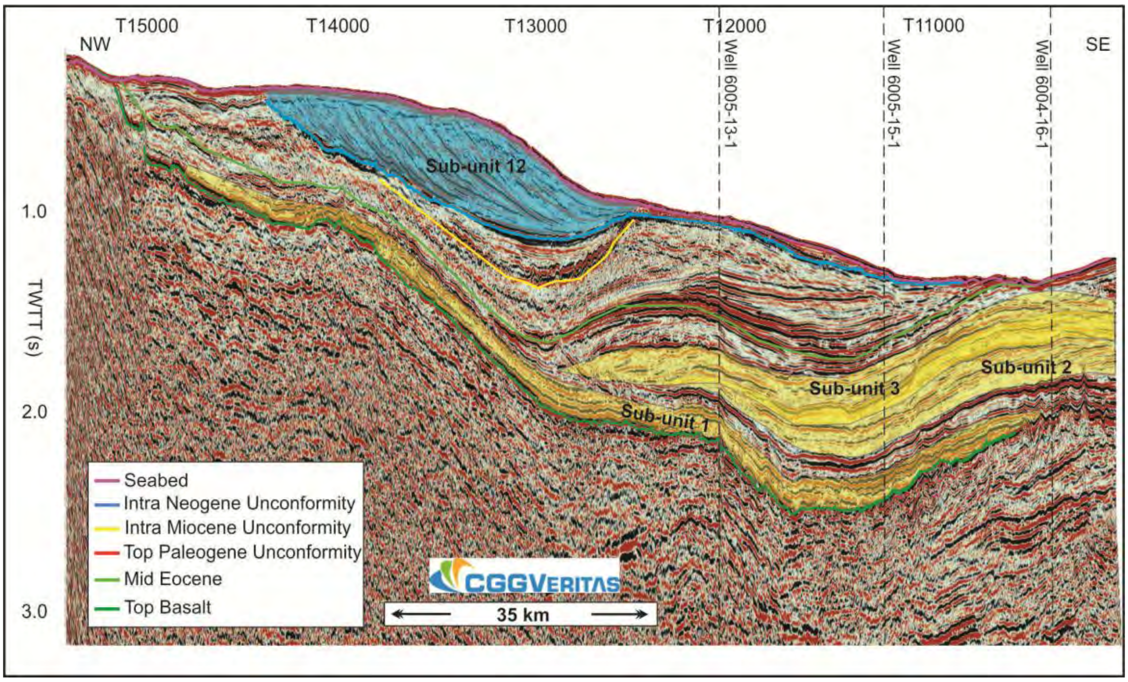


***Figure 1:*** *Typical cross section of the Faroes sector of the Faroe-Shetland Basin*

Progradational units and other nearshore indicators are only seen sporadically in units 2-4 (representing Middle Eocene through Miocene deposition). Basin floor fans constitute a considerable part of units 2-3. Overall, Eocene (unit 1 & 2) progradational and basin floor fans are of dominantly south-eastern and south-western provenance (Ólavsdóttir *et al.,* 2010). Through Oligocene to recent (unit 3-5) fans is dominated by patchy occurrences of western or northern provenance possibly reflecting renewed uplift of the Faroe Platform and Fugloy Ridge. The Middle-Upper Miocene Unit 4 is found in synclinal basins formed as the result of a mid Miocene compressional phase and as contourites in the central Faroe-Shetland Basin.

Emplacement of the Cenozoic sediments in the Faroese sector of the Faroe-Shetland Basin appear to be controlled by decelerating thermal subsidence of the basin, and local uplift of sediment source areas (e.g. Andersen *et al.,* 2002). However, the actual distribution of sediments appears to be controlled by re-activation of older, Mesozoic, structural elements controlling the sediment path way and restricting the depositional areas. Different elements being re-activated at different times caused considerable structural complexity. Understanding older, Mesozoic, structural elements control on sedimentation is a potential tool understanding deviations from “normal” thermal subsidence and for predicting the prospectivity in post-rift succession in the Faroe-Shetland Basin.

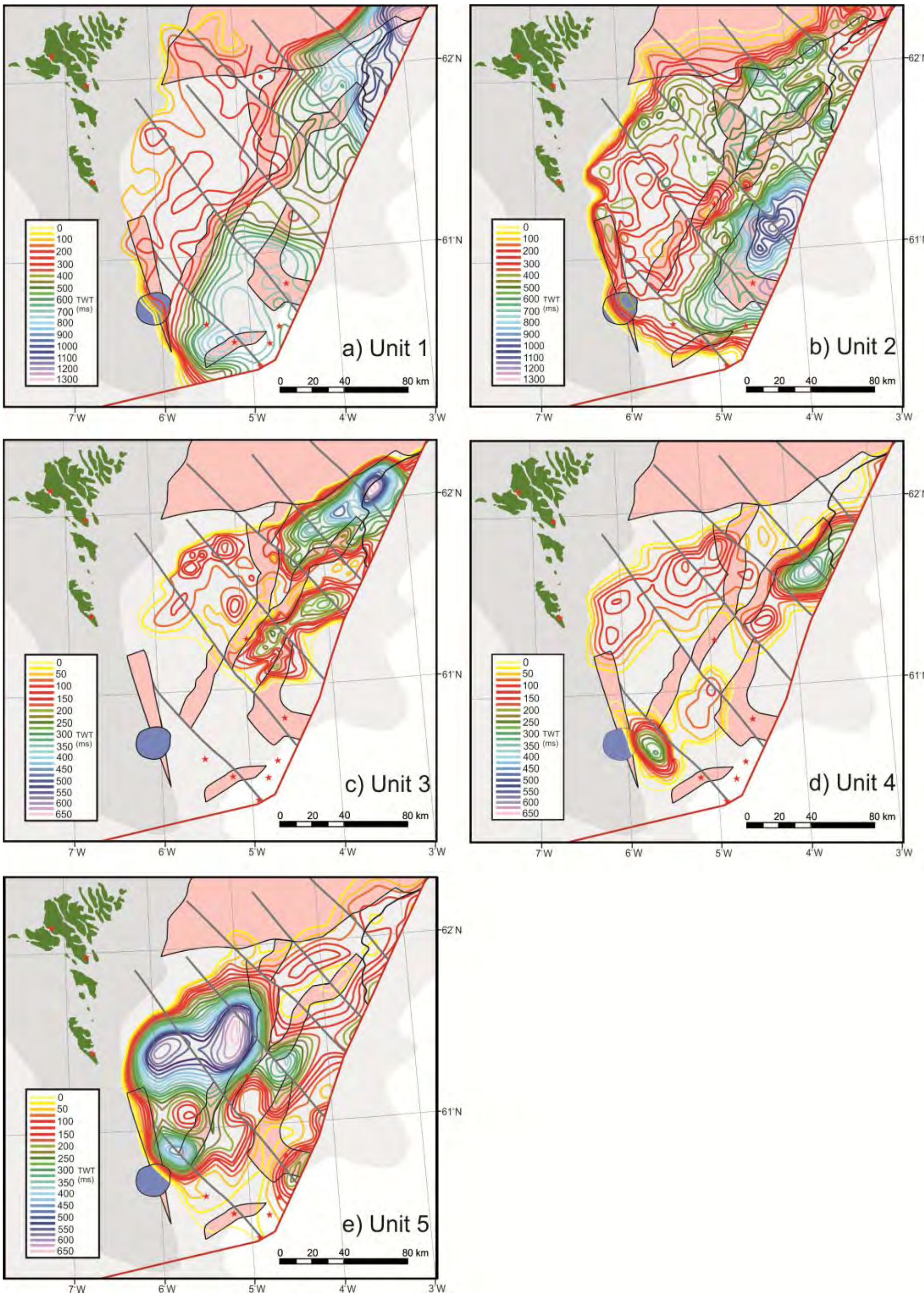


***Figure 2:*** *Isochron maps of the five major units of the Cenozoic post-rift succession in the Faroese sector of the Faroe-Shetland Basin*

**References**

Andersen, M.S., Sørensen, A.B., Boldreel, L.O. & Nielsen, T. 2002. Cenozoic evolution of the Faroe Platform: Comparing denudation and deposition. *In:* Doré, A.G. & Vining, B.A. (eds). Petroleum Geology: North-West Europe and Global Perspectives – *Proceedings of 6th Petroleum Geology Conference. Geological Society London,* 291-311.

Ólavsdóttir, J., Boldreel, L.O. & Andersen, M.S. 2010. Development of a shelf margin delta due to uplift of Munkagrunnur Ridge at the margin of Faroe–Shetland Basin: a seismic sequence stratigraphic study. *Petroleum Geoscience,* **16**(2), 91-103.

## CONTROLS ON FELDSPAR DIAGENESIS, AS SEEN IN THE LOWER CRETACEOUS SANDSTONES OF THE SCOTIAN BASIN, CANADA

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In most sandstone sequences in sedimentary basins, detrital feldspars are the second most important framework mineral after quartz. Thus, chemical changes in feldspars, both K-feldspar and plagioclase, are probably among the most significant changes occurring in sandstones during burial diagenesis. Commonly both K-feldspar and plagioclase are replaced by albite, although feldspars may also alter to calcite, kaolinite polymorphs, and illite. In the literature, there are various interpretations of the conditions which favour albitisation. Sixteen representative samples at various depths from eight exploratory wells were selected for detailed study of the diagenesis of the detrital feldspars, in order to evaluate the roles played by several variables in determining the type of alteration of feldspar. These variables included sedimentary facies (which influence porosity and permeability), geographic location (controlling the type of detrital supply), burial depth, temperature and salinity as recorded by fluid inclusions, and the structural setting of the sandstones. We were particularly interested in the relationship between albitisation, seen in the detrital feldspars, and the thermal evolution of the basin. Our recent work on the stratigraphic distribution of carbon isotopes in carbonate cements and hot saline fluid inclusions in silica and carbonate cements has demonstrated a prolonged thermal event in the Scotian basin, no older than Aptian and probably no younger than Albian (125–100 Ma; Karim *et al.,* 2012). Thermal modelling by Bowman (2010) showed that the conductive heat effects of short-lived volcanic activity in the Scotian Basin were minor and not recorded in vitrinite reflectance. However, more prolonged thermal effects result from convection of hot fluids from deeper in the basin or a period of regional high heat flow, of which the volcanism was only a surface manifestation. Convection by hot fluids generated increased burial temperatures in the Thebaud and Glenelg fields, compared with the eastern part of the basin reported by Hanley (2011). Fluid migration may have been facilitated by active crustal faults and fluids moved up-dip through permeable limestones and sandstones.

Widespread feldspathic lithic clasts in the studied sandstones were from trachytic, hypabyssal and plutonic lithologies. These clasts resemble the Lower Cretaceous sodic igneous rocks described from the Brant-87 and Mallard M-45 wells on the SW Grand Banks, which contain common albite. This explains the abundance of detrital albite in lithic clasts and as independent crystals in the study area. The trachytic clasts, because of their characteristic morphology and mineral chemistry, are useful targets to track diagenetic changes with depth. Such changes start with grain dissolution and/or dissolution voids on the grain at about 3 km depth. Beyond this depth, the overall morphology of the grain remains, but the texture changes: it is more difficult to identify individual crystals of albite, as if authigenic albite developed between the crystals and sealed the interstices. Their hot cathode cathode-luminescence is either reduced or completely lost. Such grains are termed albite pseudomorphs. Old dissolution voids in these pseudomorphs become filled with fibres or laths of illite and chlorite.

K-feldspar authigenesis starts at ~1900 m depth as K-feldspar overgrowths, with or without dissolution voids, on detrital K-feldspars, or as cement that fills fractures in fractured K-feldspars. Both overgrowths and fracture fills show dark hot cathode cathodoluminescence. No authigenic K-feldspar overgrowths have been seen below 3000 m. Textural evidence suggests that some overgrowths are synchronous with quartz overgrowths. Albitisation of K-feldspar also starts at ~1900 m, with diagenetic albite following weakness paths such as cleavage, twinning and fracture planes. At greater depths, K-feldspar disappears through dissolution and/or replacement by carbonate minerals, mainly ferroan calcite ± ankerite, with rare albite and clay minerals. The depth of K-feldspar disappearance ranges from 3,800 to 4,500 m.

Detrital plagioclase is either oligoclase or mostly albite. Criteria for diagenetic albite are straight crystal outlines, chemistry of $An_{0-2}$, and dark or reduced hot cathode cathodoluminescence. Early patches of diagenetic albite in detrital albite grains give way with depth to albite pseudomorphs or partially dissolved albite grains, containing large pores. In some samples, diagenetic albite has filled pore space engulfing earlier cements such as kaolinite and in turn engulfed or replaced by later cements such as ferroan calcite, leaving relics with straight crystal outlines. Albite pseudomorphs predate late ankerite cement. Detrital oligoclase is little affected by authigenesis, with first replacement at depths >3,700 m by diagenetic albite in the form of overgrowths or irregular patches with straight crystal outlines.

Diagenetic albite is much more abundant in thick sandstone units than in thin sandstone beds with interbedded mudstone, probably because such sandstones were pathways for flux of basinal fluids. It is more abundant, in the same facies and depth, in the Thebaud–Glenelg fields, where fluid inclusions in silica and carbonate cements are ~21% NaCl compared with the eastern part of the basin where fluid inclusions are ~10% NaCl and probably a little cooler. Dissolution of K-feldspar seems predominantly controlled by burial depth, but is most severe in permeable thick sandstone units.

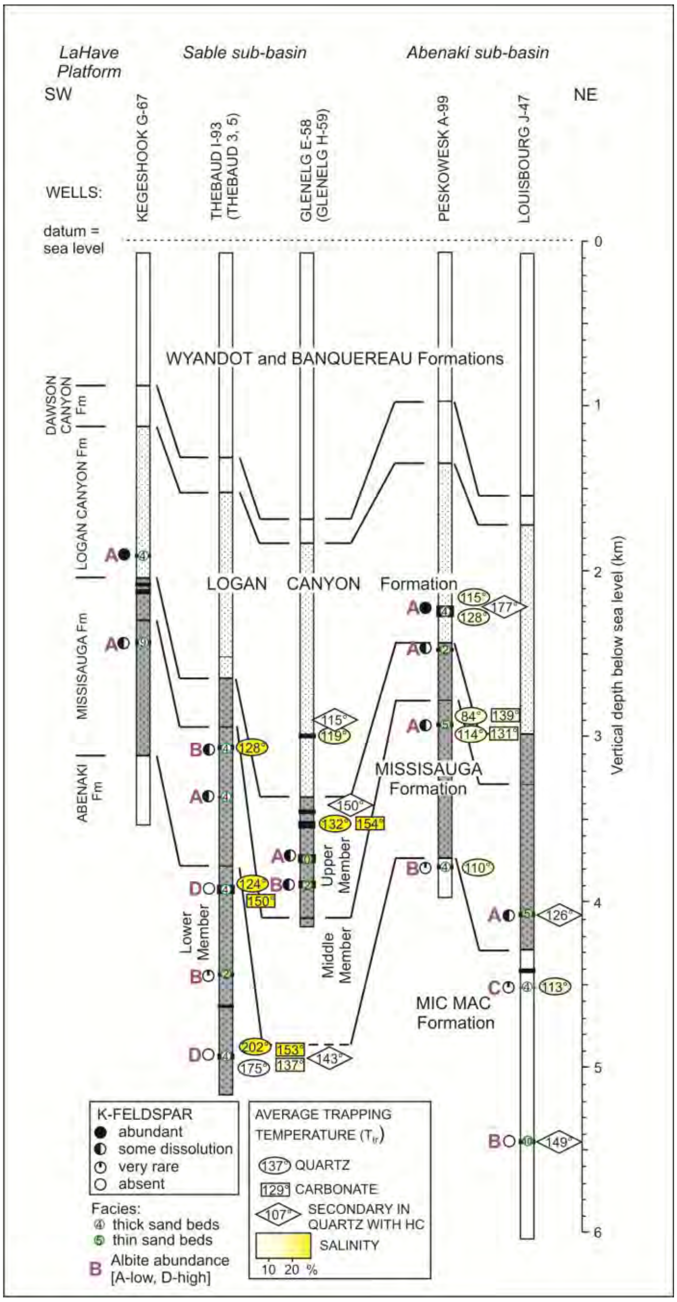


*Figure 1: Summary of abundance of K-feldspar and diagenetic albite. Fluid inclusion data from Karim et al. (2012) and Hanley (2011)*

**References**

Bowman, S.J., 2010. Cretaceous tectonism and volcanism in the eastern Scotian Basin, offshore Nova Scotia. *M.Sc. thesis, Saint Mary's University,* 195p.

Hanley, J.J., 2011. The conditions of primary and secondary fluid inclusion entrapment in clastic sedimentary rocks in the Scotian Basin, and the relationship between inclusion entrapment and reservoir charging. Annex 11. *In:* OETR (Offshore Energy Technical Research Association). *Play Fairway Analysis Atlas - Offshore Nova Scotia*. Nova Scotia Department of Energy Report 88-11-0004-01, 349p. http://www.novascotiaoffshore.com/analysis

Karim, A., Hanley, J.J., Pe-Piper, G. & Piper, D.J.W. 2012. Palaeohydrogeological and thermal events recorded by fluid inclusions and stable isotopes of diagenetic minerals in Lower Cretaceous sandstones, offshore Nova Scotia, Canada. *American Association of Petroleum Geologists Bulletin* (in press)

## TECTONO-STRATIGRAPHIC EVOLUTION OF THE SOUTHWEST IBERIAN MARGIN: A TAIL OF THE CENTRAL ATLANTIC

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Southwest Iberia, located on the transitional domain of the Central and North Atlantic Ocean, records the complete rift-to-drift evolution of a magma-poor rifted margin (Manatschal, 2004; Tucholke *et al.,* 2007), is revealed herein as a key province to understand the intricate evolution of this domain of the Atlantic.

The Southwest Iberian margin evolved within the context of a complex geodynamic setting of an oceanic triple point bounded by the Azores-Gibraltar transfer zone and the Atlantic ridge. Hence, the rift evolution of the margin was controlled by the E-W to NW-SE continental extension, which resulted in an elaborate interplay of N-S to NNE-SSW normal and listric faults and basin-bounding transfer zones (some inherited from the Palaeozoic), revealing the oblique nature of extension in some areas of southwest Iberia.

As a result eight distinct unconformity bounded Megasequences with tectonostratigraphic and lithostratigraphic affinities can be identified, each defining 2$^{nd}$ order sequence stratigraphic cycles.

Onset of continental crust segmentation (Rift Phase I) initiated in the Late Triassic within a generalised wide rift mode extension throughout the West Tethys and the Central and North Atlantic. By this time the Iberian micro-plate was migrating to the northwest away from northern Africa. The interplay between rift extension and plate migration resulted in the formation of several distinct basins, which accommodated unconformable Carnian to Norian continental siliciclastic red beds over the folded Palaeozoic metasediments (sequence 1a), later overlain by shales and evaporitic beds of Norian-Hettangian age (sequence 1b).

A new phase of extension (Rift Phase II, Hettangian-Callovian) reveals the substantial Central Atlantic controls on the evolution of the SW Iberian margin, not only by the occurrence of earliest Jurassic magmatic activity of the Central Atlantic Magmatic Province (CAMP), but also by the inception of marine deposition, dominantly characterised by the formation of retrograding dolomites and limestones. Such deposits include on the proximal margin the formation of a widespread carbonate ramp. Seismostratigraphic units and burial history models reveal that tectonic subsidence was significant on the outer proximal and distal margin, which allowed the formation of thick growth strata during the Sinemurian-Pliensbachian Rift Climax (sequence 2a). During the Toarcian-Aalenian deposition was disrupted in the proximal margin resulting in the formation of a durable hiatus. This event is interpreted to represent the rift shoulder effect of the coeval and synchronous continental breakup at the northern Morocco-Nova Scotia conjugate margin, from where similar tectono-stratigraphic evolution is recorded (e.g. Sable Basin, Nova Scotia). Deposition resumed on the proximal margin by the Bajocian (sequence 2b), with the deposition of a widespread retrograding carbonate ramp revealing a Late Rift pulse with limited tectonic subsidence and the increased control of eustasy in deposition. Locally rimmed carbonate build-ups can be identified, revealing the progressive variations of the base level. Ultimately, the progressive infill of the margin is marked by a widespread unconformity of Callovian-Oxfordian age.

The last phase of extension recorded in the SW Iberian margin (Syn-Rift III), occurs from the late Callovian to the earliest Cretaceous (Berriasian?). This phase is broadly synchronous to the extension occurring in northwest Iberia, Newfoundland or the North Sea. It is mainly expressed on the outer proximal and distal margin by the formation of thick growth strata (Megasequence 3), depicting the transition to seafloor spreading west of the Tagus Abyssal

Plain. Rift Initiation retrogradational strata are identified since the latest Callovian, progressively recording the final phase of continental extension with its paroxysmal maxima (the Oxfordian-Early Kimmeridgian the Rift Climax) that resulted in the formation of a Maximum Flooding Surface. From the Kimmeridgian to the Tithonian (Berriasian?) reduced subsidence throughout the margin records a Late Rift pulse, marked at the top by a widespread unconformity interpreted to depict the end of continental extension. In contrast, rift subsidence continues in the northern distal basins of the West Iberian margin (Peniche, Porto and Galicia) until the Aptian-Albian.

Megasequence 4 (Berriasian-Aptian) is characterised by generalised progradation of siliciclastics towards the distal margin, which is interpreted as the result of relative tectonic quiescence and limited uplift subsequent to seafloor spreading, later overlain by siliciclastics and limestones of Albian to Campanian (?) age (Megasequence 5).

By the latest Cretaceous significant uplift of the proximal margin, associated with generalised magmatism and the initiation of the counter-clockwise rotation of Iberia, the first evidences of inversion and shortening are recorded. This interval, likely extending into the early Paleogene is also characterised by widespread and intense erosion on the proximal margin and voluminous bypass of sediment towards the distal margin.

From this period onwards, eastwards migration of the Iberian plate and its collision with North Africa, results in generalised deformation and shortening, which affects dissimilarly and diachronically the distinct sectors of the margin and largely affects the Cenozoic deposition on the continental margin. Shortening of the margin is not only controlled by the reactivation of a deep continental crust detachment, but also by the distinct rheological behaviour of inherited growth strata and the fragmented continental crust, that resulted in the reactivation of rift-related faults, revealing localised thin-skin and thick-skinned tectonics.

Cenozoic deposition thus comprises three discrete Megasequences (6, 7 and 8) bounded by two main unconformities denoting the major pulses of shortening throughout the margin, namely during the middle Eocene and the Oligo-Miocene. Deposition in these intervals is characterised not only by the extensive accumulation of deep-water contourites or turbidites off the continental shelf, but also by the noticeable incision of canyons (e.g. the São Vicente Canyon).

In the south, the offshore segment of the Messejana-Plasencia Fault Zone is revealed as a first-order transfer zone, bounding the southern limit the SW Iberian margin and a major hinge zone also controlling the incision of the São Vicente Canyon. During the rift phase this major strike-slip zone initially acted as a dextral releasing bend with the formation of thick growth strata and was later reactivated as a left-lateral transpressional segment. This segment is therefore a critical area to understand the palaeogeographic evolution of the southernmost North Atlantic and how deformation was accommodated during the rift-to-drift transition of the margin.

**References**

Manatschal, G. 2004. New models for evolution of magma-poor rifted margins based on a review of data and concepts from West Iberia and the Alps. *International Journal of Earth Sciences,* **93**(3), 432-466.

Tucholke, B.E., Sawyer, D.S. & Sibuet, J.-C. 2007. Breakup of the Newfoundland Iberia rift. *In:* Karner, G.D., Manatschal, G. & Pinheiro, L.M. (eds*). Imaging, Mapping and Modelling Continental Lithosphere Extension and Breakup.* Geological Society London, Special Publications, **282**, 9–46.

## SIGNIFICANCE OF THE "OUTER MARGINAL DETACHMENT" (OMD) IN RIFTING: SEISMIC EXAMPLES FROM FLORIDA AND AROUND THE WORLD

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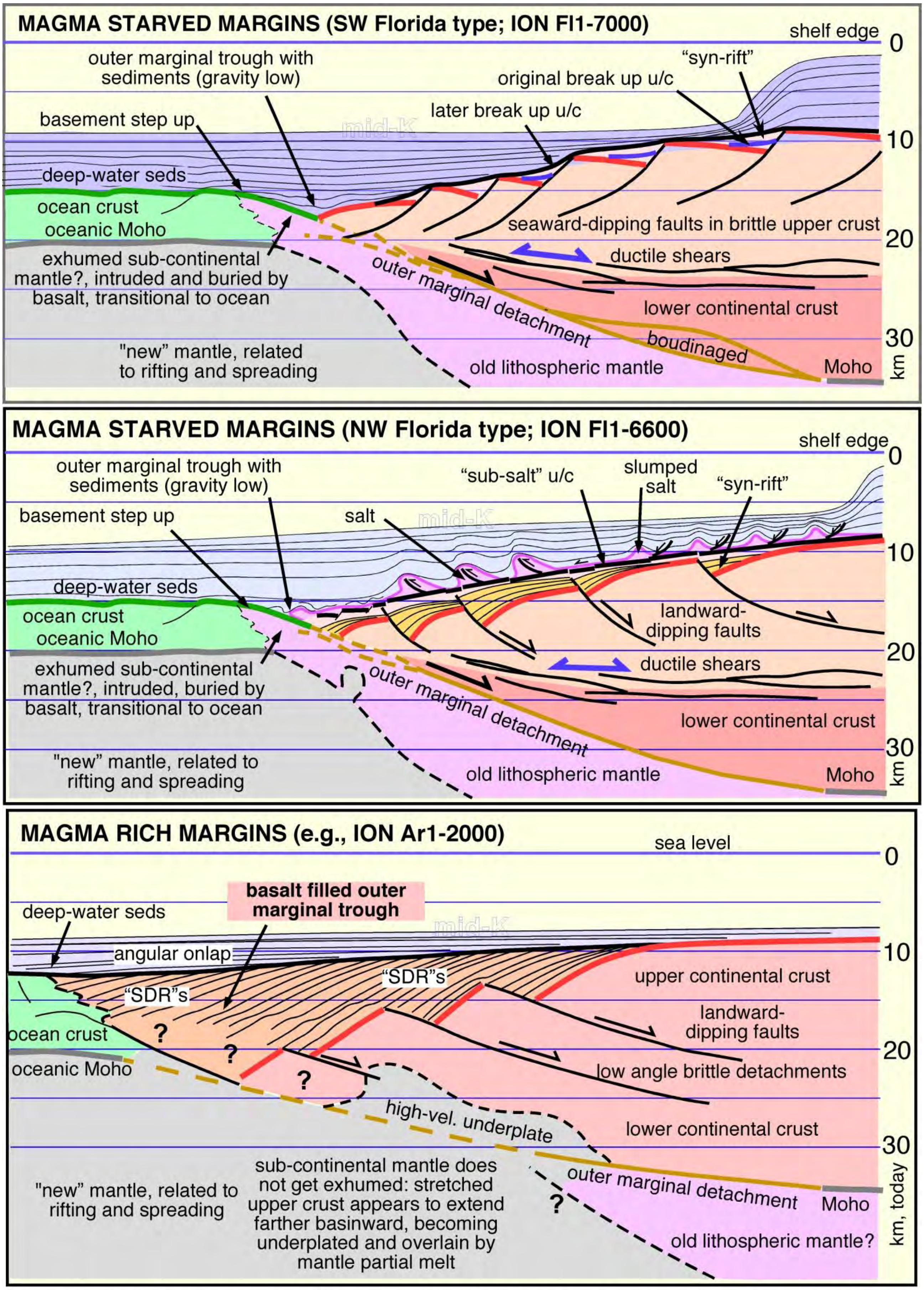
Recent analysis of ION long-offset seismic reflection data over the western Florida shelf/slope provides new insights for GoM rifting. In Florida, evolutionary interpretation benefits from (1) presence of Jurassic salt, thereby constraining palaeo-water depth; (2) ocean crust (or exhumed mantle) outside the continent-ocean transition whose backstrip indicates accretion at >2km below sea level; and (3) relative lack of post-rift sedimentary overburden, allowing good visualisation of basement. The "northern" and "southern" segments of west Florida (see upper and middle figures) have different basement structures. In the north, landward dipping faults frame half grabens filled with volcanics/red beds overlain by a nearly planar but basinward dipping sub-salt unconformity that is overlain by a slumped salt section that was originally ~1 km thick. In the south, faults dip basinward and no salt or volcanics are observed. A boundary between the two is not recorded in the data set, but we suspect that rifting in the southern segment was sufficiently younger, due to SE-ward rift propagation, so as to postdate most of the volcanism and salt deposition seen in the north. Both the sub-salt unconformity (and salt) in the north, and the post-rift unconformity in the south, are buried with little change in depth by the same sequences that define the basal cover on the deep water ocean crust/mantle. Thus the outer margins had subsided to oceanic depths immediately after subaerial erosion and DURING salt deposition. At depth in both segments, middle and lower crustal reflectors are cut by a landward dipping surface that reaches continental Moho and rises to the top of exhumed mantle/ocean crust at the continent-ocean transition (COT). We interpret this as a primary shear zone that allowed detachment of the continental crust off the rising plastic mantle welt at the end of the rifting process, and call it the "Outer Marginal Detachment", or OMD. The paucity of faulting in the sub-salt unconformity shows that the OMD carried the majority (>90%?) of extension during the rift-drift transition. Motion on the OMD was responsible for the rapid collapse and basinward tilting of the outer margin (2-3 km at the COT) in a mega-half graben geometry (called here the "Outer Marginal Trough"), which triggered down-slope salt migration and established deep-water conditions as seafloor spreading began. The rate of this change cannot be explained by thermal subsidence, requiring a tectonic mechanism that we identify as normal detachment faulting facilitated by serpentinisation (at shallow level) and ductile shear (at depth) along the OMD. Such shear represents the primary means by which continents are sloughed off of rising plastic mantle material during rifting. We believe rapid (sub-faunal zonation), large (2 km) drowning of "breakup" unconformities recorded in various stratigraphic successions such as the Alps, where abyssal radiolarites rest depositionally on subaerial beds, is controlled by this process. ION-GXT seismic data appear to provide the explanation for how that rapid subsidence occurs. Exploiting the Florida example, ION-GXT data from around the world were examined to test, refine, or generalise these concepts (Brazil, W and E Africa, Greenland, India, Arctic, Australia), showing general confirmation, allowing for added complexities from volcanism and late brittle faults that can cut the OMD at some margins. A major and perhaps defining difference in magma-starved vs. magma rich margins seems to be that the Outer Marginal Troughs of the latter are filled with SDRs/basalt flows (see following figure).




Pindell, Graham, and Horn, Dublin Conjugate Margins Meeting, 2012

## CRETACEOUS BASEMENT TECTONICS OF NOVA SCOTIA: WHAT WAS THE DRIVER?

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Early Cretaceous tectonic deformation of Nova Scotia and the basement rocks of the Scotian Basin is recognised from fault offsets, basin subsidence and syn-sedimentary tectonic deformation. It is likely correlative with evidence in New England for differential uplift and rotation of crustal blocks determined from thermochronological data and from the US Atlantic Coastal Plain where reverse faults offset Cretaceous strata. Three possible causes of this deformation are evaluated: it is possible that all three played a role.

1. Ridge push from the spreading Atlantic Ocean and particularly from the elevated J-Anomaly ridge of Barremian age.

2. Propagation of rifting forces related to the extension of Iberia from the Grand Banks.

3. Propagation of rifting forces related to the extension of Labrador from Greenland.

The Valanginian–Albian Chaswood Formation accumulated in fault-bound basins and shows syn-sedimentary fault deformation along predominant NE-trending faults, many of which are re-activated late Palaeozoic structures. Structural style suggests a component of strike-slip deformation along these faults. The work of Baum *et al.* (2008) on the inversion of the Fundy Basin, which is arguably correlative with the Chaswood Formation, demonstrates NNE-directed shortening. NE-trending transfer faults are characteristic of the rifting of the Labrador margin, which based on ages on volcanic rocks started in the Valanginian (Dickie *et al.,* 2011). Direct evidence of continuity of the Humber Fault and of a fault system to the northwest is provided by the presence of fresh detrital zircons from the Makkovik province in Lower Cretaceous sandstones of the Scotian Basin. Mass-balance calculations on the abundance of fresh Grenvillian zircons in the Scotian Basin sandstones suggest that the Long Range inlier is not a sufficient source and that significant amounts of sediment were derived from the rift shoulder of southern Labrador. Thus in chronology of deformation, sediment supply and orientation of fault motion, there appears to be a link between formation of Chaswood basins and intervening horsts and the early rifting of the Labrador Sea.

On the Grand Banks, Early Cretaceous extension, resulting from the separation of Iberia, was concentrated in three episodes that culminated near the end of Berriasian, Hauterivian and Aptian time (Tucholke *et al.,* 2007). The first two episodes were correlated by these authors with step-wise opening of the rift from south to north and the third with exhumation of sub-continental mantle lithosphere at the plate boundary, culminating in the onset of sea-floor spreading at the Aptian-Albian boundary. Regional unconformities in the Berriasian, mid Hauterivian, and at the end of the Aptian are recognised in the Scotian Basin (OETR 2011) and unconformities of similar age can be traced along the margin of the basin from Orpheus graben to the southwestern Grand Banks (Bowman, 2010). Biostratigraphic data are insufficient to prove that unconformities within the Chaswood Formation are correlative with these regional unconformities, but a correlation appears probable. The style of deformation of the Chaswood Formation and the NNE directed shortening of Baum *et al.* (2008) are not obviously related to the rifting of Iberia from the Grand Banks. However, the termination of major deformation in the Chaswood Formation and at the margin of the Scotian Basin correlates with the onset of sea-floor spreading between Iberia and the Grand Banks. With the apparent complexity of the impacts of Grand Banks and Labrador rifting, it is difficult to independently recognise any effects in the Barremian from ridge push from the J-anomaly Ridge.

**References**

Baum, M.S., Withjack, M.O. & Schlische, R.W. 2008. The ins and outs of buttress folds: Examples from the inverted Fundy Rift Basin, Nova Scotia and New Brunswick, Canada. *Central Atlantic Conjugate Margins Conference, Halifax 2008*, Extended Abstracts, 53–61.

Bowman S.J. 2010. Cretaceous tectonism and volcanism in the eastern Scotian Basin, offshore Nova Scotia. *M.Sc. thesis, Saint Mary's University, Halifax, N.S*.

Dickie, K., Keen, C.E., Williams, G.L. & Dehler, S.A. 2011. Tectonostratigraphic evolution of the Labrador margin, Atlantic Canada. *Marine and Petroleum Geology,* **28**, 1663-1675.

OETR (Offshore Energy Technical Research Association) 2011. *Play Fairway Analysis Atlas - Offshore Nova Scotia*. Nova Scotia Department of Energy Report 88-11-0004-01, 349p. Also available online at: http://www.novascotiaoffshore.com/analysis

Tucholke, B.E., Sawyer, D.S. & Sibuet, J.-C. 2007. Breakup of the Newfoundland-Iberia rift. *In:* Karner, G.D., Manatschal, G. & Pinheiro, L.M. (eds). *Imaging, Mapping and Modelling Continental Lithosphere Extension and Breakup.* Geological Society London, Special Publications, **282**, 9-46.

## CONTINENTAL BREAKUP AND THE FORMATION OF CONJUGATE MAGMA-POOR MARGINS IN NORTH ATLANTIC: MECHANISM, SYMMETRY AND THE EXTENSION DISCREPANCY

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Conjugate rifted margins form by the rifting, extension and eventual breakup of the continents. As a result, the structure of conjugate rifted margins reflects the long history of rifting and extension from initial rifting through to final crustal and lithospheric separation and the onset of seafloor spreading. We investigate the progressive development of such systems based on our understanding of the evolving rheology of the continental lithosphere as it is extended and thinned, on seismic reflection images particularly from the Porcupine Basin and the west Iberia margin, and on a synthesis of data from all North Atlantic magma poor margins and marginal rifts. In particular we focus on the role of polyphase faulting, detachment faults and serpentinisation in the extension leading of breakup.

The Porcupine Basin is an ideal place to study the evolution of conjugate margins, as the crust has in places been thinned to at most 2-3 km, i.e. on the point of breakup, and yet both margins can be imaged by single continuous seismic profiles. We have interpreted depth images of six transects that cross the basin at different latitudes where the axial crustal stretching factor increases from ~ 5 in the north to ~ 15 in the south. The images document the initiation, development and abandonment of the "P" detachment fault, overlain by crustal fault blocks. The P detachment is first evident at latitudes where axial stretching factors reach ~ 10. Here P cuts down from the eastern margin of the basin, beneath the Porcupine Arch, rooting to the west beneath the Porcupine Bank. As extension increases further to the south, P appears to be cut by steeper faults, indicating that the detachment was only one phase in the evolution of the extensional system.

The truncation of detachments by later steep faults is also inferred from studies of the extensional systems preserved in the Alps, and from seismic images to the west of Iberia. There, the S and H detachments can be shown (Reston and McDermott, 2011) to be cut by later west-dipping faults that accommodated the final separation of the crust and led to the exhumation of partially serpentinised peridotites (Figure 1). The west-dipping root zone of P, S and H are thus abandoned under the Porcupine Bank, Flemish Cap and Newfoundland Basin margins respectively. With increasing separation, successive detachments cut across the footwall of earlier ones, leading to the unroofing of a broad expanse of mantle (Reston & McDermott, 2011).

However, a remaining puzzle is how the crust is thinned from ~ 30 km to ~2 km prior to final crustal separation and mantle exhumation. Depth-dependent thinning can be ruled out as there is nowhere the missing crust can have gone, no evidence from the crustal velocity structure for any excess thinning of the lower crust, and plenty of evidence from ODP drilling for the presence of upper and lower crustal rocks within the continent-ocean transition zone. Instead the question focuses on how the crust can be thinned dramatically but the thinning not be imaged on seismic data. Two mechanisms have been proposed: polyphase faulting in which multiple generations of faults produce complex geometries that cannot be fully resolved on the seismic images (Reston, 2005), and sequential faulting (RPG - Ranero and Perez-Gussinye, 2010) in which extension is accommodated on a single faults which rotate to lower angles, are abandoned and replaced sequentially by new faults that form in their hangingwall. However, as all the faults are imaged in the RPG model, restoration of the movement of those faults should lead to a successful reconstruction of the margin. Reconstructions of four transects across the West Iberia margin show that the sequential faulting model does not explain the formation of these margins (Figure 2), and requires rather that not all the faulting are fully resolved. By identifying subtle evidence for earlier, dismembered faults, we are able to fully reconstruct these margins and demonstrate that polyphase faulting took place.

**References**

Ranero, C.R. & Perez-Gussinye, M. 2010. Sequential faulting explains the asymmetry and extension discrepancy of conjugate margins. *Nature*, **468**, 294-299

Reston, T.J. 2005. Polyphase faulting during the development of the west Galicia rifted margin. *Earth and Planetary Science Letters*, **237**, 561-576

Reston, T.J. & McDermott, K. 2011. Successive detachment faults and mantle unroofing at magma-poor rifted margins. *Geology*, **39,** 1071-1074

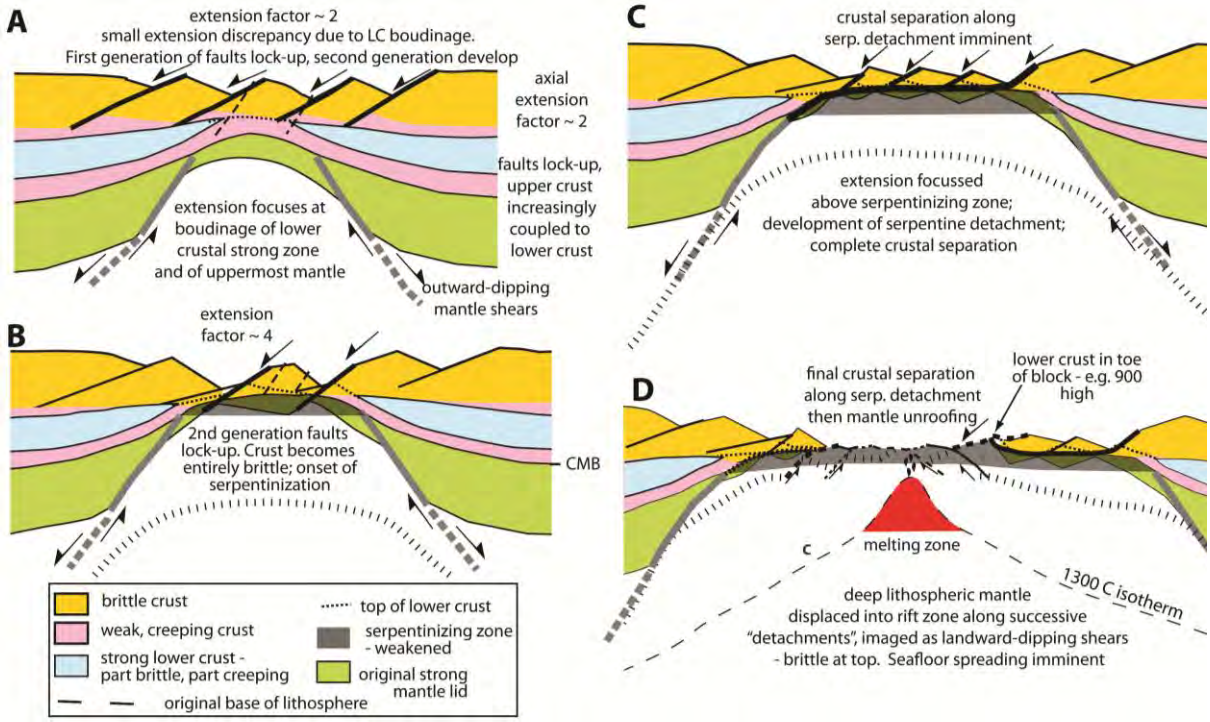


***Figure 1:*** *A: Initial lithospheric extension by ~100% ($\beta$ of 2). Rift focuses above axis of mantle thinning: polyphase faulting in the crust thins this to less than a quarter of its original thickness, until the entire crust is brittle. (B). Crustal embrittlement allows the passage of water to the mantle, forming weak serpentinites at the base of the thinned crust (B, C), and the development of serpentine detachment (C) as observed west of Iberia (S, H) and in the Porcupine Basin (P). D: The serpentine detachment is cut by later faults that allow crustal separation, and mantle exhumation: subsequent detachments produce a wide region unroofing of mantle rocks within the COT (Reston and McDermott, 2011).*

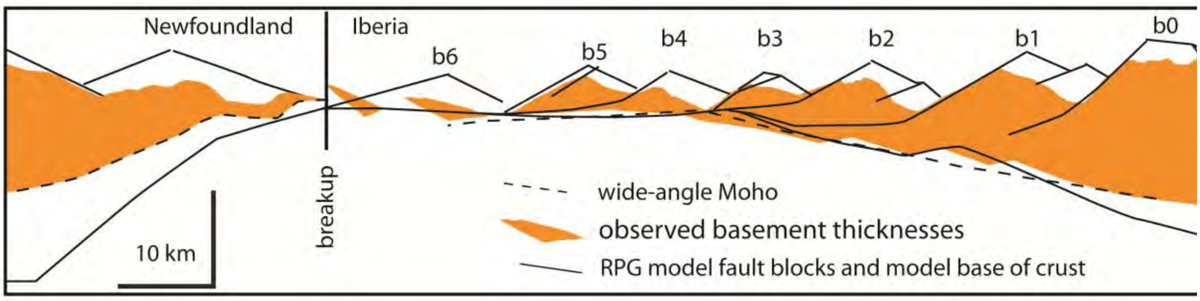


***Figure 2:*** *Comparison between the seismic structure of the Galicia-Flemish Cap conjugate margin pair (shaded blocks, in general agreement with the wide-angle Moho) and the predictions (outline) and of the sequential faulting RPG model (Ranero & Perez-Gussinye, 2010). The crustal basement thickness predicted by the model is on average ~ twice that observed. As the crust thins towards zero close to the line of breakup, the discrepancy is even greater. The RPG model does not explain the observed crustal thinning.*

## THE THERMAL HISTORY OF THE MESOZOIC ALGARVE BASIN (SOUTH PORTUGAL) AND ITS IMPLICATIONS FOR HYDROCARBON EXPLORATION

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The Algarve Basin is the southernmost geological province of mainland Portugal, outcropping along the entire south coast area and extending offshore, where it is recognised on seismic lines and in hydrocarbon exploration wells. It mainly comprises Jurassic and Lower Cretaceous limestones and marls making a succession over 3 km thick. This sedimentary basin belongs to a series of basins that were initiated by rifting associated with the opening of the North and Central Atlantic Ocean, following the breakup of Pangaea.

Sedimentation in the Algarve Basin commenced with Upper Triassic continental red beds and evaporites which unconformably overlie folded and faulted Carboniferous strata. These strata are overlain by Early Jurassic (Hettangian) volcanic rocks associated with the Central Atlantic Magmatic Province (CAMP). After this important magmatic episode, Sinemurian to Tithonian marine carbonate sedimentation became well-established across the Algarve Basin. During this period, lateral facies changes observed in the limestone lithologies across the basin allow its division into the Western (Sagres), the Budens-Lagoa, and the Eastern (Faro) sub-basins. These sub-basins are separated by major north-south trending faults, which were probably active during deposition.

Three main sedimentary cycles separated by regional unconformities are recognised in the Sinemurian to Tithonian marine carbonates. These cycles consist mainly of shallow water limestones, sometimes with reef facies and alternations of marls with pelagic limestones, which are related to sea level variations or regional tectonic events. The first cycle extends from the Sinemurian to early Toarcian, the second from the Aalenian to Callovian and the third from the mid Oxfordian to Tithonian.

The Lower Cretaceous is represented by a carbonate and siliciclastic succession, deposited in nearshore and continental settings. During the Late Cretaceous a major uplift episode occurred, related to Alpine tectonism and the emplacement of the Late Cretaceous (Campanian, ca. 72 Ma) syenite of Monchique. Therefore, no Upper Cretaceous to Palaeogene strata are found in the exhumed Algarve Basin. After this event, sedimentation only resumed during the Miocene, with bioclastic limestones and silts which unconformably overlie the Jurassic and Lower Cretaceous succession.

Investigation of almost 200 samples of mudrocks and marls by means of vitrinite reflectance, spore fluorescence and colour, indicates that the Mesozoic stratigraphic succession of the Algarve Basin is within the oil-window. Vitrinite reflectance values increase with the age of the sedimentary rocks from: 1 – 1.2%$R_r$ in the top Triassic – Hettangian, 0.8 – 0.9%$R_r$ in the Middle Jurassic, 0.7 – 0.9%$R_r$ in the Upper Jurassic and 0.5 – 0.6%$R_r$ in the Lower Cretaceous. These results suggest that subsidence under normal burial conditions was the main mechanism of organic maturation.

Four maturation profiles ($R_r$ *vs*. depth) were constructed across the basin for the Sagres – Lagos, Albufeira, Faro and Tavira regions. These profiles are linear with good correlation factors. Palaeogeothermal gradients ranging from 23.5 – 39°C/km were calculated for the eastern sub-basin, whereas a higher palaeogeothermal gradient of 62°C/km was calculated for the western sub-basin. The palaeogeothermal gradients indicate that a 2.2 – 2.7 km thick succession of post-Aptian age in the eastern sub-basin, and a 1.22 km thick succession of post Albian age, was necessary to account for the measured maturation levels. The most likely age for this eroded sedimentary cover is Upper Cretaceous – Lower Tertiary, suggesting that sedimentation in the Algarve Basin continued through this time period and did not end in the early Cretaceous. Upper Cretaceous to Lower Tertiary sediments could be preserved in non-inverted or less exhumed areas located in the offshore part of the basin. The offshore Mesozoic succession penetrated by the Ruivo and Corvina wells is also within the oil-window.

The organic maturation results from the Miocene sediments in the Tavira region (Cacela) and in the offshore Ruivo and Corvina wells, indicates that this part of the succession is immature regarding the oil-window, with vitrinite reflectance ranging from 0.3 to 0.45%$R_r$. The presence of reworked vitrinite and Mesozoic palynomorphs in the Miocene sediments with organic maturation levels which match the levels measured for the onshore Upper Jurassic – Lower Cretaceous sediments is significant. This implies that part of the Mesozoic succession of the Algarve Basin was exposed and being eroded during Miocene times and it also constrains the timing of the maturation for the Mesozoic succession to the Late Cretaceous – Early Tertiary interval.

Further evidence of the timing of the maturation is provided by the maturation levels of the diapirs in Loulé and Albufeira and the adjacent sedimentary rocks. The age of the evaporites in the two diapirs is Hettangian. In Loulé a value of *ca.* 1.1%$R_r$ was measured in clay rich beds within the diapir, whereas values of *ca.* 0.7 – 0.8%$R_r$ were obtained from for Late Upper Jurassic beds intruded by the evaporites. In Albufeira, the movements of the evaporites tilted the Late Jurassic and Early Cretaceous beds closed to the diapir walls to vertical. A value of 1.13%$R_r$ was measured for the diapir and a value of 0.6%$R_r$ was measured for the vertical Early Cretaceous beds close to the diapir wall. This implies that peak temperatures related to the maturation levels in the Algarve Basin were achieved prior to the salt movements of both diapirs, probably during Late Cretaceous (Early Tertiary?) times.

## PLATE KINEMATICS OF THE BAY OF BISCAY

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Parameters of plate kinematics based on well-recognised magnetic anomalies allow to calculate stage poles between them and to describe the relative motions between plates. If kinematic phases are short, they may coincide with geological phases. If longer, they may integrate several geological phases. In the Bay of Biscay and Pyrenean domain, kinematic reconstructions were proposed at M25 (Kimmeridgian), M0 (Late Barremian) and C34 (Santonian) (Sibuet *et al.,* 2004). The motion is extensional from Kimmeridgian to Late Barremian as also shown by the geology. However, due to the lack of recognised magnetic lineations during the Quiet Magnetic period (M0-C34) the Iberia/Eurasia (IB/EU) motion in the Pyrenean domain was convergent for a ~40 Ma time period (Sibuet *et al.* 2004). However, we know that extensional tectonics occurred during most of this period. In this paper we propose to show from a new kinematic work that extension took place in the Pyrenean domain from Kimmeridgian to Santonian (M25-C34), except for a very short period of time restricted to the Bedoulian (early Aptian), eventually during the whole Aptian.

### Reference

Sibuet, J.-C., Srivastava, S. & Spakman, W. 2004. Pyrenean orogeny and plate kinematics. *Journal of Geophysical Research*, B08104, doi:10.1029/2003JB002514.

# The Lithospheric breakup Surface and the breakup sequence: the Syn- to Post-Rift Transition on the West Iberian Margin - Newfoundland

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A comprehensive set of 2D seismic reflection lines from proximal and distal margin settings, borehole data from Industry wells, and DSDP/ODP, are used to characterise the Late Aptian Earliest Albian syn- to post-rift transition in Northwest Iberia (Porto Basin, Peniche Basin and Iberian Abyssal Plain) and Newfoundland (East Canada) (Figure 1). At the time of continental lithospheric breakup, the Porto and Peniche basins were the active marginal depocentres of the crustal segment where distally DSDP leg 47b and ODP legs 103, 149 and 173 were drilled (Alves *et al.,* 2006). Previous studies showed that continental rifting on these two margins comprised two phases of lithospheric extension, (1) extension on the continental crust followed by (2) continental upper mantle exhumation, extension on the distal margin and eventually complete lithospheric breakup occurring during the transition Aptian-Albian (*e.g.* Boillot *et al.,* 1987). This phased process was responsible for a basinward migration of the extensional locus as continental breakup evolved, reducing tectonic subsidence rates observed in proximal areas after upper mantle exhumation.

The interpreted data highlight the development of a basin-wide surface at the time of complete continental lithospheric breakup, usually called *"breakup unconformity"* (*sensu* Falvey, 1974). We rename it as lithospheric breakup surface (LBS), since it is generated by the complete rupture of the continental lithosphere and not merely the continental crust and it is not developed as an unconformity throughout all rift-related basins on the proximal, outer proximal and distal margins. The LBS character changes across the margin, from a diastem or a correlative conformity in distal settings to a basal surface of forced regression in proximal settings and landward it becomes a composite subaerial erosional surface since it merges with previously existent subaerial erosion surfaces.

Important architectural depositional changes occur across the LBS in association with the Late Aptian lithospheric breakup event, promoting the deposition of a breakup sequence (BS). Ranging from the uppermost Aptian to Cenomanian, in Porto Basin the BS include: i) a basal forced regressive Unit 1 (Aptian(?)-Albian), prograding to the shelf edge and generating a hiatus landwards; ii) a transgressive Unit 2 topping the forced regressive package, with carbonates materialising a maximum transgressive surface; iii) an Albian-Cenomanian (Unit 3) showing predominant aggradation. Unit 4, transgressive, tops the BS, reflecting the complete establishment of a passive margin in a transgressive regime. In more distal environments (Iberia Abyssal Plain) is observed a sudden change from episodic mass wasting to hemipelagic deposition with a strong continental influence (black shales). The BS is therefore the expression of the breakup event *per se*, triggering its deposition during the interval between the breakup event and the final establishment of the post-breakup thermal relaxation as the major cause of subsidence in passive margins.

The differences in character that both the LBS and the BS display from the proximal to the distal parts of the margin derive from changes in the way that the sedimentation controlling factors, such as palaeodepth, distance from sediment source, palaeotopography and the position relatively to the extensional locus and tectonic style affected the LBS development and the deposition of the BS.

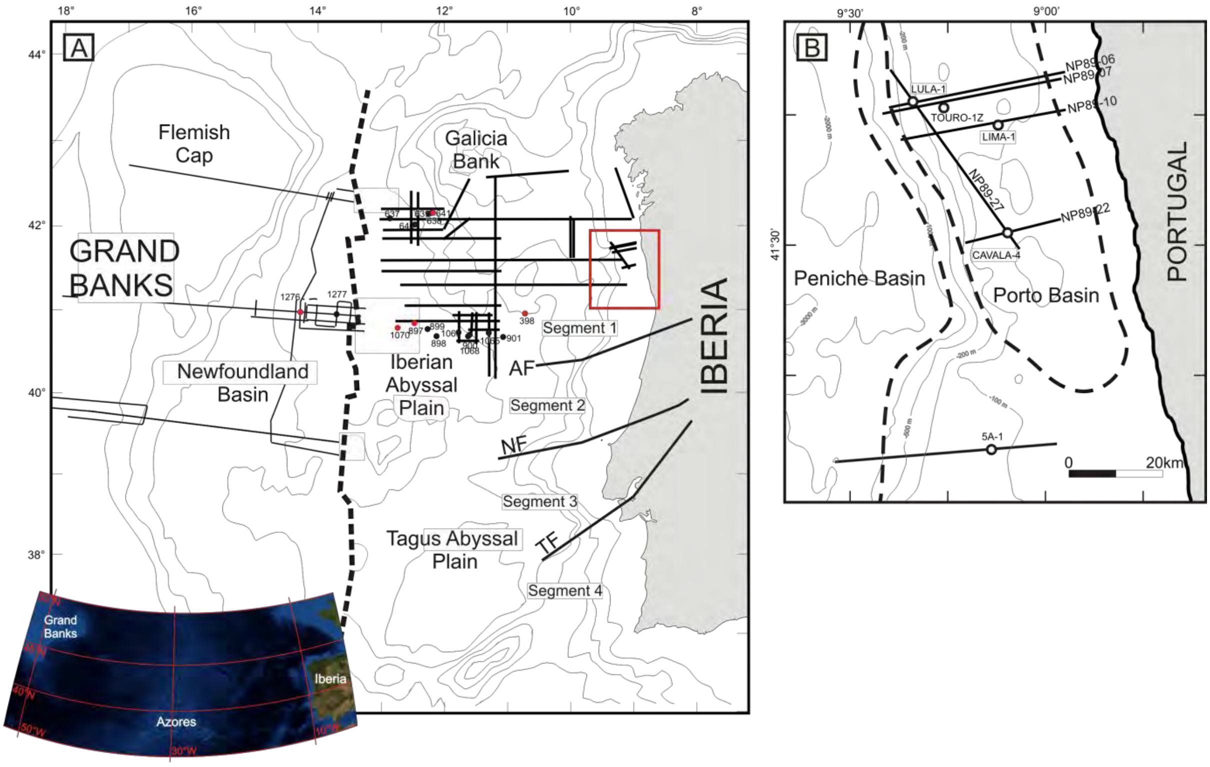


***Figure 1:*** *Maps showing the location of the study area and data sets used in this study. A: Reconstruction of the Iberia-Newfoundland rift margins at chron M0 (~125Ma) before lithospheric* breakup *(after Srivastava et al., 2000 with the Iberian plate fixed relatively to its present geographic coordinates). DSDP/ODP sites are shown in the image, with red circles indicating the sites where Lithospheric* breakup *surface was cored. Seismic data from the Grand Banks region is taken from SCREECH (Shipley et al., 2005) whilst seismic data from NW Iberia is from ISE 97 . AF - Aveiro fault; NF - Nazaré fault; TF - Tejo fault. Area in red indicates the position of B. Inset: present day position of the conjugate margins. B: Location proximal margin key seismic lines and industry boreholes used in this study.*

## References

Alves, T.M., Moita, C., Cunha, T., Monteiro, J.H. & Pinheiro, L. 2006. Meso-Cenozoic Evolution of North-Atlantic Continental Slope Basins: The Peniche Basin, Western Iberian Margin. *American Association of Petroleum Geologists Bulletin* **90**, 31-60.

Boillot, G., Recq, M., Winterer, E.L., Meyer, A.W., Applegate, J., Baltuck, M., Bergen, J.A., Comas, M.C., Davies, T.A., Dunham, K., Evans, C.A., Girardeau, J., Goldberg, G., Haggerty, J., Jansa, L.F., Johnson, J.A., Kasahara, J., Loreau, J.P., Luna-Sierra, E., Moullade, M., Ogg, J., Sarti, M., Thurow, J. & Williamson, M. 1987. Tectonic denudation of the upper mantle along passive margins: a model based on drilling results (ODP leg 103, western Galicia margin, Spain). *Tectonophysics* **132**, 335-342.

Falvey, D.A. 1974. The development of continental margins in plate tectonic theory. *Journal of Australian Petroleum Exploration Association* **14**, 95-106.

## NEW INSIGHTS INTO THE REGIONAL MESOZOIC AND CENOZOIC EVOLUTION OF THE IRISH OFFSHORE CONTINENTAL MARGIN

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### Introduction

Extensive Mesozoic and Cenozoic strata of variable thicknesses are preserved in offshore sedimentary basins along the Irish continental margin. Legacy seismic data, largely of 1980s and 1990s vintage, are characterised by generally poor seismic resolution below the Base Cretaceous level. Recent 2D high-resolution deep seismic reflection data provide improved data quality below Early Cenozoic lavas, show good seismic resolution beneath the Cretaceous and image Jurassic and older tilted fault blocks. As a result, the data reveal new details on the structural and sedimentological evolution of the Porcupine, Rockall, Hatton and Goban Spur regions.

### Results

Jurassic strata in the Rockall and the Porcupine basins were deposited during a syn-rift phase, now preserved in tilted fault blocks with divergent and parallel-bedded seismic reflectors. The interpretation suggests variable preservation of Jurassic strata in the studied basins. In the Porcupine Basin, erosional remnants of Middle and Upper Jurassic successions are commonly preserved in the deepest part of the basin, ranging in thickness from c. 1 to 5.5 km. In contrast, Lower to Upper Jurassic strata in the Rockall Basin are primarily identified along the basin margins (up to 2 km thick) but are only locally interpreted as undifferentiated Jurassic succession in the central part of the basin (max. of 1 km thick). The variability in the location and presence of Jurassic strata in the Rockall and Porcupine basins may reflect different stages of basin development between the basins, with the Porcupine Basin being a relatively wide rifted basin by Middle to Upper Jurassic times, whereas the Rockall Basin was still narrow at this time. Alternatively, these variations may be the result of different amounts and styles of extension during latest Jurassic/Early Cretaceous rifting. In the Goban Spur region, the Jurassic succession thins to the west: an inner catenary-shaped c. 55 km wide basin consists of up to 3 km thick Lower to Middle Jurassic strata whereas two outer 20-30 km wide half-grabens contain a Jurassic succession that is thin (max of c. 1 km) or absent. A similar situation is interpreted along the northern Galicia margin with interpreted thick Jurassic strata preserved in the Galicia Interior Basin and thin or absent Jurassic successions along the outer part of the continental margin.

In contrast to the Jurassic syn-rift phase, the Cretaceous interval is traditionally viewed as a post-rift sequence. However, the regional Lower Cretaceous stratal geometries are not consistent with a simple post-rift subsidence model and suggest instead a combination of fault-controlled and thermal subsidence during Early Cretaceous times. For example, the interpretation suggests that the Aptian/Albian strata were deposited in fault-controlled depocentres along the margins of the Hatton Basin. In the central and northern parts of the Porcupine Basin, Lower Cretaceous (Hauterivian – Barremian) strata were deposited in a series of restricted marine basins. The shapes of these basins were controlled by syn-sedimentary faults and pre-existing Jurassic palaeotopography. These basins are overlain by sheet or drape-like Aptian and Albian strata which passively infill earliest Cretaceous palaeotopography. The southern part of the Porcupine Basin and the Goban Spur region show contrasting Albian and Aptian stratal geometries. These thick successions are usually preserved in fault-controlled depocentres and show growth faulting. Hence, Early Cretaceous rifting was still active in the southern part of the studied region (unlike the northern part of the

Porcupine Basin) and was coeval with the onset of sea floor spreading at Goban Spur margin.

The Rockall and Porcupine basins show similar Upper Cretaceous stratal geometries. They overstep Lower Cretaceous depocentres, are largely unfaulted, and are interpreted to reflect a stage of thermal basin subsidence. However, the new data provide evidence of a latest Cretaceous inversion phase, well illustrated above a late Palaeozoic to Jurassic horst complex located in the southwestern end of the Porcupine Basin. A similar timing of inversion is interpreted in the southeastern Hatton Basin, where an inverted Cretaceous succession is onlapped by Paleocene basalt. A subsequent latest Eocene/Early Oligocene inversion episode occurred in the southwestern Porcupine Basin and possibly in the central part of the Rockall Basin.

## Conclusions

The results of a new analysis of both recent and older 2D seismic data contributed to constraining the timing of, and structures resulting, from tectonic events including Middle/Upper Jurassic and Early Cretaceous rifting, Late Cretaceous thermal subsidence and latest Cretaceous/Paleocene inversion. Erosional remnants of wedging or parallel-bedded Jurassic strata exhibit variable thicknesses (less than 1 to 5.5 km) and ages (Early to Late Jurassic) in the studied basins. Stratal geometries of Early Cretaceous successions reflect deposition during both fault-controlled and thermal subsidence. The rifting prevailed into Aptian/Albian times in the southern Porcupine Basin and the Goban Spur region. Late Cretaceous thermal subsidence uniformly affected all major offshore basins. The mechanism which caused the latest Cretaceous/Paleocene inversion phase in the southernmost part of the margin remains unclear while the latest Eocene / early Oligocene pulse is probably related to the Pyrenean Orogeny. In the Goban Spur region, the interpretation indicates two subsequent (Jurassic and Cretaceous) laterally offset rift phases. The locus of the rifting shifted progressively westwards through Cretaceous times, towards the final continental breakup site. A similar pattern is documented along the northern part of the Galicia margin, offshore Portugal. This suggests that the two margins (currently separated by the Bay of Biscay) may have had a similar development in Jurassic and Cretaceous times.

### Acknowledgements

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## THE IRISH ATLANTIC MARGIN: PETROLEUM SYSTEM ANALOGIES FROM THE UK CONTINENTAL SHELF AND ATLANTIC CONJUGATE MARGINS

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The Irish Atlantic margin is blessed with the luck of the Irish because it benefits from the presence of petroleum systems from two lucrative analogous areas: the UK continental shelf and the Atlantic conjugate margins. Thereby benefiting from comparisons to both established, mature regimes in the North Sea, Irish Sea and UK Onshore basins, but also from recent equatorial Atlantic conjugate successes and diverse North American margin plays. Such diversity of petroleum systems in the Irish sector illustrates the running room in the Atlantic margin of Ireland, an area that is vastly under explored. Very little drilling has taken place in the last 20 years in this region, with most exploration efforts focused on shallow water targets. The area has not benefited from modern 3D acquisition to de-risk targets that has matured exploration opportunities in other areas.

This presentation will give examples of these proven petroleum systems in the above areas and will present potential analogies in the Irish offshore. The presented analogies are from a wide variety of geologic timescales, reservoir types and trapping configurations. This will illustrate the diverse play potential of the Irish Atlantic margin. Specific examples from the margin will be used to show the potential of structures already identified, and how they closely relate to discoveries in known settings from the UK continental shelf, North American and equatorial Atlantic margins.

# REGIONAL VARIATIONS IN SOURCE ROCK MATURATION IN THE LUSITANIAN BASIN (PORTUGAL) – THE ROLE OF RIFT EVENTS, SUBSIDENCE, SEDIMENTATION RATE, UPLIFT AND EROSION

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The Lusitanian Basin developed in the Mesozoic in the western Iberia margin (Figures 2A and 2B) and comprises sediments from the Late Triassic to Cretaceous (Pena dos Reis *et al.,* 2010). Its evolution has close relations with the opening of the North Atlantic, as well as the opening and closure of the Western Tethys. Two main rift phases are classically considered, and have been used for modelling, in Late Triassic (229-199 Ma) and Late Jurassic (159-140 Ma). The total thickness of the Mesozoic infill is up to 5 km, mainly of Jurassic age, locally covered by Tertiary basins related with alpine inversion (Stapel *et al.,* 1996). Three sectors may be defined (North, Central and South), separated by major NE-SW faults - Nazaré and Tagus Valley. The Central sector presents the main depocenter of the basin, with three sub-basins (Turcifal, Bombarral and Arruda) developed in Upper Jurassic times.

The main intervals with hydrocarbon generating potential are Lower Jurassic (Água de Madeiros and Vale das Fontes Formations) and Upper Jurassic (Cabaços/Vale Verde Formation). The Upper Jurassic interval is geochemically more variable, but presents better TOCs and HIs basin-wide, with higher net thickness for hydrocarbon generation, than the Lower Jurassic units (*see* Teixeira, 2012).

Ten oil exploration wells have been analysed along the basin, regarding thickness and age of its sedimentary infill (Teixeira, 2012). Maturation evaluation was based in the PetroMod 1D software from IES Schlumberger (Figure 1). Backstripping of wells allowed to infer tectonic subsidence and to estimate stretching factors (Beta) of each of the two rift phases. Beta values were used to model heat flow in each rift phase. Sedimentation rates were evaluated, in order to identify large sedimentary input periods in the basin, associated with rifting phases.

For the first rift phase (Upper Triassic), stretching factors are higher in the northern sector (~1.05 – 1.18), as well as in the offshore and the Turcifal sub-basin of Central sector (~1.09 – 1.19). For the second rift phase (Upper Jurassic), stretching factors are higher in the Bombarral and Arruda sub-basins of the Central sector (~1.11 – 1.19) and in the Southern sector (~1.06 – 1.09).

According to PetroMod modelling (Teixeira, 2012), the main factor controlling and ruling the maturation evolution in the Lusitanian Basin is the heat flow increase, induced by the Late Triassic and Late Jurassic rift phases (Figure 1). Secondary factors, yet extremely important are: a) North sector - Cretaceous infill, prior to Aptian uplift and erosion; b) Central sector - high Upper Jurassic sedimentation rates, mainly induced by the sub-basins tectonics; c) South sector - high Cenozoic sedimentation rates, in times with low heat-flow, may explain maturation (more wells need to be studied).

Lower Jurassic source rocks are mature, for oil or gas, in all the three sectors of the Lusitanian Basin, while Upper Jurassic source rocks are only mature in the Central sector, for oil, being immature in the other two sectors (Figures 2C and 2D).

These data need to be integrated with other regional data, such as source-rock thicknesses and palaeogeographic and organic content variations, in order to establish a robust and predictive exploration tool. This approach may be extended to other western Iberian basins, such as the Peniche and Alentejo, both offshore and a few hundred kilometres apart.

**References:**

Matos, V.G.A.E. 2009. Estudo de palynofácies e de fácies organic de uma sequência sedimentary do Jurássico inferior da Bacia Lusitânica. *Master thesis, Departmento de Ciências da Terra da Faculdade de Ciências e Technologia da Universidade de Coimbra, 108 pp*. (unpubl.)

Pena dos Reis, R., Pimentel, N., Garcia, A.J.V., Viana, A., & Bueno, G. 2010. Mesozoic subsidence and uplift history of an exposed Atlantic rifting margin – the Lusitanian basin (Portugal). *II Central & North Atlantic Conjugate Margins, Lisbon 2010, Extended Abstracts, 74.* http://metododirecto.pt/CM2010/index.php/vol/article/view/235

Stapel, G., Cloetingh, S. & Pronk, B. 1996. Quantitative subsidence analysis of the Mesozoic evolution of the Lusitanian Basin (western Iberia margin). *Tectonophysics*, **266**, 493-507.

Teixeira, B.A. 2012. Modelação da subsidência, evolução térmica e maturação de intervalos geraDorés do Jurássico na Bacia Lusitânica. *MSc Thesis, Universidade de Lisboa,* (unpubl.)

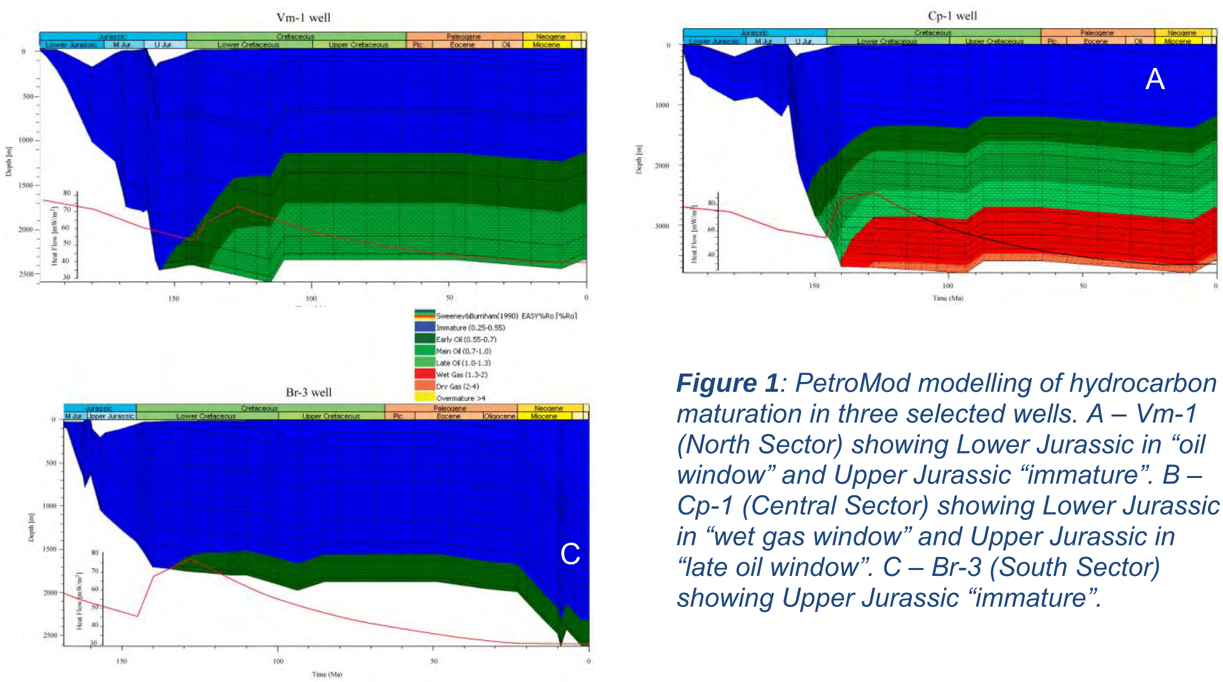
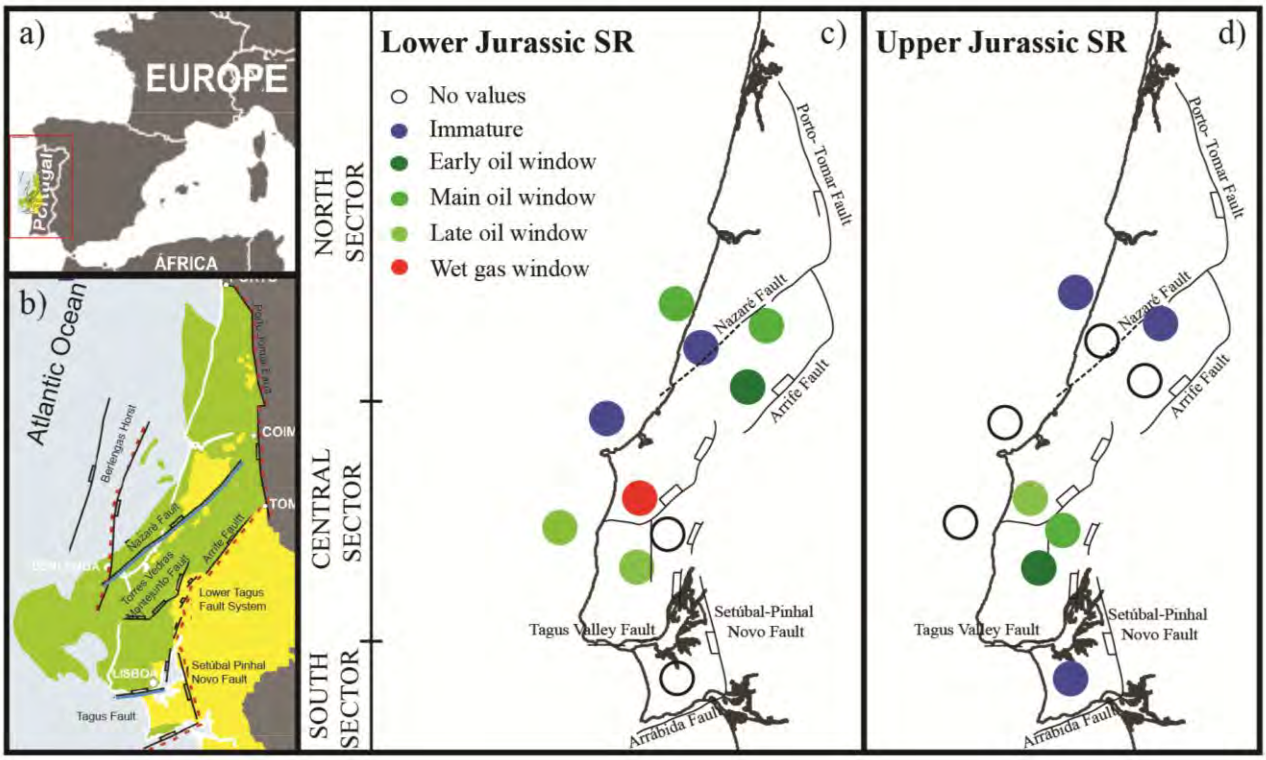



***Figure 1**: PetroMod modelling of hydrocarbon maturation in three selected wells. A – Vm-1 (North Sector) showing Lower Jurassic in “oil window” and Upper Jurassic “immature”. B – Cp-1 (Central Sector) showing Lower Jurassic in “wet gas window” and Upper Jurassic in “late oil window”. C – Br-3 (South Sector) showing Upper Jurassic “immature”.*




***Figures 2A & 2B:** Lusitanian Basin location (green), main structures and Sectors (in Matos, 2009).*
***Figures 2C & 2D:** Hydrocarbon maturation in the studied wells.*

# EARLY OPENING HISTORY OF THE AFRICAN TRANSFORM MARGIN AND ITS INFLUENCE ON UPPER CRETACEOUS DEEPWATER DEPOSITIONAL SYSTEMS IN THE DEEP IVORIAN BASIN

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*Although there has been oil and gas production in Cote D'Ivoire and Ghana for many years, the discovery of the Jubilee Field in 2007 stimulated a new phase of exploration focused specifically on Upper Cretaceous deepwater channel-levee complexes. The evaluation of multiple, large, high quality 3-D seismic volumes distributed along the margin has enabled detailed study of these deepwater depositional systems. Variations in stacking patterns, scale and orientation, related to, amongst other things, changes in depositional slope and sediment transport distances within the basin have been noted. These variations are shown to be related to the early opening history of the African Transform Margin which created the basic structural framework for later sediment deposition.*

## Introduction

The Deep Ivorian Basin stretches from Cape Three Points in western Ghana in the east to the Cote D'Ivoire-Liberia border in the west. It is situated between the St. Paul Fracture Zone to the northwest and the Romanche Fracture Zone to the southeast. Early exploration along the Ivorian margin was concentrated in shallow water along the shelf and was focused on structural targets with M-U. Albian aged reservoirs. This period of exploration resulted in several commercial discoveries such as Foxtrot, Lion, Panthere, Espoir and Baobab. Also, during this phase, a number of discoveries were made (some serendipitously) in Upper Cretaceous deepwater channel systems mainly draped over deeper structures – Belier, Gazelle, W. Tano for example. In 2007 the later renamed Jubilee field was discovered by the Mahogany-1 well and further exploration in western Ghana has discovered fields such as Tweneboa, Enyenra, Odum, Teak, Dzata, Paradise and Sankofa. Recent drilling has shifted westwards in to Cote D'Ivoire and there is now an emerging U. Cretaceous Slope Turbidite Play within the Deep Ivorian Basin. During this period Anadarko Petroleum Corporation has assembled an extensive library of 3-D data over and around its license areas and this, together with regional 2-D data has enabled us examine to depositional styles from a regional perspective (Figure 1).

## Early Opening History of the Transform Margin

The Deep Ivorian Basin of western Ghana and Cote D'Ivoire represents one of the last segments of the Atlantic Margin to open (Figure 2) (Antobreh *et al.*, 2009). An early Albian reconstruction of the Atlantic shows rifting in the Deep Ivorian Basin proceeding in a NE-SW direction in between the St Paul and Romanche FZ's with active sea-floor spreading taking place both to the north and south. Unlike other segments of the Atlantic Margin, where rifting generally followed Pan-African - Brasiliano lineaments, the African Transform Margin cut across this pre-existing structural grain (De Wit *et al.,* 2008) to produce a relatively complex rift topography. Three distinct structural trends can be recognised in the immediate post rift fabric: a N-S Pan-African – Brasiliano trend, a NW-SE Cretaceous rift trend and NW-SE shear trend. While active rifting would have dominated in the eastern part of the basin, shear movement, associated with the developing St Paul Fracture Zone, would dominate in the west. Furthermore, the eastern part of the Deep Ivorian basin is underlain by attenuated continental crust, whereas, in the west, a sharp continental/oceanic crustal boundary developed along the St Paul Fracture Zone.

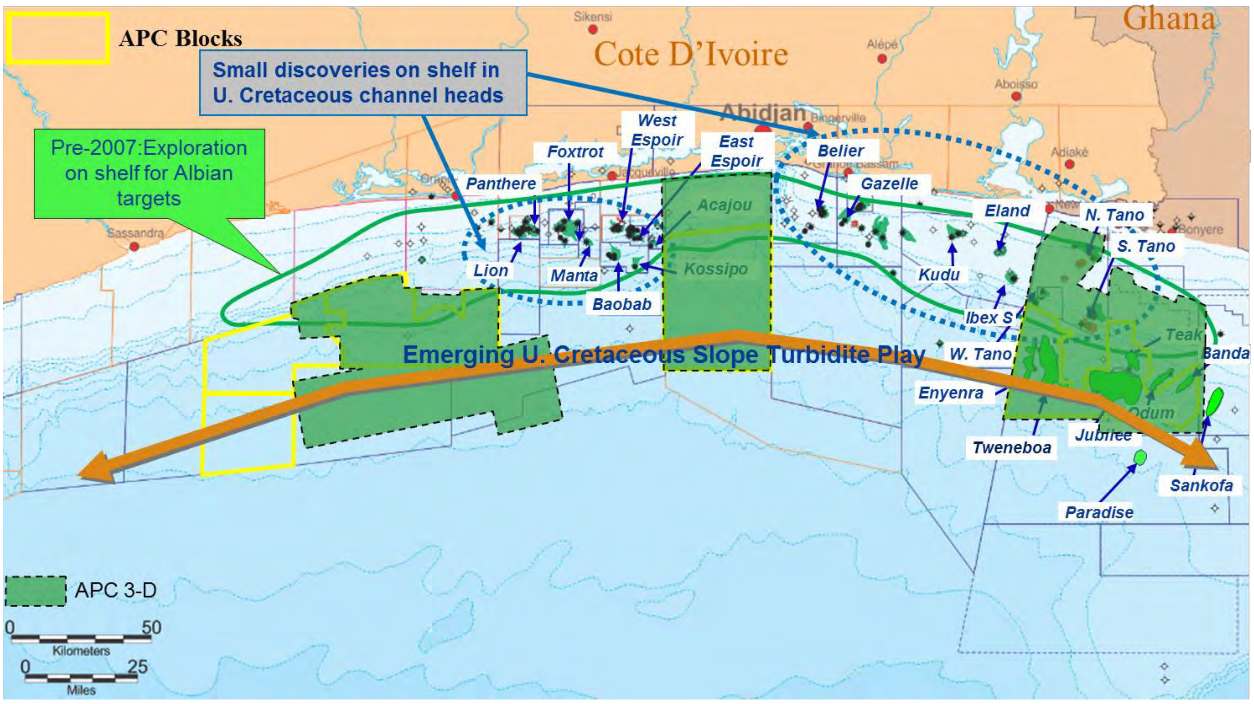



*Figure 1: Location of the Deep Ivorian Basin and exploration summary.*

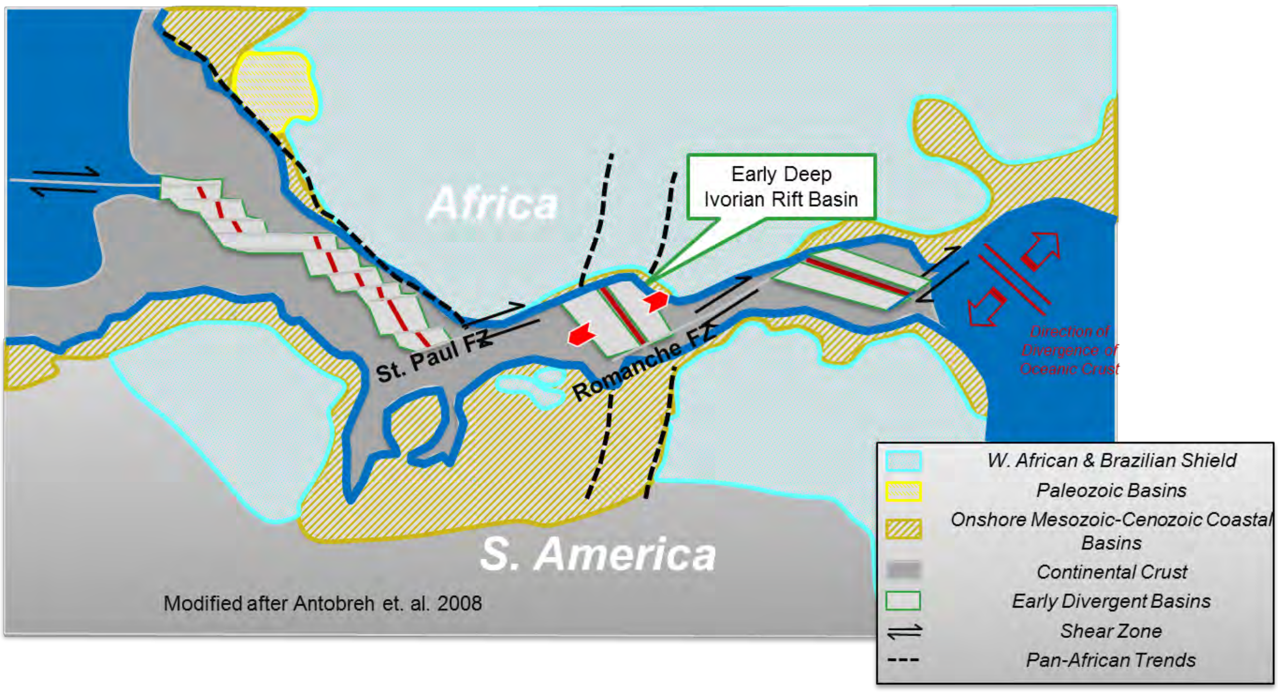



***Figure 2:** Aptian, 110ma reconstruction of the African Transform Margin (modified from Antobreh et al., 2009).*

## Influence on Upper Cretaceous Deepwater Deposystems

The emplacement of oceanic crust along a spreading centre during the mid Albian, initially located in the central part of the basin, and subsequent thermal subsidence created the ultimate floor to the basin and provides the sink for all sediment derived from the Africa continent to the north. Knowing the approximate age of the earliest oceanic crust and using generally accepted subsidence rates we were able to model the bathymetry of the basin at various stages from the mid to late Albian through to the present day. Two transects were constructed showing the modelled bathymetric slope at various times during the Cretaceous together with the present day bathymetry (Figure 3). Transect A-A' is parallel to the maximum bathymetric slope in the western shear dominated sector and transect B-B' is parallel to the maximum bathymetric slope in the eastern rift dominated sector. Throughout the post rift history of the basin the western shear dominated margin shows a steeper slope than the eastern rift dominated margin, and the ultimate basin floor (i.e. the deepest part of the basin that is underlain by oceanic crust) is much closer to the shelf edge in the west than it is in the east implying shorter sediment transport distances from shelf edge to basin floor.

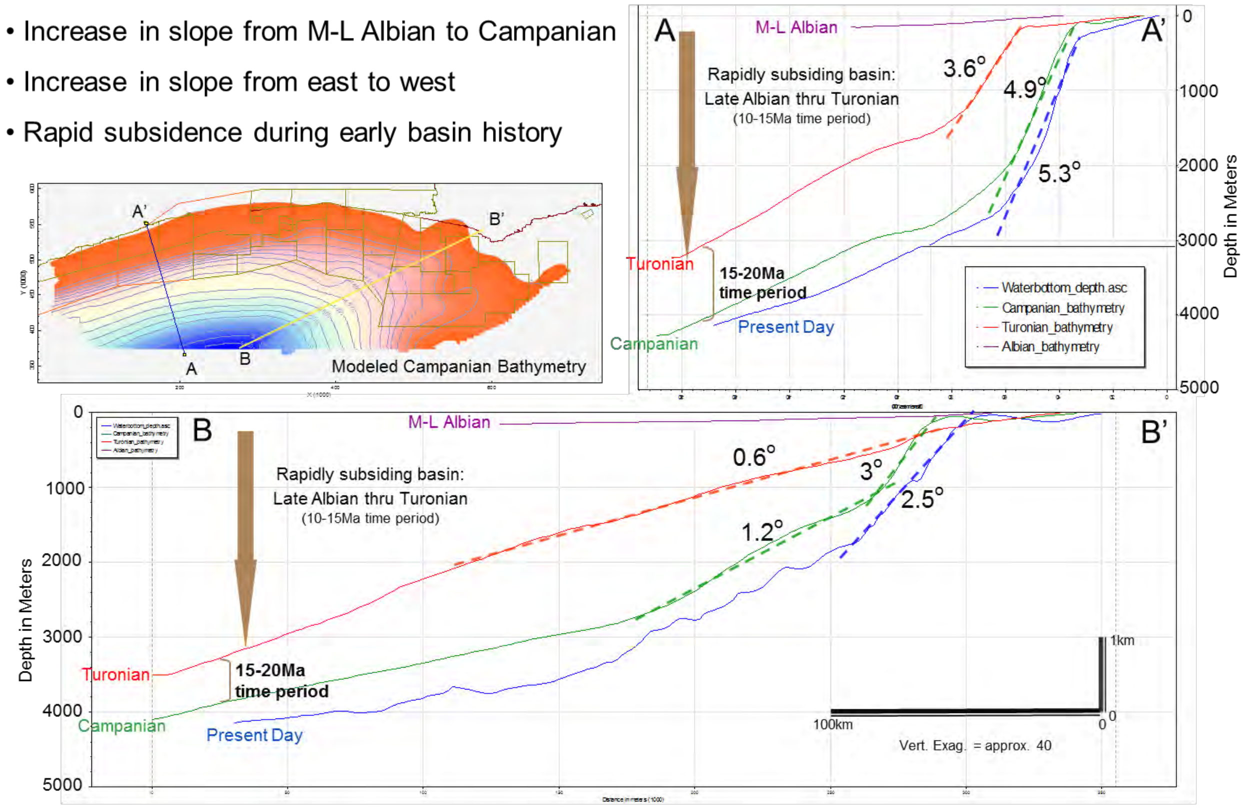



***Figure 3:** Palaeobathymetry models and depositional slope in the Deep Ivorian Basin.*

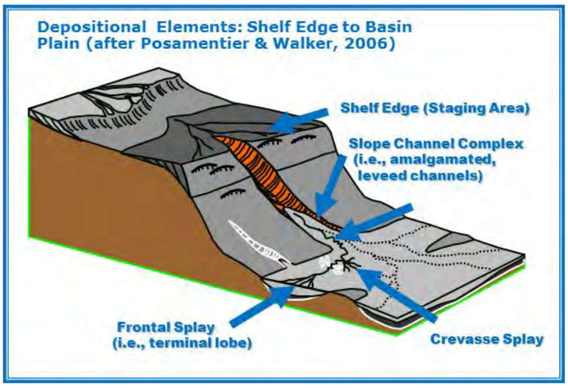
## Depositional Models

The large 3-D seismic data sets acquired by Anadarko since 2007 have enabled the examination of large scale depositional features along the Ivorian Margin. Based on the data available it is evident that the characteristics and morphology of the Upper Cretaceous deepwater depositional systems show clear differences between the shear dominated margin in the west and rift dominated margin in the east. The slope gradient is greater in the west compared to that in the east and this can be shown to have persisted during the entire basin history from onset of sea-floor spreading to the present day and this has certainly impacted the character of the depositional systems along the margin.

In the east, the lower slope and complicated rift topography created by rift trends cutting across pre-existing Pan African lineaments has resulted in the development of intra-slope basins particularly in the earlier post-rift deposits prior to extensive infilling of the basin. Sediment transport distances from shelf to sink are greater in the east compared to west and on a comparably sized data set in the west we can clearly see almost all of the slope system and a large part of the basin plain deposits whereas in the east it is only the shelf to upper slope that is imaged. Stacking patterns, scale and orientation of the deepwater depositional systems are different in the two regions. Deposystems in the east are dominantly compensationally stacked while those in the west appear to aggrade vertically and have followed much the same course throughout the history of the basin from earliest Upper Cretaceous times to the present day. The upper slope channels-levee complexes in the east are much broader than those in the west, perhaps reflecting the lower slope gradient and finally the slope channels in the west are orientated largely N-S whereas those in the east have a more NE-SW direction, again reflecting the palaeobathymetry (Figure 4).

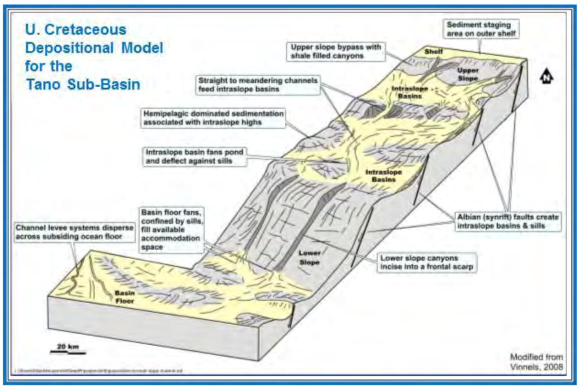
### Conclusions

The basin configuration is the result of the early opening rift history of the margin and this has created the framework for subsequent deepwater deposystems throughout the Upper Cretaceous and later. Those deposystems reflect, at least in part, the basin morphology and variations in stacking pattern, scale and orientation can be determined.




**Shear Dominated Margin**

- Higher Slope Environment
- Shorter Transport Distance from Shelf to Basin Floor
- Intra-slope Basins Unlikely




**Rift Dominated Margin**

- Lower Slope Environment
- Long Transport Distance from Shelf to Basin Floor
- Potential for Intra-slope Basins

***Figure 4:*** *Characteristics and depositional models for the western shear dominated margin and eastern rift-dominated margin of the Deep Ivorian Basin.*

### References

Antobreh, A.A., Faleide, J.I., Tsikalas, F. & Plamke, S. 2009. Rift-shear architecture and tectonic development of the Ghana margin deduced from multichannel seismic reflection and potential field data. *Marine and Petroleum Geology,* **26**, 345-368.

De Wit, M.J., Stankiewicz, J. & Reeves, C. 2008. Restoring Pan-Africa-Brasiliano connections: more Gondwana control, less Trans-Atlantic corruption. *In:* Pankhurst, R.J., Trouw, R.A.J., Brito Neves, B.B. & De Wit, M.J. (eds). *West Gondwana: pre-Cenozoic correlations of the South Atlantic Region.* Geological Society London, Special Publications, **294**, 399-412.

## ANALOGUES FOR ATLANTIC CANADA RESERVOIRS FROM THE WESSEX (ENGLAND) AND LUSITANIAN (PORTUGAL) BASINS

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Coastal exposures of Cretaceous-age, reservoir prone sediments in the Wessex Basin and Channel Sub-Basin (southern UK), and the Lusitanian Basin (Portugal) provide keys to the subsurface reservoirs being exploited for oil and gas development offshore Atlantic Canada. These coastal areas have striking similarities to the offshore region of Canada and provide insight to structural controls and characteristics of these reservoirs. Outcrops demonstrate a range of depositional environments from terrigenous and non-marine, shallow siliciclastic and carbonate sediments, through to deep marine sediments. The outcrops provide clearer understanding of key stratigraphic surfaces representing conformable and non-conformable surfaces. Validation of these analogue sections and surfaces can help predict downdip, updip and lateral potential of the petroleum systems, especially source rock and reservoir. Many unconformities visible at outcrop are not readily apparent on examination of subsurface data and demonstrate the interplay of eustatic and tectonic controls and the effect of geodynamics along the margin that demonstrate of the episodic opening of the central and north Atlantic.

Hiscott *et al.* (1990) helped to establish the tectono-stratigraphic events and determined rates of sedimentation were relatively constant along the basin margins. Sinclair *et al.* (1994) examined wells from the Jeanne d'Arc basin offshore Newfoundland with those of the Porcupine and Outer Moray Firth basins with the objective of determining similarities in basin fill. The Channel and Wessex basin outcrops have been investigated in several studies (e.g. Channel Basin- Ruffell and Wach, 1991; Wessex Basin- Hesselbo *et al.,* 1990). Lusitanian Basin studies include those of Cunha and Pena dos Reis (1995) and Dinis *et al.,* (2008 and references therein).

The Wessex (Channel) and Lusitanian basins have relatively complex geological histories, multiple sources of sediment input, source rock analogues and variable depositional settings. The Lusitanian Basin is an epeiric basin on the west coastal areas and offshore western Portugal, bounded to the east and west by emergent Palaeozoic highlands that provided the source of siliciclastic sediments to the basin. The Berlenga highlands separate the Peniche Basin, deep offshore to the west, from the Lusitanian Basin. The basin provides good outcrops analogues for a range of depositional environments ranging from fluvial to estuarine mixed sediments and coastal platform carbonates. The predominance of carbonates in the Lower Cretaceous sections compared to the Wessex Basin to the north is likely a factor of palaeo-latitude and climatic controls.

Three major fault zones divide the Wessex Basin into five sub-basins, including the southernmost Channel Basin. Lower sea level in the latest Jurassic to Early Cretaceous created two depocentres separated by the London Brabant Massif with slower sedimentation rates in the northern basins. Within the basin there are minor unconformities and non-sequences due to eustatic changes and variable rates of local tectonic and regional tectonism. These were superseded by a major unconformity cutting the Mesozoic section in southern England associated with later Cimmerian tectonism, with the unconformity formed in an extensional setting. The deposition of the Lower Greensand in southern England marked the end of the late Cimmerian event.

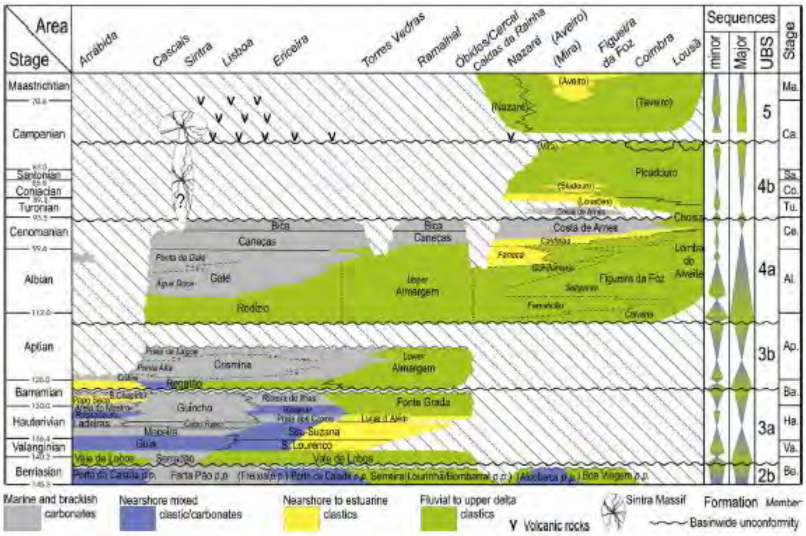
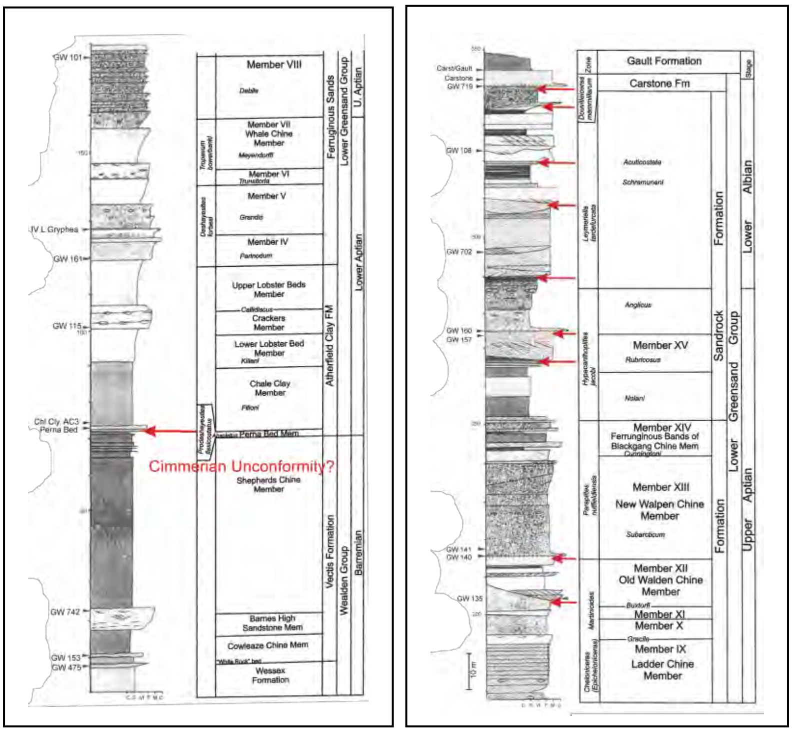



*__Figure 1:__ Lithostratigraphic chart of the Cretaceous unconformity bounded surfaces of the western Portuguese margin (from Dinis et al., 2008; modified from Cunha and Pena dos Reis, 1995).*

*__Figure 2:__ The Channel Basin demonstrates unconformities due to eustatic changes and variable rates of local and regional tectonics. These were superseded by a major unconformity cutting the Mesozoic section in southern England associated with later Cimmerian tectonism. The deposition of the Lower Greensand in southern England marked the end of the late Cimmerian event (from Wach and Ruffell, unpublished, 1998).*



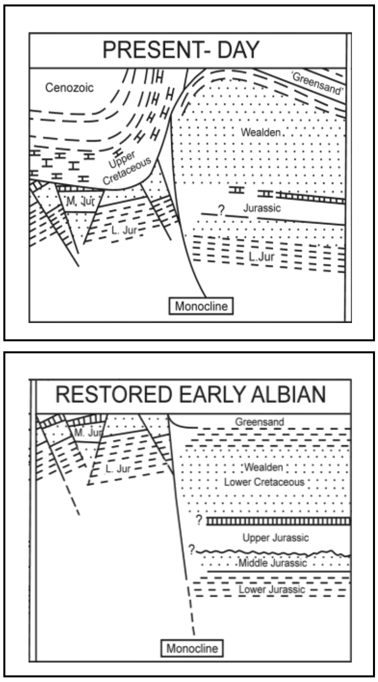




*__Figure 3:__ Lower Cretaceous lithostratigraphy and unconformity bounded surfaces (red arrows) of the Channel Basin. Does the Barremian/Aptian boundary mark the end of the Late Cimmerian event? (modified from Ruffell and Wach, 1991).*

**References**

Cunha, P.P. & Pena dos Reis, R. 1995. Cretaceous sedimentary and tectonic evolution of the northern sector of the Lusitanian Basin (Portugal). *Cretaceous Research,* **16**, 155-170.

Dinis, J.L., Rey, J., Cunha, P.P., Callapez, P. & Pena dos Reis, R. 2008. Stratigraphy and allogenic controls of the western Portugal Cretaceous: an updated synthesis. *Cretaceous Research,* **29**, 772-780

Hesselbo, S.P., Coe, A.L., Batten, D.J. & Wach, G.D. 1990 Stratigraphic relations of the Lower Greensand (Lower Cretaceous) of the Calne area, Wiltshire. *Proceedings Geological Association,* **101**, 265-278.

Hiscott, R.N., Wilson, R.C.L., Gradstein, F.M., Pujalte, V., Garcia-Mondejar, J., Boudreau, R.R. & Wishart, H.A. 1990. Comparative stratigraphy and subsidence history of Mesozoic rift basins of North Atlantic. *American Association of Petroleum Geologists Bulletin,* **74**, 60-76.

Ruffell, A.H. & Wach, G.D., 1991. Sequence stratigraphic analysis of the Aptian-Albian Lower Greensand in southern England, *Marine and Petroleum Geology,* **8**, 341-353.

Sinclair, I.K., Shannon, P.M., Williams, B.J.P., Harker, S.D. & Moore, J.G., 1994. Tectonic controls on sedimentary evolution of three N. Atlantic borderland Mesozoic basins. *Basin Research,* **6**, 193-217.

## CORRELATING CALEDONIDE-APPALACHIAN TERRANES AND STRUCTURES BENEATH THE CONJUGATE MARGINS OF ATLANTIC CANADA AND NW EUROPE

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The Appalachians of Atlantic Canada and the Caledonides of Europe are segments of a formerly continuous orogen constructed during the amalgamation of Pangaea. Both orogens have been subdivided using a variety of zonal and terrane-based schemes, leading to several proposed correlations between the North American and European segments of the orogen. Although there is general agreement on the correlation of major units such as the Laurentian foreland and the Avalonian platform, major differences have arisen from different fundamental assumptions.

One significant source of variability is the Mesozoic fit assumed prior to Atlantic opening. Most Caledonide-Appalachian reconstructions have been based on a 'loose' fit that does not take into account Mesozoic stretching. A more realistic fit taking into account the thinning of the conjugate margins reduces the distance between the reconstructed Palaeozoic terranes of Newfoundland and Ireland by as much as 50%.

A second variable is the extent of late Palaeozoic orogen-parallel strike-slip. Up to 300 km of dextral strike-slip motion may have reconfigured Appalachian terrane boundaries during development of the transtensional Maritimes sedimentary basin beneath the Gulf of St. Lawrence. In contrast, Caledonide reconstructions have suggested dominantly sinistral strike-slip during terrane amalgamation and terminal collision. The overall kinematics of late Palaeozoic strike-slip are thus unresolved, but most early Palaeozoic reconstructions have ignored the potential for post-Caledonide strike-slip displacements.

Detrital zircon U/Pb provenance studies provide further insights into early Palaeozoic terrane relationships. Precise control on the depositional age, typically from fossils, is essential in the interpretation of these data sets. Laurentian margin sources can be recognised based on a large 'Grenville' peak close to 1 Ga, with an asymmetric 'tail' of Meso- and Palaeoproterozoic components back to 2.0 Ga; ages between 2.0 and 2.5 Ga are rare, but most data sets contain a proportion of Archaean (>2.5 Ga) grains. This component can be used to time the docking of peri-Gondwanan terranes with Laurentia during closing of Iapetus. West African sources in these terranes are dominated by Pan-African zircons (~ 0.6 Ga) and typically show a distinct Eburnean age peak between 1.95 and 2.2 Ga. These sources shed zircon into both North Wales and the Meguma Terrane of southern Nova Scotia during the Cambrian; subsequent plate motions in the early Palaeozoic dispersed these terranes from their original locations on the margin of Gondwana. The Ganderia domain, comprising several terranes in Atlantic Canada, is characterised by a broad spread of Mesoproterozoic and Palaeoproterozoic zircon. Based on these criteria it can be traced into the Leinster-Lakesman and Rosslare-Monian terranes of the British Isles.

These differences have implications for the distribution of basement units beneath the present-day continental margins, which in turn may have affected both the thermal and the mechanical behaviour of the margins during rifting and subsequent evolution of the North Atlantic. An understanding of the Palaeozoic basement is thus important to understanding Mesozoic-Cenozoic rift and passive margin evolution.

## EXPLORATION IN THE WEST PORCUPINE BASIN: PALEOCENE POTENTIAL

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The Irish Atlantic Margin has recently had an increase in exploration activity with particular interest focused on the Dunquin Prospect, Porcupine Basin and the Barryroe discovery, North Celtic Sea. The recent (2011) Atlantic Margin licensing round saw Two Seas Oil & Gas Ltd (60%) and Petroleum Geo-Services Nominees (40%) pick up prospective acreage in the western Porcupine basin covering blocks 34/19, 20, 24, 25, 35/16 and 35/21.

The Porcupine Basin is one of many Cenozoic and Mesozoic sedimentary basins located along the North Atlantic failed rift margin, containing as much as 10 kms of post-Palaeozoic sediments. The basin is of particular interest for hydrocarbon exploration due to the presence of proven source intervals and a number of undrilled reservoirs. The Porcupine Basin has been linked to other North Atlantic hydrocarbon bearing basins such as those offshore Newfoundland.

Three main play types have been identified in the west Porcupine Basin; 1) Jurassic fault blocks, 2) Lower Cretaceous wedges and, 3) Upper Paleocene slope channels and fans. Figure 1 is a Northwest-Southeast seismic profile across the acreage which depicts the regional western margin geology, highlighting potential plays.

The main source interval has been identified in the Upper Jurassic with TOC's of 1-1.9% at wells 34/15-1, 34/19-1 and 35/6-1. However, Butterworth *et al.* (1999) state that there is additional source potential for Middle Jurassic lacustrine algal shales, with TOC's of 1.3-3.9% and hydrogen indices of 143-573. Seismic interpretation and well correlation suggest that a large Jurassic source depocentre lies directly beneath the held acreage.

Wells have intersected the Paleocene fan equivalent intervals and have recorded encouraging results. Wells 34/15-1 and 34/19-1 encountered Late Paleocene and Early Eocene shallow marine sands with oil shows equivalent to the prospective sands identified in the Two Seas/PGS acreage.

Uplift of the western margin is thought to have been the main control on the oversteepened shelf-slope erosional margin (Ryan *et al.,* 2009). In this environment sediment bypass, canyon fill and mass transports complexes (MTC's) would have been prevalent. The erosional margin transformed into a progradational margin as the gradient of the shelf-slope basin floor profile was lowered. Then nearshore systems dominate and prograde across the deep-water systems (Ryan *et al.,* 2009).

Paleocene fan geometry and size can be well defined by the use of modern RMS attribute analysis. Figure 2, an RMS amplitude extraction at the top of the Paleocene fan interval, highlights these geometries and reveals the seismic character of the fan lobes. Fans have typical mounded fan geometry with onlap updip and downlap downdip. The fans are of moderate continuity and low amplitude with variable high amplitude internal anomalies which could be associated with lithological or fluid variations. Additional RMS analysis illustrates the impact of shelf-slope instability and the formation of MTC's.

Two Seas and PGS hold significant acreage over a highly prospective area with an aim to provide an alternative Tertiary reservoir target in the west Porcupine Basin. Encouraging well results, seismic interpretation and attribute analysis show encouraging signs for the Paleocene fan story and analogies can be made to other Tertiary systems.

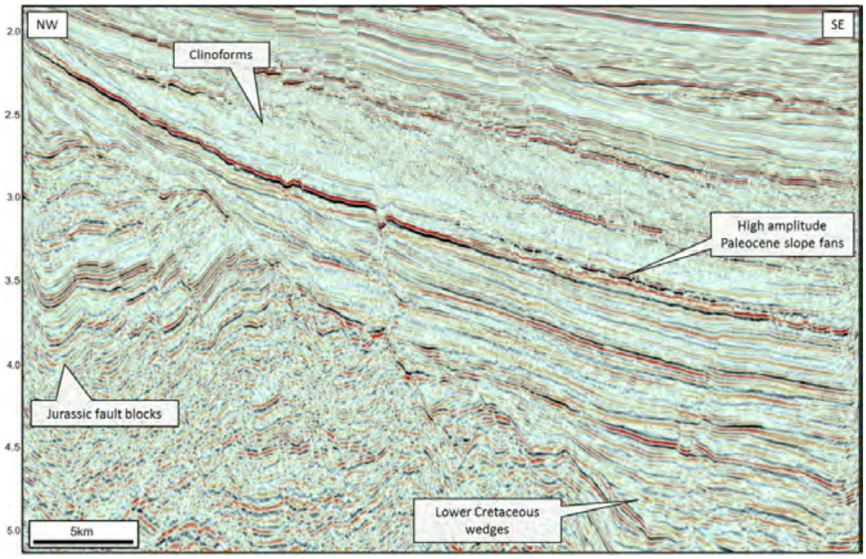


***Figure 1:*** *NW-SE seismic profile of the west Porcupine Basin.*

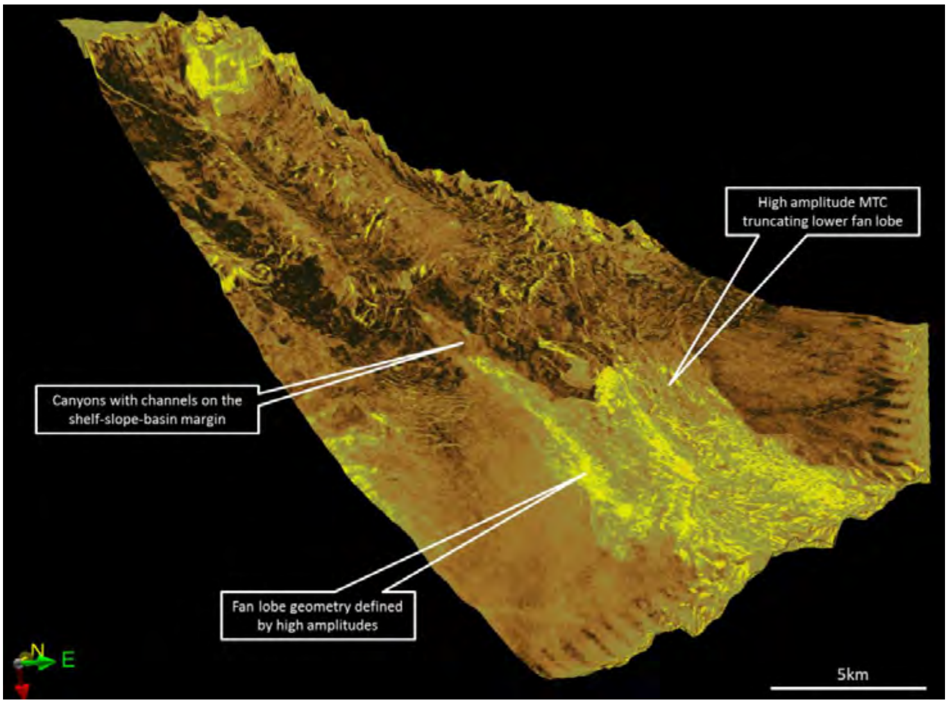


***Figure 2:*** *20ms RMS extraction of a Paleocene prospect.*

## References

Butterworth, P., Holba, A., Hertig, S., Hughes, W. & Atkinson, C. 1999. Jurassic non-marine source rocks and oils of the Porcupine Basin and other North Atlantic margin basins. *In:* Fleet, A.J. & Boldy, S.A.R. (eds) *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference, Geological Society London,* 471-486.

Ryan, M.C., Helland-Hansen, W., Johannessen, E.P. & Steel, R.J. 2009. Erosional vs. accretionary shelf margins: the influence of margin type on deepwater sedimentation: an example from the Porcupine Basin, offshore western Ireland. *Basin Research,* **21**, 676-703.

# DEFORMABLE PLATE RECONSTRUCTIONS FOR THE NORTH ATLANTIC AS A BASIS FOR PALAEOGEOGRAPHIC MAPPING AND THE CONSTRUCTION OF PALAEO-DIGITAL ELEVATION MODELS

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Reconstructions of the Earth's tectonic plates and geological datasets intersected with them are essential for the interpretation of tectonic evolution and for palaeogeographic mapping. However traditional rigid plate reconstructions are unable to provide realistic interpretations of pre-rift plate geometries. Deformable plate models are required to accurately take into account the effects of orogenesis at convergent plate boundaries and lithospheric stretching and thinning at divergent plate boundaries. In this regard the opening history of the North Atlantic is particularly problematic. It is complicated by the presence of a triple junction west of Galicia Bank that propagated northwards and caused the splitting of the main mid-oceanic ridge to form the Labrador/Baffin seaway and the concurrent breakup between Greenland and Norway. Plate boundary definitions between Greenland and Europe are additionally complicated by the presence of large volumes of igneous rocks that have built up the topography of the Faroes-Iceland Ridge and the Jan Mayen Microcontinent.

New deformable plate reconstructions for the North Atlantic have been created using the Plate Wizard deformable model. The rifting history has been established for each margin and the trajectory of the deformation was determined for appropriate timeslices. For each rifting episode, stretching factors have been calculated across the plate margins and to ensure consistency were then compared to published stretching factors. These stretching factors were then applied within the plate model during plate reconstructions to warp each plate and any associated datasets by the calculated amount. The result is more accurate pre-rift plate geometries, without the overlap and underfit problems that are detrimental for all rigid model plate reconstructions. These deformable plate models were used to reconstruct well and outcrop data points, and geophysical data, as the basis for constructing palaeogeographies and palaeo-digital elevation models (palaeotopography and palaeobathymetry maps). These reconstructions are subsequently used for palaeoclimate modelling and source and reservoir facies prediction.

## COMPARISON OF LITHOSPHERE STRUCTURE ACROSS THE ORPHAN BASIN/FLEMISH CAP AND IRISH ATLANTIC CONJUGATE CONTINENTAL MARGINS FROM CONSTRAINED 3-D GRAVITY INVERSIONS

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Regionally-constrained 3-D gravity inversion results on the Orphan Basin/Flemish Cap and the Irish Atlantic conjugate continental margins are compared in order to investigate crustal structure, early rifting history and geological evolution of this part of the North Atlantic (Figure 1). The full-crustal density anomaly distributions provide some of the first depth images of how rifted structures compare along and across these conjugate margins. Broad similarities in crustal structure are identified with some noticeable differences, linked to rifting and crustal stretching processes. Extreme crustal thinning (stretching factors >3.5) is indicated beneath much of the southern Porcupine Basin, the western half of West Orphan Basin, the eastern half of Jeanne d'Arc Basin, the southeastern half of East Orphan Basin and in pockets beneath Rockall Basin. This appears to have resulted in the serpentinisation (and possible exhumation) of mantle lithosphere on the Irish Atlantic and Flemish Cap margins but not beneath Orphan Basin. A simple evolution model is proposed for the early stages of rifting between the margins. It is suggested that ancient orogenic sutures played an important role in controlling the northward migration of rifting and the rotation and displacement of Flemish Cap out of Orphan Basin.

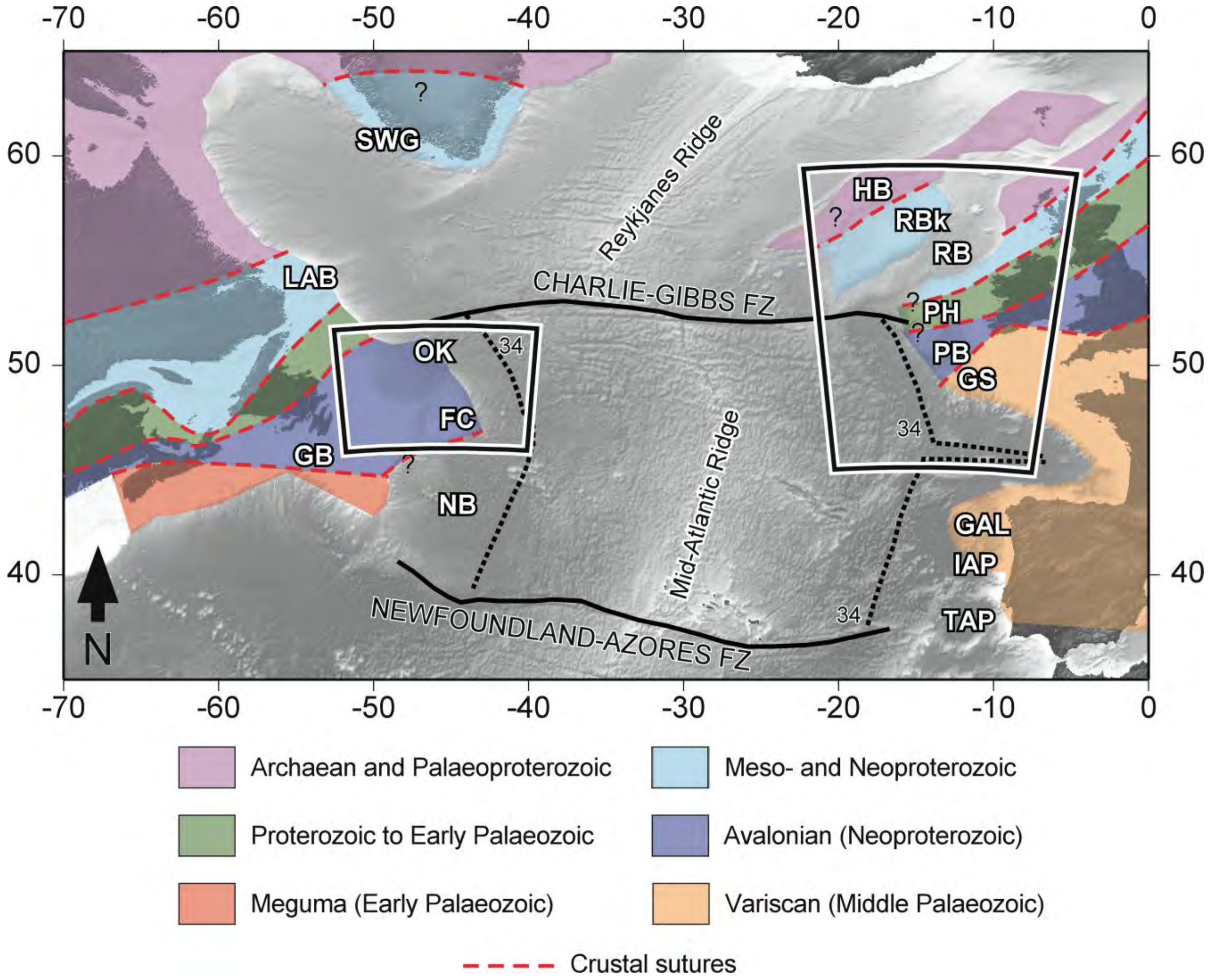


***Figure 1:*** *Bathymetric map of the North Atlantic region subdivided by inferred basement affinity of continental crust.*

## GEOLOGICAL CONSTRAINTS FOR A NEW PLATE RECONSTRUCTION OF THE NEWFOUNDLAND CONTINENTAL MARGIN

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### Introduction

A regional seismic grid has been interpreted on the Newfoundland margin using a combination of high quality deep long-offset industry data, and reflection and refraction seismic profiles from government and academia. A similar regional seismic interpretation was carried out on the conjugate margins of Ireland and northern Iberia (Štolfová *et al.,* this conference) and the results were used to help develop *A New Kinematic Plate Reconstruction of the North Atlantic between Ireland and Canada* (Ady and Whittaker, this conference). On the Newfoundland margin, seismic data made available to the project included modern (2002), high-resolution seismic data in the Orphan Basin (courtesy of TGS-Nopec). Major tectonostratigraphic sequences defined from seismic interpretation around the margin were mapped for each time interval.

### Interpretation

The seismic interpretation of the Newfoundland margin illustrates that complex and multi-phase deformation related to large-scale plate movements has occurred. Seismic evidence for multiple stage breakup and rifting is seen, together with periods of uplift. Crustal extension which eventually led to the breakup of the Ireland and Newfoundland is generally accepted to have begun in the Triassic. This initial Late Triassic to Early Jurassic rifting event was followed by a major Late Jurassic to Early Cretaceous event. The nature and relative importance of later Cretaceous and Tertiary tectonic events that have affected the margin are less well documented. A period of relative uplift during the Hauterivian to Barremian has been recognised in the Jeanne d'Arc Basin, followed by the development of west- to northwest-striking detached normal faults during the mid-Aptian to Middle to Late Albian. These two Early Cretaceous events extending northwards into the East Orphan and Flemish Pass basins are also recognised in this study.

Rifting was initiated in a series of north to northeasterly trending half-grabens with salt tectonics active to the south of the Orphan Basin. In the southwestern Grand Banks this rifting was abandoned as tectonic activity became focused towards the present day continental margin. No evidence for active salt tectonics is seen on seismic data north of the Jeanne d'Arc Basin although Triassic to Early Jurassic sediments are likely to be present at depth, and detachment faulting on the margins of the East Orphan Basin may follow evaporite and shaley strata of this age.

The major Late Jurassic to Early Cretaceous rift event was initiated in the Tithonian and active rifting continued to the early Valanginian. The dominant trend of this faulting was north to northeast. This is interpreted to correspond with the progressive breakup of Newfoundland and Iberia which eventually broke apart in the Barremian. Hauterivian to Barremian uplift and faulting is also believed to be associated with this breakup event.

Seismic data from the East Orphan Basin show that major faulting with prominent detachment zones is related to the Tithonian to Valanginian rift event and Lower Cretaceous sediments infill irregular basin topography in a series of restricted basins which trend northwest. The basin was affected by a distinct later faulting event that is interpreted to be of mid-Aptian to Late Albian age and related to the breakup of Ireland and Newfoundland in the north. Growth faulting of this age appears on the seismic data to have an E-W trend, approximately parallel to the breakup direction. The magnitude of this pre-breakup rifting event is on a relatively small scale compared to the main Late Jurassic rifting. The West Orphan Basin has a very different structural style to the East Orphan Basin and the basins are divided by the Orphan Knoll in the north and a series of tilted fault blocks in the south. These fault blocks are highly rotated and form basement highs at the crests. Detachment surfaces are interpreted within the basement section. Early Cretaceous faulting cannot be identified on seismic data in the deeper part of the West Orphan Basin and is either not present or obscured by Cretaceous volcanics. These volcanics are interpreted to be present along the axis of the basin and overstep the western basin margin and are probably related to the Early to Mid-Cretaceous Barra Volcanics of the Rockall Basin on the conjugate margin of Ireland.

## Conclusions

The identification of multiple rift events in the East Orphan Basin has been correlated with an Early Triassic to Early Jurassic rift followed by two separate breakup events in the Late Jurassic to early Valanginian and Aptian to Albian. The good quality modern seismic data in the central part of the basin clearly shows that post-Valanginian extension was relatively small scale and that most extension in the basin had taken place at by the end of the Valanginian. In contrast, seismic resolution is poor in the West Orphan Basin due to Cretaceous volcanism. Most of the extension predicted by the plate model from late Valanginian to Barremian is therefore likely to have taken place in the West Orphan Basin. By analogy with the Newfoundland margin, it is proposed that the Rockall Basin shared a similar structural evolution to the West Orphan Basin and the Porcupine Basin to the East Orphan Basin.

The interpretation of regional seismic data from the conjugate margins of Newfoundland and Ireland has enabled a comparison of both margins and has resulted in a better understanding of the evolution of the margin. The development of a new plate model has helped to identify potential source rock development at several intervals on the margins and predicts the likelihood of source rock preservation due to faulting and extension. Potential reservoir development has also been correlated with the main tectonic events and their distribution can be mapped and predicted more accurately using the modelled basin geometry.

### References

Ady, B.E. & Whittaker, R.C. 2012. A New Kinematic Plate Reconstruction of the North Atlantic between Ireland and Canada. Abstract, *Central Atlantic Conjugate Margins Conference, Dublin, 2012*.

Štolfová, K., Whittaker, R.C. & Shannon, P.M. 2012. New insights into the regional Mesozoic and Cenozoic evolution of the Irish offshore continental margin. Abstract, *Central Atlantic Conjugate Margins Conference Dublin*, 2012.

### Acknowledgements

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## PLAY RISKS AND VOLUMES - OFFSHORE NOVA SCOTIA

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A systematic play fairway analysis (PFA) is used to evaluate the hydrocarbon potential of offshore Nova Scotia (Figure 1) (OETR 2011). This structured approach builds a detailed play assessment on the foundation of understanding the structural evolution of the basin.

Four main plays, as defined by reservoir, have been identified:

1. Upper Jurassic delta system
2. Mid/Upper Jurassic Carbonate bank
3. Hauterivian delta system
4. Albian delta system

The main hydrocarbon production and exploration to date has focused on the Albian and Upper Jurassic delta system and Jurassic carbonate bank. Recent exploration has failed due to a lack of understanding of the sediment dispersal pathways from the shelf to slope. Therefore reservoir prediction is a critical element of the PFA project. A detailed well and seismic sequence stratigraphic analysis has been done, that establishes the evolution of the shelf slope break through time. This is used to predict sand channel systems from shelf to slope. Further amplitude modelling work supports reservoir prediction into the deep water

These plays are charged from two main source rock systems:

1) Terrigenous source horizons corresponding to maximum flooding surfaces in the Tithonian, Hauterivian and Albian. These source horizons are mature to over mature today and are likely to have sourced the hydrocarbons in the gas producing fields on the margin. As an example the present day maturity of the Early Cretaceous source rocks is shown in Figures 2a and 2b.
2) A regional Lower Jurassic syn to early post rift restricted marine source rock is postulated. This presence of this source rock is supported by an evaluation of the rift mechanism, combined with oil typing from both Nova Scotia and Morocco. Oil seeps, traces in seabed piston cores and in salt fluid inclusions provide evidence for this regional source, outside the extent of the Jurassic and Cretaceous delta systems. The maturity of this regional Lower Jurassic source rock is shown in Figure 3.

Petroleum systems modelling has provided timing of hydrocarbon generation and expulsion for each of these source horizons and is used to create charge risk maps. These maps have been combined with common risk segment (CRS) maps for reservoir and seal to produce composite common risk segment maps (CCRS). Examples of these composite “play maps” are shown in Figures 4a and 4b. These show an integration of all the play elements for the particular reservoir interval (i.e. reservoir presence and effectiveness, seal presence and effectiveness as well as hydrocarbon charge). These CRS maps show the relative chance of the play being effective in a simplified “traffic light scheme” (red = high, yellow = moderate and green = low risk).

As well as giving a robust view of the distribution of each play, the analysis also allows the estimation of likely trapped hydrocarbons. 3D petroleum systems modelling predicts total trapped volumes of ~120 tcf of gas and 8 bnbbls of oil in place. These figures are unrisked. The regional distribution of trapped oil and gas is analysed as shown in Figure 5: As expected from the petroleum systems modelling, the oil play is restricted mainly in Areas 1 and 2 in Figure 5: This is driven by the depth of burial of the Lower Jurassic marine source rock. Further to the east the charge becomes predominantly gas with a lower chance of oil. Although it is worth noting that there is a proven oil play on the present day shelf and this is in agreement with the petroleum systems modelling results. There is an oil rim play (proven in Area 3) in Areas 3 and 5, which will be economically very valuable albeit likely based on relatively small pools.

Following the regional analysis described here, some further more detailed work at the level of leads shows that in fact the volume potential is likely to be even larger than predicted by the petroleum systems modelling. Using a conventional map based volume estimation approach (locating individual traps on structure maps, use of reasonable reservoir and fluid parameters for the given play level) shows that, for example, in the area highlighted in Figure 6 for the Barremian-Aptian interval the estimated in place volume for the identified leads is ~11 bnbbls oil and ~23 tcf gas mmboe. It is also important to note that there are several traps with sizes > 250 mmboe, which is the scale needed for economic exploration in such water depths (~1 to 3 km water depth).

The geological story has been used to influence the provinces call for bids strategy and the decision to release acreage in well signalled tranches. The presentation will focus on the resource potential in the deep offshore associated with the upcoming license rounds. These are likely to be gas charged with multi TCF sised features.

The regional play fairway analysis has been broadly endorsed by a large number of major and super major oil companies. The work has generated strong interest in further exploration offshore Nova Scotia. For example the play fairway model has been endorsed by Shell who bid $970mm on a work programme in the deep water to the south west of the basin (Call for Bids NS11-1). The resultant drilling will de-risk the deep water plays and will enhance the attractiveness of the offshore.

It is clear from the industry's response that a robust regional appraisal of hydrocarbon potential based on a play based exploration approach, is key to attracting investor interest. The play based approach is built on a very thorough first principles analysis of tectono-stratigraphy. It is this uncompromising integration of multiple disciplines that provides confidence and in the results and also exposes the possibility of new play ideas.

**Reference**

OETR (Offshore Energy Technical Research Association) 2011. *Play Fairway Analysis Atlas – Offshore Nova Scotia.* Nova Scotia Department of Energy Report 88-11-0004-01, 349p. Also available online at: http://www.novascotiaoffshore.com/analysis

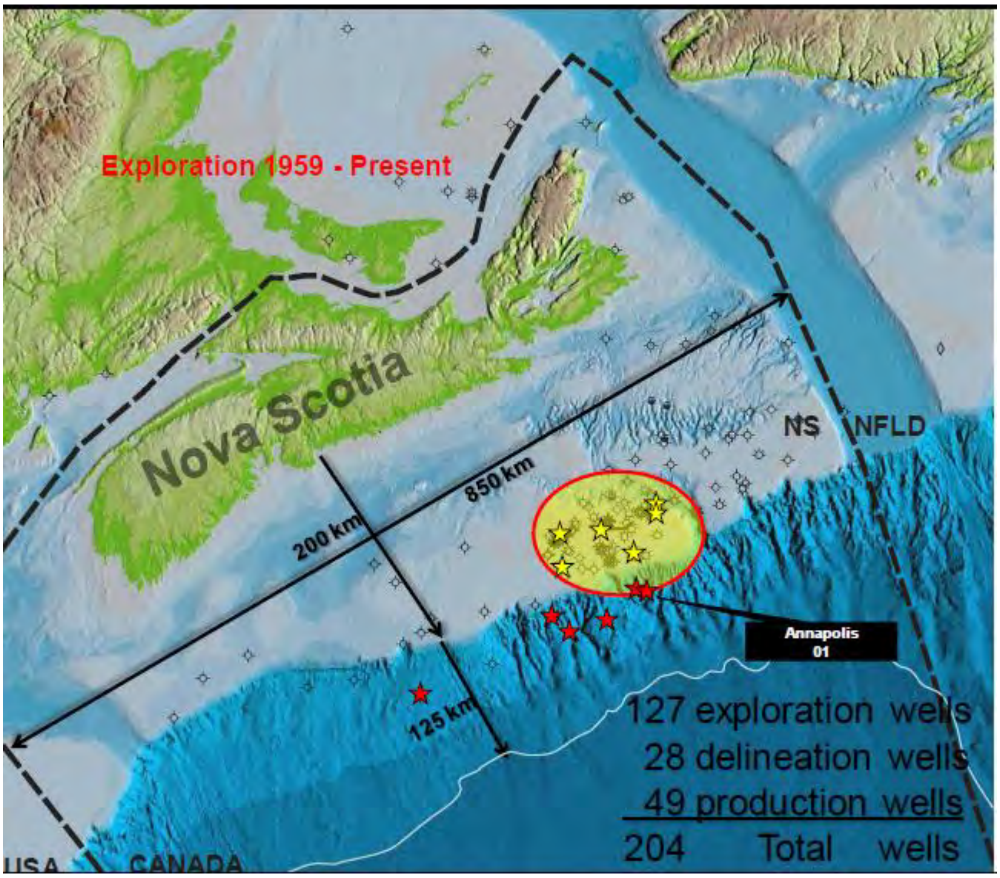


***Figure 1:*** *Play Fairway Analysis study area.*

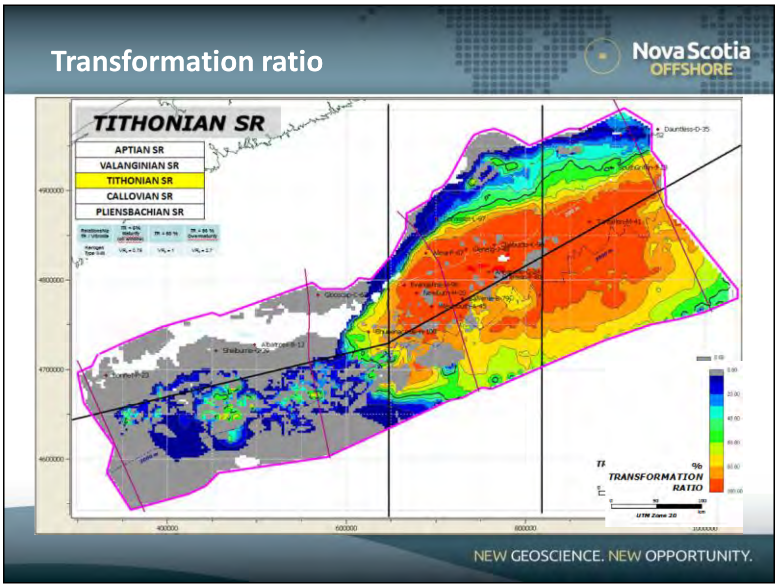


***Figure 2a:*** *Transformation for Tithonian source rock.*

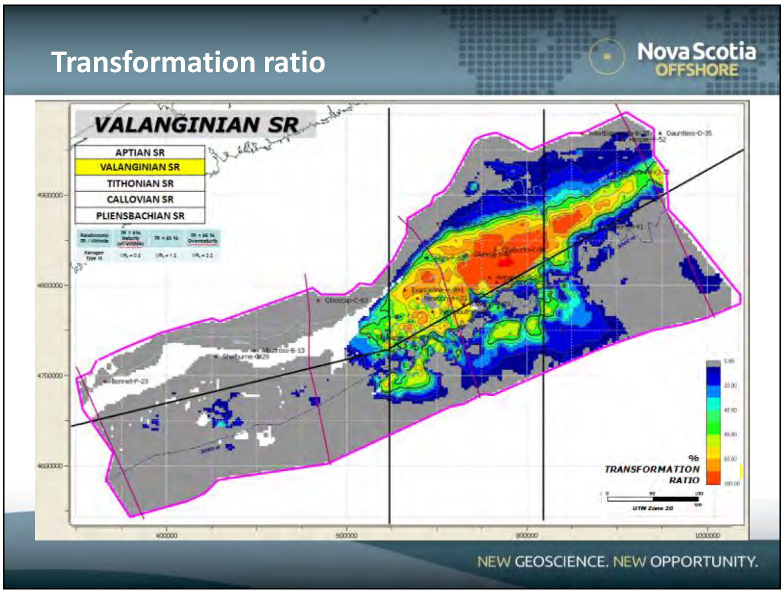


***Figure 2b:*** *Transformation for Valanginian source rock.*

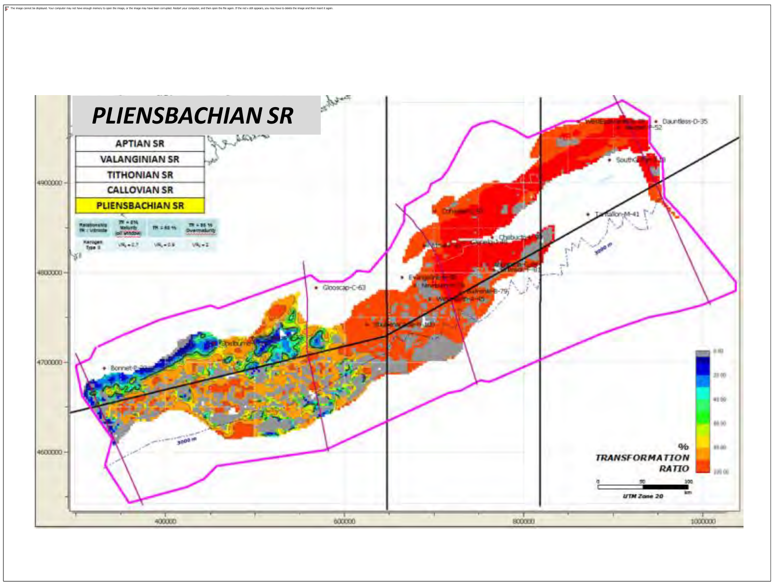


***Figure 3:*** *Transformation for Pliensbachian source rock.*

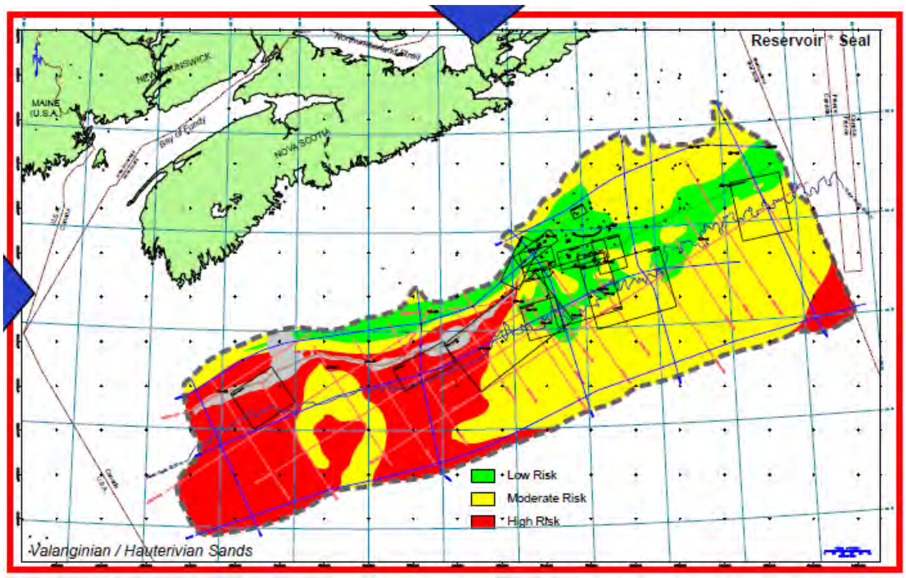


***Figure 4a:*** *Combined Common Risk Segment map for the Valanginian/Hauterivian play.*

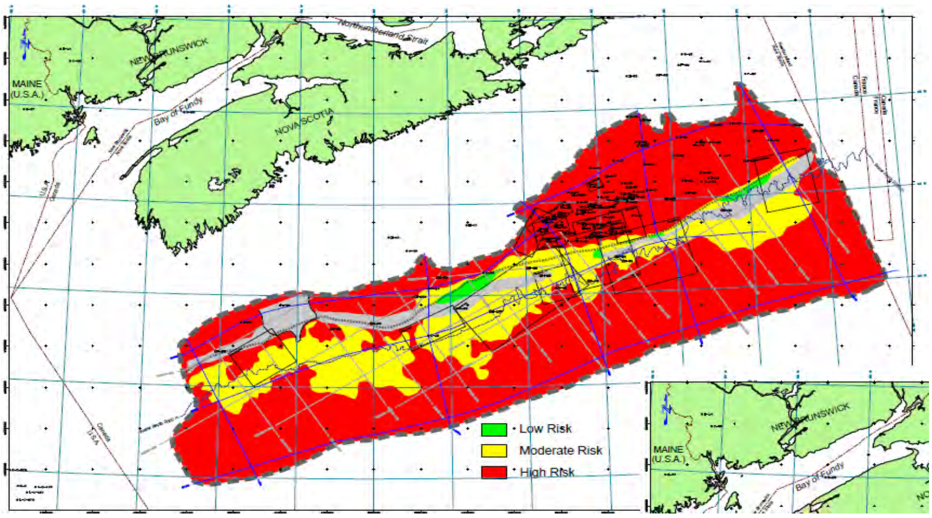


***Figure 4b:*** *Combined Common Risk Segment map for the Late Albian Low Stand play.*

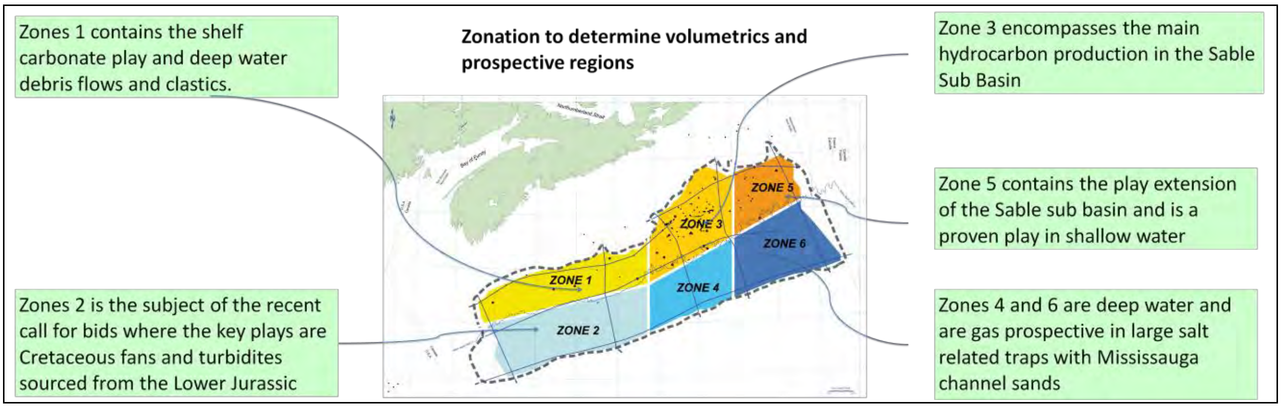


***Figure 5:*** *Zonation used for analysing the distribution of trapped in place hydrocarbon resource from 3D petroleum systems modelling.*

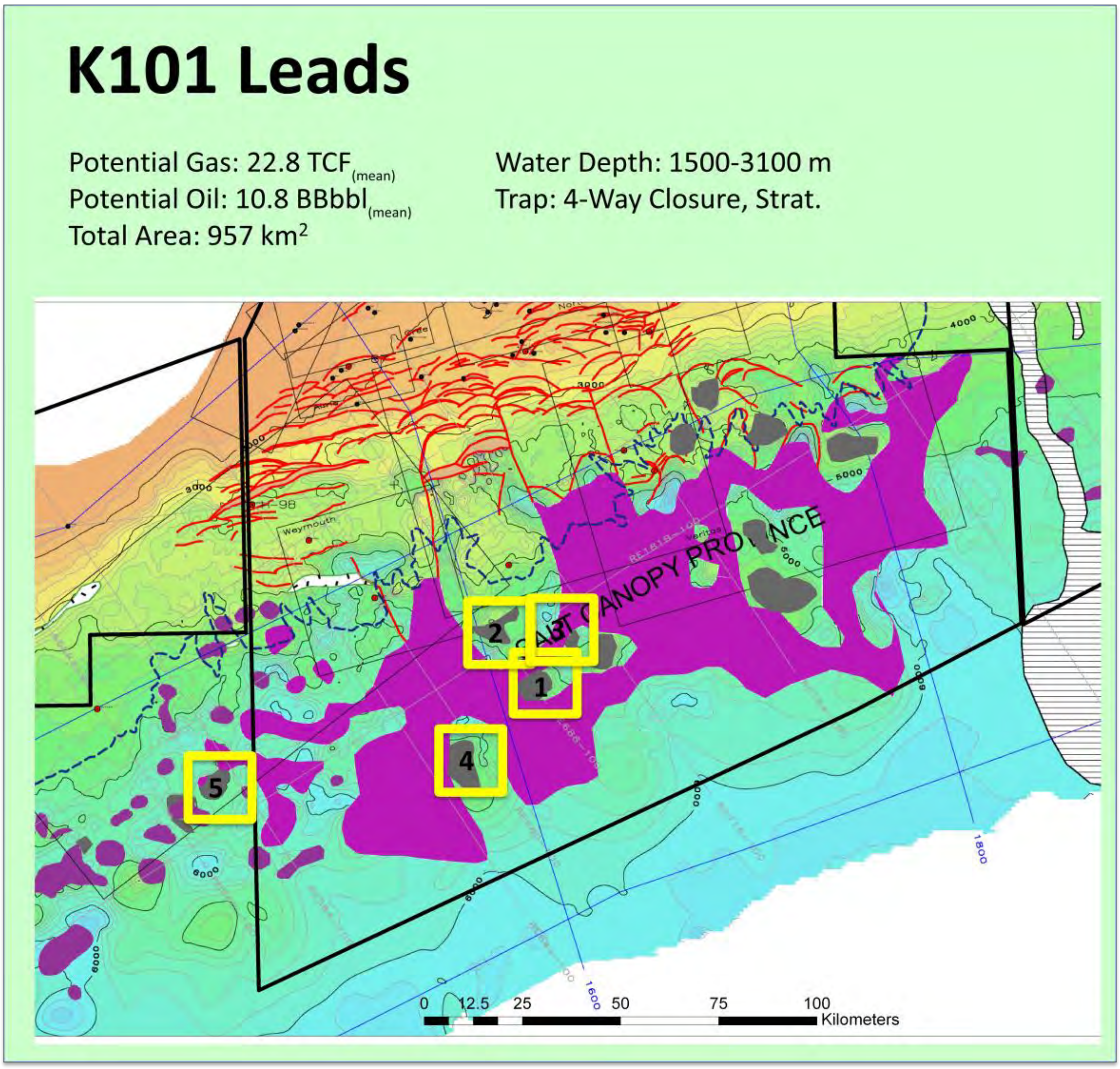


***Figure 6:*** *Five large leads identified through detailed seismic mapping in the Aptian-Barremian play interval.*

# Poster Presentations

# A NEW KINEMATIC PLATE RECONSTRUCTION OF THE NORTH ATLANTIC BETWEEN IRELAND AND CANADA: POSTER PRESENTATION

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A two-year government-sponsored research project to develop *A New Kinematic Plate Reconstruction of the North Atlantic between Ireland and Canada* is nearing completion. The new kinematic model project takes into account the wide range of geological processes responsible for basin development by incorporating interpretations of recently acquired industry seismic data and older seismic data (Whittaker *et al.,* this conference; Štolfová *et al.,* this conference) with analytical techniques that include 2D and 3D gravity inversion, flexural backstripping, fault restoration and forward modelling (Kusznir *et al.,* this conference), detailed local studies around the margin and deformable plate reconstruction analyses.

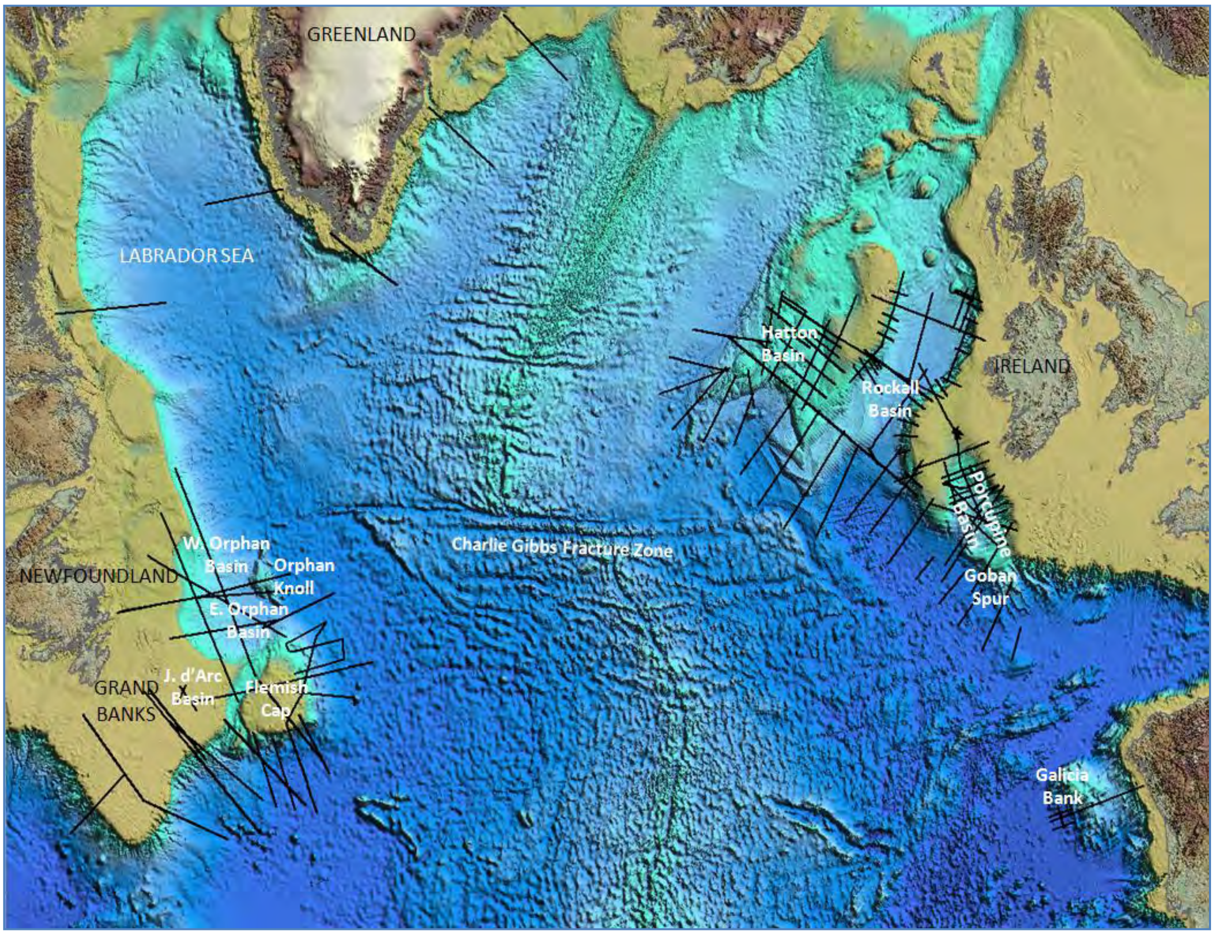


***Figure 1:** Bathymetry map showing the regional seismic database for the Irish and Newfoundland margins interpreted for the project.*

The new kinematic model has provided fresh insights into the evolution of the Ireland and Newfoundland margins. It has helped to identify potential source rock development at several intervals on the margins and predict the likelihood of source rock preservation. The integration of a deformable plate model with a plate kinematic model allows basins to be restored to their pre-breakup geometry prior to breakup and represents a major advance over the rigid plate models. Restored structure maps, palaeogeography maps, reconstructed pre-rift subcrop maps showing Carboniferous and structural trends, sediment source area maps, source rock and reservoir facies maps have been reconstructed to their palaeo-position.

These have been used to evaluate source rock and reservoir potential and provide us with an enhanced understanding of the major controls and mechanisms for basin formation and evolution in offshore Atlantic Ireland and offshore Newfoundland. Potential reservoir development has also been correlated with the main tectonic events and their distribution can be mapped and predicted more accurately using basins restored to their palaeo-geometry.

The deformable plate analysis provides techniques to back-strip Beta stretching factors (β) from total β derived from gravity inversion and other methods for time intervals associated with tectonic events. Major tectonostratigraphic sequences and tectonic events have been defined for the project and the amount of crustal extension is sub-divided into individual tectonic events or time intervals and converted to a stack of β grids (ßeta-Stack). These β grids are constrained both by the plate kinematic model and by all available onshore and offshore geological data. The ßeta-Stack forms the key component of the deformable plate model and can be fully integrated with the plate kinematic model.

The ßeta-Stack and new kinematic model enable us to produce a set of derived maps showing the distribution of source rock preservation. High extension factors result in highly rotated fault blocks, detachment faulting and even exhumation which result in removal and erosion of potential source rocks. This source rock preservation index can be quantified using deformable plates analytical techniques. The ßeta-Stack and new kinematic model also enable us to calculate detailed maps of strain rate for each major tectonic event. These maps show variations in strain rate across the basin. These strain rate maps can be used to determine heat flow which is used in basin modelling of source rock maturity.

**References**

Kusznir, N., Roberts, A., Alvey, A., Whittaker, R.C. & Štolfová, K. 2012. Crustal Structure, Subsidence History and Stretching within the Ocean-Continent-Transition of the Conjugate Ireland and Newfoundland North Atlantic Margins. *Abstract, Central Atlantic Conjugate Margins Conference, Dublin, 2012*.

Štolfová, K., Whittaker, R.C. & Shannon, P.M. 2012. New insights into regional Mesozoic and Cenozoic evolution of the Irish offshore continental margin. *Abstract, Central Atlantic Conjugate Margins Conference Dublin*, 2012.

Whittaker, R.C. 2012. Geological Constraints for a New Plate Reconstruction of the Newfoundland Continental Margin. *Abstract, Central Atlantic Conjugate Margins Conference Dublin*, 2012.

**Acknowledgements**

*This project is jointly funded by the Irish Shelf Petroleum Studies Group (ISPSG) of the Petroleum Infrastructure Programme and Nalcor Energy (on behalf of the Offshore Geoscience Data Program with the Government of Newfoundland and Labrador).*

## NUMERICAL MODEL INVESTIGATION OF SALT TECTONICS DURING CONTINENTAL RIFTING: EFFECTS OF CRUSTAL EXTENSION, MARGIN TILT, SALT FLOW AND SEDIMENT LOADING

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Evaporite deposition is common at rifted margins both during and shortly after syn-rift extension of the lithosphere. Although numerical and analogue models have been used to investigate both lithospheric deformation during rifting and salt tectonics without deformation of the underlying crust, there are few studies that combine both processes. Here we investigate the coupled system, particularly focusing on the effects of crustal deformation during extension, the accommodation available for evaporite deposition, syn-rift tectonic and thermal subsidence and tilting of the salt basins, and the flow of evaporite under the effect of tilting and loading by overlying sediments. We show, using 2D cross-sectional finite element models, that final salt geometry is strongly influenced by the strength of the crust, timing of salt deposition, and style of sedimentation both before and after salt deposition.

Previous studies have identified independent controls on lithospheric deformation during rifting and salt tectonics. In particular, it has been shown that the strength of the crust strongly influences the evolutionary style of rifted margins, with weak crust tending to produce wide, symmetric margins and strong crust narrow, asymmetric margins (Huismans and Beaumont, 2008). Considering salt tectonics, previous numerical experiments kinematically defined simple geometries for syn-rift salt basins or assumed salt deposition occurred after completion of extension and rifting (e.g. Albertz *et al.,* 2010). In both cases salt deformation was influenced by uneven sediment loading, with different deformation styles achieved through variations in sedimentation style, rate, and strength of the overburden. Aspects of the combined system have been studied using physical analogue experiments (e.g. Del Ventisette *et al.,* 2006), however these analyses are limited both by scaling of available materials, and geometry of the apparatus.

Numerical modelling of the coupled system poses a significant problem in that the model must consider lithospheric extension at the upper mantle scale and yet have sufficient resolution to calculate the geometry of the rift basins and salt deformation under relatively thin sediment loads. This is achieved by using nested (sub-grid) modelling in which a small-scale model, SS (resolution 1 km x 1 km) is embedded in a large, upper mantle scale model, LS (resolution 3 km horizontally by 4 km vertically).

We consider four controls on the deposition and deformation of salt during continental rifting: strength of the crust, timing of salt deposition, margin tilt, and differential loading by overlying sediments. Two end member lithosphere conditions were considered, in which the crust is strongly and weakly coupled to the mantle lithosphere (strong and weak crust, respectively). The resulting contrasting extension styles lead to isolated or continuous salt basins. Timing of salt deposition has a similar effect; deposition during the early syn-rift period is generally limited to isolated graben, while in the late syn-rift or early post-rift phases salt is deposited in laterally extensive, continuous sheets. Both strong crust and early salt deposition are associated with impeded lateral movement of salt in response to gravity and tilting, owing to the presence of intervening horst blocks. Weak crust and later salt deposition are conducive to lateral salt movement, due to either minimal roughness of the crust surface or smoothing of the basement by previous sediment deposition. Loading by post-evaporite sediments either helps expel the salt toward the distal margin, or traps the salt as diapirs (walls) between minibasins, depending on the progradational or aggradational style of the sedimentation. Figure 1 shows results for two models with strong crust, and contrasts salt deposition in the early and late syn-rift periods.

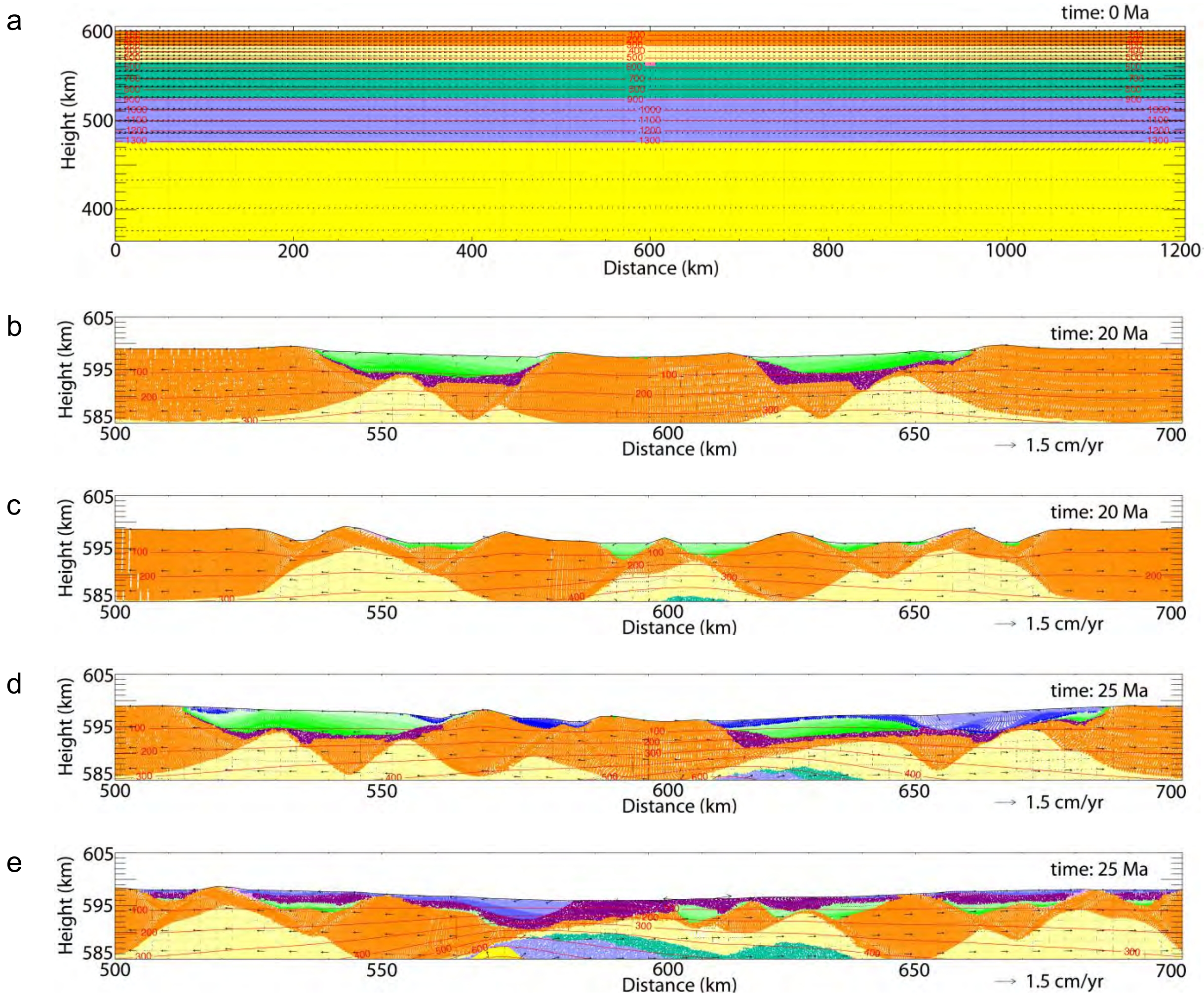


***Figure 1:*** *Early and late syn-rift deposition of salt, with subsequent progradation of clastic sediments, for a strong continental crust. The top panel shows the upper portion of the model domain, with continental crust shown in orange and sand, lithospheric mantle in blue and green, and sublithospheric mantle in yellow. Subsequent deformation at 20 Ma (b and c) and 25 Ma (d and e) is shown for the cases with early syn-rift salt deposition directly onto the continental crust (b and d) and late syn-rift salt deposition following early syn-rift clastic sediment deposition (c and e). In both cases salt deposition is followed by prograding clastic sediments. Salt is magenta, and clastic sediments have graded colouration in green and blue, to show internal structure.*

**References**

Albertz, M., Beaumont, C., Shimeld, J.W., Ings, S.J. & Gradmann, S. 2010. An investigation of salt tectonic structural styles in the Scotian Basin, offshore Atlantic Canada: 1: Comparison of observations with geometrically simple numerical models. *Tectonics*, **29**(4), TC4018.

Del Ventisette, C., Montanari, D. & Bonini, M. 2004. Basin inversion and fault reactivation in laboratory experiments. *Journal of Structural Geology, **28**, 2068–2083.*

Huismans, R.S. & Beaumont, C. 2008. Complex rifted continental margins explained by dynamical models of depth-dependent lithospheric extension. *Geology*, **36**, 163-166.

## IMPACT OF INCONSISTENT DENSITY SCALING ON PHYSICAL ANALOGUE MODELS OF CONTINENTAL MARGIN SCALE SALT TECTONICS

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The influence of inaccuracies in density scaling on the structural evolution of physical analogue experiments of salt systems has been debated, and is here investigated considering a gravity spreading example. Plane strain finite element numerical analysis was used to systematically evaluate the impact of changes in density scaling on buoyancy force, sediment strength, and pressure gradient. Distinct structural styles were observed for models with nature-equivalent densities and comparable models with densities typical of physical analogue experiments. The densities of typical analogue materials resulted in an overestimation of the buoyancy force and an underestimation of both sediment strength and pressure gradient which, combined, favoured the formation of diapir-minibasin pairs over an expulsion rollover structure.

Physical analogue models have been used extensively to study the deformation of salt under various applied loads and deformation constraints, and in particular as influenced by pressure gradients induced by sedimentation (e.g., Dooley *et al.,* 2007). These models have the distinct advantage that they can produce fully three-dimensional results. One limitation of the physical analogue models, however, lies in the availability of suitable materials with properties which can fulfil the requirements of dynamic scaling. Analogue models commonly use viscous materials, such as silicone elastomer, to represent salt (rocksalt, halite), and sand or other granular materials, which have a frictional-plastic rheology, to represent siliciclastic sediments, such as shale and sandstones. If we accept that sand and silicone have appropriate rheological properties which can be scaled to natural conditions, one potential problem remains in that the densities of sifted silica sand and silicone do not have the required dynamical similarity to the natural prototype in sedimentary basins. As recently as 2011, it has been argued that the density scaling in analogue models is acceptable (e.g. Brun and Fort, 2011) but little has been done to test this assertion.

This work examined the structural evolution of a simple salt system including an originally flat, rectangular salt basin onto which clastic sediments were prograded, for a range of densities typical of natural systems (including compacting sediment) and physical analogue experiments. A fundamental shift in the structure of the salt-sediment system, from diapir-minibasin pairs to expulsion rollover, was observed when sediment and salt densities were altered from values typical of physical experiments (1600 and 990 kg/m$^3$) (Weijermars and Schmeling, 1986) to those most often found in nature (1900-2300 and 2150 kg/m$^3$). Figure 1 demonstrates this shift in structural style. Experiments equivalent to physical analogue models but with reduced sediment density showed diapir-minibasin pair geometry, persisting to sediment densities of ~1300 kg/m$^3$. Salt burial by pre-kinematic sediments was found to suppress diapir formation for thicknesses greater than ~750 m (0.75 cm at the laboratory scale). The relative importance of disproportionately high buoyancy force, low sediment strength, and pressure gradient in physical experiments (all resulting from inaccuracies in density scaling) was investigated by isolating each of these errors in turn. Buoyancy was found to be most influential in the development of diapir-minibasin pairs versus expulsion rollover geometry. Finally, we demonstrate that dry physical analogue experiments with sediment density reduced to ~1140 kg/m$^3$ (possibly through mixing with ceramic beads) would provide a reasonable approximation of submarine salt systems in nature (including water load and hydrostatic pore fluid pressure).

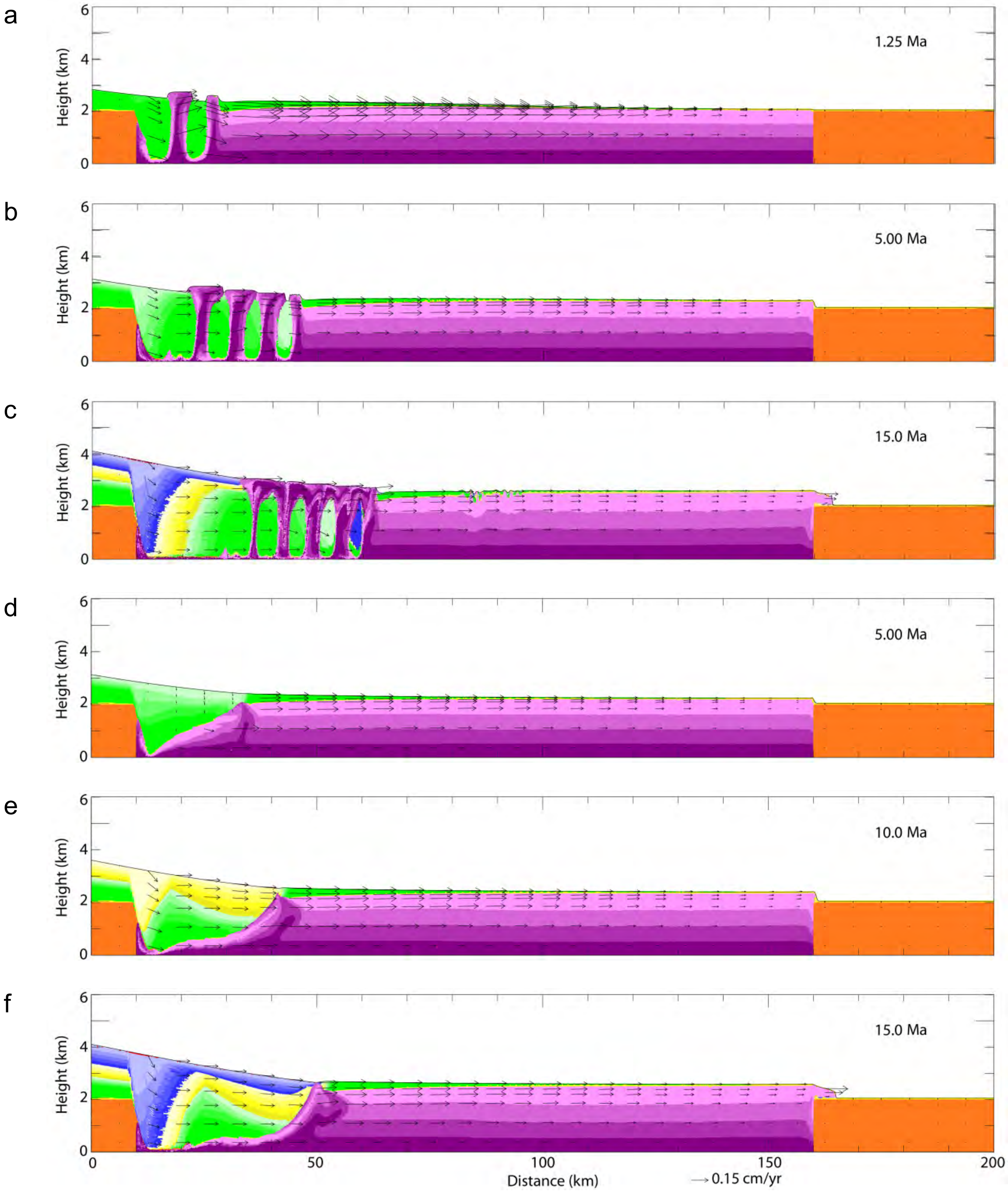


***Figure 1:*** *Deformation of salt and overlying sediments for experiments with salt and sediment densities typical of physical analogue experiments, 990 kg/m$^3$ and 1600 kg/m$^3$, respectively, (panels a-c), and nature-equivalent densities, 2150 kg/m$^3$ for salt, with compacting sediment (panels d-f). The former develops a series of minibasin-diapir pairs while the latter is characterised by an expulsion rollover. Salt is magenta, pre-kinematic sediments are orange, and prograding syn-kinematic sediments have graded colouration to show internal deformation.*

## References

Brun, J.P. & Fort, X. 2011. Salt tectonics at passive margins: Geology versus models. *Marine and Petroleum Geology,* **28**, 1123-1145.

Dooley, T.P., Jackson, M.P.A. & Hudec, M.R. 2007. Initiation and growth of salt-based thrust belts on passive margins: results from physical models. *Basin Research,* **19**(1), 165-177.

Weijermars, R.H. & Schmeling, H. 1986. Scaling of Newtonian and non-Newtonian fluid-dynamics without inertia for quantitative modelling of rock flow due to gravity (including the concept of rheological similarity). *Physics of the Earth and Planetary Interiors*, **43**(4), 316-330.

## EO-CRETACEOUS MAGMATISM ALONG SOUTH ATLANTIC CONJUGATE MARGINS DURING GONDWANA BREAKUP: PALEOSTRESS DATA FROM THOLEIITIC MAFIC DYKE SWARMS

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The tholeiitic to alkaline magmatism that affected the southwestern margin of Gondwana, prior to the complete separation of South America and Africa, is distributed over a wide area on both plates, comprising Brazil, Paraguay, Uruguay and Argentina (on the South American side) and South Africa, Lesotho, Botswana, Namibia and Angola (on the African counterpart). In this area the large igneous provinces (LIPs) of Paraná-Etendeka, the Karoo intrusives and several dyke swarms and magmatic centres show considerable differences in shape, size and chemical/mineralogic composition. The magmatic events are also widely distributed in time, ranging from the Upper Triassic (Rhaetian) to Early Cretaceous (Late Aptian/Early Albian).

We used dyke emplacement features to evaluate the paleostress field during the initial opening that resulted in Gondwana breakup. Kinematic indicators as asymmetric features were used to infer the sense and the amount of strike-slip component (SLC) relative to the normal extension associated with dyke emplacement. All dykes show an extension normal to the walls much larger than lateral displacements, but when it is consistent along individual dykes and across the dyke swarm, they were considered as indicators of oblique paleostress field. Hundreds of measurements were collected in the Eo-Cretaceous dyke swarms, mainly in coastal outcrops where both walls are exposed.

In the Brazilian margin the ages of the tholeiitic dyke swarms span a large time interval from ~193 Ma to ~112 Ma, and they are distributed along the coast between the Pelotas Basin in the south, towards Santos, Campos and Espírito Santo basins. Five main dyke swarms have been described in this area: Vitória-Colatina (VCDS), Serra do Mar (SMDS), Resende (RDS), Ponta Grossa-Guapiara (PGDS) and Florianópolis (FDS). The NW- to NNW-trending VDS and RDS record the oldest ages, from 193 to 144 Ma and the NNE- to NE-trending SMDS, PGDS and FDS intruded between 135 and 105 Ma.

In the African counterpart, at least four dyke swarms converge at Nuanetsi in southern Zimbabwe. Those are named: Okavango, Orange River, Olifants River and Lebombo. They form a giant linear structure across Botswana and they were previously interpreted as a failed branch of a rift triple junction centred over Nuanetsi. Radiometric dating of the Okavango Dyke Swarm (ODS) shows that it was emplaced within a short time interval between 178–181 Ma, therefore preceding the fragmentation of Gondwana. The magmatic record of the Paraná-Etendeka Large Igneous Province is well constrained in west Africa, spanning a very short time interval of about 1 to 2 m.y., with most radiometric ages concentrated at 131-132 Ma; and this also occurs in South America.

Tholeiitic dykes from the Kwanza basin in Angola are very similar to those of the Paraná-Etendeka province, both in age and composition. Two geochronologically distinct magmatic episodes were identified. The first magmatic pulse is represented by Early Cretaceous tholeiitic lava flows and dykes generated at ca. 132 Ma, which are found at the base of the sedimentary succession, and are coeval with the flood basalts of the Paraná- Etendeka province. The second episode consists of a tholeiitic magmatism represented by coast-parallel dykes that intruded the crystalline basement at 126 Ma. This event is contemporary to the coast-parallel dyke swarms of Florianópolis, Santos and Rio de Janeiro, along the South Atlantic continental margins, and it is possibly related to the precursory events that led to the rifting of the crust and the opening of the South Atlantic Ocean. Another event, which probably extends in time from Neocomian up to Late Aptian, is related to the emplacement of large wedges of seaward-dipping volcanic layers (seaward-dipping reflectors) that occur from Argentina to South Brazil and from South Africa to Namibia.

In the African margin the dyke swarms are mainly oblique to the coast line, as in southwest Angola. There, as well in the Resende area, it is observed that the concentration of magmatic centres and dykes is related to a high density of fractures and faults, characterising corridors of intense brittle deformation. These highly fractured corridors constitute crustal weakness zones that were recurrently reactivated, as observed in the Okavango and Florianópolis dyke swarms. These crustal weakness zones are mostly controlled by discontinuities in the basement produced by ductile shear zones, sutures and lithological boundaries. The rifting process started as triple junctions situated mainly in orogenic belts and follow them northwards. The failed arms of Vitória-Colatina, Resende-Ilha Grande, SW-Angola, and Ponta Grossa-Guapiara, and the alkaline centres of Jacupiranga Complex, Namibian and Santa Catarina were also controlled by previous weakness zones, predominantly within orogenic belts.

In the VCDS only one clear dextral SLC was recognised, and none in the RDS. In these two dyke swarms only the normal extension was considered. In the SMDS there is a clear sinistral SLC, especially in the northern portion. In PGDS the SLC was predominantly dextral, although based on a small number of observations. In the FDS the lateral displacement is ambiguous, including both sinistral and dextral kinematic indicators, thus normal extension is inferred.

The Late Jurassic NNW-trending VDS and RDS developed with sub-horizontal $\sigma 3$ tensor at ~ N70, configuring an E-W extension. The Early Cretaceous SMDS, PGDS and FDS swarms are displayed as a triple junction with sub-horizontal $\sigma 3$ at ~ N100. The NW-trending PGDS underwent dextral extension, but remained as a failed arm. In the SMDS and FDS dykes become progressively abundant and younger towards offshore, indicating an increasing lithospheric thinning extension from ~135 Ma to the final breakup, and the initiation of organised spreading in the mid-ocean ridge at ~115 - 105 Ma, as suggested by the reduced number of radiometric ages younger than 115 Ma. Magmatism in the incipient continental margin between SE Brazil and West Africa ceased by ~105 Ma (Early Albian), when it was flooded by the shallow waters of an elongated gulf and carbonate sedimentation replaced the evaporites that were deposited in the late Aptian.

## CHARACTERISATION AND CORRELATION OF QUATERNARY SEDIMENTS IN THE DEEP ROCKALL TROUGH, NE ATLANTIC

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The Rockall Trough is a NE-SW oriented, deep-water bathymetric depression lying west of Ireland and the UK. It is an important oceanographic gateway in the North Atlantic circulation system, and the anti-clockwise circulation pattern has been important in the shaping of the margin through contour current sedimentation and erosion on the basin floor and margins. A striking feature of the north-western margin of the Rockall Trough is the Rockall Bank Mass Flow, a large submarine landslide covering 24,000 km$^2$. On the northeastern margin of the Rockall Trough lies the Donegal/Barra Fan, a large trough-mouth fan formed by remobilisation of sediment carried to the shelf break by drainage associated with the British Irish Ice Sheet.

This research is focused on the morphology and distribution of distal flow deposits, aiming to identify the sources of Quaternary sedimentation in the area and to distinguish the interplay of downslope transport and alongslope oceanic circulation systems. The poster presents the results of correlation of seven cores selected from approximately 24 cores, each up to 4 m in length, collected from the deepest part of the Rockall Trough during *RV Celtic Explorer* cruise CE10008 in 2010. They are organised in two intersecting transects: a NW-SE orientated transect of approximately 100 km length which follows the axis of the Rockall Trough and a NE-SW orientated transect of 60 km length perpendicular to the axis of the Rockall Trough. Core correlation was made using sediment colour, grain size distribution, relative stratigraphic position, physical properties (obtained from multi-sensor core logging) and geochemical composition (obtained from XRF-ITRAX). Additionally, radiographs were used to study the internal sedimentary structures.

Three facies have been identified:

Facies 1 comprises brownish/greyish clays, presents low density and low magnetic susceptibility and is subdivided into: i) heavily bioturbated light brown muds rich in Ca and Sr, and ii) dark brown/grey muds, rich in Fe but low Ca content, occasionally containing pebbles and lithic fragments characterised by high magnetic susceptibility. Due to the large size of lithic fragments and pebbles they cannot have been transported by ocean currents, and are thus interpreted as having been carried by icebergs. This facies is interpreted as hemipelagic sediments.

Facies 2 comprises graded beige and grey to dark grey sands and silts, 1-40 cm thick, usually with high density and high magnetic susceptibility. Beds commonly have sharp basal contacts, sometimes erosional, and also sharp top contacts. Facies 2 is interpreted as deposits of turbidity currents that are probably winnowed by strong bottom currents generating the sharp top contacts. Two different turbidites have been identified based on the colour and geochemistry of this facies. The geochemical composition of these turbidites, was obtained based on the correlations with turbidites geochemically described by Georgiopoulou *et al.* (2011), therefore T1 is defined as a foraminiferal sand with high content in glauconite, Sr and Ca, whereas T2 is rich in Si and Ti.

Facies 3 comprises compact muds which are characterised by a distinctive light colour interbedded in darker-coloured hemipelagic deposits and by high density and magnetic susceptibility peaks. This facies is disposed as one single layer of 1-2 cm thick and it contains high carbonate and manganese. The physical properties, combined with the high carbonate content, suggest it may be a Heinrich layer, which would have derived from a massive discharge of ice from the British Irish Ice Sheet. Heinrich layers are commonly found in the North Atlantic associated with Northern Hemisphere ice discharges during cold events within the last glacial period and are characterised by the presence of detrital carbonate (limestone and dolomite).

In this study three hemipelagic layers, the two facies 2 turbidite deposits and the light-coloured facies 3 muds were correlated with confidence between several of the cores along distances from 40 to 110 km. The analyses of geochemical composition and physical properties combined with changes in thickness of turbidites, have allowed us to track the slope failure deposits towards the likely sources on the Rockall Trough margins. One of the sources was located in the northwest margin of the Rockall Trough, possibly associated with the Rockall Bank Mass Flow, whereas the other source was located in the northeastern margin likely linked with the Donegal/Barra Fan. However this is an ongoing project and additional core transects will be used to better understand the 3D architecture in order to evaluate likely sediment transport pathways. The sharp top contact of the turbidites provides evidence of the importance of erosion by bottom currents and the interplay between downslope and alongslope processes that has occurred during the Quaternary, but more cores are required to understand the architecture of the slope failures, the direction of the flow, and to determinate the erosion generated by bottom currents.

### Reference

Georgiopoulou, A., Benetti, S., Shannon, P.M., Haughton, P.D.W. & McCarron, S. 2011. 'Gravity Flow Deposits in the Deep Rockall Trough, Northeast Atlantic' *In:* Yamada, Y., Kawamura, K., Ikehara, K., Ogawa, Y., Urgeles, R., Mosher, D., Chaytor, J. & Strasser, M (eds). *Submarine Mass Movements and their Consequences*. Advances in Natural and Technological Hazards Research, **31**. Springer Science and Business Media: Dordrecht, Holland, 695-707.

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## NORTH ATLANTIC CONJUGATE MARGIN SEISMIC RECONSTRUCTIONS

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### Summary

A new exploration strategy is being developed around the world using conjugate margins. This is not a new idea but recent drilling success has highlighted the fact that the geologic model for the discovery has a geologic model in its conjugate margin. The advance of plate reconstruction models has further enhanced the understanding of the conjugate margin and has allowed a sense of direction to the explorationist. A sense of direction that is defining the exploration strategy, not only for the exploration teams, but for companies and governments in general to understand the depositional geologic models of the North Atlantic conjugate margin.

### Introduction

Petroleum Geo-Services (PGS) is working with TGS/Nopec and Getech to study this new exploration concept. The aim is to focus on the geological models associated with the conjugate margins and define the exploration fairways of these plays in the North Atlantic. In the North Atlantic conjugate margin alone, PGS/TGS will acquire up to 22,000 km 2D GeoStreamer East Coast Canada and PGS has access to 10,000 sq km 3D and 60,000 km 2D in the Atlantic Margin Irish Sea (Figure 1). Getech provides the Global Plate Model (Figure 2) which has information on basin geodynamics, juxtaposition of play elements, boundary conditions for palaeo-geographic mapping and reconstruction of exploration data (including seismic). The combination of the two will highlight proven conjugate margin geologic models and prospectivity.

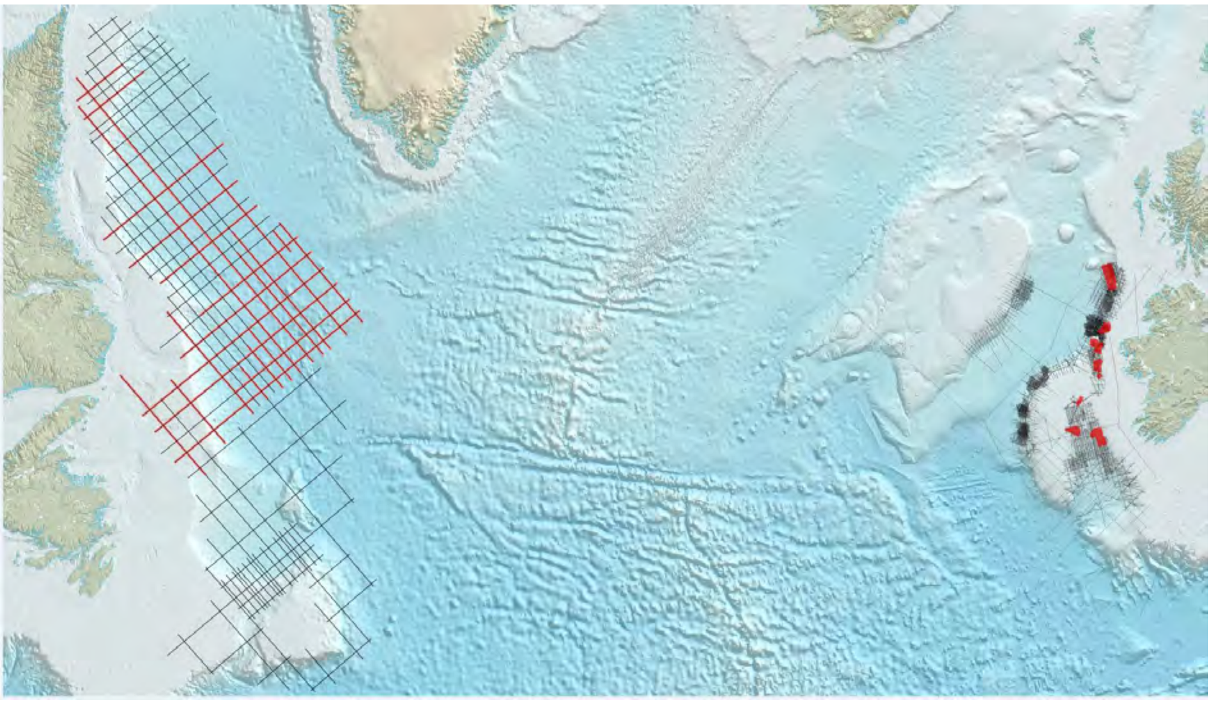

***Figure 1:*** *Seismic data conjugate margin.*

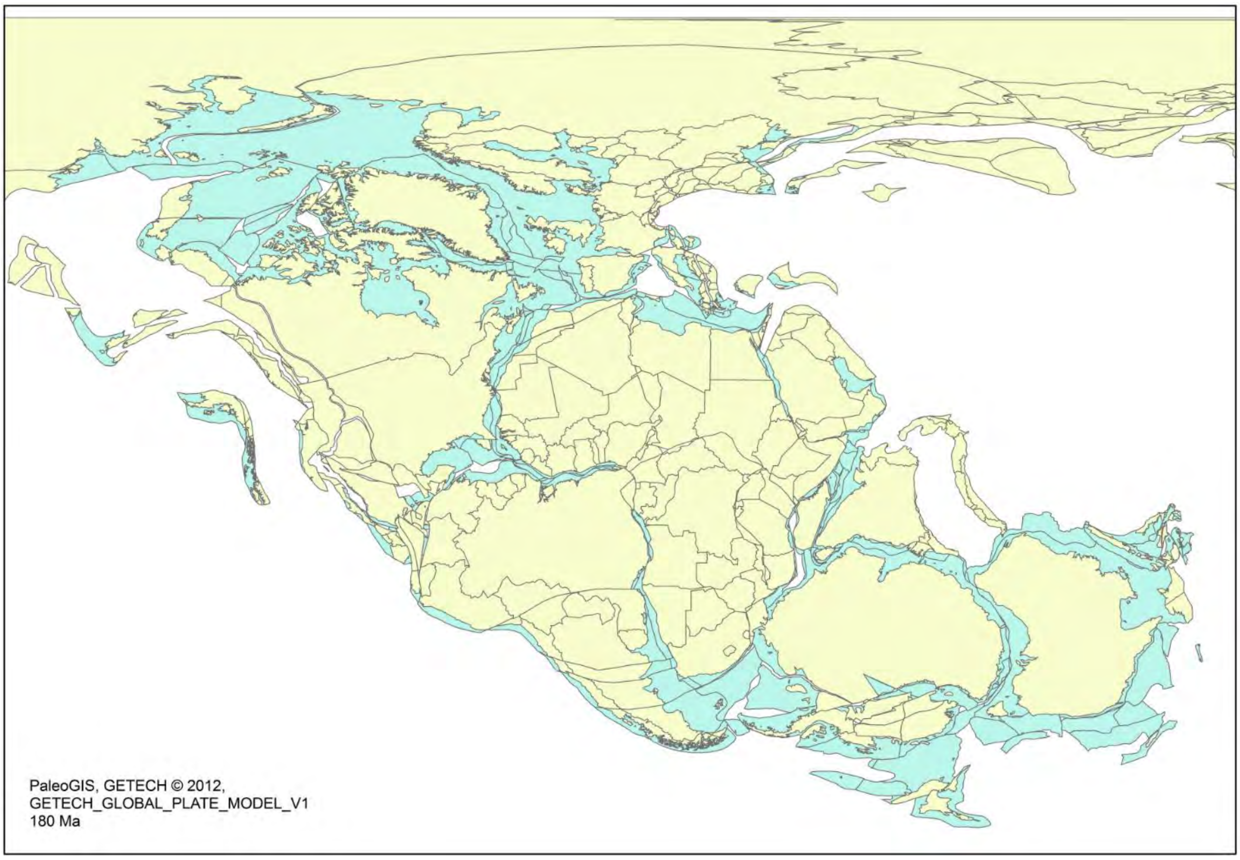


***Figure 2:*** *Getech Global Plate Model.*

**Method**

Using the existing seismic data, global palaeo-reconstructions were done starting from the initiation of rifting and displayed for present day, 50, 90, 100, 150, 200, 250, 300 Ma year intervals. Existing seismic data positions were reconstructed back in time to what their positions would have been at each of these date intervals along with published basin configurations (Figure 3). Seismic data that lines up at time of deposition will be interpreted focusing on the prospectivity of the specified geologic model. Fixing the geologic model at time of deposition will outline the fairway of prospectivity. Templates will be constructed of successful conjugate margin discoveries creating a database of proven conjugate models.

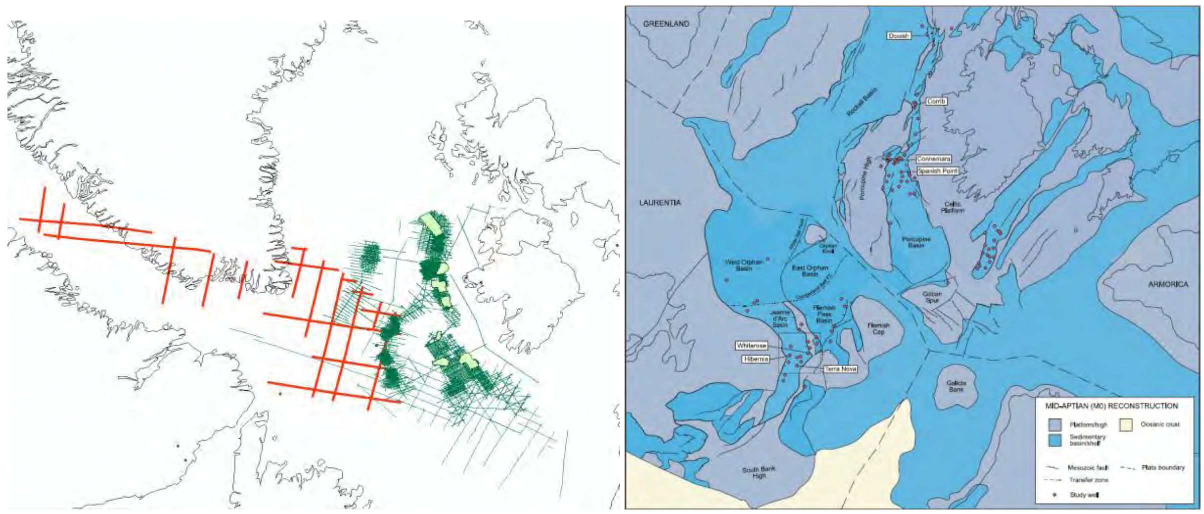


***Figure 3:*** *Reconstructed 2011 Canada GeoStreamer/Atlantic Margin Irish Sea Data and basin configurations.*

## Examples

Template examples will be shown from existing discoveries. The existing discoveries are located in the Porcupine Basin offshore western Ireland and the Jeanne D'Arc Basin offshore eastern Canada. Discoveries in these basins include White Rose (283 mmbbls, 2.7 tcf), Hibernia (865 mmbbls, 1.32 tcf) and Terra Nova (354 mmbbls) in the Jeanne D'Arc Basin and Spanish Point (160 mmbbls, 1.4 tcf) and Connemara (200 mmbbls) in the Porcupine Basin. These templates will outline the remarkable similar geologic models of these plays at deposition before and after rifting. Seismic reconstruction examples (Figure 4) will also be shown to outline the similar geology from one margin to another.

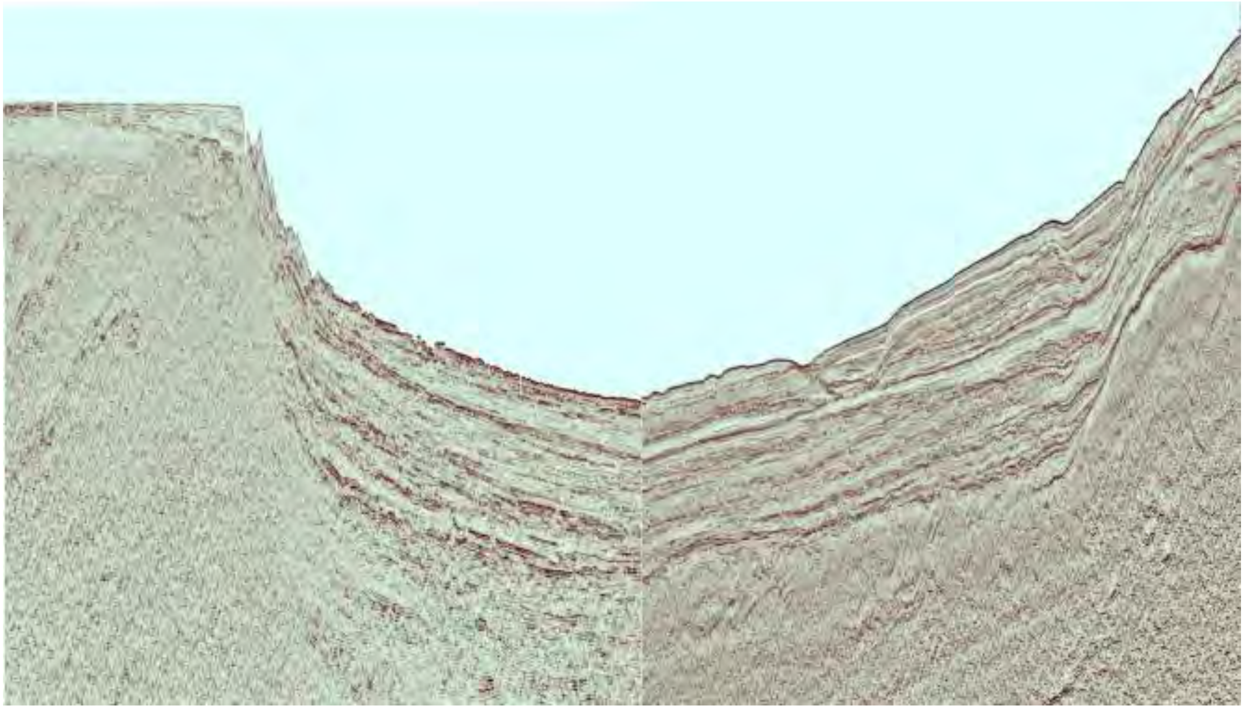

***Figure 4:*** *Representative example of reconstructed seismic across a conjugate margin.*

## Conclusions

Conjugate margin prospects are proven and prolific in their reserve potential. Understanding the geologic model and reconstructing the deposition history of the play can give great insights into the regional extent and structural framework of the North Atlantic. This geologic understanding is very important and lessens the risk in the exploration strategy. A successful exploration strategy is the key to finding reserves. Seismic reconstructions show the remarkable consistency of the geologic model on both sides of the conjugate margin. This consistency is already proven by the discoveries made on each side of the North Atlantic.

### References

Markwick, P. 2011. Tectonics, Geodynamics and Landscapes: *Setting the Framework for New Ventures Exploration*, Presentation: Prospectivity Workshop, London, UK.

Irish Petroleum Affairs Department, License Round Promotional Material, 2011.

### Acknowledgements

We would like to thank Petroleum Geo-Services, TGS-Nopec & Getech for permission to publish this work and also the many contributors within both organizations.

## CONJUGATE MARGINS: AN EXPLORATION STRATEGY

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### Summary

A new exploration strategy is being developed around the world using conjugate margins. This is not a new idea but recent drilling success has highlighted the fact that the geologic model for the discovery has a geologic model in its conjugate margin. Plate reconstruction models have further enhanced the understanding of the conjugate margin and have provided a sense of direction for the explorationist. This sense of direction helps to define exploration strategy, not only for the exploration teams, but for companies and governments in general.

### Introduction

Petroleum Geo-Services (PGS) is working with Getech to study this new exploration concept. The aim is to focus on the geological models associated with the conjugate margins and define the exploration fairways of these plays in the South Atlantic, Equatorial Margin and North Atlantic. PGS has extensive seismic coverage both 2D and 3D. In the South Atlantic Conjugate Margin alone, PGS has access to 200,000 sq km 3D and 300,000 km 2D in Brazil and 180,000 sq km 3D and 35,000 km 2D in West Africa (Figure 1). Getech provides the Global Plate Model (Figure 2) which has information on basin geodynamics, juxtaposition of play elements, boundary conditions for palaeo-geographic mapping and reconstruction of exploration data (including seismic). The combination of the two will highlight proven conjugate margin geologic models and prospectivity.

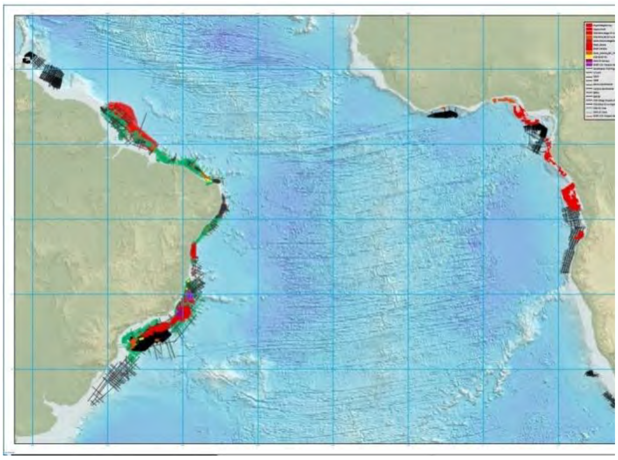

***Figure 1:*** *Seismic data Conjugate Margin.*

***Figure 2:*** *Getech global plate model.*

### Method

Using the existing seismic data, global palaeo-reconstructions will be done starting from the initiation of rifting and displayed for 105, 110, 115, 118, 120, 122 Ma year intervals. Existing seismic data positions will be reconstructed back in time to what their positions would have been at each of these date intervals (Figure 3). Seismic data that lines up at time of deposition will be interpreted focusing on the prospectivity of the specified geologic model. Fixing the geologic model at time of deposition will outline the fairway of prospectivity. Three conjugate margin areas will be looked at for this study. These are the South Atlantic, Equatorial Margin and North Atlantic. This presentation will focus on the South Atlantic and Equatorial Margins with some discussion on the North Atlantic. Templates will be constructed of successful conjugate margin discoveries creating a database of proven conjugate models. A prospectivity database will also be created to show the fairways of specific geologic reservoir facies - a fairway that can be used for an exploration strategy, capital business plans or government planning of resources.

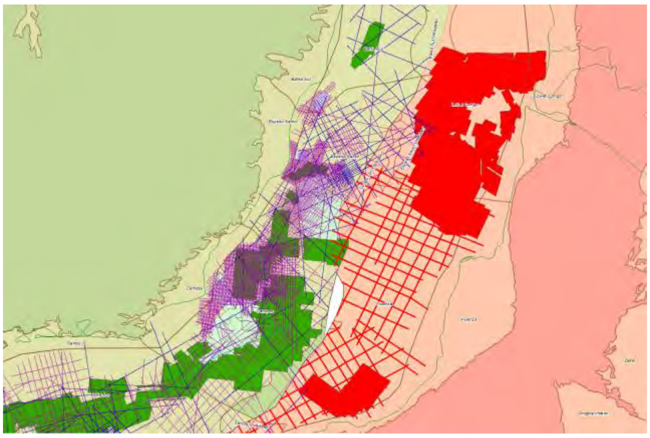

***Figure 3:*** *Reconstructed seismic to Aptian Time.*

## Examples

Template examples will be shown from pre-salt discoveries and post-salt discoveries. The pre-salt will include the Lulu Field offshore Brazil (Oolitic Carbonate 5-8 bbls) and associated discoveries in Gabon by Harvest and Angola by Maersk and Cobalt. The post-salt will include the Jubilee Field Offshore Ghana (Turonian Sandstone 1 billion bbls) and associated discovery in French Guiana of the Zaedyus Field by Tullow. These templates will outline the remarkable similar geologic models of these plays at deposition before and after rifting. Prospectivity examples will also be shown in the presentation to outline the potential that exists for conjugate margin plays. Prospects will be shown in the South Atlantic, Equatorial Margin and North Atlantic to give evidence of the large regional extent, consistent geologic model and defined fairway. This is a tool that can be used to define an exploration strategy.

## Conclusions

Conjugate margin prospects are proven and prolific in their reserve potential. Understanding the geologic model and reconstructing the deposition history of the play can give great insights into the regional extent and structural framework. This geologic understanding is very important and lessens the risk in the exploration strategy. A successful exploration strategy is the key to finding reserves. A company needs a strategy that is regional and offers multiple opportunities to find success. A portfolio of prospects is only as good as the growing inventory past what the company is currently working on. An exploration strategy needs to feed the inventory with low risk high reward opportunities. The conjugate margin offers the scope for prospects. Governments can also benefit from understanding their conjugate margins. It helps them focus on what blocks to license, defines the resource plan and promotes the drilling and production of reserves. The resulting revenue stream aids the country. The extent of the conjugate margin idea on exploration strategy is vast. It affects the geoscientist, exploration team, company and governments. There have been regional geologic models but none that offer a worldwide calibre opportunity.

### References

Markwick, P. 2011. *Tectonics, Geodynamics and Landscapes: Setting the Framework for New Ventures Exploration,* Presentation: Prospectivity Workshop, London, UK.

### Acknowledgements

We would like to thank Petroleum Geo-Services & Getech for permission to publish this work and also the many contributors within both organizations.

## POTENTIAL FOR LACUSTRINE SOURCE ROCKS IN TRIASSIC SYNRIFT BASINS OFFSHORE EASTERN NORTH AMERICA

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Recent discoveries of super giant pre-salt oil fields in Brazil's offshore basins, and related discoveries in its African conjugates, have highlighted the great importance of synrift / pre-breakup fluvial-lacustrine successions to the success and efficiency of the petroleum systems. Improvements in seismic acquisition and processing technologies were keys in imaging the architecture of the underlying rift basins, and interpreting the basin fill and internal depositional facies later confirmed by drilling.

Middle Triassic to Early Jurassic age synrift basins are exposed onshore eastern North America (Newark Supergroup) and extend into adjacent offshore areas. Equivalent basins are found in Morocco / Northwest Africa (Figure 1). Organic-rich lacustrine successions occur in a number of the onshore U.S. synrift basins although no commercial discoveries have been made. However, hydrocarbon shows in outcrops and a few wells are documented confirming that a working petroleum system existed at some point in time.

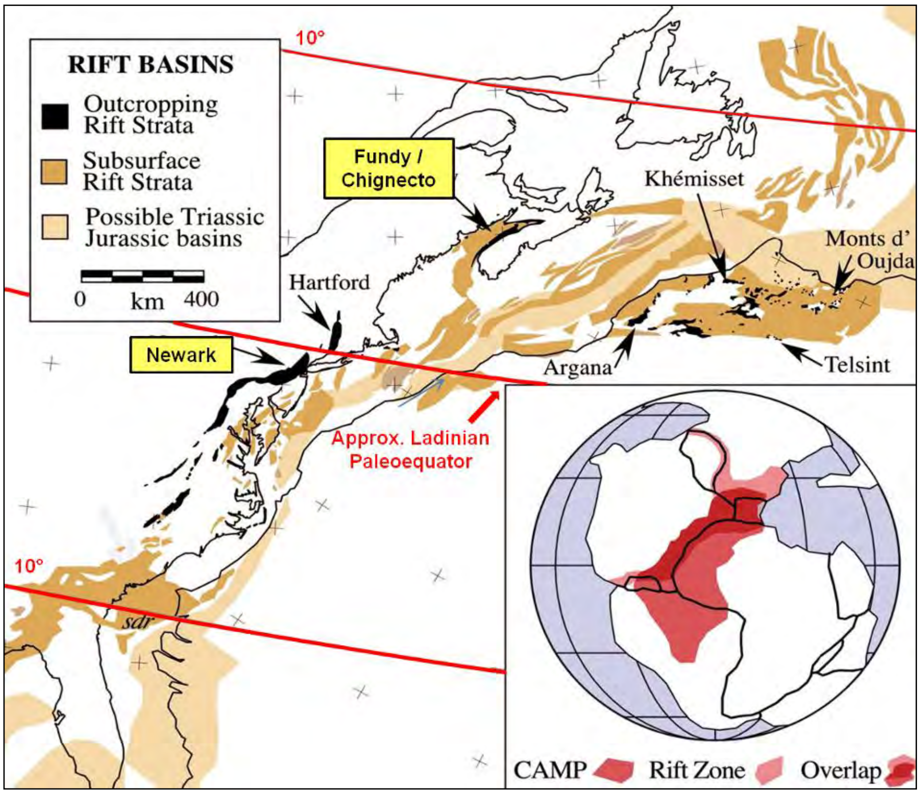


*Figure 1: Plate reconstruction and distribution of synrift basins of the Central Atlantic at the end of the Triassic. Revised palaeo-latitudes for approximately Ladinian time (modified after Olsen, 2010; Olsen & Et-Touhami, 2008).*

The basin-fill model for these extensional basins' sedimentary successions defines four tectonostratigraphic (TS) units (Olsen 1997). TS-I is an unconformity-bounded, early synrift fluvial-lacustrine sequence of Late Permian age. TS-II is composed of dominantly fluvial (and some lacustrine) strata believed representative of an underfilled, hydrologically-open basin (subsidence < sedimentation). This is followed by either a closed basin or one in hydrological equilibrium (subsidence ≥ sedimentation) dominated by lacustrine (TS-III) and later playa / lacustrine (and basal CAMP volcanics) successions (TS-IV). The lacustrine facies - especially in TS-III - are known to be exquisite recorders of palaeoclimate, and with palaeomagnetic data refine the determination of the basins' palaeo-latitudinal positions.

Seismic profiles in the Fundy / Chignecto (Canada) and Newark (USA) basins reveal high amplitude, laterally continuous reflections adjacent to the respective boarder faults. They are distal to TS-II fluvial successions and interpreted to represent deepwater fine grain lacustrine facies. This architecture would infer high levels of tectonically-driven extension resulting in the basins being closed from their inception (subsidence ≥ sedimentation) and facilitating lake formation as proposed by Leleu and Hartley (2010). At the time of TS-II deposition in the Middle to Late Triassic (approximately late Anisian to early Carnian), palaeomagnetic data would place these basins within a north equatorial humid belt (Figures 1 & 2). This tropical location would place these basins in a position favourable for the evolution of lakes with conditions for organic matter creation and preservation. If correct, this interpretation would have a significant impact on the potential for hydrocarbons sourced from lacustrine successions in pre-salt syn-rift basins offshore Nova Scotia and Morocco.

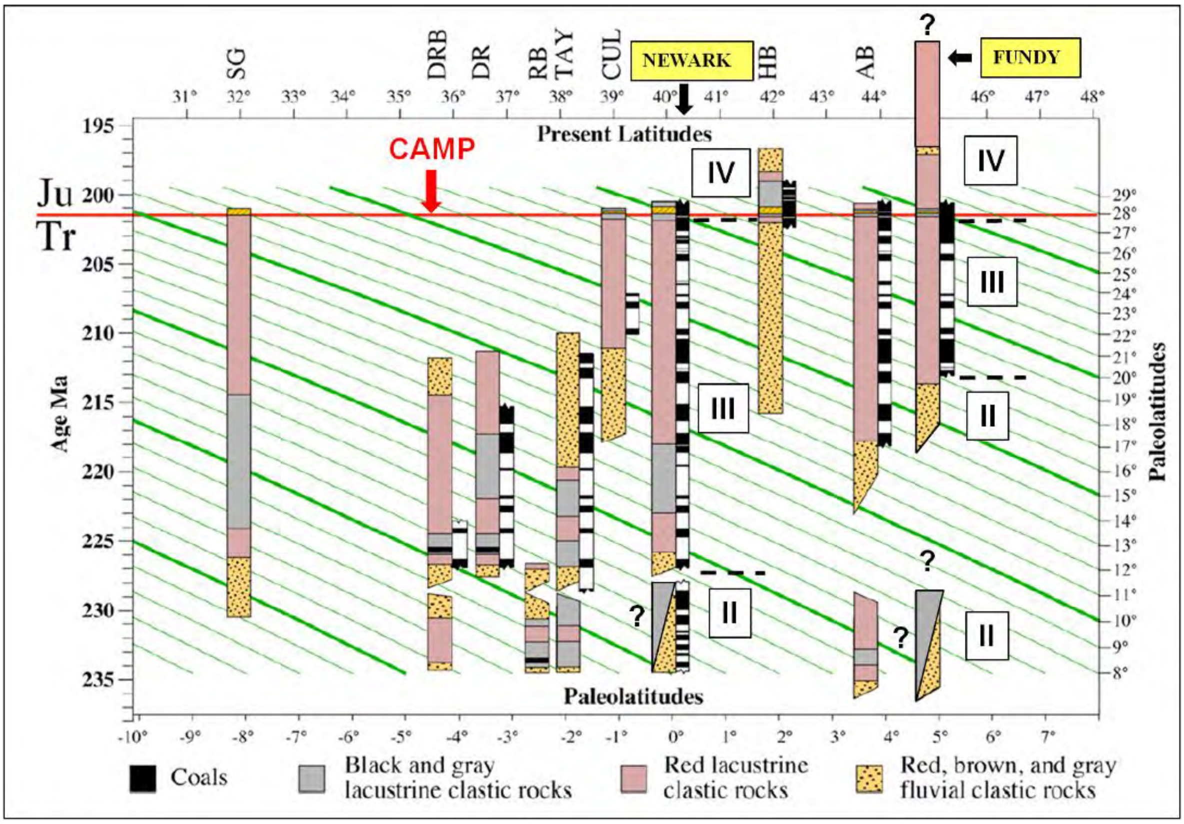


***Figure 2:*** *Time / geography nomogram for the Newark Supergroup, eastern North America illustrating the response of sedimentation through time and northward plate movement. Fundy Basin TS-II successions are shown to have been deposited within the 4-8°N palaeo-latitude tropical belt in the late Middle Triassic (Ladinian). Seismic attributes in the lower TS-II units of the Newark (Stockton Fm.) and Fundy (Wolfville Fm.) basins are interpreted to be lacustrine facies. At least 3000 m of post-CAMP strata (McCoy Brook Fm.) were deposited in the Fundy Basin that may be as young as Aalenian (Wade et al., 1996) (modified after Olsen & Et-Touhami, 2008).*

**References**

Leleu, S. & Hartley, A.J. 2010. Controls on the stratigraphic development of the Triassic Fundy Basin, Nova Scotia: implications for the tectonostratigraphic evolution of Triassic Atlantic rift basins. *Journal of the Geological Society,* **167**, 437-454.

Olsen, P.E. 1997. Stratigraphic record of the early Mesozoic breakup of Pangea in the Laurasia-Gondwana rift system. *Annual Reviews of Earth and Planetary Science* **25**, 337-401.

Olsen, P.E. 2010. Fossil great lakes of the Newark Supergroup – 30 years later. *In:* Benimoff, A.I. (ed) *Field Trip Guidebook*, New York State Geological Association, 83rd Annual Meeting, College of Staten Island, New York, 101–162.

Olsen, P.E. & Et-Touhami, M. 2008. Field Trip #1: Tropical to subtropical syntectonic sedimentation in the Permian to Jurassic Fundy rift basin, Atlantic Canada, in relation to the Moroccan conjugate margin. *Central Atlantic Conjugate Margins Conference, Halifax, Nova Scotia, Canada, 2008*, *Abstracts Volume,* 121p.

Wade, J.A., Brown, D.E., Fensome, R.A. & Traverse, A. 1996. The Triassic-Jurassic Fundy Basin, Eastern Canada: regional setting, stratigraphy and hydrocarbon potential. *Atlantic Geology*, **32(3)**, 189-231.

## JURASSIC SUBSIDENCE VARIATIONS IN THE CENTRAL SECTOR OF THE LUSITANIAN BASIN (PORTUGAL) – THE ROLE OF THE MAIN FAULTS

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The Lusitanian Basin was initiated during a late Triassic rifting phase and belongs to a family of periatlantic basins (e.g. Jeanne d'Arc Basin, Scotia Basin). It is located on the Portuguese part of the Western Iberia margin and was developed during the Mesozoic. The sedimentary infill of the Lusitanian Basin is mainly composed of Jurassic sediments. During Early Jurassic marly sedimentation predominated, becoming gradually more carbonated towards the Middle Jurassic. The transition to the Upper Jurassic is marked by a basinwide unconformity and hiatus, with a major change in basinal configuration. Siliciclastic sedimentation increased and sub-basins (Bombarral, Turcifal and Arruda – Figure 1) developed from Oxfordian to Kimmeridgian. Since the Late Cretaceous, the western border of the Iberian Plate suffered a compressive deformation that led to a progressive inversion of the central axis of the basin.

This study provides a regional interpretation about thickness variations in different Jurassic depocentres, based on detailed information from 11 exploration wells onshore (Figure 1). To improve the understanding of Jurassic evolution and its geodynamic meaning, five sedimentary packages were defined, separated by stratigraphic surfaces. Graphic representation used these surfaces as successive horizontal data: i) D5, top of Tithonian (Unit 5), ii) D4, top of Kimmeridgian (Unit 4), iii) D3, top of Oxfordian (Unit 3), iv) D2, Callovian unconformity (Unit 2), v) D1, Sinemurian unconformity (Unit 1). Some wells do not reach the lower units, so below Unit 1 the successions are not always complete. On the other hand some of the wells do not reach the top unit, especially in the Turcifal and Arruda sub-basin, thus Unit 5 is not present or is incomplete in those cases.

Unit 1 (Figure 1) does not show much information, mainly because the wells did not always reach this unit. The available information shows small thickness variation across the study area. Unit 2 (Figure 1) seems to indicate a thickness growth to the northern part of the area. It is also perceptible the great thickness of the Unit 2 in Ga-1, which indicates that the Callovian unconformity was irregular throughout the basin, with different rates of uplift and erosion. Unit 3 (Figure 1) shows significant differences in thickness for the Oxfordian deposits. These deposits are present in all the study area but are more important in the Bombarral and Turcifal sub-basins. This clear asymmetry in thickness is related with the Upper Jurassic rift phase. Unit 4 (Figure 1) indicates that in Kimmeridgian times the deposition occurred essentially in the Central sub-basins, asymmetrically, mainly in the most subsident Arruda Sub-Basin. Unit 5 (Figure 1) is more expressive in the Bombarral Sub-Basin and shows a great regional thickness variation.

The Lower and Middle Jurassic successions (Units 1 and 2), essentially carbonatic, seem to be regular throughout the study area, with increasing thicknesses to North. The Upper Jurassic with dominant siliciclastics, especially in the central sub-basins, presents a complex history, with stronger variations depending on location and age. During Oxfordian (Unit 3) the subsidence was higher in Bombarral and Turcifal sub-basins, with Torres Vedras-Montejunto and Runa fault acting as listric faults dipping West. In the Kimmeridgian (Unit 4) the subsidence was transferred to the Arruda Sub-Basin, east of the mentioned faults, and in the Turcifal Sub-Basin the depocenter should be located in the southern part (Sb-1 region). Throughout Tithonian (Unit 5) the infill was thicker in Bombarral Sub-Basin, controlled by the Torres Vedras-Montejunto and Lourinhã faults. This period is characterised by the end of the rifting phase, filling-up the basin with prograding deposits.

Lower and Middle Jurassic evolution shows mainly tectonic stability and minor thickness changes. Upper Jurassic subsidence variation in the sub-basins shows that the active fault movements were different through time, with their growing geometry attested by differential movement and infill.

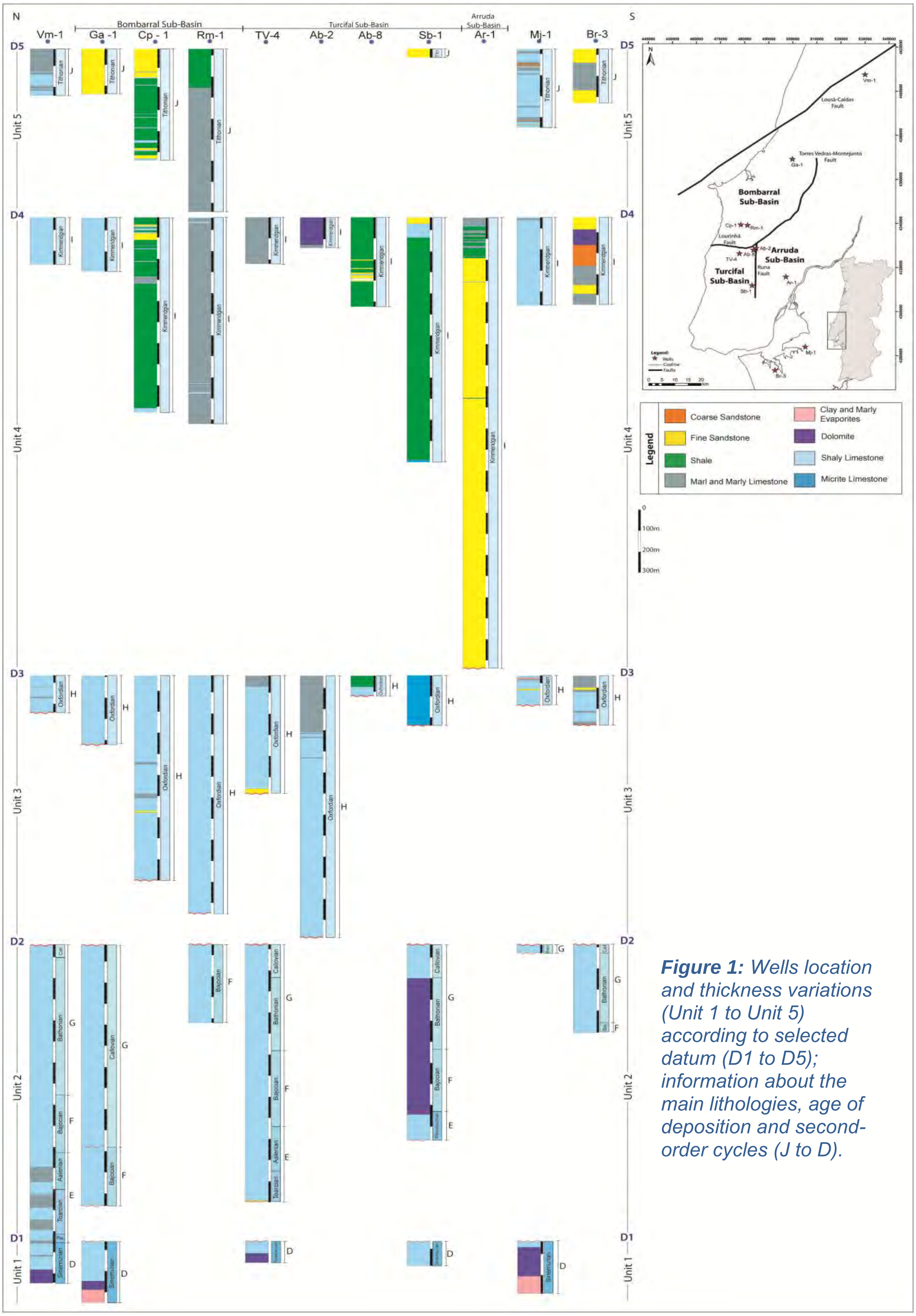


*Figure 1: Wells location and thickness variations (Unit 1 to Unit 5) according to selected datum (D1 to D5); information about the main lithologies, age of deposition and second-order cycles (J to D).*

## APATITE AS A PROVENANCE INDICATOR IN SEDIMENTARY SYSTEMS

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Apatite is a common accessory mineral in igneous, metamorphic and clastic sedimentary rocks. It is a nearly ubiquitous accessory phase in igneous rocks, and is common in metamorphic rocks of pelitic, carbonate, basaltic, and ultramafic composition. It is also virtually ubiquitous in clastic sedimentary rocks.

Apatite is widely employed in low-temperature thermochronology studies with the apatite fission track and apatite (U-Th)/He thermochronometers yielding thermal history information in the 60-110°C and 55-80°C temperature windows, respectively. Apatite has also been employed in high-temperature thermochronology studies, which demonstrate that the U-Pb apatite system has a closure temperature of ca. 450-550°C. Apatite has also been employed in Lu-Hf geochronology studies and as an Nd isotopic tracer.

Detrital apatite analysis has many potential applications in sedimentary provenance studies. To date, the majority of apatite provenance studies have focused on detrital thermochronology (deciphering the thermo-tectonic history of source regions by studying the chronology of their erosional products) using the apatite fission track or (U-Th)/He thermochronometers. Apatite can incorporate nearly half of the elements in the periodic table in its crystal structure and many trace elements in apatite display a large range of concentrations. Unlike zircon, the trace-element partition coefficients in igneous apatite are very sensitive to changes in magmatic conditions and hence the trace element chemistry of detrital apatite provides a link to the parent igneous rock type in provenance studies (Jennings *et al.,* 2011).

Similar to zircon, apatite can also be dated by the LA-ICPMS U–Pb method, which offers low-cost, rapid data acquisition and sample throughput. U-Pb dating of apatite is more challenging than zircon as apatite typically yields lower U and Pb concentrations and higher common Pb to radiogenic Pb ratios which nearly always necessitate common Pb correction, but these limitations can be overcome (Chew and Donelick, 2012). In contrast to the well-documented polycyclic behavior of the stable heavy mineral zircon, apatite is unstable in acidic groundwaters and weathering profiles and has only limited mechanical stability in sedimentary transport systems. It therefore more likely represents first-cycle detritus, and hence U-Pb apatite dating would yield complementary information to U-Pb zircon provenance studies. U-Pb apatite standard data from this study are presented in Figure 1.

This poster focuses on integrating apatite fission track (in particular uranium concentration measurements) and U-Pb dating by the laser ablation-ICPMS method. The two methods yield complementary information, with the apatite fission track system yielding low-temperature exhumation ages and the U-Pb system yielding high-temperature cooling ages which help constrain the timing of apatite crystallisation (Figure 2). Other chemical composition data (e.g. trace elements and the REE) can be acquired at the same time as uranium concentration data, and these data are very useful in detrital apatite provenance studies. We present new apatite fission track data acquired using the fission track dating system in Trinity College Dublin, which has been integrated with our new laser ablation-ICPMS system. Potential applications of combined apatite fission track and U-Pb dating and future trends in apatite provenance analysis are discussed at the end of this poster.

### References

Chew, D.M. & Donelick, R.A. 2012. Combined apatite fission track and U-Pb dating by LA-ICPMS and its application in apatite provenance analysis. Mineralogical Association of Canada Short Course: *Quantitative Mineralogy and Microanalysis of Sediments and Sedimentary Rocks*.

Jennings, E.S., Marschall, H.R., Hawkesworth, C.J. & Storey, C.D. 2011. Characterisation of magma from inclusions in zircon: Apatite and biotite work well, feldspar less so. *Geology*, **39**, 863.

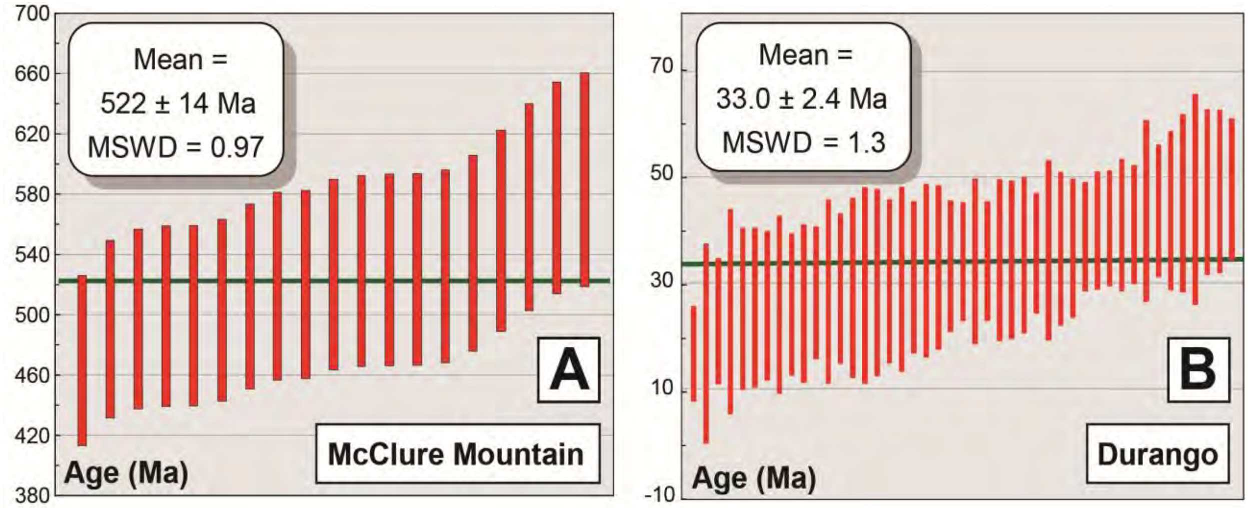


***Figure 1:*** *Apatite U-Pb standard data for the 521.5 Ma McClure Mountain syenite (A) and 31.44 Ma Durango apatite (B).*

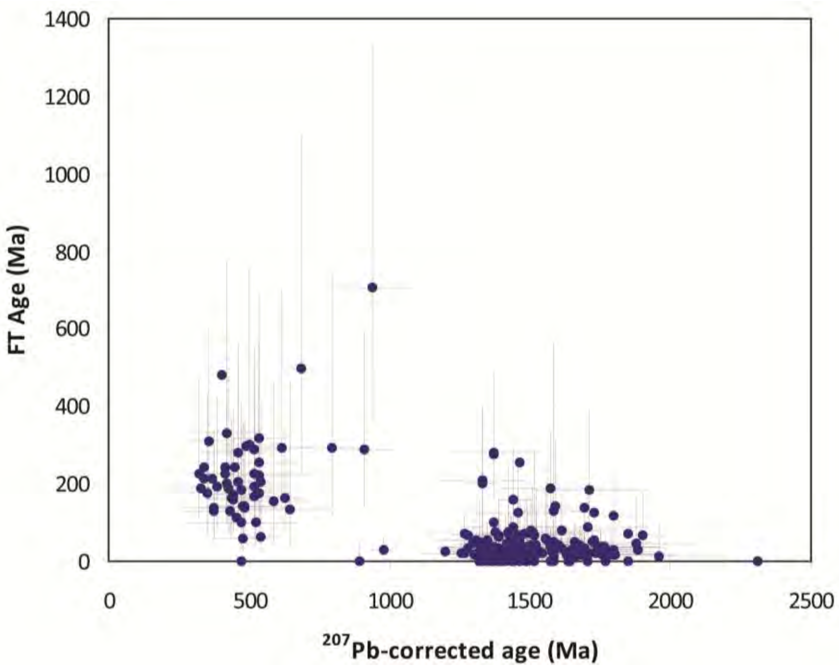


***Figure 2:*** *Example apatite fission track and U-Pb age data from a Triassic sandstone from Utah (Chew and Donelick, 2012). Combining the apatite fission track and U-Pb dating methods allows for more diagnostic provenance constraints.*

## A RE-EXAMINATION OF PLEISTOCENE TUNNEL VALLEY DISTRIBUTION ON THE CENTRAL SCOTIAN SHELF

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Tunnel valleys are a special kind of erosional channel characterised by anastomosing, steep-sided channel systems formed by subglacial, confined meltwater flow. On the Scotian Shelf, partially infilled tunnel valleys are recognised on the sea floor in bathymetry data, but previous workers have also found buried examples. In this poster, 2D industry seismic near Sable Island is used to better constrain the geometry of tunnel valleys in the area. Our interpretation shows V- to U-shaped buried channels north and west of Sable Island averaging 2-5 km wide and 150-400 m deep with a north-south orientation that extensively branch, reconnect, and meander. The buried channels are similar to channels exposed on the sea floor further north. Immediately to the south and west of Sable Island, the channels become narrower (0.5-1.5 km) and more widely spaced. Contrary to previous interpretations, the orientations remain roughly N-S and there is a gap of 20-30 km between the ends of detectable tunnel valleys and the shelf edge south of Sable Island. With the input of three, higher resolution, 2D geotechnical surveys (Adamant, North Eagle and South Sable) were used to investigated the termination of tunnel valleys south of Sable Island. These surveys show that tunnel valleys are present south of Sable Island, but are significantly smaller and have varying geometries. Some of the valleys appeared to match up with the systems north of Sable Island. At their narrowest, southern end, tunnel valley systems were difficult to follow in map view and a broad irregular erosion surface was evident with scoop-shaped in the southern halves of North Eagle and South Sable. This may indicate that the glacier terminus was at or near to this area and that tunnel valleys may be exiting into the marine environment and/or becoming R-channels within the ice.

## 'PALYNOMORPH DARKNESS INDEX' – A NEW METHOD FOR DETERMINING THERMAL MATURITY

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Palynomorph Darkness Index (PDI) is a new thermal maturity indicator. It is calculated from measurement of the red, green and blue (RGB) intensities of light transmitted through palynomorphs, using standard palynological microscopes and digital cameras. Laboratory heated, Early Permian *Tasmanites* show a progressive increase in PDI with increasing temperature and suggest that the technique is applicable through a broad temperature range, encompassing the whole of the oil window and at least part of the zone of dry gas generation (Figure 1).

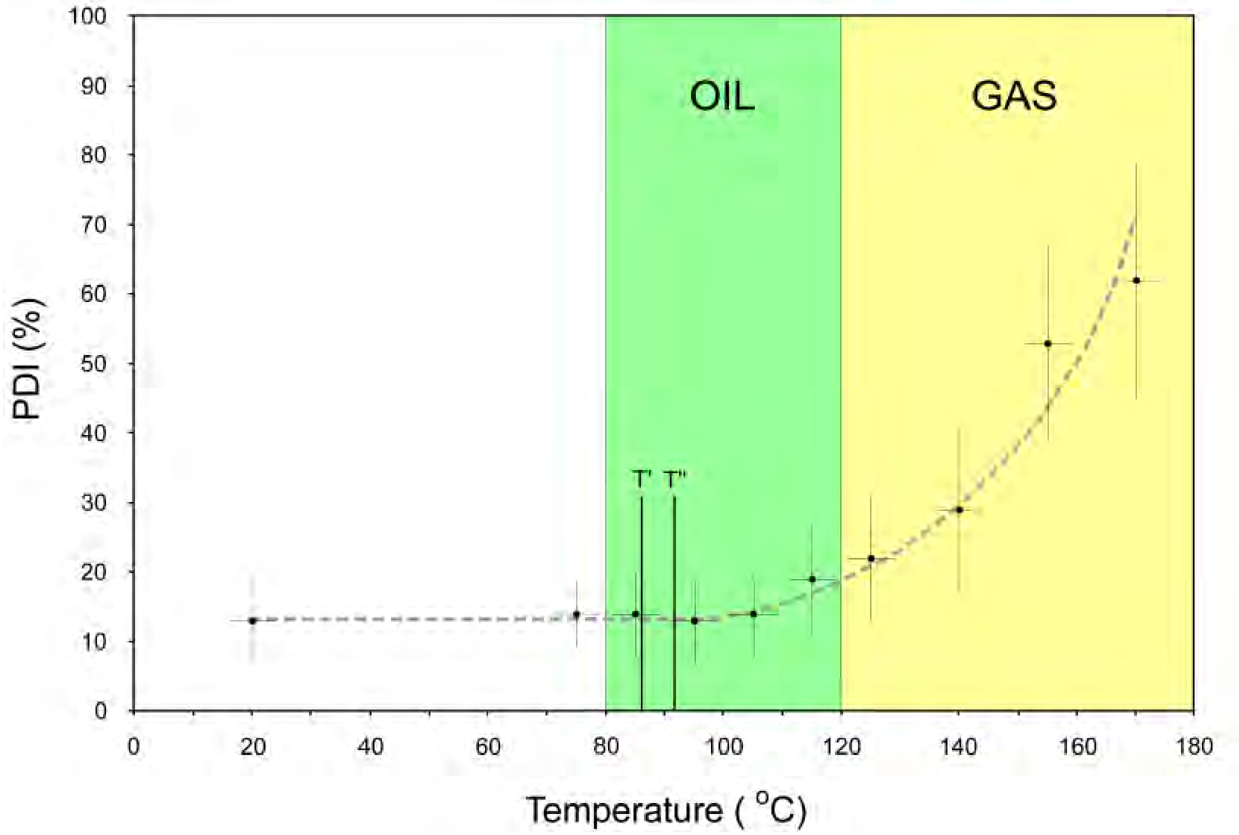


***Figure 1:** Correlation of furnace temperatures used to heat Early Permian Tasmanites with PDI values from RGB measurements on 50 specimens per sample (after Goodhue & Clayton, 2010). Lines T' and T'' indicate the peak palaeotemperature attained naturally by the unheated sample using calculations of Barker (1991) and Barker & Goldstein (1990) respectively.*

Potential applications of this inexpensive method include the estimation of thermal maturity of sections deficient in vitrinite, such as including pre-Devonian strata and many marine black shales. Standard mounts of organic residues on glass slides are used, so PDI can be determined readily during routine palynological investigations. PDIs determined by different microscope and camera combinations show excellent correlation, suggesting that the method is largely platform-independent (Figure 2). Calibration is achieved using photographic filters as standards.

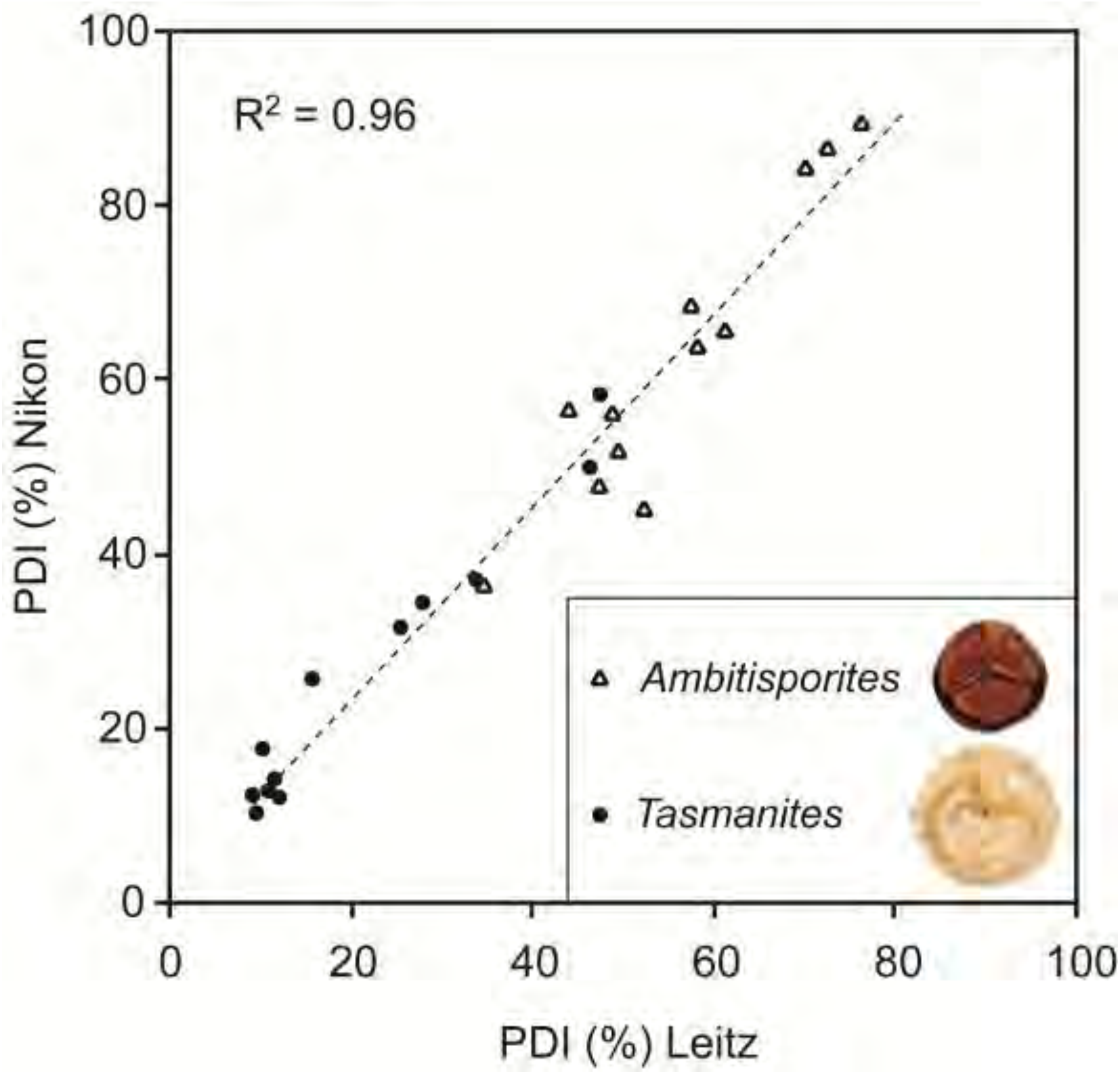


***Figure 2:*** *Correlation of calculated PDI values from RGB measurements of unoxidised Palaeozoic Tasmanites (prasinophytes) and Ambitisporites (plant spores), using two different microscope/camera combinations (after Goodhue & Clayton, 2010).*

## References

Barker, C.E. 1991. Implications to organic maturation studies of evidence for a geologically rapid increase and stabilisation of vitrinite reflectance at peak temperature: Cerro Prieto Geothermal System, Mexico. *American Association of Petroleum Geologists Bulletin,* **75**, 1852-1873.

Barker C.E. & Goldstein R.H. 1990. Fluid-inclusion technique for determining maximum temperature in calcite and its comparison to vitrinite reflectance geothermometers. *Geology,* **18**, 1003-1006.

Goodhue, R. & Clayton, G. 2010. Palynomorph Darkness Index (PDI) - a new technique for assessing thermal maturity, *Palynology*, **34**, 147-156.

## THE WESTERN AND CENTRAL ALGARVE BASIN (SOUTH OF PORTUGAL) – MESOZOIC SUBSIDENCE EVOLUTION AND TECTONIC CONTROLS

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The purpose of this study is to understand the structure and sedimentary infill of the Mesozoic Algarve Basin, located in the South of Portugal. To do so, we tried to understand the Palaeozoic basement structuration and how it influenced and conditioned the Mesozoic subsidence evolution and depocenter migration, from the late Triassic until the early Cretaceous.

The origin of the Algarve Basin is related to the sedimentary infill of a passive continental margin, related with the repeated phases of the North Atlantic opening, which followed the breaking of Pangaea in late Triassic times. (*see* Terrinha, 1998). Predominant extension promoted sedimentation throughout all the Jurassic and early Cretaceous. From late Cretaceous onwards, subsidence in the Algarve Basin has been reduced, suffering tectonic inversions in a compressive setting related to the Iberian plate position between the African and European colliding plates.

The Palaeozoic basement is structured by fault sets trending mainly NE-SW and NW-SE, with sinistral and dextral slips movement components, respectively, formed at the end of Variscan orogeny and before the late Triassic extension (300 to 250 Ma) (Terrinha, 1998). The Mesozoic infill has been controlled by the reactivation of inherited basement structures, with the NW-SE faults compartmentalising the basin in three sectors: Eastern sector, Central sector and Western sector (*see* also Matias, 2007). The Mesozoic overall thickness tends to increase towards SSE, controlled by NE-SW structural steps, diapirs and salt walls. Thickness also tends to increase towards SW, controlled by the NW-SE-faults.

This study is focused on the onshore Western Algarve Basin, based on the analysis of four onshore locations and two offshore wells (Santos *et al.,* 2011). The interpretations were based on sedimentation and subsidence rates, calculated from decompacted thicknesses and palaeo-water depths inferred from depositional system. It is important to refer that subsidence rates are very similar to sedimentation rates, due to the very small palaeo-water depth variations associated with a long-lived carbonate platform in the Mesozoic of the Algarve Basin (*see* Santos *et al.,* 2011). However, erosional hiatuses were not considered due to lack of quantitative data about well-known stratigraphic unconformities, leading to some underestimation of both rates.

From the comparison between three onshore locations: Sagres (S), Lagos (L) and Albufeira (A), shown in Figure 1, it has been possible to address W-E spatial variations of the onshore depocentres. During the first phase ($T^3$-$J^2$) the depocenter was located in Sagres (S), the westernmost region of the basin, with a thickness three times higher than the other locations. During the second phase ($J^3$), a migration of the depocenter towards E is evident, but the Sagres region (S) still shows a significant thickness of sediments. During the final phase ($K^1$), Sagres (S) lost importance and the depocenter migrated towards W, lying in the central part of the studied sector: Lagos (L).

From the integration of all the variables studied in the six locations, a preliminary regional geodynamic interpretation shows that the SE offshore (wells) and the NW onshore areas (Carrapateira and Sagres) are the most subsident in the first phase, suggesting a structural control by the basement's NE-SW fault movements, responsible for the tectonic uplift of the central block (Lagos and Albufeira). In the second phase there is evidence of another structural control by approximately N-S to NW-SE late Variscan faults, reactivated during the Mesozoic: Aljezur fault (AF) and Portimão fault (PF). During the third phase a modification occurs in the basin, with clearly lower subsidence rates and no clear structural individualisation. It is possible to assign the apparently random control of the sedimentary infill during the third phase ($K^1$) mostly to halokinesis, in agreement with other published works, which show the structural and halokinetic control of the depocentres in the Mesozoic Algarve basin (Terrinha, 1998; Matias, 2007).

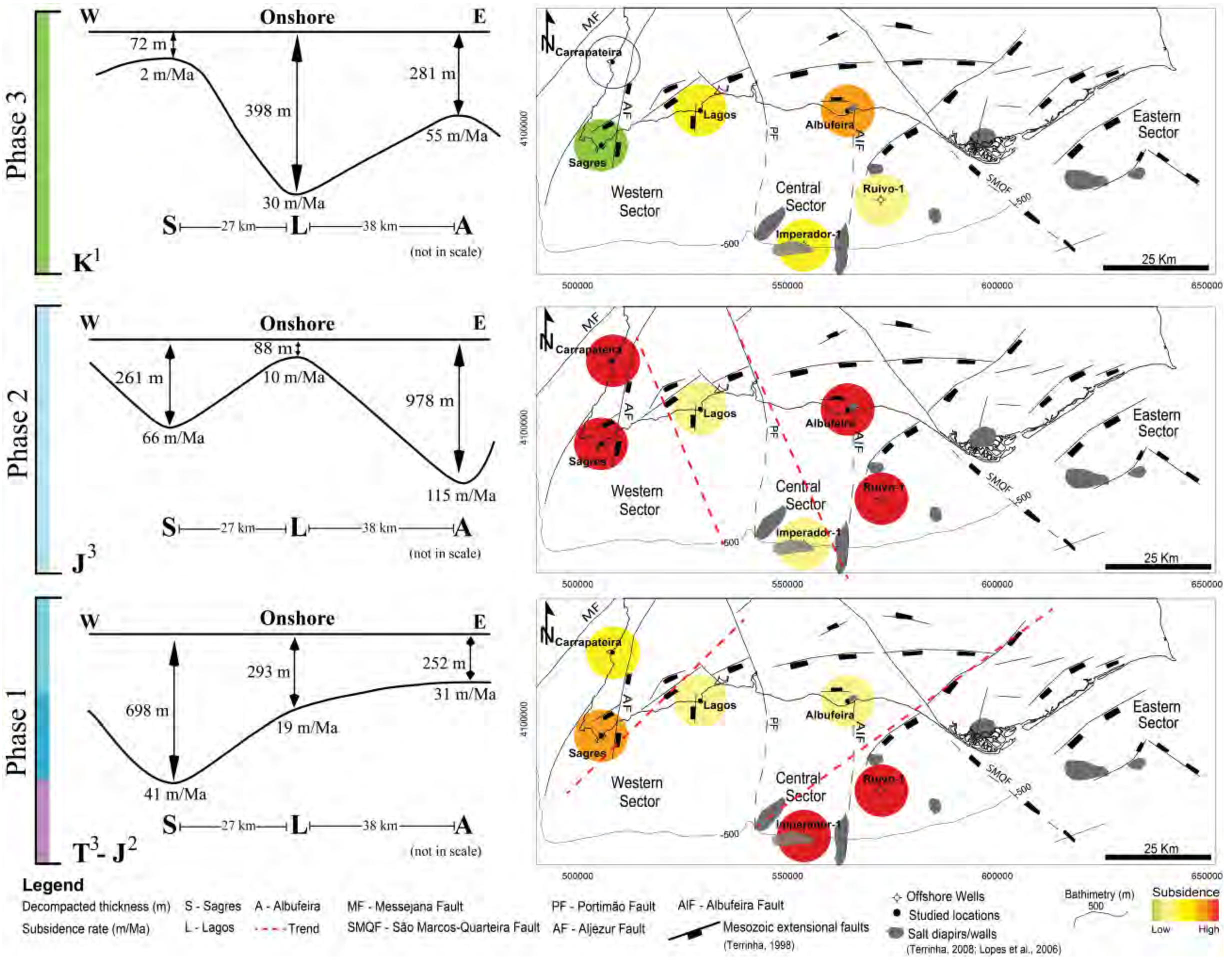


***Figure 1:*** *Mesozoic subsidence evolution and tectonic controls in the Western and Central Algarve Basin (S Portugal). Left - decompacted thicknesses and maximum values of subsidence rates showing W-E spatial migration of the depocentres; Right - qualitative subsidence rates in the six studied locations, showing different tectonic controls in different evolution phases (modified from Santos et al., 2011).*

## References

Matias, H. 2007. *Hydrocarbon Potential of the Offshore Algarve Basin*. PhD thesis, University of Lisbon, Lisbon, 324p.

Santos, S., Correia, U., Leitão, M., Moreira, B., Rodrigues, A. & Pimentel, N. 2011. Mesozoic of Western Algarve – Characterization, Tectono-Sedimentary Evolution and Petroleum System Elements. *In:* I Congresso de Jovens Investigadorés em Geociências, *Abstracts Volume,* 65-68.

Terrinha, P. 1998. *Structural Geology and Tectonic Evolution of the Algarve Basin, South Portugal*. PhD thesis, Imperial College, London, 430p.

## MAGMATISM AND SEGMENTATION ALONG THE SCOTIAN MARGIN

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Determining the nature of rifting between Morocco and Nova Scotia has proved challenging. The margins began forming during the Late Triassic rifting and Middle Jurassic separation of the North American and African plates. Small rift basins, bounded by long, sinuous faults, formed during the initial stages of rifting, whereas a broad sag basin developed during the post-rift stage of subsidence. Deeper crustal structure, faulting style and basin geometry vary considerably along the margin. Crustal thinning and thermal subsidence were greater beneath the central and northeastern Scotian margin, where thinning of up to 50% occurred over 150 to 200 km distance across the margin, and a thick post-rift succession was deposited which partially obscures basement and deeper structure. In contrast, the margin to the south of Nova Scotia has clearly recognised characteristics of a volcanic-style rifted margin, including seaward-dipping reflector (SDR) sequences that are interpreted as rift-related volcanic flows overlying basement. These SDRs are coincident with a strong linear magnetic anomaly (Figure 1), the East Coast Magnetic Anomaly (ECMA), which shares many characteristics with the West African Coast Magnetic Anomaly (WACMA). Seismic evidence for these reflector sequences is absent along all but the southwestern segment of the Scotian margin. Magnetic anomalies on the Nova Scotia and Moroccan margins change character and fade significantly in amplitude midway along the margins, although newer magnetic compilations allow the anomalies to be traced further to the north than previously possible. Understanding the source of the ECMA and WACMA is regarded as being critical to understanding the nature of rifting.

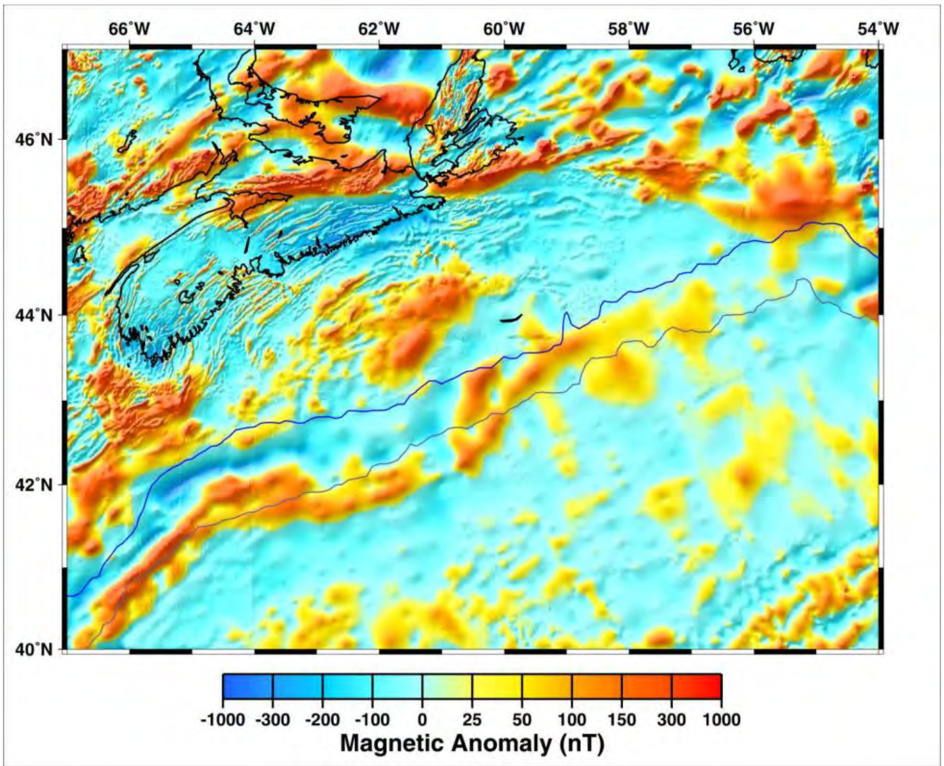


***Figure 1:*** *Magnetic anomalies along the Scotian margin, showing variations in trend and amplitude of the ECMA which meanders across the slope and outer shelf.*

New models of the magnetic anomalies along the Scotian margin show good correlation of the ECMA with the seaward edge of thinned continental crust. The ECMA can be satisfied with modest amounts of igneous material, emplaced at or near the edge of the thinned continental crust (Figure 2). The reduced amplitude along the central and northeastern sections of the margin is a function of both thinning of the volcanic unit and the increasing thickness of overlying sedimentary rocks. The greatest change in ECMA amplitude and character occurs midway along the margin, consistent with other indications of changes in crustal thickness and extensional style based on seismic and gravity models. Segmentation of the margin may explain both the changes in magnetic signature and the variability in predicted melt volume, and additional insight may be gained through correlation with the conjugate Moroccan margin.

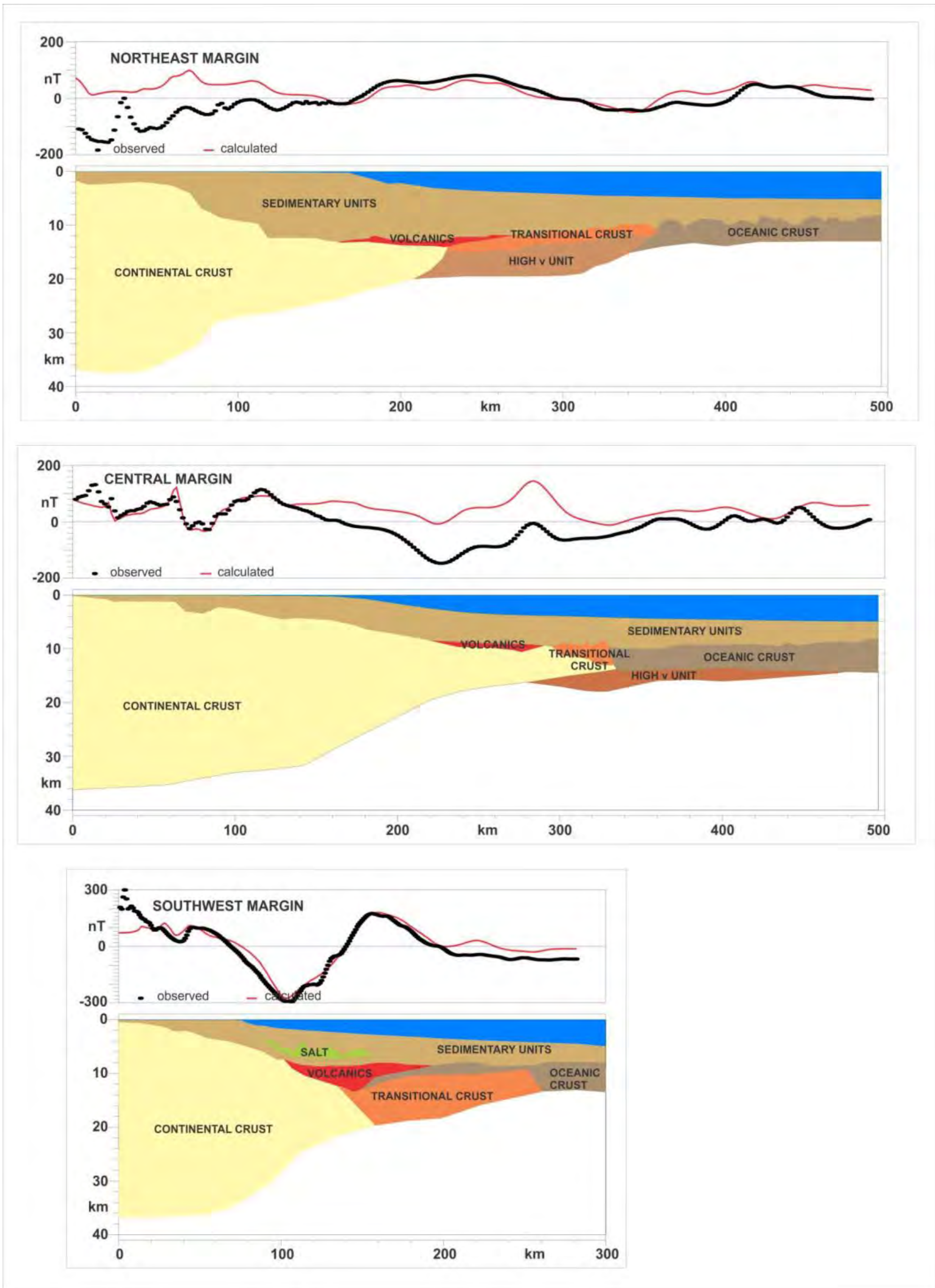


***Figure 2:*** *Magnetic models across the Scotian margin. The positive ECMA anomaly is best matched with a relatively thin volcanic unit near the edge of thinned continental crust.*

## Lateral and Proximal to Distal Variations in Salt Tectonic Styles on the Central and Western Scotian Margin, Offshore Nova Scotia, Canada

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A major Late Triassic to Early Jurassic (?) synrift salt basin underpins much of the Scotian Margin, and formed as Nova Scotia rifted and ultimately broke apart from its Moroccan conjugate. Like other salt basins, the distribution, style and timing of salt-related structures varies widely. Using available 2D/3D seismic data-sets, we contrast two considerably different salt tectonic styles that dominated the western versus the central parts of the margin, and provide a higher order structural subdivision of each. In the west, only a small portion of the primary salt basin is found under the present day continental shelf, where minor amounts of post-rift subsidence took place. Most of the salt basin is now located in deepwater after subsiding up to 8 km after continental breakup. Increased subsidence seaward of the margin hinge zone tilted the landward parts of the salt basin, generating a major region of gravity gliding and raft tectonics above the autochthonous salt layer. Though it is possible that some seaward inflation of the primary salt basin took place immediately following breakup, vertical diapirism and sediment downbuilding dominated and our preferred interpretation is that increased rift subsidence allowed more salt to accumulate in the seaward parts of the salt basin prior to continental breakup. Proximal to distal variations in salt tectonic style in the west are believed to be controlled by variations in the amount, rate, and symmetry of post-rift basement subsidence, but preconditioned by the synrift basement fabric (including transfer zones) and development of rift-related accommodation that controlled the original thickness and distribution of salt. In contrast, much of the primary salt basin on the central parts of the margin occupied a more landward position below the present day shelf. Increased Jurassic and Cretaceous sedimentation here more efficiently expelled salt up to 60 km seaward of its source layer, emplacing amalgamated salt tongues and canopies, or their equivalent welds, in deepwater settings. Two seaward salt expulsion styles dominate the canopy complex: expulsion rollovers and allochthonous salt-based detachments (e.g. roho systems). The relative importance of each can be linked to the density of seaward leaning salt feeders extending from the autochthonous salt layer. In contrast to the west, gravity loading associated with increased sedimentation was a more important process in the central part of the margin.

## LONG OFFSET SEISMIC REFLECTION DATA PROVIDE FIRST COMPLETE LOOK AT CRUSTAL STRUCTURE OF THE NE GREENLAND MARGIN

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Deep long-offset seismic data (Northeast Greenland SPAN™) have been acquired across the NE Greenland shelf and slope from 2009, 2010 and 2011. The main obstacle to acquisition traditionally has been heavy sea ice, which was overcome by (1) employing a proprietary streamer and deployment technology to acquire data below the pack ice, and (2) using a lead icebreaker to clear first-year ice from the path of the acquisition vessel.

**Processing:** The data were pre-stack time (PSTM) and pre-stack depth migrated (PSDM) to show 16 sec and 40 km profiles of the continental margin. Interpretation was tested iteratively against gravity and magnetic models.

**Survey coverage:** The data extend from the Jan Mayen Fracture Zone in the south to the Spitsbergen Fracture Zone in the north, some 250 km farther north than any previous seismic survey. A first pass tectono-stratigraphic interpretation documents the following geological elements: 1) the Danmarkshavn Basin (DB); 2) the Thetis Basin (TB); 3) Northeast Greenland Volcanic Province; 4) the offshore Wandel Sea transpressive mobile belt; 5) the continent-to-ocean transition; 6) the newly recognised Ob Basin to the northwest of the DB adjacent to coast with a Carboniferous section; and 7) the newly recognised Westwind Basin, adjacent to the Wandel Sea Miocene breakup margin, and which appears to be an Eocene to Recent Basin connected to the rift-drift history of that northernmost segment of the margin.

**Observations:** Highlights of the three surveys thus far have been: a) moderate inversion throughout and across the margin; b) extension of the salt diapirism and Permo-Carboniferous salt basins within the DB to 80° N; c) observation of Mesozoic reflectors beneath the volcanic province and on the outer marginal high; d) well defined seaward-dipping reflectors along two segments of the margin; e) a 7 km plus thick sedimentary sequence in the southern parts of the DB and TB where the Danmarkshavn Ridge intervenes both including a thick Mesozoic section; and f) a Lower Crustal Body similar to that observed in the Lofoten passive margin of Norway.

Several of the lines cross the continent-ocean transition (COT) that is largely healed by a magmatic volcanic belt. Beyond, oceanic crust is confirmed by magnetic and gravity anomalies, and a Moho reflector at 10-12 km. The reflector dips west to 22-25 km depth under the Greenland continental crust. Older Palaeozoic sediments are also thought to be present in the DB and subcrop along the DR, which forms a prominent structural high separating the two basins. Connections between the two basins around the DR to the north and via the Loon High (new) structure indicate at least Cretaceous and possibly older sediments occur in the TB. These new data have important implications for reconstructions of the plate relationships between Greenland and Eurasia and for the understanding of the role of the Mesozoic to Cenozoic intra-continental De Geer Megashear, as well as for hydrocarbon exploration.

**Note:** *This poster presentation is supplementary to the oral technical presentation by J.A. Helwig, R.C. Whittaker, M.G. Dinkelman, P.A. Emmet, and D.E. Bird, - "Interpretation of Tectonics of Passive Margin of NE Greenland from New Seismic Reflection Data and Geological - Geophysical Constraints"*

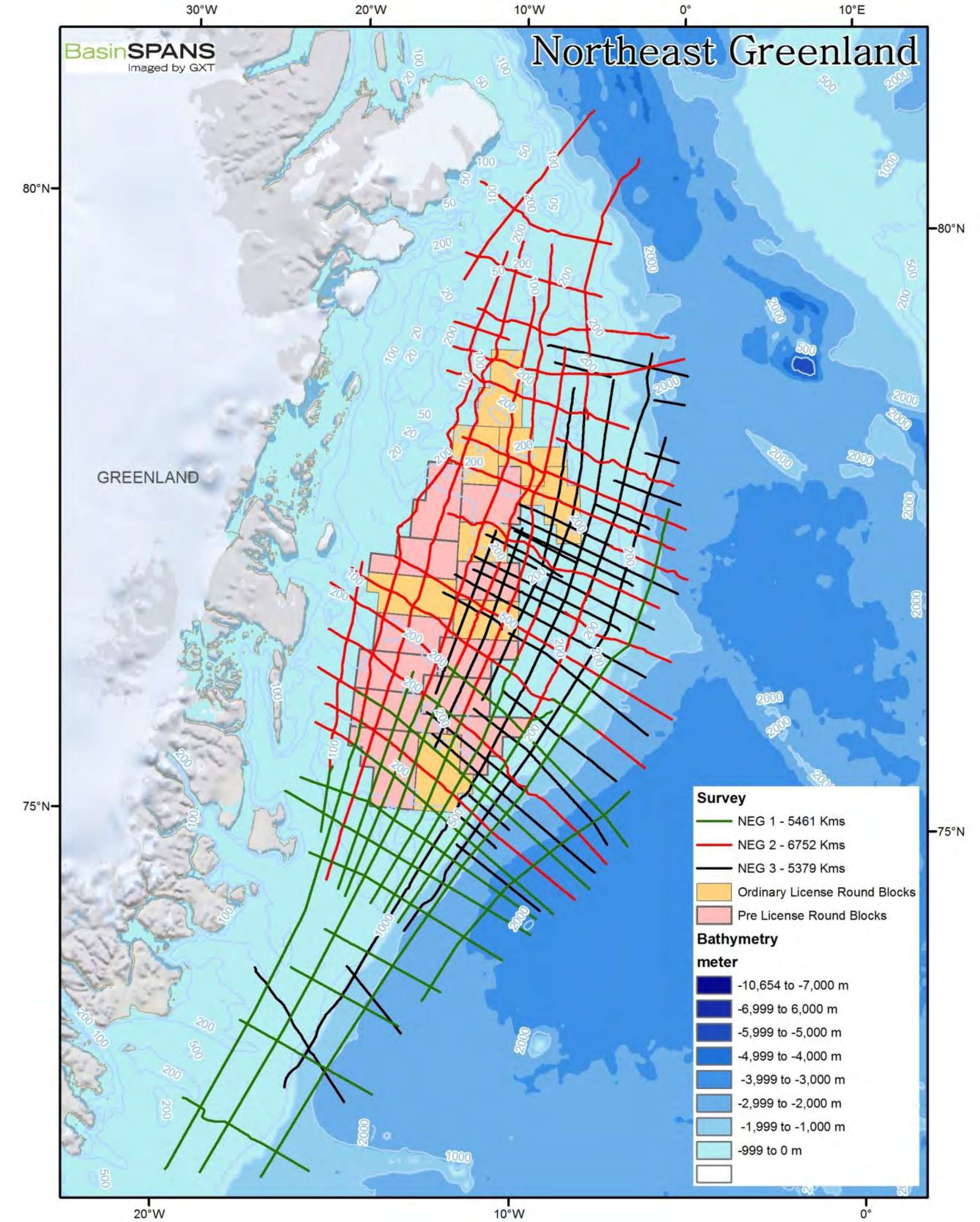


***Figure 1:** Map of the Northeast GreenlandSPAN surveys and seismic grid layouts for Phases I, II and III shown on a bathymetric base and with the blocks nominated for upcoming licensing rounds.*

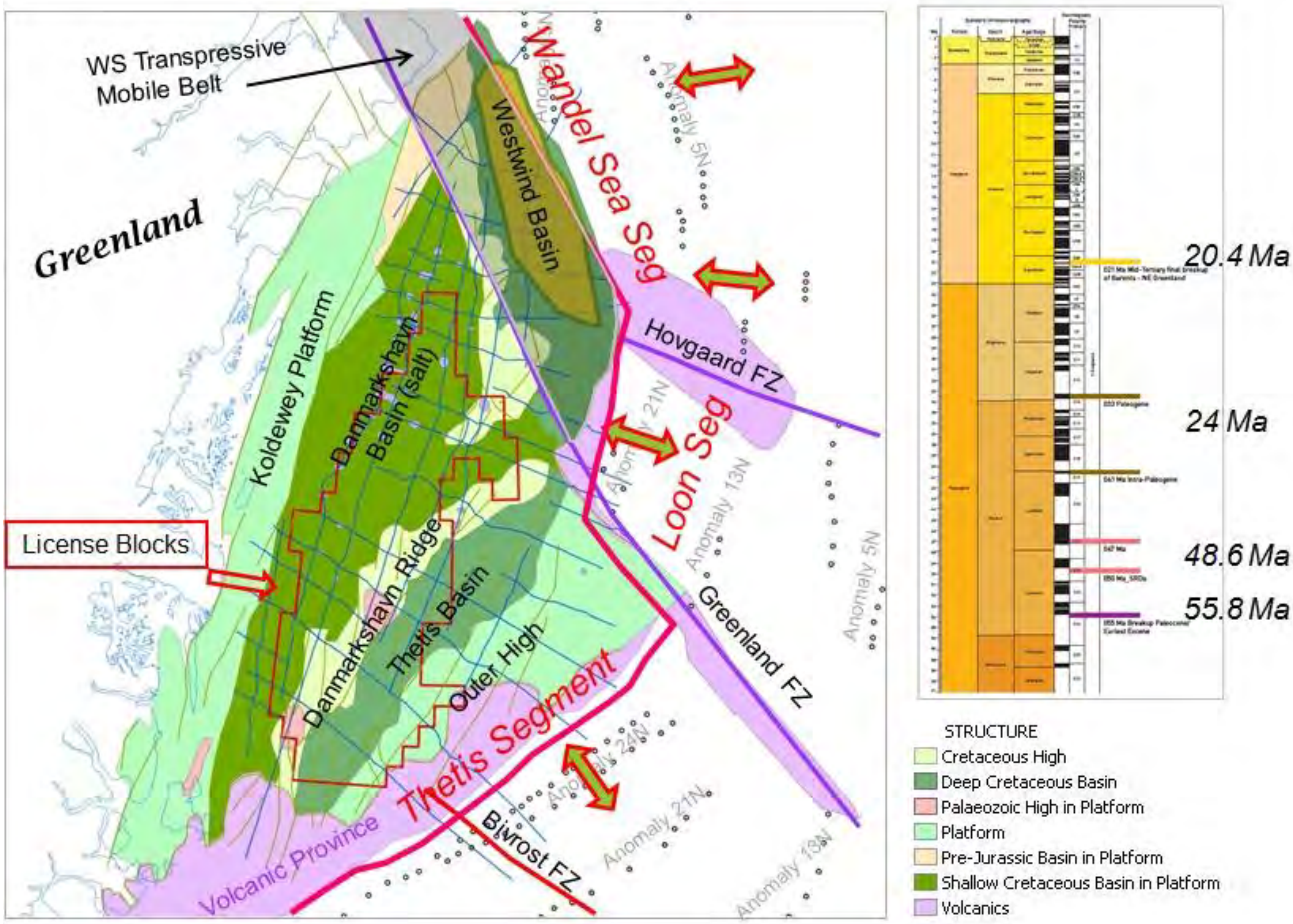


***Figure 2:*** *Main tectonic events associated with the* breakup *of NE Greenland from the Mid-Norway and Barents Shelf Conjugate Margins. Timescale at right shows the key to the Tertiary seismic horizons.*

## MODELLING THE THERMAL STRUCTURE OF ONSHORE IRELAND AND ITS OFFSHORE BASINS

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The Cenozoic exhumation history of Ireland and Britain has major implications for understanding the development of the onshore geology of Ireland and Britain, intra-plate exhumation studies and the distribution of hydrocarbon resources. This project is characterising the timing and causes of exhumation of onshore Ireland and Britain and their offshore basins to address the Cenozoic exhumation history. This includes modelling the thermal evolution, evaluating regions of high heat flow (onshore) as targets for geothermal purposes and the timing of basin inversion (offshore) for the hydrocarbon industry.

For this project we are collecting samples from mainland Ireland and Britain and also boreholes from the offshore basins where accessible (Figure 1). Sampling is being undertaken on both a regional scale (to detect regional exhumation trends) and local scale (employing vertical sampling). The vertical sampling will utilise steep escarpments combined with onshore boreholes, including an approx. 500 m deep borehole within the Mourne Mountains Granite. Offshore sampling will utilise existing petroleum exploration boreholes where material is accessible.

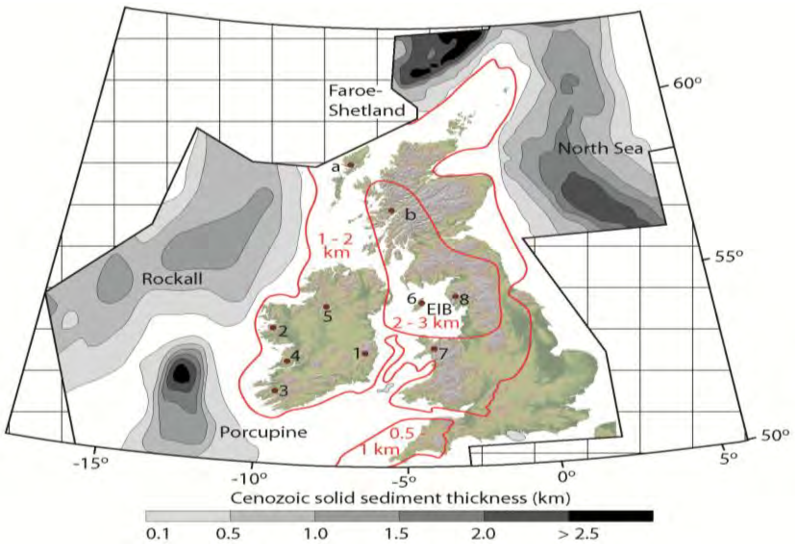


***Figure 1:*** *NW European shelf with isopachs of Cenozoic solid sediments (Jones et al., 2002) and estimates of onshore denudation (Allen et al., 2002).*

The analysis of these samples will be made by low temperature radiometric chronometers such as apatite fission track (AFT) and (U-Th-Sm)/He on apatite (AHe). The AFT research is taking place in the fission track lab at Trinity College Dublin (TCD) and the AHe studies in East Kilbride are being undertaken in conjunction with Dr. Finlay Stuart (Scottish Universities Environmental Research Centre). Vitrinite reflectance studies will be undertaken in cooperation with Prof. Geoffrey Clayton (TCD).

The AFT and AHe provide thermal history information on rock samples between 120°C to 40°C. Employing typical upper crustal geothermal gradients, it is therefore possible to investigate the exhumation history of the uppermost crust (1 to 4 km). These methods are ideal for determining the small amounts of exhumation that took place in Ireland and Britain during Cenozoic times. The results from the AFT and AHe analysis will then be modelled to yield 2D and 3D thermal models of Ireland and Britain. The 3D model will also be integrated into a GIS visualisation suite.

This combination of AFT and AHe studies is ideally suited to investigate the thermal history of sedimentary basins (including detection of inversion episodes). It is thus of interest to hydrocarbon exploration, particularly as the oil maturation window is within the temperature range of AFT and AHe (between 120˚C and 40˚C). Therefore, the causes and timing of the exhumation in Ireland and Britain is of significant economic interest for the hydrocarbon industry, including yielding information on:

- The distribution of reservoir sands
- Trap breaching and probability of encountering effective top-seals
- The timing of source maturation
- The quality of reservoir rocks due to higher levels of reservoir diagenesis

**References**

Allen, P.A., Bennet, S.D., Cunningham, M.J.M., Carter, A., Gallagher, K., Lazzaretti, E., Galewesky, J., Densmore, A.L., Phillips, W.E.A., Naylor, D. & Solla Hach, C. 2002. The post-Variscan thermal denudational history of Ireland. *In:* Doré, A.G., Cartwright, J.A., Stoker, M.S., Turner, J.P. & White, N. (eds). *Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration.* Geological Society London, Special Publications, **196**, 371–399.

Jones, S.M., White, N.J., Clarke, B.J., Rowley, E. & Gallagher, K. 2002. Present and past influence of the Iceland plume on sedimentation. *In:* Doré, A.G., Cartwright, J.A., Stoker, M.S., Turner, J.P. & White, N. (eds). *Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration.* Geological Society London, Special Publications, **196**, 13–25.

## IMPROVING SEISMIC REFLECTION DATA FROM GOBAN SPUR RIFTED MARGIN AND ASSESSING THE IMPACT ON MODELS OF CRUSTAL STRUCTURE

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The hydrocarbons industry routinely uses seismic reflection data as an initial tool to probe continental margins beneath deep waters. Excellent images are produced from modern 2D data with 8km streamers, 10s record lengths and greater than 150 fold of coverage. In this paper we investigate the improvement that modern processing techniques can bring to older data and we additionally demonstrate the utilisation of information from coincident seismic refraction, gravity, magnetics and swath bathymetry. Such an integrated approach is not normally utilised in hydrocarbon industry studies. We concentrate on the BIRPS (British Institutions Reflection Profiling Syndicate) WAM (Western Approaches Margin) profile which was shot from oceanic to continental crust across the Goban Spur rifted margin by BIRPS in 1985.

Signal to noise ratio is moderate, and the low 30 fold and short 3 km offset limited the efficacy of multiple suppression that could be applied during the original processing of WAM. Multiples hamper the interpretation of deep crustal reflectors in the critical zone between continental and oceanic crust. We utilise modern interpolation, surface related multiple elimination (SRME), diffracted multiple attenuation and high resolution residual moveout based methods to remove multiples. Most recently Bullock and Minshull (2005) interpreted a 70 km wide zone of exhumed mantle between thinned continental and oceanic crust. The velocity depth model was constructed using an integrated wide angle seismic refraction experiment with coincident gravity, magnetics and swath bathymetry. We use the Bullock and Minshull (2005) velocity-depth model to prestack depth migrate the data following the new multiple suppression. Improved multiple suppression results in a more confident interpretation of the deep seismic reflections in this continental margin setting.

### Reference

Bullock, A.D. & Minshull, T.A. 2005. From continental extension to seafloor spreading: crustal structure of the Goban Spur rifted margin, southwest of the UK. *Geophysical Journal International*, **163,** 527–546, doi: 10.1111/j.1365-246X.2005.02726.x

# MESOZOIC EVOLUTION OF THE ORPHAN BASIN: UPPER CRUSTAL ARCHITECTURE AND AMOUNTS OF EXTENSION DURING THE ATLANTIC RIFTING

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The Orphan Basin lying along the Atlantic Newfoundland rifted margin is a continental rift basin which formed during the opening of the North Atlantic Ocean in Mesozoic times.

Using regional seismic profiles (seismic data courtesy of TGS) and well data (Figure1), we were able to image the upper crustal architecture of the basin and describe the tectonic evolution of the basin during rifting.

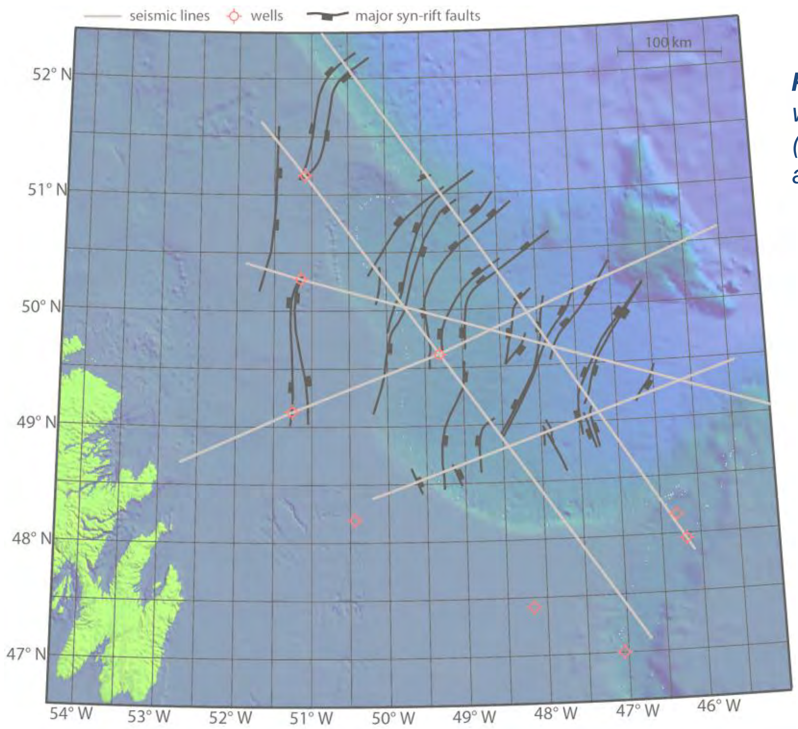


***Figure1:** Map of the Orphan basin, with location of the seismic lines (seismic data courtesy of TGS), wells, and the major syn-rift faults.*

## *Tectonic evolution*

Extension associated with the dislocation of the Pangaea supercontinent started in the Early Mesozoic and resulted in several rift basins along the eastern Canadian margin. The sedimentary infill of the graben and half-graben documents a polyphase deformation of the Precambrian-Palaeozoic basement, characterised by deferent phases of rifting during Late Triassic – Early Jurassic, Late Jurassic, and Early Cretaceous (Sinclair, 1988; Ziegler, 1989; Enachescu *et al.,* 2005). Each rifting phase shows a period of crustal extension controlled by normal faults and a strong tectonic subsidence, followed by a period of substantial uplift and erosion, and a (short) period of thermal subsidence.

The stratigraphic architecture of the Orphan basin described by seismic and well data reveals the presence of two syn-rift tectono-stratigraphic units (Figure 2), namely the Upper Jurassic unit and the Lower Cretaceous unit, separated by angular and truncation unconformities.

The major normal faults bounding the rift structures are NNE-SSW in the northern part of the basin and tend to be N-S in south (Figure 1). The deformation style along the faults is very diverse as the seismic lines show tilted blocks, simple shear along listric faults, parallel fault flow and growth structures.

The Lower Cretaceous sediments seal most of the rifting faults, indicating the end of crustal stretching and the initiation of the thermal-driven subsidence of the post-rift phase during the Late Cretaceous.

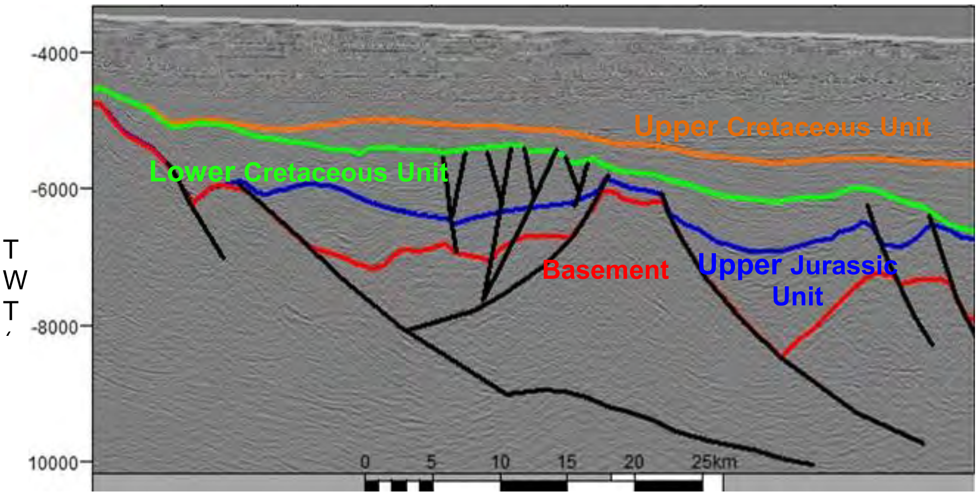


***Figure 2:*** *Seismic reflection (seismic data courtesy of TGS) showing the different tectono-stratigraphic units and an example of the syn-rift structures observed in the Orphan basin.*

### *Amounts of crustal extension*

The seismic lines were time-to-depth converted and restored to infer extension values. The 2D restoration of the constructed profiles was accomplished using the MOVE software.

While the amounts of upper crustal stretching vary from 48km to 82km, the corresponding beta values are fairly consistent along the different profiles and range between 1.1 and 1.2. Along the SW-NE direction, there is as much extension during the Jurassic as in the Lower Cretaceous, but along the NW-SE direction, 60 to 70% of the extension occurred during the Jurassic phase of rifting. This extension variation through time and space is not readily compatible with a simple rotation model of the Flemish Cap out of the Orphan Basin (Srivastava *et al.,* 2000; Enachescu et al., 2005; Sibuet *et al.,* 2007).

The low values of stretching documented by the upper crustal faults are not compatible with crustal seismic data (Chian *et al.,* 2001; van Avendonk *et al.,* 2009) and 2D-3D gravity models (Welford and Hall, 2007) which, however, indicates a strong crustal thinning underneath the Newfoundland margin with thinning factors between 1.6 and 6. Such discrepancy between structural reconstructions and gravity inversion models can be explained either by (i) differential thinning models where detachment faults, unrevealed by our reflection seismic data, play a substantial role in the extension of the basin during rifting; or (ii) a crust already thinned prior to the initiation of continental rifting.

**References**

Chian D., Reid I. & Jackson H. 2001. Crustal structure beneath Orphan basin and implications for non-volcanic continental rifting. *Journal of Geophysical Research*, **106**, 10923-10940.

Enachescu M.E., Kearsey S., Hardy V., Srivastava S., Sibuet J., Hogg J., Meyer K., Fagan P., Thompson T. & Ferguson R. 2005. Evolution and petroleum potential of Orphan Basin, offshore Newfoundland, and its relation to the movement and rotation of Flemish Cap based on plate kinematics of the North Atlantic. *In: Post E.J. et al. Petroleum Systems of Divergent Continental Margin Basins*, *GCSSEPM Perkins Conference, Houston, Texas,* 75-131.

Sibuet, J.-C., Srivastava S. & Manatschal, G. 2007. Exhumed mantle-forming transitional crust in the Newfoundland-Iberia rift and associated magnetic anomalies. *Journal of Geophysical Research,* **112**, B06105.

Sinclair, I.K. 1988. Evolution of Mesozoic-Cenozoic sedimentary basins in the Grand Banks area of Newfoundland and comparison with Falvey's (1974) rift model. *Bulletin of Canadian Petroleum Geology*, **36**, 255-273.

Srivastava S.P., Sibuet J.-C., Cande S., Roest, W.R. & Reid, I.D. 2000. Magnetic evidence for slow spreading during the formation of the Newfoundland and Iberian margins. *Earth and Planetary Science Letters*, **182**, 61-76.

van Avendonk, H.J., Holbrook, W.S., Nunes G.T., Shillington D.J., Tucholke B.E., Louden K.E., Larsen H.C. & Hopper J.R. 2009. Seismic velocity structure of the rifted margin of eastern Grand Banks of Newfoundland, Canada. *Journal of Geophysical Research,* **111**, B11404.

Welford K. & Hall, J. 2007. Crustal structure of the Newfoundland rifted continental margin from constrained 3-D gravity inversion, *Geophysical Journal International*, **171**, 890-908.

Ziegler, P.A. 1989. Evolution of the North Atlantic – an overview. *In: Tankard A.J. & Balkwill H.R. (eds)*. *Extensional Tectonics and Stratigraphy of the North Atlantic Margins*. American Association of Petroleum Geologists *Memoir,* **46**, 111-129.

## THE CHALLENGE OF PORE PRESSURE PREDICTION IN COMPLEX ENVIRONMENTS – JEANNE D'ARC BASIN, EASTERN CANADA

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The dominant mechanism for generating pore pressure in shales is disequilibrium compaction, the inability of fluids to escape from a compacting sediment under increasing vertical load. Disequilibrium compaction requires a constantly increasing load to inhibit fluid escape. By contrast a sand-rich sediment may have sufficient porosity/permeability to allow fluids to escape, therefore maintaining normal pressure.

Where sand-rich sequences exist the depth at which overpressure develops beneath can be much deeper than in a clay-rich sequence. The impact of deep onset of overpressure is that the rapid transition from normal pressure to high magnitudes of overpressure leads to potential drilling/well control issues, e.g. Nautilus C-92.

Recognising the existence of a pressure regime dominated by rapid transitions from normal pressure to high overpressure is very important when planning exploration wells in frontier areas. If accurate predictions of the shale pressure cannot be made then there is the chance for wells to penetrate highly overpressured sediments with a low mud weight leading to a potentially hazardous kick.

Pressure prediction in shales from wireline data is reliant on the ability to define a normal compaction trend, and deviations from this trend allow calculation of the magnitude of pore pressure. Standard practice is to calibrate the normal compaction curve to the shallowest data as these data are most likely to be normally pressured. In areas with variable clay type and particle distributions, there may be more than one normal compaction curve required to solve for pore pressure.

The Jeanne d'Arc Basin (JDB) in Eastern Canada has a complex history of extension and compression, tectonic evolution and contains mixed lithologies (e.g. sand, shale, carbonate). Carbonate intervals, e.g. Rankin Formation, can have complex diagenetic histories which do not provide a relationship between porosity and pore pressure/effective stress.

There are multiple wells in the JDB that contain data (WFT, Kick, Mud weight) showing rapid pressure transitions to highly overpressured sediment. The pressure transitions are not linked to a single stratigraphic interval, therefore forecasting the depth of the onset of high overpressure difficult.

Prediction of the pore pressure in the Jeanne d'Arc Basin is further complicated by the presence of regional unconformities that are major breaks in the sedimentary sequence. The rocks above and below the unconformity will have had very different compaction histories and, as such, may need to be treated as separate intervals with the correct calibration data applied.

Prediction of pore pressure in the Jeanne d'Arc Basin relies not only on derivation of the normal compaction trend(s) for shales and accurate measurement of the reservoir pressure but also on a geological understanding of the depositional, structural and diagenetic history.

## THE MESO-CENOZOIC ALENTEJO BASIN (SW PORTUGAL) – LITHOLOGICAL CORRELATION FROM OUTCROP AND WELL DATA

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The Alentejo basin is one of the west Iberian Mesozoic basins, developed in relation with the North-Atlantic opening. First sediments are dated from Upper Triassic and the sedimentary infill includes Jurassic mostly carbonate and Cretaceous mostly siliciclastic sediments. A Cenozoic cover is also present, including Paleogene to Quaternary mostly siliciclastic sediments.

Subsidence has been important during the Mesozoic, with thick Jurassic carbonate sequences, especially during the Upper Jurassic. However, basin inversion has also been important, with a first mild event in Callovian times, marked by a sub-aerial unconformity and intraformational conglomerates. Stronger inversion events are documented in late Cretaceous and Cenozoic times, related with the alpine orogeny and Africa-Iberia plates collision.

The only outcrops of this basin are located around the town of Santiago do Cacém, 150 km South of Lisbon and halfway between the southern edge of the Lusitanian Basin and the western edge of the Algarve basin (Figure 1). These outcrops show uplifted complete sections of the Upper Triassic to Lower Jurassic sequence, including Silves Fm. (red beds), Dagorda Fm. (red clays), CAMP related volcanic and Fateota Fm. (dolomites) (Figure 2). Above a regional depositional hiatus, Middle Jurassic units are represented by the Rodeado and Monte Branco (limestones) and a second hiatus precedes a thick Upper Jurassic sequence including intraformational conglomerates and limestones of the Deixa-o-Resto Fm. (Inverno *et al.,* 1999; Pereira & Alves, 2012). These Mesozoic sequences are affected by listric faults towards the west; folded, eroded and unconformably covered by Tertiary sands (Figure 3).

Around 40 km NW of these outcrops, an exploratory well (Pescada – 1) has been drilled by Texaco in 1975, reaching the basement at a total depth of 3115 m. The targets were Jurassic limestones in a closed anticline trap, but no oil shows were found. The cross section shows Upper Triassic dolomitic siltstones and volcanics, Lower Jurassic dolomites, Middle Jurassic limestones, Upper Jurassic carbonates, Lower Cretaceous calcareous sandstones and Tertiary (Oligocene and Mio/Plio-Pleistocene) sands. Biostratigraphic dating was restricted to the Middle and Upper Jurassic section, with lithological correlation for the rest of the well.

Between these two places with significant information (Pescada-1 well and Santiago do Cacém outcrops), an on-shore well (Monte Paio) has been drilled in the '70s by the Portuguese Geological Survey (SGP) with engineering purposes, related with the development of the Sines harbour close to that area. This well reached the basement at a depth of 1100m, crossing Upper Triassic siliciclastics and evaporites (Silves and Dagorda Fm.), Jurassic carbonates (Fateota, Rodeado and Deixa-o-Resto Fm.) and Cenozoic sands (Miocene and Plio-Pleistocene). However, its lithostratigraphy is poorly known and there is only one very short and synthetic public report about it, with a basic lithological column and supposed ages. Some specific studies on Upper Jurassic biostratigraphy have been promoted but have not been published.

From preliminary comparative observations of these three sections (Figure 2), we underline the absence of volcanics and the thin Lower Jurassic sequence in Monte Paio, as well as the important facies differences in the Upper Jurassic sequence, with intermediate characteristics between shallow water in SC and deeper water in Pe-1. This work will include a detailed lithological description of the Monte Paio well, to identify facies variations, providing a better approach to the lithostratigraphic correlation between the outcrops of Santiago do Cacém area and the report data of the Pescada – 1 well. This study will provide a better knowledge of the inner proximal margin of the Alentejo Basin and will improve the knowledge of the tectono-stratigraphic evolution of the whole Basin during the Mesozoic and Cenozoic.

## References

Inverno, C.M.C., Manupella, G., Zbyszewski, G., Pais, J. & Ribeiro, M.L. 1993. Notícia explicativa da folha 42-C Santiago do Cacém. *Serviços Geológicos de Portugal, Lisboa*.

Oliveira, J.T. 1984. Carta Geológica de Portugal, Escala 1:200.000, Folha 7. Notícia Explicativa, 77p., *Serviços Geológicos de Portugal, Lisboa*.

Pereira, R.N. & Alves, T.M. 2012. Tectono-stratigraphic signature of multiphased rifting on divergent margins (deep-offshore Southwest Iberia, North Atlantic). *Tectonics*, **31**, doi:10.1029/2011TC003001.

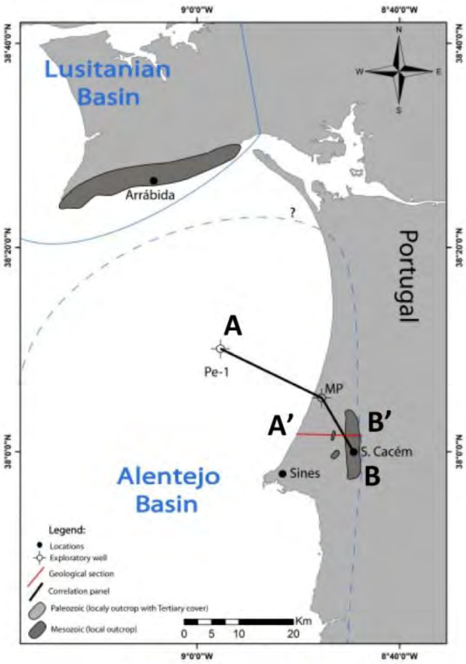


*Figure 1: Location of the three studied sites in SW Portugal: Pe-1 well, Monte Paio (MP) well and Santiago do Cacém outcrops.*

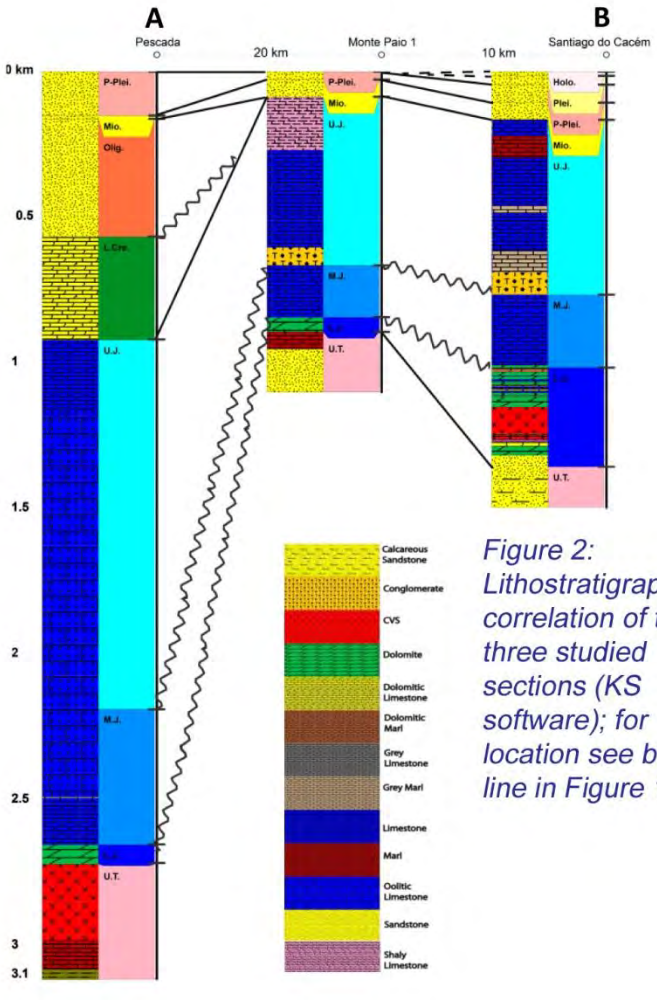


*Figure 2: Lithostratigraphic correlation of the three studied sections (KS software); for location see black line in Figure 1.*

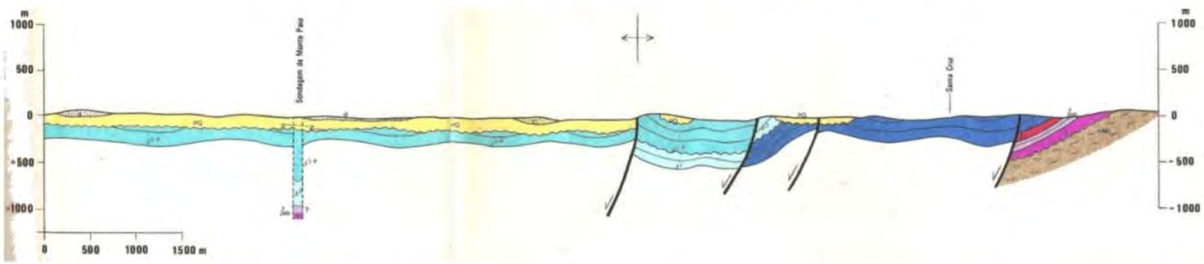


*Figure 3: Geological section from Santiago do Cacém towards W, with projection of the MP well (left side) (in Oliveira, 1984); for location see red line in Figure 1.*

## ALASKA AND CHUKCHI BORDERLAND RIFTED MARGINS – INSIGHTS FROM NEW SEISMIC DATA AND CALIBRATION OF GRAVITY MODELS

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The Arctic margins of Alaska and Canada are considered conjugate margins formed during Jurassic-Early Cretaceous opening of the Canada Basin (Grantz *et al.,* 2011). The Chukchi Borderland (microcontinent) separated from Arctic Alaska during or following opening of the Canada Basin, forming the North Chukchi Basin in its wake (Figure 1), and became tectonically isolated from regional sediment dispersal systems. Thus, although the Alaska and Chukchi Borderland rifted margins share an orthogonal juncture and likely had similar geometries during rifting, they now display significant contrasts owing to subsequent geologic history. Analysis of these adjacent rifted margins using new reflection seismic data and recent compilations of free-air gravity data provides a basis for interpreting other rifted margins in the Arctic, and perhaps beyond.

The outboard margins (hinges) of the Alaska and Chukchi Borderland rift shoulders, inferred to represent boundaries between continental crust and highly attenuated continental or transitional crust, are defined by significant offset in acoustic basement. Along the Alaska margin, acoustic basement steps downward more than 6 km over a distance of 20–25 km. The step is marked by an abrupt increase in the number and magnitude of growth faults in the overlying sediment prism, which is more than 10 km thick outboard of the hinge. The huge volume of sediment that mantles the Alaska margin mostly was derived from the Chukotka and Brooks Range orogenic belts. Sediment was delivered to the Alaska margin by dispersal systems that traversed the Arctic Alaska plate, filled the Colville foreland basin, overstepped the ancestral rift shoulder, and built the extant continental terrace. Lithofacies range from hemipelagic and sediment-gravity-flow deposits in deep basin and slope strata to deltaic and nonmarine deposits in shelf strata.

Along the Chukchi Borderland margin, acoustic basement steps downward 4–5 km over a distance of 20–25 km, and the hinge profile is entirely resolved in seismic data owing to a thin sediment cover. The Chukchi Borderland was sediment starved because the Chukotka – Brooks Range sediment dispersal systems did not reach the isolated and high standing microcontinent. Instead, sediment was dispersed through structural grabens into the North Chukchi Basin on the west and the Canada Basin on the east (Figure 1). Consequently, the high-standing parts of the Chukchi Borderland are mantled by a thin veneer of pelagic(?) sediment and air-fall volcanic ash (Grantz *et al.,* 1998), whereas the lower parts of the hinge are onlapped by mostly hemipelagic and sediment-gravity-flow deposits that are distal parts of the sediment dispersal systems emanating from the Alaska margin and Mackenzie River delta.

Contrasting geology across the Alaska and Chukchi Borderland rift shoulders is manifest in the magnitude, size, and geometry of free-air gravity anomalies (FAAs). The Alaska margin displays a series of lobate FAA highs (“string of sausage”), oriented parallel to the hinge and centred a short distance outboard of the hinge. These anomalies are interpreted to delineate depocentres comprising Cretaceous–Paleogene strata that are well compacted (higher density). The Chukchi Borderland margin displays a narrow and mostly continuous FAA high that lies above the high-standing rift shoulder and a narrow and continuous FAA low that lies directly above the hinge. These gravity responses are interpreted to be driven mostly by contrasts in bathymetry and crustal thickness. Our initial observations suggest that the new seismic data across Arctic margins provide the opportunity to calibrate models of gravity anomalies and that refined interpretations of Arctic rifted margins using calibrated gravity models may be possible.

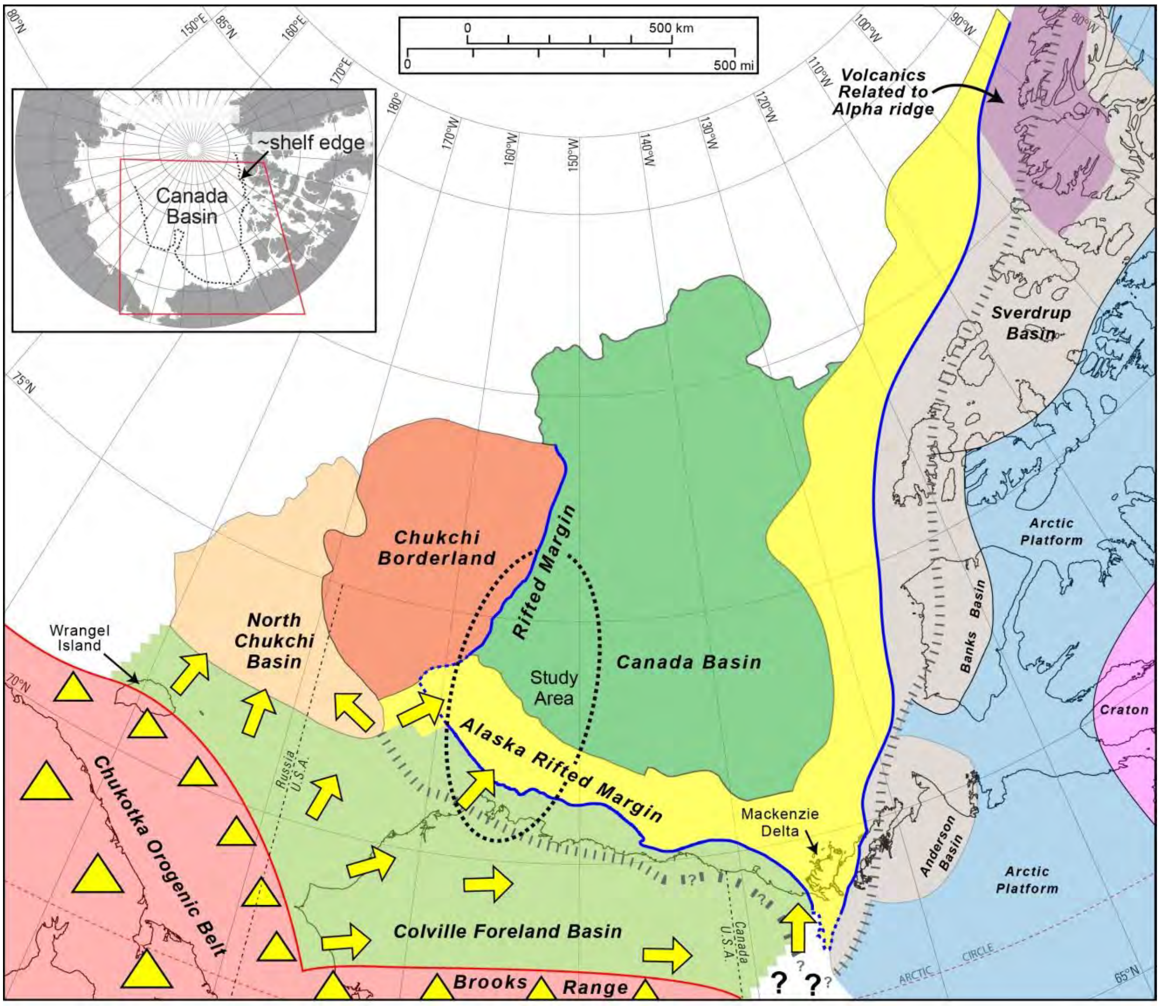


***Figure 1:*** *Map of the Canada basin, rifted margins of Alaska and Chukchi Borderland, and adjacent parts of Russia, Alaska, and Canada showing geologic provinces during Early Cretaceous. Rift shoulders are defined by abrupt basinward margins (hinges, heavy blue lines, dashed and queried where uncertain) and gradational inboard margins (grey lines, broad with short dashes). Yellow triangles depict uplifted provenance areas and yellow arrows depict generalised sediment dispersal patterns from source to sink. Modified from Houseknecht and Bird (2011).*

## References

Grantz, A., Hart, P.E. & Childers, V.A. 2011. Geology and tectonic development of the Amerasia and Canada Basins, Arctic Ocean. *In:* Spencer, A.M., Embry, A.F., Gautier, D.L., Stoupakova, A.V. & Sørensen, K. (eds) *Arctic Petroleum Geology*. Geological Society London, Memoirs, **35**, 771-799.

Grantz, A., Clark, D.L., Phillips, R.L. & Srivastava, S.P. 1998. Phanerozoic stratigraphy of Northwind Ridge, magnetic anomalies in the Canada Basin, and the geometry and timing of rifting in the Amerasia Basin, Arctic Ocean. *Geological Society of America Bulletin*, **110**, 801-820.

Houseknecht, D.W. & Bird, K.J. 2011. Geology and petroleum potential of the rifted margins of the Canada basin. *In:* Spencer, A.M., Embry, A.F., Gautier, D.L., Stoupakova, A.V. & Sørensen, K. (eds) *Arctic Petroleum Geology*. Geological Society London, Memoirs, **35**, 509-526.

# CHARACTERISATION OF RESERVOIR HETEROGENEITY IN A SANDY BRAIDED STREAM ANALOGUE, MINAS SUB-BASIN, BAY OF FUNDY, NOVA SCOTIA, CANADA

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The overall aim of this research is to understand and characterise fluvial deposits quantitatively in three-dimensions, and using the resulting geostatistical information to produce realistic geocellular reservoir analogue models. The well exposed outcrops of Late Triassic fluvial sandstones in the Fundy Rift Basin of Canada present exceptional analogues for hydrocarbon reservoirs in the North Sea and other similar fluvial systems, making them ideally suited to this project.

This study focuses on the quantification of different scales of reservoir heterogeneity and their effect on fluid flow. Accurate assessment of reservoir heterogeneity is critical in field development and exploitation, and must be taken into consideration in the construction of a flow simulation model. Traditional sedimentological logging methods are combined with LIDAR digital data capture techniques and high resolution digital photography to describe and interpret changes in facies geometry and distribution in great detail. The study section consists of channel sandstone bodies alternating with limited overbank mudstone deposits. We observed reservoir heterogeneity in the form of rapid lateral and vertical changes in lithology, texture, sorting, presence of discontinuous shales, fractures, faults and diagenetic effects (Figures 1, 2 & 3).

Maximum hydrocarbon recovery in clastic reservoirs is a function of how well we understand reservoir heterogeneity and barriers to fluid flow. Modelling of fluvial reservoirs can be very unreliable when only conditioned to seismic and well data as is the case in the sub-surface. By using outcrop analogue data to condition the geological model, the uncertainty in the facies distribution is reduced.

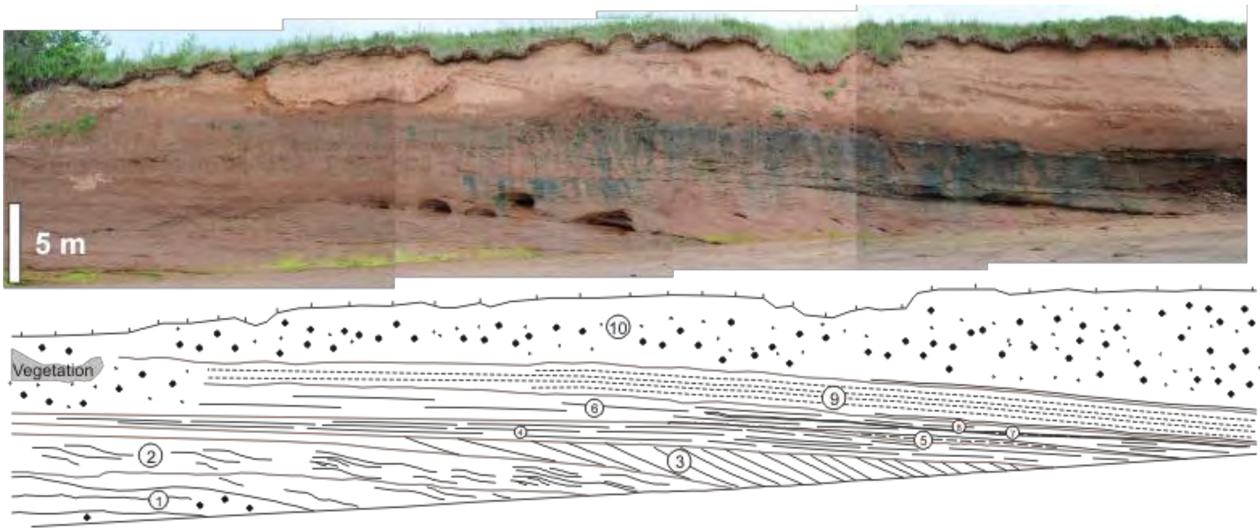


***Figure 1:** From top: uninterpreted photograph; interpretations of the photograph with numbers corresponding to the various lithofacies. 1,2,3,4,6,8 &10 are sands with various sedimentary structures as illustrated graphically. 5,7 & 9 are mud. This section has the thickest mud unit 9, 1.2 m, interpreted as abandoned channel fill, which could act as an effective permeability barrier. Notice the stacking patterns and the heterogeneity.*

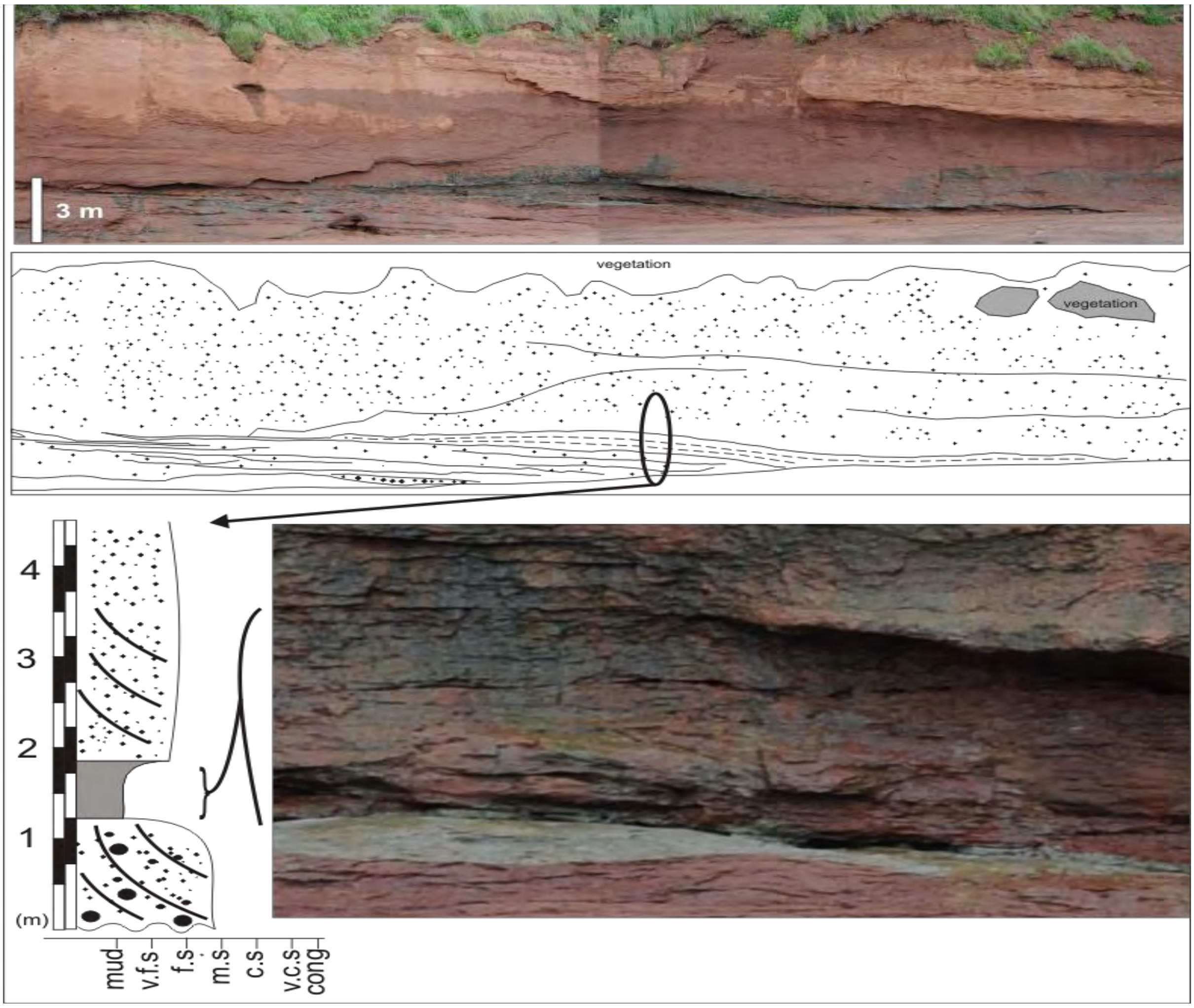


***Figure 2:*** *From top: uninterpreted photograph; interpretations of the photograph with the logged point circled; discontinuous mud, 0.6 m thick and less than 50 m along section, encased in a thin lens of pale green sandstone; and a graphic log.*

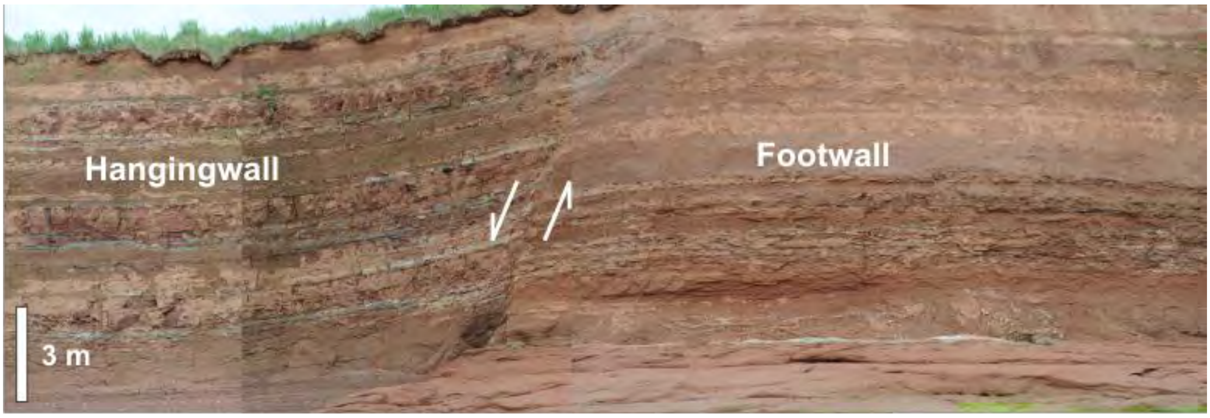


***Figure 3:*** *This figure shows fault interpretation. The fault dips at about 70$^0$ with a thin clay smear, 5 cm on the fault plane. Notice the geometries of the beds and changes on the depositional environments on the hangingwall and footwall of the fault. Beds on the hangingwall show concave-upwards fold deposited in a lacustrine environment in contrast to the footwall.*

## THE VOLCANIC MARGIN OFF NORTHERN LABRADOR

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A new interpretation of seismic reflection data on the northern Labrador rifted margin (Keen *et al.,* 2012) shows a variety of basement features which are commonly observed in the igneous crust at volcanic margins. These include seaward dipping reflections (SDR), volcanic plateaus, and lava deltas. Below the SDRs, wide angle seismic and gravity data suggest the presence of a thick (~15 km) igneous crust. Comparisons with the conjugate west Greenland margin show similar structures there, where there is good definition of the crustal structure (e.g. Gerlings *et al.,* 2009).

Magnetic chron 27n (~61 Ma) is coincident with the volcanic plateaus, connecting the timing of emplacement of the thick igneous crust to Paleocene volcanism in the Davis Strait region to the north. These observations extend the region of excess volcanism about 500 km south along the Labrador rifted margin and indicate the presence of conjugate volcanic margins in the northern Labrador Sea. While the thick igneous crust is fairly symmetrically distributed across the conjugates, the zone of thinned continental crust is asymmetric, with a much wider region of thinned crust on the west Greenland margin. Transitions to non-volcanic margins occur to the south on both sides of the Labrador Sea; however, it is not clear whether the transition is correlated to major pre-existing crustal or lithospheric lineaments.

Almost all of the excess magmatism at these volcanic margins appears to lie seaward of the thinned continental crust and there is, at most, minor underplating of the seaward edge of continental crust. This observation, and the age and distribution of Mesozoic igneous rocks on land in coastal West Greenland and Labrador and below the shelves, is consistent with recent models for the formation of non-volcanic margins. These models suggest that a broad zone of rifting in Early Cretaceous time progressively narrowed and localised seaward of the present continental shelves in late Cretaceous time, creating a relatively narrow zone of lower lithospheric thinning and mantle upwelling. This is in accord with the presence of Early Cretaceous and the absence of Late Cretaceous volcanic rocks in coastal and shelf regions (Larsen *et al.,* 2009). In the early Paleocene, perhaps connected with the influence of a proto-Icelandic mantle plume in Davis Strait, magmas were channelled into this narrow zone, with no significant magmatic underplating of the continental hinterlands. Thus the margins of the Labrador Sea may have been entirely non-volcanic through Cretaceous time and only in the Paleocene, at the onset of sea floor spreading, were the northern regions affected by the observed magmatism.

### References

Gerlings, J., Funck, T., Jackson, H.R., Louden, K.E. & Klingelhöfer, F. 2009. Seismic evidence for plume-derived volcanism during formation of the continental margin in southern Davis Strait and northern Labrador Sea, *Geophysical Journal International*, **176**, 980-994, doi: 10.1111/j.1365-246X.2008.04021.x.

Keen, C.E., Dickie, K. & Dehler, S.A. 2012. The volcanic margins of the northern Labrador Sea: Insights to the rifting process. *Tectonics*, TC1011, doi:1029/2011TC002985.

Larsen, L.M., Heaman, L.M., Creaser, R.A., Duncan, R.A., Frei, R. & Hutchison, M. 2009. Tectonomagmatic events during stretching and basin formation in the Labrador Sea and the Davis Strait: evidence from age and composition of Mesozoic to Palaeogene dyke swarms in West Greenland, *Journal of the Geological Society, London,* **166**, 999-1012.

# SHELF AND SLOPE DEPOSITS OUTBOARD THE SABLE SUB-BASIN, OFFSHORE NOVA SCOTIA: IMPROVED UNDERSTANDING OF CRETACEOUS FLUVIAL-DELTAIC SYSTEMS, SHELF-EDGE TRAJECTORIES AND EQUIVALENT DEEPWATER STRATA

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The Cretaceous shelf to slope transition outboard the Sable Sub-Basin, offshore Nova Scotia, Canada, is often inadequately imaged and therefore poorly understood. In part this is because of the complex structural geology across this important boundary. Even the simple mapping of shelf-edge trajectories has been problematic and there is significant uncertainty about how to correlate shelf strata onto the equivalent slope. Consequently, there has been disagreement about palaeogeography and shelf-slope gross depositional environments. In this poster we present two composite seismic sections to be used as type sections for the central and western Sable Sub-Basin and to aid correlation of seismic markers across the Cretaceous shelf-slope transition. Line locations were carefully chosen to intersect features commonly found at or near shelf breaks, such as offlap geometries and canyon heads. These profiles also avoid salt structures and areas affected by large amounts of listric faulting while still remaining within the coverage of 3D seismic data. These lines demonstrate that high confidence correlations to deep water are still possible when care is taken to select a route that avoids geologic features that degrade seismic imaging. Seismic geomorphology of fluvial-deltaic deposits from 3D seismic surveys, and identification of numerous canyon heads aids in our interpretation of shelf-edge trajectories through time. On the slope, 3D seismic attributes coupled with time-thickness maps have been used to identify sediment transport corridors interpreted to connect to shelf margin canyon systems. This work, coupled with our improved understanding of slope morphology at the time of deposition, provides a clearer understanding of the five existing Cretaceous deepwater well penetrations outboard the Sable Sub-Basin. These results can be used to guide deepwater exploration off Nova Scotia.

## IRISH AND NEWFOUNDLAND RIFTED MARGINS: CRUSTAL CROSS-SECTIONS FROM GRAVITY INVERSION

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We have determined Moho depth, crustal thickness and continental lithosphere thinning factors for the conjugate margins of Ireland and Newfoundland using a new gravity inversion method which incorporates a lithosphere thermal gravity anomaly correction. We use these to map the ocean-continent transition structure, the distribution of oceanic crust, thinned continental crust and micro-continents. This work forms part of the North Atlantic plate reconstruction project (Ady *et al.,* this conference).

3D gravity inversion, using public-domain gravity and sediment-thickness information, has been used to produce regional maps of (i) Moho depth, (ii) crustal thickness and (iii) continental lithosphere thinning for the North Atlantic. In addition gravity inversion using the interpreted sediment thickness from seabed to top-basement produced during the seismic-interpretation phase of the North Atlantic project (Whittaker *et al.,* this conference) has been used to produce a new set of 17 2D depth-transects across both margins (10 for Ireland, 1 for Galicia and 6 for Newfoundland).

Moho depth, crustal thickness and continental lithosphere thinning (1- 1/β) have been determined using gravity inversion incorporating a lithosphere thermal gravity anomaly correction (Greenhalgh & Kusznir, 2007; Chappell & Kusznir, 2008). The gravity anomaly inversion is carried out in the 3D spectral domain (using Parker, 1972) to determine 3D Moho geometry. The gravity anomaly contribution from sediments assumes a compaction controlled sediment density increase with depth. Lithosphere thermal model re-equilibration (cooling) times, used to calculate the lithosphere thermal gravity anomaly correction, are conditioned by ocean isochron information (Mueller *et al.,* 2008), and continental rifting and breakup ages. The gravity inversion method provides a prediction of ocean-continent transition location which is independent of ocean isochron information. The gravity inversion includes a parameterisation of the decompression melting model of White & McKenzie (1989) to predict volcanic addition generated during continental breakup lithosphere thinning and seafloor spreading.

Our analysis of the 2D and 3D gravity inversion results, together with subsidence analysis, suggests that the conjugate, paired, deep-water basins of Rockall – West Orphan and Porcupine – East Orphan each represent a failed attempt at breakup prior to the eventual Ireland/Newfoundland separation which cut across these previously-formed failed breakup basins.

### References

Chappell A.R. & Kusznir, N.J. 2008. Three-dimensional gravity inversion for Moho depth at rifted continental margins incorporating a lithosphere thermal gravity anomaly correction. *Geophysical Journal International*, **174**(1), 1-13.

Greenhalgh, E.E. & Kusznir, N.J. 2007. Evidence for thin oceanic crust on the extinct Aegir Ridge, Norwegian Basin, N.E. Atlantic derived from satellite gravity inversion. *Geophysical Research Letters*, **34**, L06305, doi:10.1029/2007GL029440.

Müller, R.D., Sdrolias, M., Gaina, C. & Roest W.R. 2008. Age, spreading rates and spreading symmetry of the world's ocean crust. *Geochemistry Geophysics Geosystems*, **9**, Q04006, doi:10.1029/2007GC001743.

Parker, R.L. 1972. The rapid calculation of potential anomalies. *Geophysical Journal, Royal Astronomical Society*, **31**, 447-455.

White, R.S. & McKenzie, D.P. 1989. Magmatism at rift zones: the generation of volcanic continental margins and flood basalts. *Journal of Geophysical Research*, **94**, 7685-7729.

**Acknowledgements**

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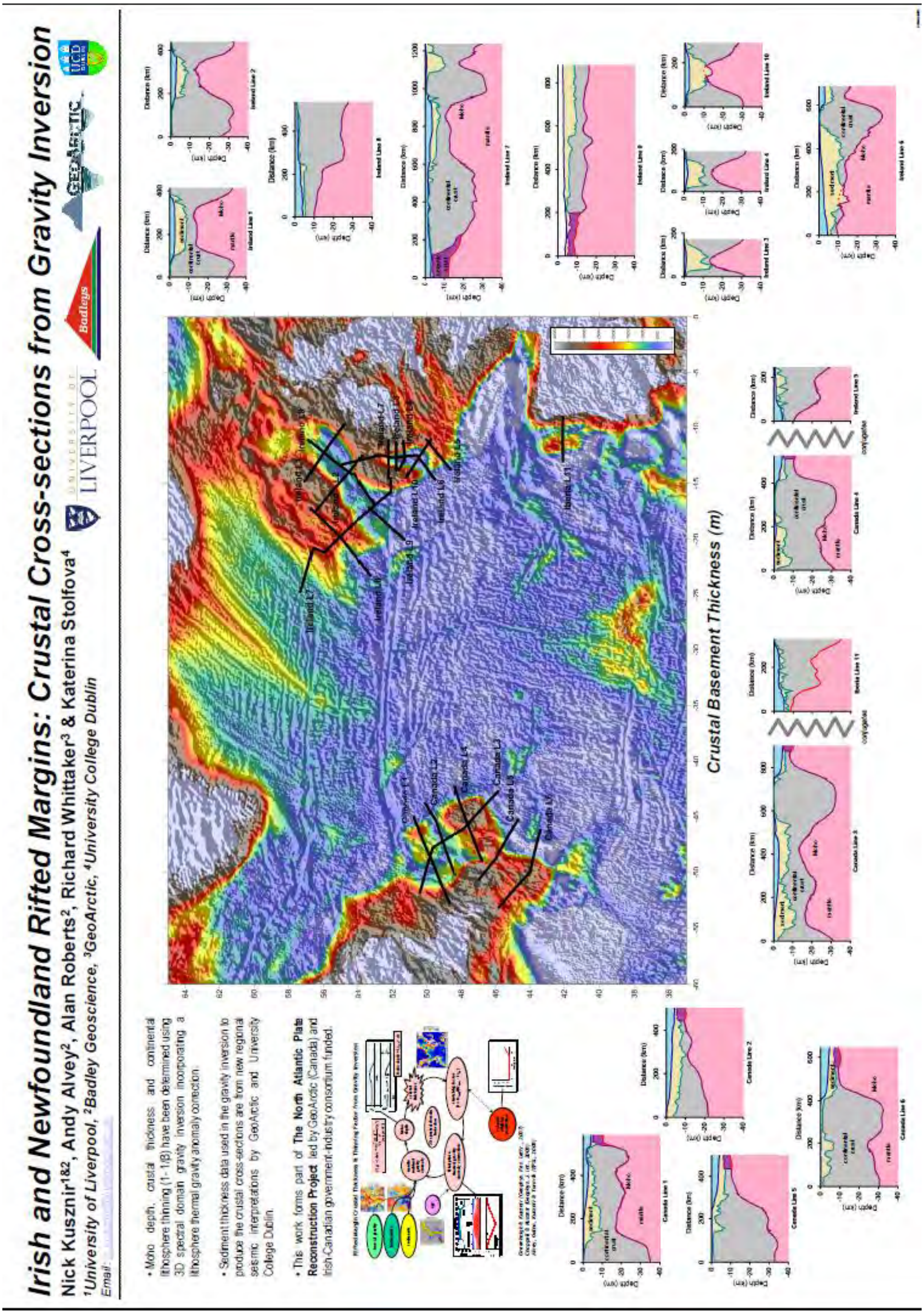

# SALT TECTONICS IN THE ONSHORE NORTHERN LUSITANIAN BASIN: INTERPLAY BETWEEN LATE-VARISCAN HERITAGE AND REGIONAL AND LOCAL STRESS FIELDS

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Salt structures can play an important role in the tectono-sedimentary evolution of basins. In west Iberia, the Alpine regional stress field had a horizontal maximum compressive stress striking NNW-SSE, related to the Late Miocene inversion event. However, this stress field cannot produce most of the observed and mapped structures in the onshore of the northern Lusitanian Basin. Therefore, we paid special attention to diapir tectonics, which can impose a local stress field (vertical maximum compressive stress) and be responsible for significant vertical movements of Meso-Cenozoic cover rocks.

Based on fieldwork, tectonic analysis and interpretation of geological maps (Portuguese Geological Survey, 1:50000 scale), our work shows: (1) the presence of high angle faults and anticlines with N-S, NNE-SSW, ENE-WSW or WNW-ESW trends, which cannot be the result of Alpine compression; (2) some structures can be related to late-Variscan fracturing, by reactivation of basement faults with NNE-SSW and ENE-WSW trends; (3) the anticlines show radial faulted Jurassic cores which points to diapir upward pushing; (4) some anticlines are aligned with exposed salt diapirs, showing lateral continuity between these structures; (5) geometry and sedimentary filling (up to the Pliocene) of basins show relationship to salt-related anticlines, with salt withdrawal from the base of the basin (subsidence) and movement into the neighbouring anticlines/diapirs; and (6) unconformities and folded unconformities, which means that there have been several deformation events prior to the Late Miocene Alpine event.

These data suggest that: (1) most of these structures result from local diapir tectonics, initiated before the Cretaceous; (2) some of the structures may be related to reactivation of inherited late-Variscan basement fracturing; and (3) considerable vertical movements can be deduced from salt-related anticlines and neighbouring basins.

# RESERVOIR QUALITY AND ARCHITECTURAL ELEMENTS OF MESOZOIC RIFT BASIN SEDIMENTS, SCOTIAN MARGIN

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The Scotian margin (Figure 1) is a passive conjugate margin recording 250 million years of fluvial-deltaic-lacustrine deep water sedimentation to recent post-glacial deposition, offshore Nova Scotia, Canada. Sedimentation began during initial rifting and opening of the Atlantic Ocean at sub-equatorial latitudes with Early- to Late-Triassic continental breakup of conjugate margins of North America and Africa. Following active rifting the Scotian margin became a passive margin marked by deposition of thick sequences of fluvial, deltaic, and deep water deposits. The Scotian margin comprises a number of similar juxtaposed and interconnected siliciclastic and evaporitic filled sub-basins offshore Nova Scotia (Wade *et al.,* 1989; Wade and Maclean, 1990). Wade *et al.* (1996) describe the sedimentary fill of the Scotian margin. The earliest sediments were syn-rift mid- to late-Triassic mixed siliciclastic and carbonate red beds of the Eurydice Fm. (Figure 2). Continental rifting furthered plate separation allowing episodic incursion of marine waters into the basins of the Scotian margin. Cyclic arid conditions led to evaporation Fm. of extensive salt and anhydrite deposits (Argo Fm.) (Figure 2). Continued tectonic activity in the Early Jurassic resulted in the final separation of North America and Africa and is marked by complex faulting and erosion shown by the Breakup Unconformity. Post-rift, passive margin sedimentation followed, creating thick sequences of fluvial-deltaic-lacustrine deep water sediments.

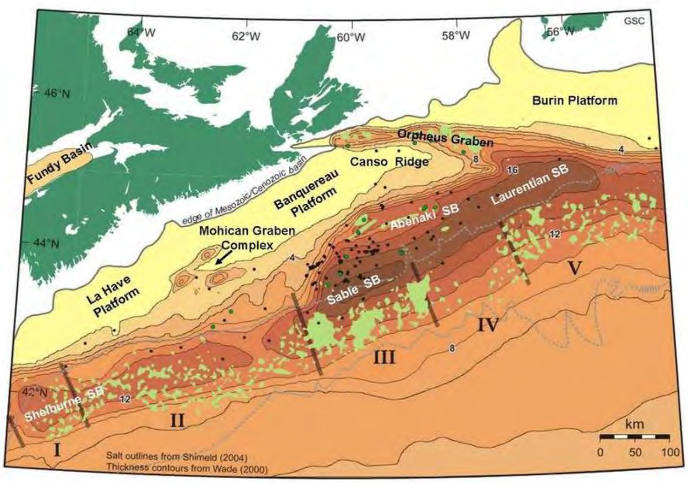


***Figure 1:** Generalised isopach map of the Scotian margin, offshore Nova Scotia, illustrating the thickness of siliciclastic sediments and location of subsurface salt diapirs and canopies (from Shimeld, 2004).*

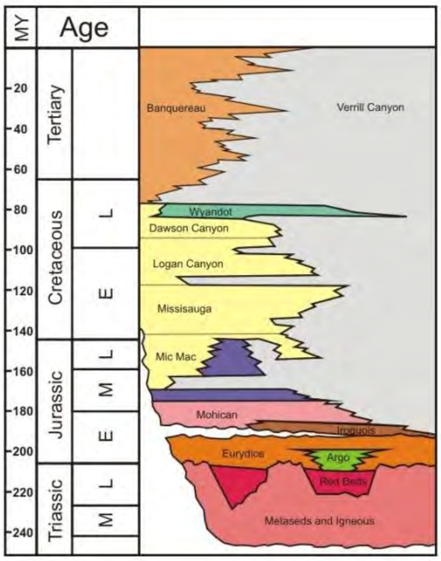


***Figure 2:** Generalised stratigraphy of the Scotian margin with Eurydice Fm., Argo Salt and Red Beds illustrated near the base (after Wade et al., 1996)*

The Fundy Basin (Figure 1) is a failed rift system along the eastern flanks of Nova Scotia comprising sub-basins representing Triassic, stratigraphically complex half grabens (Wade *et al.,* 1996; Leleu & Hartley, 2010). The Minas Sub-Basin contains the Wolfville (800 m thick) and Blomidon (250 m thick) Fms. extending from onshore to offshore (Leleu & Hartley, 2010). Sediments of the mid- to Late Triassic Wolfville Fm. are coarse- to fine-grained sandstones representing alluvial and fluvial to aeolian environments, that unconformably overlie Carboniferous sediments (Wade *et al.,* 1996; Leleu & Hartley, 2010). Investigations into outcrops along the Fundy Basin by Mulcahy (2006), Kettanah (2008), Nickerson (2010), and Vaughan (2011) demonstrate the potential reservoir complexities associated with architectural elements of these fluvial braid and sheet deposits.

Drilling in the 1970s yielded hydrocarbon shows in the Orpheus Graben but their occurrence remains unexplained. A two stage study will 1) assess the Eurydice Fm. reservoirs; 2) compare these to the stratigraphically equivalent Wolfville Fm. in the Fundy basin where past and current outcrop studies provide data for calibration and characterisation of reservoirs of the Eurydice Fm. in the Orpheus Graben. Core, cuttings, log and seismic data from the Orpheus Graben will be re-examined. The use of thin sections, core Gamma Ray (GR) (scintillometer), and core permeameter readings will provide higher resolution detail to the past well records of the Eurydice Fm. Nickerson (2010) demonstrated these tools were feasible for recording laminae and bed scale for the Wolfville Fm., illustrating their potential application for the Eurydice Fm.

In our previous reservoir characterisation studies of the Wolfville Fm. new tools were used to innovatively create a high-resolution, subsurface 3D digital model (Vaughn, 2011). Using Digital GPS surveys and ground penetrating radar (GPR), a series of tightly spaced 2D profile lines (Figure 3), created a pseudo 3D volume showing the range of dielectric properties of the variable lithology of the Wolfville Fm. The interpreted volume illustrated the 3D bar forms comprising the braid channel intervals. When these data are integrated with digital LiDAR data and high resolution photogrammetry of the cliff section of the Wolfville Fm., the beds, bedsets and fault planes can be accurately extrapolated beyond the outcrop into the subsurface. This allows for determination of the vertical and lateral continuity of Wolfville Fm. beds, a potential analogue for reservoir connectivity in the Eurydice Fm.

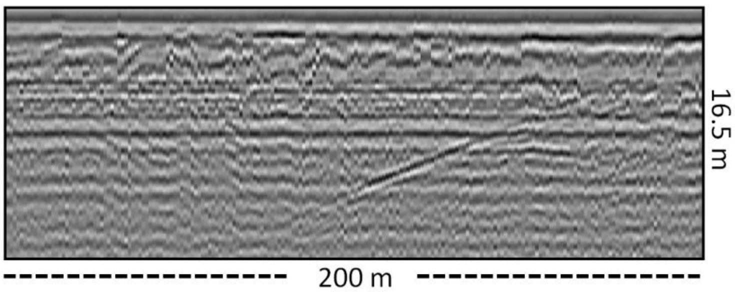


***Figure 3:*** *GPR profile illustrating the base of channel incision.*

Understanding the 3D variability of the architectural elements and heterogeneity will provide more control when describing the potential hydrocarbon reservoirs of the Mesozoic rift sediments of the Orpheus Graben, with implications on potential fluid flow for hydrocarbon development and potential liquid phase $CO_2$ injection.

**References**

**Kettanah, M.** 2008. Reservoir Quality, Diagenetic History, and Provenance of the Late Triassic Sandstones of the Wolfville Fm., Cambridge Cove, Bay of Fundy, Nova Scotia, *Unpublished Research Project, Dalhousie University*; **Leleu, S. & Hartley, A. J.** 2010. Controls on the stratigraphic development of the Triassic Fundy Basin, Nova Scotia: implications for the tectonostratigraphic evolution of Triassic Atlantic rift basins, *Journal of the Geological Society, London*, **167**, 437-454. **Mulcahy, P.** 2006. Reservoir modelling and simulation of a braided channel complex at Cambridge Cove, N.S., *Master of Engineering thesis, Dalhousie University*; **Nickerson, J.** 2010. Architecture and geometry of braided channel complex in the Triassic Wolfville Fm. *BSc. Hons. Thesis, Dept. Earth Sciences, Dalhousie University*; **Shimeld, J.** 2004. A comparison of salt tectonic sub-provinces beneath the Scotian slope and Laurentian Fan. *In:* Post, P.J et al. (eds). *Salt-sediment interactions and hydrocarbon prospectivity: Concepts, applications and case studies for the 21st century*: 24th GCSSEPM Bob F. Perkins Research Conference Proceedings, 291-306, CD-ROM, ISSN 1544-2462; **Vaughan, M.** 2011. High Resolution Stratigraphy (GPR) of Braided Channel Complexes in the Triassic Wolfville Formation: Controls on Reservoir Heterogeneity. *BSc. Hons. Thesis, Dalhousie University*; **Wade, J.A., Campbell, G.R., Procter, R.M. & Taylor, G.C**. 1989. Petroleum Resources of the Scotian Shelf. *Geological Survey of Canada Paper 88-10*, 26p; **Wade, J.A. & MacLean, B.C.** 1990. The geology of the southeastern margin of Canada, Part 2: Aspects of the geology of the Scotian Basin from recent seismic and well data. *In:* Keen, M.J. & Williams G.L. (eds). *Geology of the continental margin of eastern Canada*. Geological Survey of Canada, Geology of Canada No.2, 190-238; **Wade, J.A., Brown, D.E., Traverse, A. & Fensome, R.A.** 1996. The Triassic-Jurassic Fundy Basin, eastern Canada: Regional setting, stratigraphy and hydrocarbon potential. *Atlantic Geology*, **32**, 189-231.

## LATERAL DRAINAGE IN THE JEANNE D'ARC AND FLEMISH PASS BASINS, EAST CANADA

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In wells in the Jeanne d'Arc Basin (e.g. Fortune G-57) mud-weights used to drill wells start low and increase rapidly, in order to handle deep reservoirs (Lower Hibernia, Fortune Bay and Jeanne d'Arc) with overpressures up to 6400 psi. In detail it is found that reservoir horizons shallower than the Base Tertiary Unconformity are normally pressured. Between the Top Lower Hibernia and the Base Tertiary Unconformity overpressures are highly variable, ranging from normally pressured up to 3000 psi overpressure, often at the same depth/stratigraphic level. Such variable overpressure distribution has proved to be problematic in drilling programs, as evidenced by kicks taken in these horizons, reflecting unexpectedly high pressures. Understanding the proper framework for pore pressure prediction is therefore essential.

Shale-based pore pressure prediction has established that in many wells shale pressures are significantly higher than found in associated pressures taken in both clastic and carbonate reservoirs in the Jeanne d'Arc Basin. Similarly in the Flemish Pass Basin, pressure regressions (deeper reservoirs with less overpressure in reservoir than shales above) are observed. These observations from both basins suggest that some porous horizons have lost pressure relative to their associated shales – this phenomenon is called "lateral drainage". However, in some places the shales and reservoirs are at approximately the same pressures. These variations in overpressure at the same levels in different areas are related to the presence or absence of stratigraphic/structural isolation. The lateral drainage is associated with the dewatering of deep, overpressured shales into reservoirs of high lateral extent with flow focused towards leak points in the basins.

The recognition of these draining reservoirs has profound implications for the petroleum system in East Canada. These types of reservoirs are not restricted to offshore Canada, however, but found world-wide. They are associated with enhanced seal potential allowing longer than usual hydrocarbon columns to accumulate, as well as hydrodynamic aquifers, with implications for non-structurally controlled hydrocarbon distributions.

## NEW WIDE-ANGLE REFLECTION SEISMIC (WARRP) PROFILES ACROSS THE CONJUGATE MARGINS OF IRELAND AND NEWFOUNDLAND

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This poster describes plans for the acquisition of a set of new wide-angle seismic profiles across the conjugate Irish and Canadian continental margins. These are designed to fill critical gaps in base-line information on the structure and physical properties of the upper lithosphere, and on the broad sedimentary succession, in key areas of the conjugate margins. The earliest phases of acquisition across these margins began in the 1970s and 1980s and were targeted at addressing scientific questions concerning lithospheric development and sedimentary basin structure in the North Atlantic region. Acquisition continued through the 1990s into the present century in the deep-water Rockall and Hatton basins, on the Irish side, and across the Orphan Basin and Grand Banks region, on the Canadian side. These controlled source experiments resolved details of structure, hitherto unknown, within the crust and Mesozoic to Recent sediments. They have led to the development of new ideas regarding the mechanisms of extension in passive margin hyper-extended crust.

One of the main results to emerge from this research was that continental lithosphere extends unbroken from Ireland to the Hatton Continental Margin (on the Irish side) and that the early Mesozoic rifting history of both conjugate margins was largely amagmatic. The process of continental breakup and sea-floor spreading did not begin until the early Eocene and had a major stratigraphic impact on the post-Mesozoic evolution of the Irish margins. Crustal thickness varies widely (~2 km to 32 km) with the thinnest crust occurring below the Orphan, Rockall and Porcupine basins, where exhumation of serpentinised cold mantle lithosphere sporadically occurs.

Major magmatic underplating, associated with early Cenozoic volcanism, is confined to the outer fringes of the Hatton Continental Margin (Irish side).

The data have yielded new information on the sedimentary thickness and regional sedimentary architecture of the frontier Atlantic margin basins. They have also contributed much to our regional understanding of the working petroleum systems and hydrocarbon potential of the Irish and Newfoundland margins. The resulting data have also led to an improved understanding of the mechanisms of hyper-extension within passive conjugate margin settings, and have provided regional information on the likely thermal history of the component sedimentary basins.

Critical scientific questions have arisen from this early research. These centre on how the conjugate margins fitted together and evolved tectonically in the geological past. Answering these questions has implications for the development of linked hydrocarbon systems within the North Atlantic region. A multi-scale observational approach is required to understand the interlinked syn-rift tectonic/seismic-stratigraphic development of the entire system.

The data acquired during the proposed new programme of WARRP acquisition is fundamental in this approach. A key part of the seismological component of the research strategy is the combined use of long-streamer low frequency airgun sources, with ocean bottom seismometer systems to resolve both shallow and deep structure. The frequency bandwidth can be further significantly increased still, below very low frequencies (~ 2 - 3 Hz) generated by controlled underwater sources, with information carried by ultra-low frequency (< 0.1 Hz) passive teleseismic sources, which are generated by distant earthquakes.

## INFLUENCES OF THE AVALONIA-GONDWANA COLLISION STRUCTURES IN THE EVOLUTION OF NORTH ATLANTIC BASINS – THE EXAMPLE OF THE WEST IBERIAN BASIN

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The early Mesozoic fragmentation initiation of the Pangaea supercontinent gave origin to the North Atlantic Ocean through a complex and multistoried process, involving old and new structures and terranes. As frequently seems to occur in similar contexts, the late Palaeozoic closure suture of the Rheic ocean controlled, at least in part, the orientation of the later continental crust fragmentation, originating the Iberian margin to separate from the Newfoundland conjugate margin, along it. This event took place as early as late Triassic, recorded by red beds in both the western Iberian margin and the Newfoundland margin.

The Rheic suture was also responsible for putting together a pattern of different basement terranes from both the Avalonia and Gondwana, influencing the geometry of the Palaeozoic sub-basins and also the distribution of their potential source-rocks. As a consequence, the predictability of the occurrence of some integrated elements of petroleum systems, such as the Silurian shales and Carboniferous turbidites source rocks, together with a proper understanding of migration pathways of the generated hydrocarbons, are strongly dependent on the detailed knowledge of the rock structural orientations and surfaces resulting from the geometry of the collision model of the Rheic closure.

This heterogeneous and structured basement underlies different Mesozoic basins such as the Lusitanian Basin, the Peniche Basin and the Alentejo Basin, this one more to the south. Therefore, it controlled the structural orientation and evolution of these Mesozoic basins, namely its regional dips and depocentres, up-lifted and subsident blocks, lithology of provenance areas, etc. Also the presence of potential source-rocks beneath the Mesozoic infill is crucial to explain possible occurrences of gas in some Mesozoic reservoirs.

In order to achieve a better understanding of the complex basement structure, geological and geophysical data must be integrated - both rock data and indirect evidences, namely through gravimetric and magnetic responses, must be addressed. However, appropriate answers to questions such as the kinematics of the Porto-Tomar Shear Zone, the position of the westwards underling boundaries between the Central Iberian Zone, the Ossa Morena Zone and the South Portuguese Zone, or the detailed Avalonia-Gondwana frontier, need to be searched to fully understand the regional framework.

The exploration activities that are going on in the deep offshore basins of the western Iberian margin should provide relevant data and new perspectives about the composition of the basement, the control on the Mesozoic crustal fragmentation and the resulting present-day geometry of the Palaeozoic elements of the oil systems.

### References

Alves, L.S., Heilbron, M., Gaspar, D. & Almeida, J. 2012. Western Iberia continental margin – insights from regional gravity data. *30$^{th}$ Nordic Geological Winter Meeting, Abstracts*, 165.

FrOG Tech 2012. Lusitanian basin Structural GIS and SEEBASE™ Study. *Confidential report prepared for Mohave Oil and Gas Corporation*.

Simancas, J.F., Azor, A., Martinez-Poyatos, D., Tahiri, A., El Hadi, H., Gonzalez-Lodeiro, F., Perez-Estaun, A. & Carbonell, R. 2009. Tectonic relationships of Southwest Iberia with the allochthonous of Northwest Iberia and the Moroccan Variscides. *Comptes Rendus Geoscience*, **341**, 103-113.

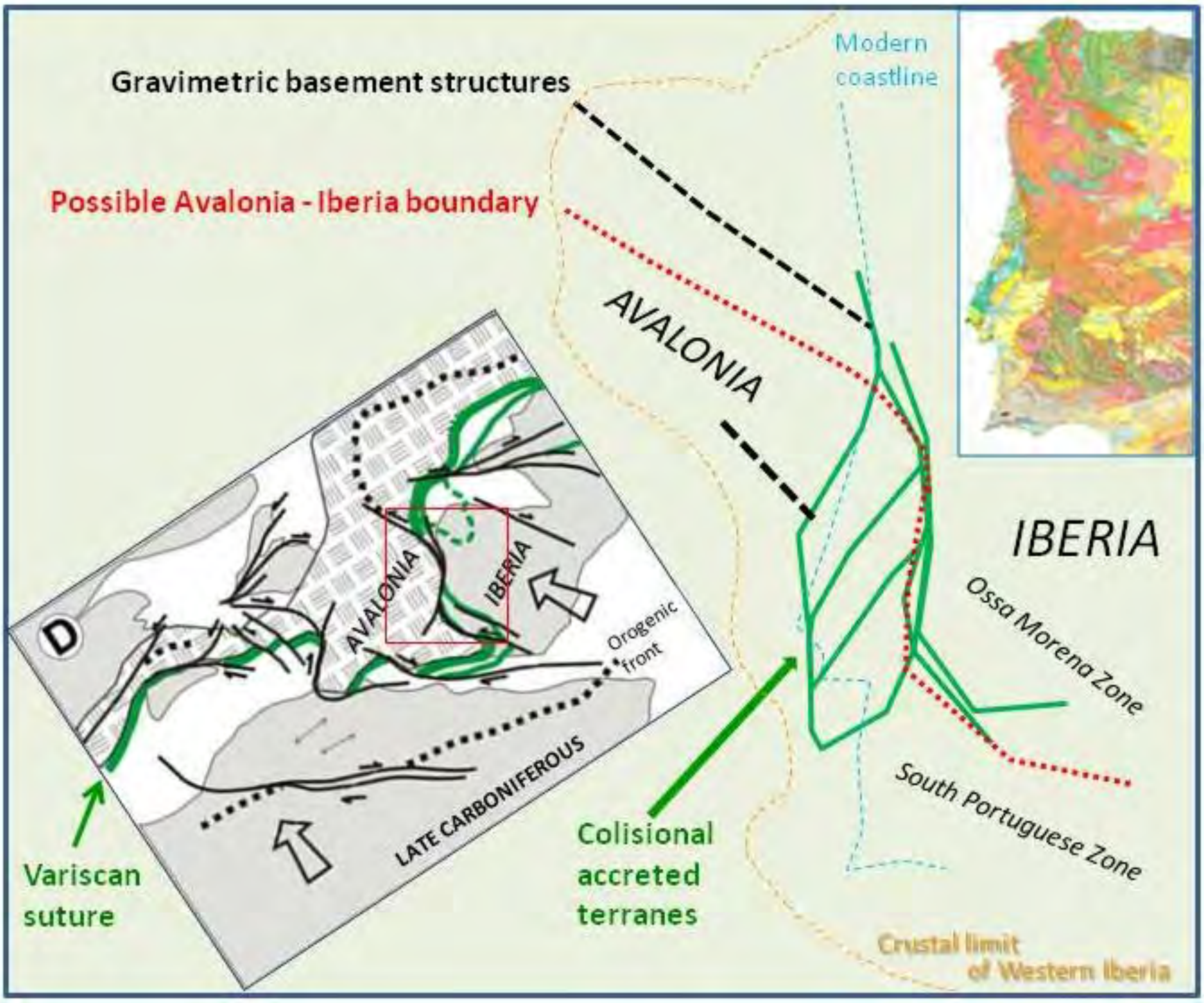


***Figure 1:*** *Sketch of the Avalonia-Iberia collision structures within the present day orientation of the Western Iberian Margin; based in Alves et al., 2012 and FrOG Tech, 2012. Insert map D is taken from Simancas et al., 2009.*

## IS SOUTHWEST IBERIA AN UPPER PLATE OR A LOWER PLATE MARGIN?

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West Iberia and Newfoundland are type-examples of asymmetric magma-poor rifted margins in the North Atlantic that underwent prolonged continental extension since the Late Triassic until the Early Cretaceous, when continental breakup ultimately gave place to the formation of oceanic crust (Manatschal, 2004; Tucholke *et al*., 2007).

The southwest Iberian margin, located on the transitional domain of the Central-North Atlantic and the West Tethys, records the multiphased fragmentation of the continental crust towards seafloor spreading that occurred west of the Tagus Abyssal Plain (Tucholke *et al*., 2007). However, the evolution of its southern province (the Southwest Iberia and South Newfoundland conjugate margins), is still poorly investigated and key questions remain unclear, such as: 1) the exact nature, extension and geometry of the continental crust, 2) the processes controlling the transition to the oceanic domain, 3) the significance of first-order transfer zones on intra-plate stress accumulation and 4) the role of inherited crustal heterogeneities on post-rift shortening. Such aspects regarding the geodynamic evolution of the Southwest Iberian margin are discussed in the context of the large scale tectonic model of asymmetric rift margins, namely the upper plate or lower plate tectonic setting (sensu Lister et al., 1986).

The multiphased segmentation of the continental crust during rifting resulted in the formation of discrete structural styles, broadly coinciding with the distinct sectors of the margin, i.e., the proximal and distal margin. The architecture of the crustal tilted blocks and their related growth strata shows distinct subsidence patterns, contrasting with the geometry of its conjugate of South Newfoundland and those from the Galicia margin. The geometry of growth strata and their estimated subsidence reveal not only the multiple events of extension, but also the ocean-wards rift locus migration. Such segmentation is related with the geometry of the continental crust and the model invoked to explain the asymmetry of these Atlantic margins.

Throughout the study area, the tilt block geometry of the outer proximal and distal margin reveals that listric master faults are likely rooted at an upper continental crust level. The analysis of high-quality 2D multichannel seismic data imaging the SW Iberian margin reveals an East dipping lower continental crust detachment, above which the thickness of the continental crust varies from about 5 km on the distal margin, to over 25 km on the proximal margin. This deep crustal reflector can be traced throughout the margin and ends near the Ocean-Continent Transition zone.

Although commonly described as a magma-poor rifted margin, the southwest Iberian margin reveals several events of magmatism since the Triassic-Jurassic boundary, which contrasts markedly with what has been described from other areas in Iberia-Newfoundland. Igneous activity includes extrusive toleitic basalts of Central Atlantic Magmatic Province, the Late Jurassic dykes, the gabbros from the Gorringe Bank and the toleitic-to-alkaline igneous intrusions and volcanics of the latest Cretaceous, altogether suggesting a common long-lived mantelic source for such events. Moreover, the latter magmatic features not only show striking similarities on their overall geochemical signature, but also the NW-SE alignment along the proximal margin. The alignment of the intrusions can be explained by the adequate upper mantle conditions underneath a thick (~30 km) highly segmented continental crust, which include the post-rift lithospheric uplift and the resulting adiabatic melting. Consequently, we postulate that underplating explains the persistent igneous activity in this specific domain of the Atlantic.

Together with the continental breakup of the Central Atlantic in the Toarcian-Aalenian, the thermal ascent resulting from underplating during rifting partly elucidates the episodic rift shoulder uplift of the proximal margin and coeval subsidence of the distal margin. An increase in temperature at deep crustal levels causing magma ascent also allows clarifying the uplift of the margin (likely since the Early Cretaceous) and the increased sediment supply towards the distal margin, as evidenced by the occurrence of thick post-rift strata deposited in a continuously subsiding basin.

Another significant aspect is the role of first-order transfer fault zones bounding the SW Iberian margin, namely the Nazaré Fault to the North, and the Messejana-Plasencia Fault Zone (MPFZ) to the South. The offshore segment of the MPFZ is revealed as a pull-apart basin, acting as a dextral strike-slip during rifting, subsequently reworked during inversion as a left-lateral transpressive feature from the latest Cretaceous onwards. Each of these transfer zones is respectively accompanied by the occurrence of uplifted hinge zones, i.e. the Estremadura Spur and the Sagres Plateau, which acted as major oceanic barriers since the early times. The Nazaré fault zone is interpreted to have worked as the northern boundary for the polarity change between the upper plate geometry of SW Iberia and the lower plate setting of NW Iberia.

The upper plate geometry of SW Iberia also allows explaining the compressive geometries and distinct shortening rates across the margin, which dominantly include the reactivation of pre- and syn-rift faults, with the formation of both thick-skin and thin-skin tectonic features. The lower continental crust detachment formed during rifting is herein invoked to be the preferred locus for the inception of convergence between the oceanic and continental domains, which resulted from collision of Iberia with the North Africa and Eurasian plates.

In conclusion, the postulate that southwest Iberia depicts an upper plate margin setting explains not only the asymmetry of the southernmost Atlantic conjugate margins, but also the late Cretaceous magmatism and its distribution and the structural architecture during post-rift inversion.

Moreover, this model brings light for future palaeogeographic reconstructions of the Central-North Atlantic, as it reveals the important implications for the assessment of possible petroleum provinces, namely on the variation of heat flow throughout the margin, the extension of source rocks and reservoirs, the regional stress field or the integrity of seals.

**References**

Lister, G.S., Etheridge, M.A. & Symonds, P.A. 1986. Detachment faulting evolution of passive continental margins. *Geology,* **14**, 246-250.

Manatschal, G. 2004. New models for evolution of magma-poor rifted margins based on a review of data and concepts from West Iberia and the Alps. *International Journal of Earth Sciences,* **93**(3), 432-466.

Tucholke, B.E., Sawyer, D.S. & Sibuet, J.C. 2007. Breakup of the Newfoundland Iberia rift. In: Karner, G.D., Manatschal, G. & Pinheiro, L.M. (eds*). Imaging, Mapping and Modelling Continental Lithosphere Extension and Breakup. Geological Society, London, Special Publications,* **282**, 9–46.

## TECTONIC CONTROL ON THE EVOLUTION OF SOUTHWEST IBERIAN BASINS: THE MIRROR-LIKE ALENTEJO AND ALGARVE BASINS

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The Western Iberian Margin (WIM) is considered to be related to the North Atlantic opening, which started to produce seafloor spreading in Lower Cretaceous times (Pena dos Reis *et al.,* 2009). The separation between Iberia and North America followed an approximate E-W trajectory, as it may be seen from post-Lower Cretaceous magnetic anomalies distribution. This configuration is well established for the Lusitanian Basin (LB, Central Western Portugal) and the Alentejo Basin (ATB, Southwestern Portugal) but is more questionable for the Algarve Basin (AGB, Southern Portugal).

At the present, the AGB outcrops along a broadly E-W oriented monocline, facing southwards to the N-African continent, giving a first impression of an orthogonal orientation regarding the LB and ATB Atlantic opening. However, the analysis of its regional characteristics, including its predominantly off-shore areas, shows clear NNE-SSW trends, not far from the NNE-SSW trends of the ATB. These AGB trends are also quite visible in regional thicknesses variations, with elongated up-lifted basement blocks and elongated depocentres, present in different geological times, since the Upper Triassic until the Cretaceous (Matias, 2007). Onshore studies of facies distribution and palaeocurrents also underline this regional Mesozoic trend.

This broadly parallel configuration of the Alentejo and Algarve basins corresponds in fact more to a "mirror configuration", with the ATB showing NNE-SSW listric faulting, opening and growing and deepening towards WNW (Pereira & Alves, 2011), whereas in the AGB the same structural direction promotes deepening and opening towards ESE (Matias, 2007). These two mirror-basins are separated by the Sagres Spur, which corresponds to an uplifted block related with the NE-SW Messejana-Plasencia Fault Zone (MPFZ), a very important tardi-Variscan structure with crustal expression and Mesozoic magmatism.

In both basins, there are clear evidences of important geodynamic gradients, with increased stretching towards the outer areas. At the ATB this resulted from the North-Atlantic opening to the W, with Jurassic syn-rift units (Pereira & Alves, 2011), whereas at the AGB this resulted mainly from the Western Tethys rifting to the South (Matias, 2007).

In both basins Late Cretaceous and Tertiary evolution has been controlled by the same alpine (Betic) compressive episodes and orientations, related to the African plate collision with the Iberian micro-plate and consequent Gulf of Cadiz allochthonous emplacement. In both basins the Mesozoic infill controlling faults have been inverted, affecting also the Tertiary sedimentary cover.

As a conclusion, it may be stated that the Alentejo and the Algarve Basins share the same late-Variscan oriented heritage, developing in Upper Triassic to Upper Jurassic times mirror-like geometries, on opposite sides of the Sagres Spur, related with NE-SW listric faults. However, their Cretaceous evolution is quite different from each other, with continued rifting stretching in the ALB outer areas and an abandoned rift-margin in the AGB.

### References

Matias, H. 2007. Hydrocarbon potential of the off-shore Algarve Basin. *PhD Thesis, Universidade de Lisboa, 297p.* (unpubl.)

Pena dos Reis, R., Pimentel, N. & Garcia, A. 2009. The Evolution of the Atlantic Margin of Iberia as recorded in the Lusitanian Basin (Portugal). *American Association of Petroleum Geologists ICE Abstracts Volume*, Rio de Janeiro (Brazil).
http://www.searchanddiscovery.com/abstracts/html/2009/intl/abstracts/reis2.htm

Pereira, R. & Alves, T. 2011. Margin segmentation prior to continental breakup: A seismic-stratigraphic record of multiphased rifting in the North Atlantic (Southwest Iberia). *Tectonophysics,* **505**(1-4), 17-34.

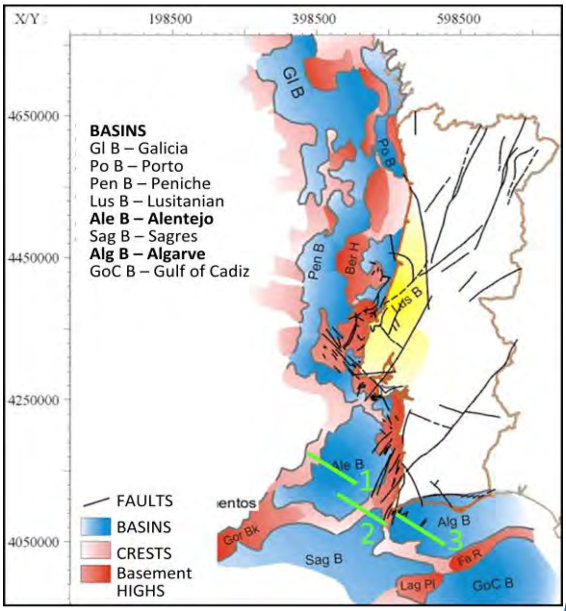

Figure1

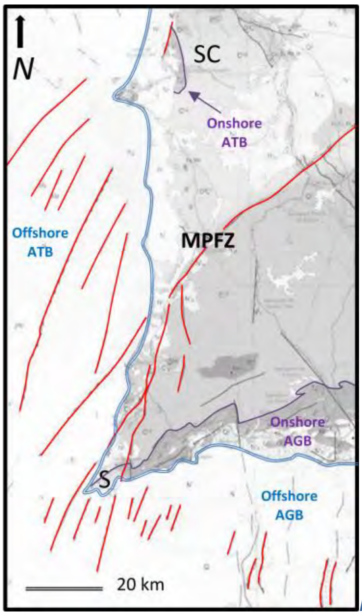

Figure 2

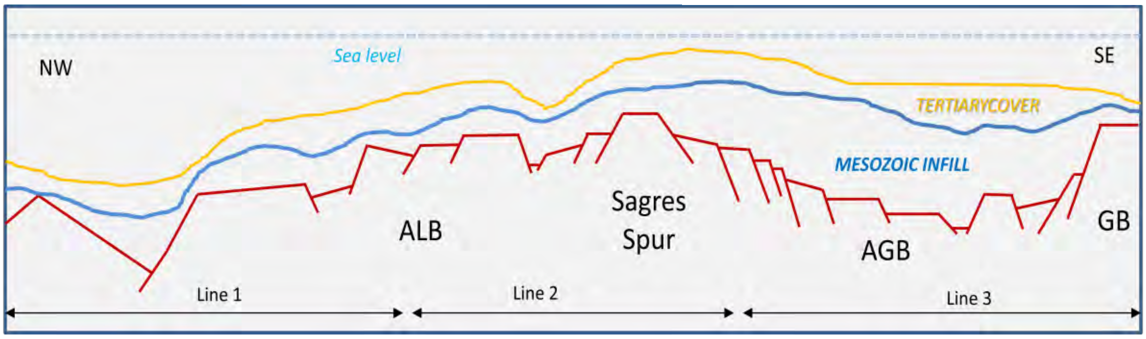

Figure 3

***Figure 1****: Location of the Alentejo and Algarve Basins in Southwestern Iberia. The green lines show the position of interpreted seismic lines used to compose the sketch of Figure 3.*

*Lines 1 and 2 = Figure 12 and Figure 8 in Pereira & Alves (2011); Line 3 = Figure 6.5 in Matias (2007).*

***Figure 2****: Tectonic framework of the Alentejo Basin (ATB) and Algarve Basin (AGB) in Southwestern Iberia, with the mains faults underlined in red (adapt. from Carta Geológica de Portugal, 1:1,000,000), MPFZ – Messejana-Placencia Fault Zone; SC – Santiago do Cacém.*

***Figure 3****: Sketch of the basement structures and Meso-Cenozoic infill of the Alentejo Basin (ALB) and Algarve Basin (AGB), based on the composition of three interpreted seismic lines (see Figure 1 for location). GB – Guadalquivir Bank.*

# IMAGING CLASTIC DEPOSITIONAL SYSTEMS ON 3D SEISMIC ON THE EASTERN MARGIN OF THE PORCUPINE BASIN: COMPLETING THE PICTURE OF THE PETROLEUM SYSTEM?

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The Porcupine Basin contains petroleum systems at Jurassic, Cretaceous and Lower Tertiary levels, almost every well having encountered oil and/or gas shows, and most wells containing potentially moveable hydrocarbon. To date, lack of viable reservoir quality has been a common cause of failure, with sandstones prone to cementation, or apparently not laterally extensive. Thus, exploring for better quality, well-connected reservoirs will be a key objective for the next phase of exploration.

Interpretation of good quality 3D seismic in parts of Quadrants 35, 36, 44 and 45 in the eastern margin of the Porcupine Basin (Figure 1) has enabled detailed imaging of fault patterns and also of canyons and relay ramps in the Cenozoic section, indicating the position of sediment input points. Depositional systems are also imaged within the Jurassic, but controls on sediment transport and deposition are less well understood in the Mesozoic. In this poster we will assess whether Cenozoic depositional patterns may be used as a guide to understand those within the Mesozoic.


*Figure 1: Location map*

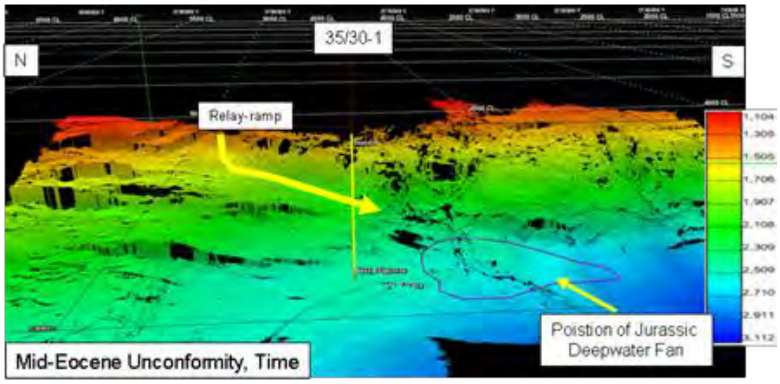


*Figure 2: Mid-Eocene Unconformity surface and position of Upper Jurassic fan*

A relay ramp has been mapped at Mid-Eocene Unconformity level (Figure 2) which marks the southern extent of a series of structural terraces, downthrown to the basin bounding fault. To the south of the relay ramp the basin is bounded by a single, steeply dipping fault. During Palaeocene time, the steep basin boundary in the southern area was characterised by erosion of canyons into the Chalk, which were filled with low-frequency chaotic reflectors. The terraced basin boundary of the northern area shows minor erosion with aggradational channel fill.

The contrasting structural style of the basin margin appears also to have influenced both deposition of sand and likely trapping geometries within the Jurassic, with downthrown traps relying on footwall seal against basement to the north, and updip pinchout of sands forming traps within the Jurassic section to the south. In the 35/30-1 well, the Middle-Upper Jurassic section has been interpreted from FMI logs, cuttings and SWC data to be a series of stacked high and low-density turbidites, with both unconfined basin-floor and confined channelised deposits. Sand provenance is uncertain. Regional studies show basin fill prograding from the north during the Jurassic, with additional contribution postulated from the basin flanks. An eastern provenance could imply increasing net sand fraction towards the east, and better reservoir quality is also expected on the fault terraces, where Middle Jurassic section is interpreted to be preserved up to 1.5 seconds TWTT shallower than at the 35/30-1 well location.

The Upper Jurassic section is not generally preserved on these terraces (whether due to non-deposition or erosion is uncertain), with a condensed, partly eroded section of Upper Jurassic preserved at 35/30-1. However, in the basinal area to the south of the well, Upper Jurassic sandy section is interpreted from seismic character, being analogous to the reservoir section at Spanish Point (35/8-2) and also to the Magnus and Burns Sandstones of the North Sea. Age equivalent sands also form a subsidiary reservoir in the Connemara discovery.

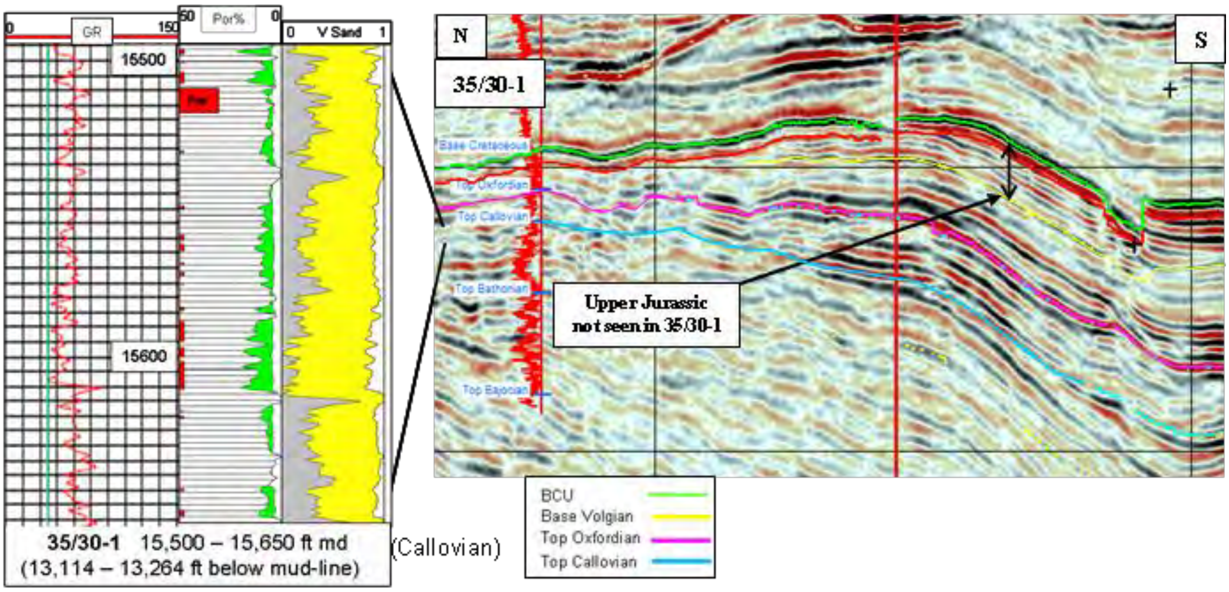


***Figure 3:*** *Summary CPI of selected interval from 35/30-1. The well found over 2,000 ft of gas-bearing Jurassic section with 10 – 13% porosity and low N:G. A deepwater depositional environment is interpreted from FMI logs, MCSTs and biostratigraphy. The well was drilled on a structural high and expanded section is developed off-flank to the north and south, with further expansion of Upper Jurassic section to the south of the drilled structure.*

These reservoirs are all acoustically hard, with a high frequency banded appearance, reflecting extensive lateral continuity of bedding. A prominent high-amplitude "fan" has been mapped on this dataset, in a location just south of both the relay ramp mapped at Eocene level, and a structural lineament which defines the change in style of the basin bounding faults. The sands were deposited towards the end of the Jurassic highstand, when basin margins had retreated, and the sands may be restricted to (palaeo) deeper parts of the Basin. However the apparent seismic signature should allow the interval to be mapped with reasonable confidence.

The Lower Cretaceous is also prospective, having tested oil in well 35/8-1, the Burren discovery. Although potential for reservoir development has been identified both above and below the Aptian Unconformity, individual depositional systems have not yet been mapped on the 3D dataset and interpretation is ongoing.

## PRESSURE REGIMES IN EQUATORIAL ATLANTIC MARGIN BASINS: GEOLOGICALLY DRIVEN GEOPRESSURE PREDICTION FROM LOG AND SEISMIC VELOCITY ANALYSIS

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Only by understanding the geological aspects of overpressured systems can we hope to predict pore pressure accurately for well design and drilling operations in frontier basins. Seismic velocity analysis techniques provide our most powerful method of geopressure prediction in underexplored basins, yet these techniques should not be used in isolation. Every effort should be made to enable any seismic-based prediction to be driven by available geological data, information, and experience of analogous basins.

Overpressure generation mechanisms in most passive margin environments are dominated by disequilibrium compaction. Other generation mechanisms such as hydrocarbon maturation can contribute to the magnitude of overpressure, but the overriding mechanism is that of undercompaction. This is invariably driven by an event with accelerated rates of deposition that significantly increases the loading on the shales below. Such loading events can be caused by any number of mechanisms, but often they are linked to large deltas, and/or their associated sedimentary systems. Identifying the significant loading event, or the fluid retention depth, will enable identification of the surface that marks the top of overpressure. This will be a depth determined by lithology, not stratigraphy.

With these models in mind, overpressure challenges in Mauritania, Ghana and French Guiana have been investigated. In some basins it was demonstrated that there was a direct relationship between depth of burial below mudline and overpressure, with no evidence of a discrete loading event. In these instances high sedimentation rates are preventing normal de-watering of shales below a certain depth (~1500 m below mudline). In other equatorial Atlantic margin basins overpressure is caused by a significant loading event in the Mid-Upper Campanian, where large basin floor fans have been deposited across the entire offshore margin in a compensationally stacked pattern. Beneath this event surface the shale pressure regime exhibits a similar straight line relationship of overpressure versus burial depth.

This poster investigates the potential improvements that can be made in geopressure analysis via intelligent use of log and seismic velocity analysis. We focus on basins where we have both good and poor well control to examine how different velocity data sets predict geopressure in shale sequences. Standard interval velocity analysis derived geopressure predictions are compared to results obtained from high-resolution velocity analysis; is there a demonstrable improvement in both the accuracy and precision of the pore and fracture pressure predictions? We also investigate calibration techniques for seismic velocity data sets from log data. What are the most suitable calibration techniques and can we exert geological control on these calibrations? Results obtained from frontier basins with poor well control can then be sense-checked against analogous basins where the geological and geophysical framework is more completely understood.

### References

Chopra, S. & Huffmann, A. 2006. Velocity determination for pore pressure prediction. *CSEG Recorder*, **31**(4), 28-46.

Eaton, B.A. 1969. Fracture gradient prediction and its application in oil field operations. *Journal of Petroleum Technology*, **21**(10), 1353-1360.

Eaton, B.A. 1972. Graphical method predicts geopressures worldwide. *World Oil*, **182**(6), 51-56.

# THE EAST GREENLAND CALEDONIDES FROM THE VIEWPOINT OF RECEIVER FUNCTIONS, GRAVITY AND TOPOGRAPHY DATA

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The topography and crustal structure of the Caledonides were shaped by various events, including the Caledonian orogeny, lithospheric extensional collapse, continental breakup and erosional processes. Before the closure of the Iapetus Ocean (480 Ma), convergence of Laurentia, Baltica and Avalonia and the subsequent major collision and orogeny (420 Ma) the Caledonian deformation included several early stages of terrain accretion along the involved continents (Roberts, D., 2003).

The high topographic elevation in the Caledonides and its longevity attract special attention, but also shallow extensional features, a lower crustal high velocity layer and the presence of a crustal root have to be considered. The understanding of this region includes the relationship of topography to crustal thickness in the background of isostatic compensation, as well as surface and subcrustal

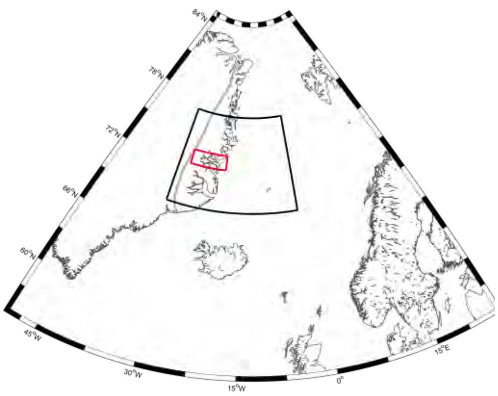

*Figure 1: Location map North Atlantic region, area of previous wide angle studies (black) and area of the Ella-Ø-array (red)*

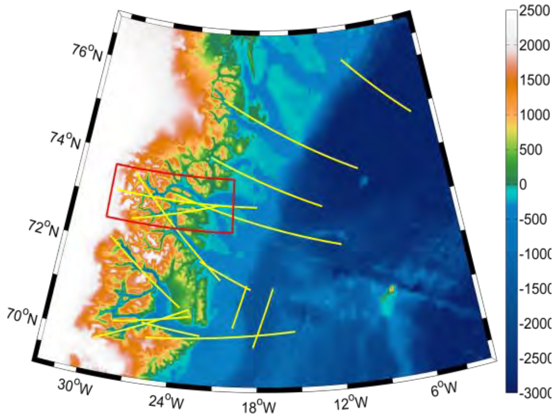


*Figure 2: East Greenland topography, previous wide angle seismic studies (yellow) and area of the Ella-Ø-array (red)*

processes.

For a period of 2 years (2009 to 2011) 11 temporary broadband stations were deployed and maintained by Aarhus University, forming the approximately 270 km long Ella-Ø-array. The profile extends from the Greenland ice sheet to the coastline, crossing the East Greenland

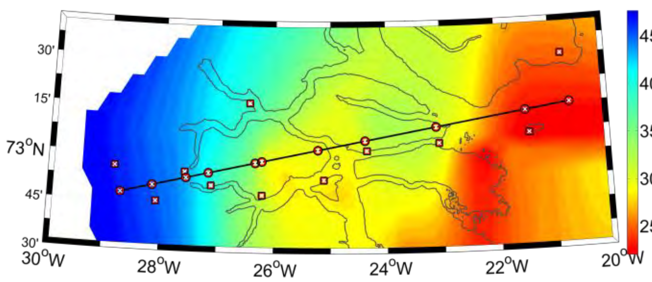


*Figure 3: Ella-Ø array and Moho depth. The seismometer positions (squares), average profile (black) and Moho depth from wide angle seismic data*

Caledonides at about 73° north. The data are of high quality.

P-S Receiver Functions, together with gravity and topography data (*Figure 4*) are initially interpreted and compared with previous wide angle seismic studies in this area (*Figures 2, 3, 4*). The results show a generally landwards thickening crust and a decreasing Bouguer-gravity, mirroring the topography and hereby promoting the idea of the presence of a crustal root and mainly Airy type isostatic compensation. Furthermore a sub-Moho eastward dipping structure is additionally observed in the Receiver Functions, possibly continuing to great depths. Its origin is not clarified yet, but might indicate the existence of a remnant collisional

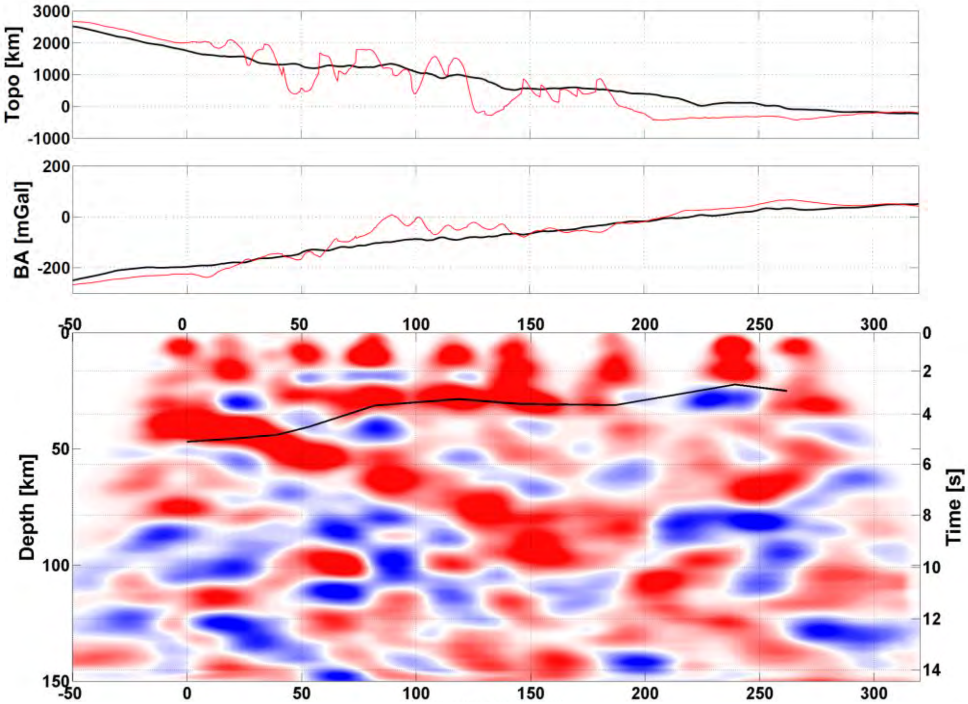


***Figure 4: Topography, Bouguer gravity and Receiver Functions***
*Topography (top, red: along profile, black: averaged over 100 km around the profile), Bouguer gravity (middle) and 3D depth projected P-S Receiver Functions along the Ella-Ø array (bottom, black line: Moho response from wide angle seismic data)*

feature.

The evolution of the East Greenland and Norwegian Caledonides along the conjugated margins is closely connected. Comparison with similar studies in Norway could give insight to what extent the areas might display similarities and correlation in topography and crustal structure, affected by a common geologic evolution and tectonic origin.

#### Reference

Roberts, D. 2003. The Scandinavian Caledonides: event chronology, palaeogeographic settings and likely modern analogues. *Tectonophysics,* **365**, 283-299.

## PALAEOGEOGRAPHIC IMPLICATIONS OF HEAVY MINERAL AND DETRITAL ZIRCON PROVENANCE OF DEVONIAN SEDIMENTS IN THE NORTH ATLANTIC REGION

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As a result of the collapse of the overthickened Caledonian crust, several extensional intramontane basins developed in the North Atlantic region (Figure 1) in the aftermath of the Caledonian orogeny. Thick successions of siliciclastic sediments formed within those continental basins during the Late Silurian to Early Carboniferous recording the late stages of the Caledonian orogeny. Previous studies have suggested that these basins were interconnected sub-basins similar to the basins in the Basin and Range Region of the United States.

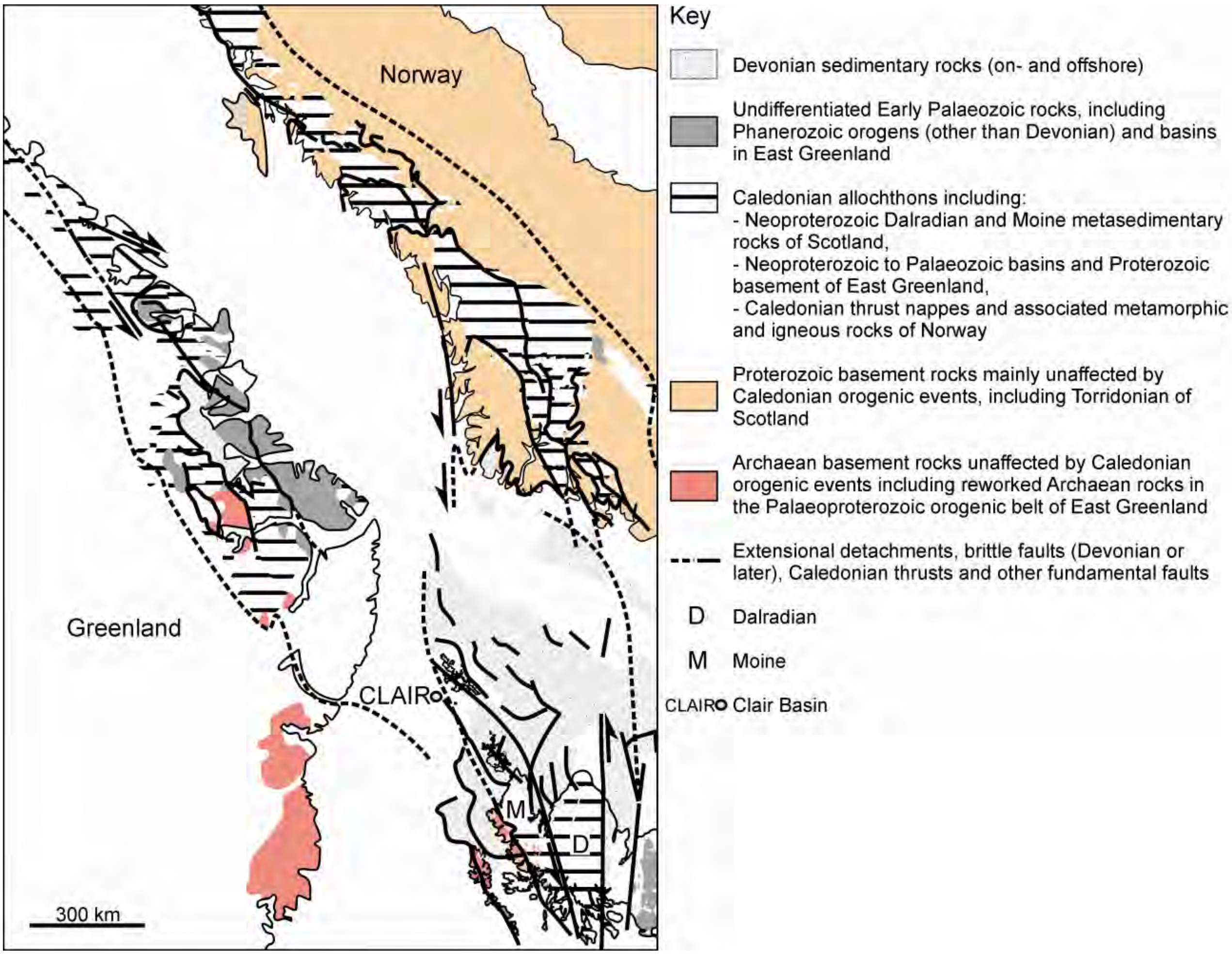


***Figure 1:*** *Palaeoreconstruction of the North Atlantic Region, showing the close relationship of Greenland, Scotland and Norway during the Middle Devonian. The map shows the distribution of Devonian sedimentary rocks in the North Atlantic Region (both offshore and onshore), the main faults active during Devonian extension and the main basement units in Scotland, Greenland and Norway.*

Here we present new detrital heavy mineral and zircon geochronology data of sedimentary successions from NE Scotland, East Greenland and SW Norway to reconstruct their provenance. Understanding the provenance of the sediments formed in this area plays an important role in the reconstruction of the regional Devonian palaeogeography. This study also demonstrates the importance of using a combined approach to the regional correlation of sedimentary successions.

Previous studies on the sediments of the Clair Basin, west of the Shetland Isles, led to a subdivision of the sediments into three groups based on the relative abundance of 'Caledonian', Proterozoic and Archaean zircons and the relative abundance of detrital heavy minerals. The Archaean-dominated 'Group 2' was derived from the local Archaean metamorphic basement, whereas the other groups seem to have more distal source areas. Sediments from the Orcadian Basin show age spectra dominated by Proterozoic zircons, similar to 'Group 1' in the Clair Basin, indicating either a common source area for these two sub-basins or different source areas containing basement of a similar age. Detrital zircon age spectra from sediments from Canning Land and Wegener Halvø in East Greenland and the Devonian basins of SW Norway are also dominated by Proterozoic zircons. However, some differences in age spectra indicate a similar but probably not the same source area for the sediments from NE Scotland and East Greenland and a local source for the Devonian sediments of SW Norway.

Assemblages of detrital heavy minerals indicate that various degrees of post-depositional diagenesis and metamorphism have influenced the Devonian sedimentary successions in the North Atlantic area. For this reason, ratios of heavy minerals with similar hydrodynamic and diagenetic behaviour have been used for this study. Both heavy mineral assemblages and heavy mineral ratios seem to reflect the influence of local sources within the different sub-basins.

The combined detrital zircon and heavy mineral data suggests that rather long rivers were draining the basement of the East Greenland Caledonides, transporting material as far as NE Scotland. The Devonian basins of the Norwegian Caledonides on the other hand, seem to have had no or only a limited connection with the basins to the east.

## THE NOVA SCOTIA/MOROCCO CONJUGATE MARGINS

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The seismic data collected during the SISMAR survey on the Atlantic margin off Morocco in 2001 (Contrucci *et al.,* 2004) reveal a transitional crust difficult to interpret. The existence of a new wide-angle seismic profile on the conjugate margin of Nova Scotia (OETR 2009) and a new interpretation of the multi-channel seismic data along SISMAR profiles (Maillard *et al.,* 2006) put forward the importance of a new modelling of the SISMAR wide-angle data. Contrary to the initial modelling, in which a trial and error approach has been used to constrain a layered velocity model (*rayinvr*, Zelt and Smith, 1992), the present study is based on a tomographic approach, which provides a smoothly varying velocity model and requires much less *a priori* information. The velocities obtained show that along the main profile, the transitional crust features a positive velocity anomaly, which might correspond to a portion of thinned continental crust with volcanic intrusions and salt tectonics transferred from the Nova Scotia margin.

On OETR2009 Profile, a 90-km long, 4-5 km thick body has been identified at the base of the crust. Velocities of 7.2 to 7.5 km/s suggest that this body is serpentinised mantle. On top of it, a 2-3 km thick layer with velocities of 5.3 km/s corresponds to a layer of highly serpentinised mantle, whose top coincides with the hummocky basement on the coincident MCS profile and probably some volcanics based on magnetic forward modelling.

Though conjugate profiles SISMAR04 and OETR2009 are 100-km offset in plate reconstructions and the western extremity of Profile SISMAR04 is located on an abnormal feature (Coral Patch Seamount), we proposed reconstructions of velocity profiles SISMAR04 and OETR2009 at the time of the rupture of the thinned continental crust and beginning of the formation of the transitional crust (chron ECMA, 195 Ma, latest Triassic) and at the time of the final breakup, when the first oceanic crust is emplaced (177 Ma, Late Toarcian). We suggest that the crust in between 195 and 177 Ma consists of exhumed serpentinised mantle.

During the first phase of rifting (late Triassic), ending at the time of emplacement of chron ECMA (195 Ma), the continental crust thinned, probably by depth-dependent extension, allowing salt to be deposited at a depth close to sea-level. During the second phase of rifting (195 Ma to 177 Ma), about 90 km of lower plate was extracted from beneath the margins. Then, the oceanic crust was emplaced after an eastward jump of the rift axis, leaving the whole exhumed mantle on the Nova Scotia side.

**References**

Contrucci, I., Matias, L., Moulin, M., Géli, L., Klingelhoefer, F., Nouzé, H., Aslanian, D., Olivet, J.-L., Réhault, J.-P. & Sibuet, J.-C. 2004. Deep structure of the West African continental margin (Congo, Zaïre, Angola) between 5°S and 8°S, from reflection/refraction seismics and gravity data. *Geophysical Journal International*, **158**, 529-553, doi:10.1111/j.1365-246X.2004.02303.x.

Maillard, A., Malod, J., Thiébot, E., Klingelhoefer, F. & Réhault, J.-P. 2006. Imaging a lithospheric detachment at the continent-ocean crustal transition off Morocco. *Earth and Planetary Science Letters*, **241**, 686-698.

Zelt, C.A. & Smith, R.B. 1992. Seismic travel time inversion for 2-D crustal velocity structure. *Geophysical Journal International*, **108**, 16-31.

## THE TRANSITIONAL LITHOSPHERE ADJACENT TO MAGMA-POOR CONTINENTAL MARGINS

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Two different types of 'transitional lithosphere' have been documented along magma-poor rifted margins. One consists of apparently sub-continental mantle that has been exhumed, brittlely deformed, and serpentinised during late stages of rifting. A second is thinned (<10 km) continental crust, which in some cases is known to have been supported near sea level at least early in the rift history and thus is interpreted to reflect depth-dependent extension. In both cases it is typically assumed that oceanic crust forms at the time that the brittle continental crust is breached or soon thereafter, and thus that transitional lithosphere has relatively limited width.

We here examine three representative cases of transitional lithosphere, one in the Newfoundland-Iberia rift and one at Goban Spur (both exhumed mantle), and one off the Angola/Congo margin (thin continental crust flanked seaward by apparently exhumed lower continental crust ± exhumed mantle). Considering the geological and geophysical evidence, it appears that depth-dependent extension (riftward flow of weak lower continental crust and/or upper mantle) may be a common phenomenon on magma-poor margins and that this can result in a much broader zone of transitional lithosphere than has hitherto been assumed. Transitional lithosphere in this wide zone may consist of sub-continental mantle, lower continental crust, or some combination thereof, depending on the strength profile of the pre-rift continental lithosphere. Transitional lithosphere ceases to be emplaced (i.e., 'final breakup' occurs) only when emplacement of heat and melt from the rising asthenosphere becomes dominant over lateral flow of the weak lower lithosphere. This model implies a two-stage breakup: first the rupture of the brittle continental crust and second, the eventual separation of the ductile sub-continental lithosphere which is coincident with emplacement of normal oceanic crust. Well-defined magnetic anomalies can form in transitional lithosphere that consists of highly serpentinised, exhumed mantle, and such anomalies therefore are not diagnostic of oceanic crust. Where present, however, the anomalies can be helpful in interpreting and dating the rifting history.

## NEW CLUES TO THE PALAEOENVIRONMENTAL DYNAMICS OF THE LOWER?- MIDDLE OXFORDIAN SERIES OF THE LUSITANIAN BASIN (PORTUGAL) TAKEN FROM COMBINED FACIES AND KEROGEN PALYNOFACIES STUDIES

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Within the evolutionary context of the Lusitanian Basin, the Middle–Upper Jurassic transition marks an important geodynamic phase, corresponding to a major basinwide disconformity and stratigraphic gap, preceded, in the western parts of the basin, by a complex forced regression that induced sharp facies variations across the depositional systems (Azerêdo *et al.,* 2002). The oldest Upper Jurassic sediments resting on the disconformity correspond to the Cabaços Formation (lower?-middle Oxfordian), deposited in freshwater/brackish lacustrine, restricted lagoonal and shallow-marine palaeoenvironments (Azerêdo *et al.,* 2002). The overall assessment of the parameters having influenced deposition and diagenesis of the Cabaços Formation is of paramount importance since this unit is currently regarded as one of the main source rock intervals of the Lusitanian Basin.

Palynofacies is one of the tools that are currently included in the full spectrum of basin analysis as it allows the direct quantification and qualification of the organic matter present in a specific rock. It gives information about organic matter provenance and palaeobiological and sedimentary dynamics in addition to providing an idea about oil and gas generation potential and thermal maturation. This approach has been applied to the lowermost Upper Jurassic deposits from the Lusitanian Basin (Portugal), having resulted in new clues of a singular nature concerning its palaeoenvironmental dynamics.

The Palynofacies characterisation of the Cabaços Formation outcrop at Pedrógão (about 150 kilometres north of Lisbon) revealed some particles in the kerogen assemblages that do not fall within the traditional groups (Amorphous Organic Matter, Phytoclasts or Palynomorphs). It is suggested that these particles correspond to the remnants of cohesive microbial mats, as they present some structures resembling mat-forming filamentous cyanobacteria (e.g. Monty, 1976). Some of these particles exhibit vertical tubes which are interpreted as impressions of filamentous cyanobacteria, embedded in a "spongy" matrix lying in-between a more compact, faintly laminated organic matrix (microbial biofilms?), including cyanobacteria filaments in horizontal disposition. Larger fragments of microbial mats and microbial laminite layers occur at Pedrógão and elsewhere in the Cabaços Formation, and, at places, also well developed cyanolites (Martins *et al.,* 2001). These facts reinforce the proposed interpretation for the uncommon particles found in the Pedrógão kerogen assemblages. As these particles do not fall within any of the usual Palynofacies groups, they are termed here as Intraclasts, because they represent fragments of material formed in a depositional environment subjected to erosion and redeposited elsewhere. The occurrence of these singular intraclasts in the kerogen assemblages of the Pedrógão section further highlights the facies diversity and complexity of the palaeoenvironmental conditions characterizing a large part of the Oxfordian in the Lusitanian Basin.

### References

Azerêdo, A.C., Wright, V.P. & Ramalho, M.M. 2002. The Middle-Late Jurassic forced regression and disconformity in central Portugal: eustatic, tectonic and climatic effects on a carbonate ramp system. *Sedimentology,* **49**, 1339-1370.

Martins, J.M., Azerêdo, A.C. & Manuppella, G. 2001. Polymorphic oncoidal/cyanophyte structures in Middle to basal Upper Jurassic limestones from the Lusitanian Basin, Portugal: palaeoecological and regional cartographic significance. *Comunicações do Instituto Geológico e Mineiro*, **88**, 99-126.

Monty, C.L.V. 1976. The origin and development of cryptalgal fabrics. *In:* Walter, M.R. (ed). *Stromatolites*, Developments in Sedimentology **20**, Elsevier, New York, 193-249.

### Acknowledgments

Ricardo L. Silva thanks the FCT-MCTES for funding through a PhD fellowship (SFRH/BD/47362/2008). This work is a contribution to the projects PTDC/CTE-GIX/ 098968/2008 and PEst-OE/CTE/UI0263/2011 (FCT-Portugal and COMPETE-FEDER).

## THE LUSITANIAN BASIN (PORTUGAL) PLIENSBACHIAN SOURCE ROCK INTERVAL AND ITS LINK TO THE BROAD SCALE GEODYNAMIC EVOLUTION OF THE NORTH ATLANTIC CONJUGATE MARGINS

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The on- and offshore sedimentary basins belonging to the North Atlantic Conjugate Margins are currently the focus of intense exploration concerning the assessment of their potential for oil and gas. The Lusitanian Basin (Portugal) is regarded either as a target to exploration or, due to the remarkable exposure and high quality of its outcrops, as a starting point to the comprehension of the less known offshore basins located along the western Iberian margin. One of the main intervals with source rock potential of the Lusitanian Basin corresponds to the Sinemurian–Pliensbachian, although mainly constrained to two temporal locations: the Polvoeira Member of the Água de Madeiros Formation (Late Sinemurian, Duarte *et al*., 2012) and the Marly limestones with organic-rich facies member of the Vale das Fontes Formation (Pliensbachian, Duarte *et al*., 2010). The ongoing studies in the later unit are focused in the multidisciplinary characterization of this series at a basinal scale. The aim of this work is to present the main advances made in the last years in the knowledge of this plausible source rock of the Lusitanian Basin and its correlation with neighbouring basins and the North American conjugate margin.

The Early–Late Pliensbachian (top of Ibex–Margaritatus ammonites zones) source rock interval corresponds to the Marly limestones with organic-rich facies member and is included in the Pliensbachian Transgressive–Regressive facies cycle (Duarte *et al*., 2010). It consists of organic-rich marl-limestone hemipelagic alternations with abundant benthonic and nektonic macrofauna, deposited on a north-westerly dipping, low-energy marine carbonate ramp. Several well defined black shales (*s.l.*) are observed throughout the studied sections, where TOC values reach up to 26.3 wt.%. Palynofacies and biogeochemistry data suggests that these black shales correspond to mucilaginous aggregates and/or microbial events (Silva *et al*., 2012), whose origin is most probably related to major palaeoceanographic and palaeoclimatic changes. Stratigraphically, this interval bears many similarities with the time equivalent series from the Atlantic and Tethyan domains. Several of these basins tend to present the same lithological features and a compatible sequence stratigraphic architecture, suggesting that deposition was most probably influenced by regional controls. For example, the carbon stable isotopic record of these series in several European basins suggest that organic matter production, deposition and preservation may have impacted the global carbon cycle, ultimately leading to a major event of decreasing temperatures (Silva *et al*., 2011 and references therein).

The Lusitanian Basin has the potential to become a reference area in the context of the North Atlantic Conjugate Margins. Its study and comparison with the available data from offshore reveal important clues to the identification and/or understanding of a possible Lower Jurassic source rock interval of regional relevance.

### References

Duarte, L.V., Silva, R.L., Mendonça Filho, J.G., Poças Ribeiro, N. & Chagas, R.B.A. 2012. High-resolution stratigraphy, Palynofacies and source rock potential of the Água de Madeiros Formation (Upper Sinemurian) of the Lusitanian Basin, Portugal. *Journal of Petroleum Geology*, **35**, 105–126.

Duarte, L.V., Silva, R.L., Oliveira, L.C.V., Comas-Rengifo, M.J. & Silva, F. 2010. Organic-rich facies in the Sinemurian and Pliensbachian of the Lusitanian Basin, Portugal: Total Organic Carbon distribution and relation to transgressive-regressive facies cycles. *Geologica Acta*, **8**, 325–340.

Silva, R.L., Duarte, L.V., Comas-Rengifo, M.J., Mendonça Filho, J.G. & Azerêdo, A.C. 2011. Update of the carbon and oxygen isotopic records of the Early–Late Pliensbachian (Early Jurassic, ~187 Ma): Insights from the organic-rich hemipelagic series of the Lusitanian Basin (Portugal). *Chemical Geology*, **283**, 177–184.

Silva, R.L., Mendonça Filho, J.G., da Silva, F.S., Duarte, L.V., Silva, T.F., Ferreira, R. & Azerêdo, A.C. 2012. Can biogeochemistry aid in the palaeoenvironmental/early diagenesis reconstruction of the ~187 Ma (Pliensbachian) organic-rich hemipelagic series of the Lusitanian Basin (Portugal)? *Bulletin of Geosciences*, **87**, 373–382

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Ricardo L. Silva thanks the FCT-MCTES for funding trough a PhD fellowship (SFRH/BD/47362/2008). This work is a contribution to the project PTDC/CTE-GIX/098968/2008 (FCT-Portugal and COMPETE-FEDER).

## A REGIONAL STRATIGRAPHIC AND STRUCTURAL SYNTHESIS OF MESOZOIC/CENOZOIC BASINS, OFFSHORE IRELAND

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Extensive occurrences of Mesozoic and Cenozoic strata are preserved in the Porcupine, Rockall and Hatton basins and in the Goban Spur region, offshore Ireland. Successions were studied using recent 2D high-resolution seismic data integrated with older seismic data (Figure 1) and available well information. The new seismic data provide improved imaging below Early Cenozoic lavas, show good seismic resolution beneath the Cretaceous and image Jurassic and older fault blocks. The new study has identified new structural and stratigraphic elements including (i) small tilted half-grabens filled with Early Cretaceous strata along the western margin of the Hatton Basin, (ii) large half-grabens filled predominantly with Early Cretaceous sediments in the Goban Spur region and (iii) inversion structures in the southern parts of the Hatton and the Porcupine basins. The seismic study has provided an improved constraint on the detailed structure and the timing of structuring, especially for Jurassic and Cretaceous periods.

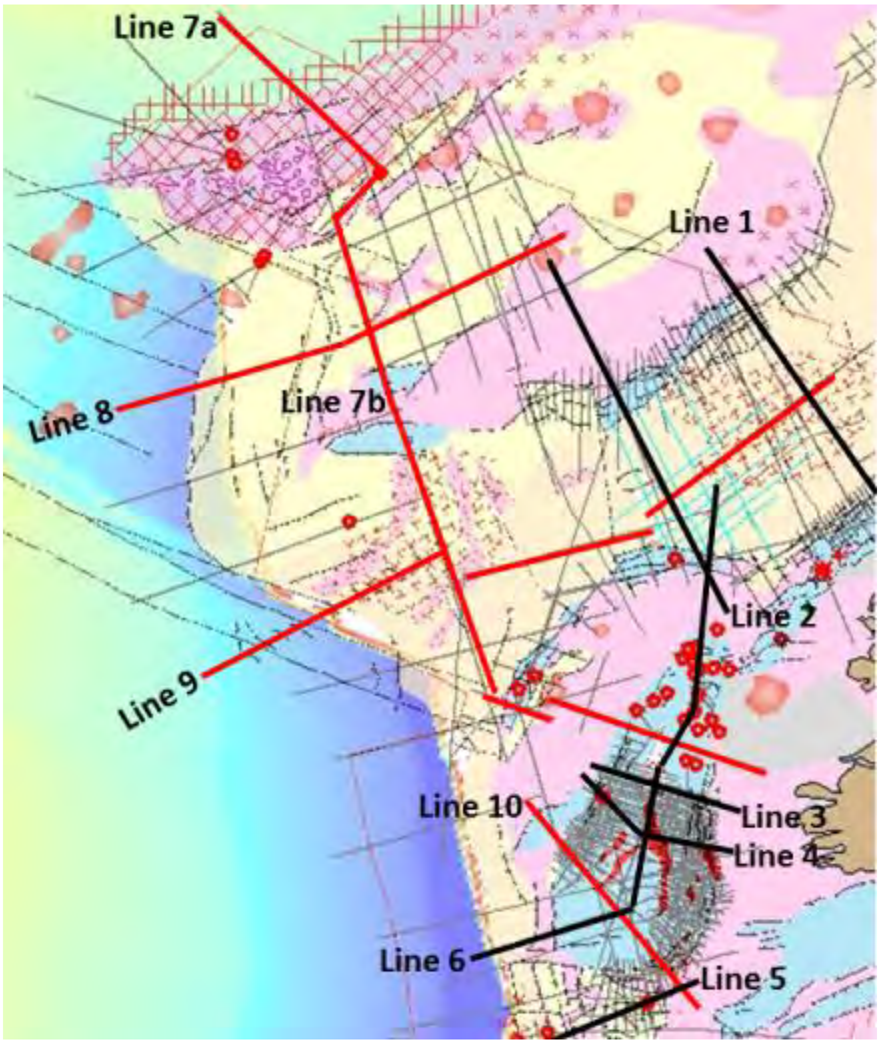


***Figure 1:*** *The map shows the seismic grid used in the project. The studied region includes the Hatton, the Rockall, the Porcupine basins and the Goban Spur region, offshore Ireland. The map shows the location of 10 regional geoseismic profiles constructed through key areas of the margin.*

Ten regional profiles, each consisting of several seismic lines across key areas, illustrate the regional and detailed structure of the Irish Atlantic continental margin (Figure 1). The Jurassic pre-rift and syn-rift successions are preserved in tilted fault blocks and indicate a major basin reorganisation and structuring during Middle and Upper Jurassic times. The Jurassic strata were interpreted in the deepest part of the Porcupine Basin whereas they are imaged predominantly along the margins of the Rockall Basin. Overlying Cretaceous strata exhibit both syn-rift and post-rift successions, which are variably distributed across the region. The best example of Early Cretaceous (Aptian/Albian) syn-sedimentary rifting is found in the southern part of the Porcupine Basin and the Goban Spur region. The Albian successions are also preserved in small, partly preserved half-grabens situated along the western margin of the Hatton Basin. Based on seismic character and correlation with neighbouring areas, Cretaceous strata are also interpreted in larger basins perched along the southeastern margin of the Hatton Basin. The Cretaceous succession was inverted during latest Cretaceous times. Similar timing of inversion is interpreted in the southwestern part of the Porcupine Basin. The southern part of the studied Irish continental margin was therefore affected by an inversion episode which predates the more well constrained Oligocene and Miocene inversion structures found in basins offshore Ireland.

Wheeler diagrams were constructed along the axial 2D seismic lines in the Porcupine Basin to illustrate spatial variations of sedimentary facies and depositional environments (Figure 2). In addition, the diagrams illustrate several intra-Cretaceous unconformities including the Early Cretaceous (Aptian/Albian) unconformity that is interpreted to be related to a final continental breakup at the Goban Spur margin.

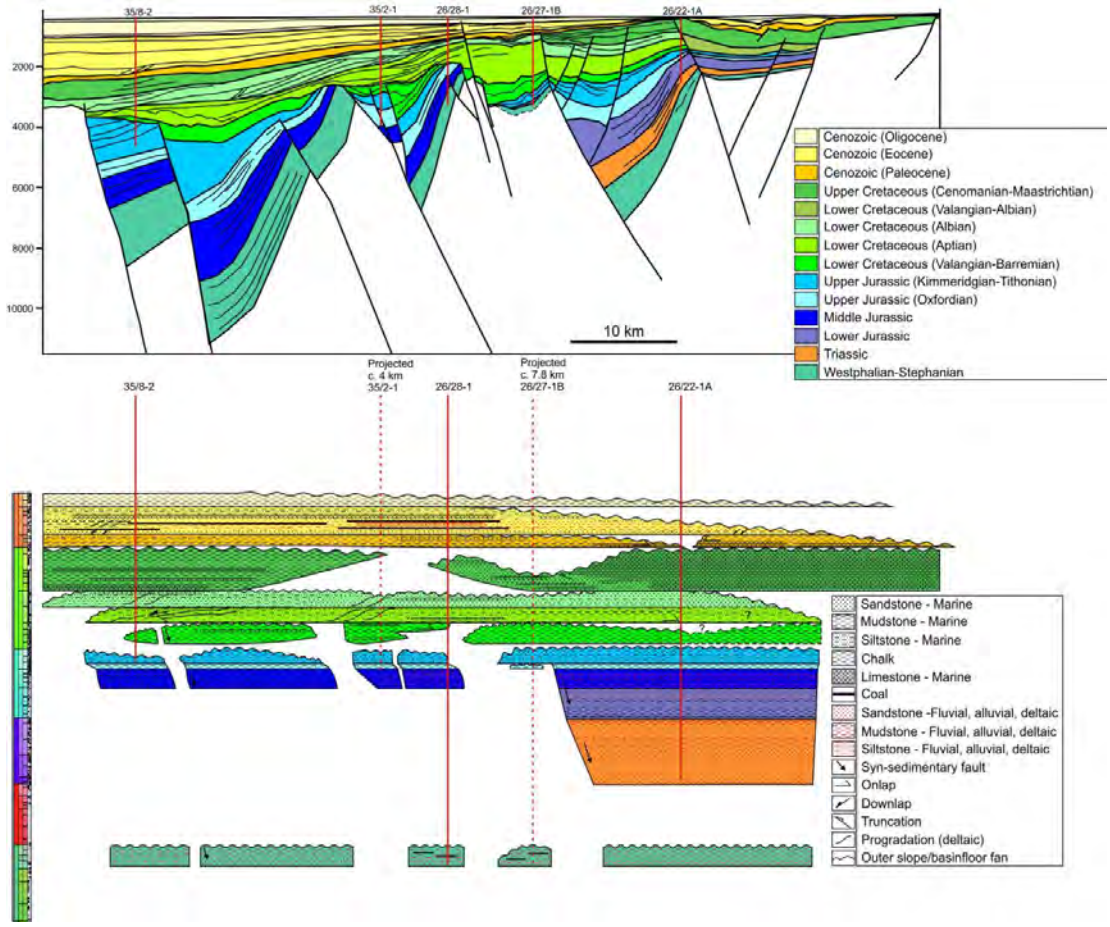


***Figure 2**: Wheeler diagram constructed for the North Porcupine Basin and the northern part of the Main Porcupine Basin.*

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## LOW LITHOSPHERIC STRETCHING IN AN ATLANTIC MARGIN BASIN: THE LUSITANIAN BASIN (WEST IBERIA, PORTUGAL)

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The Mesozoic Lusitanian Basin (Figures 1a & 1b) developed in the western Iberia margin and comprises sediments from the Late Triassic to Cretaceous (Pena dos Reis *et al.,* 2010). The basin evolution has close relations with the closure of the Western Tethys and later with the opening of the North Atlantic. Two main rift phases are classically considered - Late Triassic (229-199 Ma) and Late Jurassic (159-140 Ma). Three sectors may be defined (North, Central and South), separated by two major NE-SW fault systems - Nazaré and Tagus Valley. The Central sector presents three strongly subsident sub-basins developed in Upper Jurassic times.

Ten exploration wells have been studied along the basin. Stretching factors ($\beta$) were calculated through backstripping, mainly for the two identified rift phases. The stretching factor was assessed following the methodology of Le Pichon & Sibuet (1981). For each well a maximum and minimum palaeobathymetry was assumed, depending on the depositional environment interpreted. For the sea-level corrections, two sea-level curves were used - Watts & Steckler (1979) and Pitman (1978).

The first rift related depositional succession (Upper Triassic) has been reached only in one of the wells, in which the strong subsidence seems to continue and even increase towards the Early Jurassic. In most of the other wells, the Early Jurassic also shows intense subsidence (Figures 2a & 2b). This situation has been interpreted by some authors as a sag phase (e.g. Pena dos Reis *et al.,* 2010), while others consider it to represent a distinct rift phase (e.g. Alves *et al.,* 2003)

The first rift phase (Late Triassic-Early Jurassic) usually presents higher stretching factors than the second rift phase (Late Jurassic), except for the Central Sector of the basin. Here, the Late Jurassic tectonic re-activations promoted the development of different sub-basins and depocentres, rapidly filled-up by more than 3km thick siliciclastics. The subsidence curves show that rift phases aren't strictly synchronous across the basin, with slight variations in time. This may be due to the multiple graben and half-graben geometries of the basin, with fault movements occurring within a 5 Ma time-frame.

Considering the Mesozoic opening of the North Atlantic, the calculated stretching factors are low. For the first rift phase the stretching factors range between 1.02 and 1.19 and for the second rift phase they range between 1.01 and 1.19 (Figure 1c). In terms of total stretching, the values range from 1.09 to 1.27 (Figure 1c). Despite some differences between sectors and rift phases, the stretching factors may be considered quite low and homogenous throughout the basin. These low values are interpreted as corresponding to an Atlantic basin's margin, close to the unstretched basement to the East. Therefore, the Lusitanian basin, with a thick sedimentary infill, extending over 200km by 100km, may be looked as an exposed "inner proximal margin" of an Atlantic non-magmatic basin (*see* Pereira & Alves, 2011). However, the over 5 km thickness of the basin's infill may not be explained by these low stretching factors - according to McKenzie (1978), such a thickness would imply $\beta$ values around 2. Therefore, the role of regional tilting or, more probably, local sub-vertical faulting in upper Jurassic Central Sector sub-basins, should be taken into account to explain the observed thick infill.

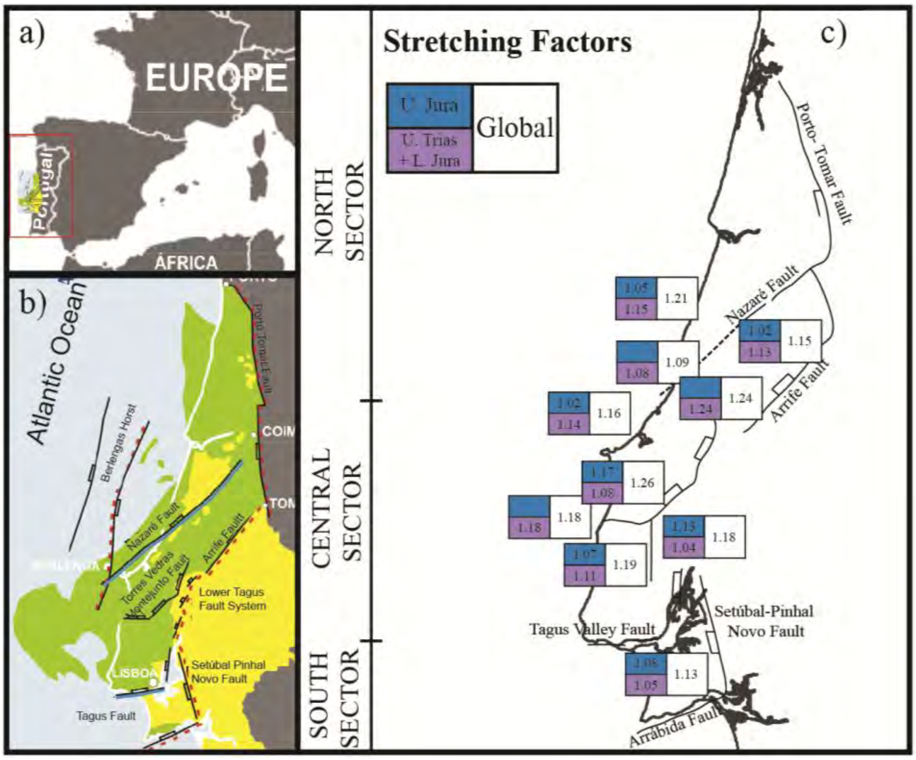
Considering the border position of the Lusitanian basin, it may be postulated that a few tens of kilometres towards West, namely in the deep-offshore Peniche Basin, stretching factors could go up to values around 1.5 to 2.0, such as in the West Atlantic conjugate margin, e.g. in the Jeanne D'Arc and Orphan basins. With higher values, not only thicker sequences should be present in the Peniche Basin, but also the heat flow for organic matter maturation should be significantly higher.

### References

Alves, T.M., Manuppella, G., Gawthorpe, R.L., Hunt, D.W. & Monteiro, J.H. 2003. The depositional evolution of diapir-and fault-bounded rift basins: examples from the Lusitanian Basin of West Iberia. *Sedimentary Geology*, **162**, 273-303

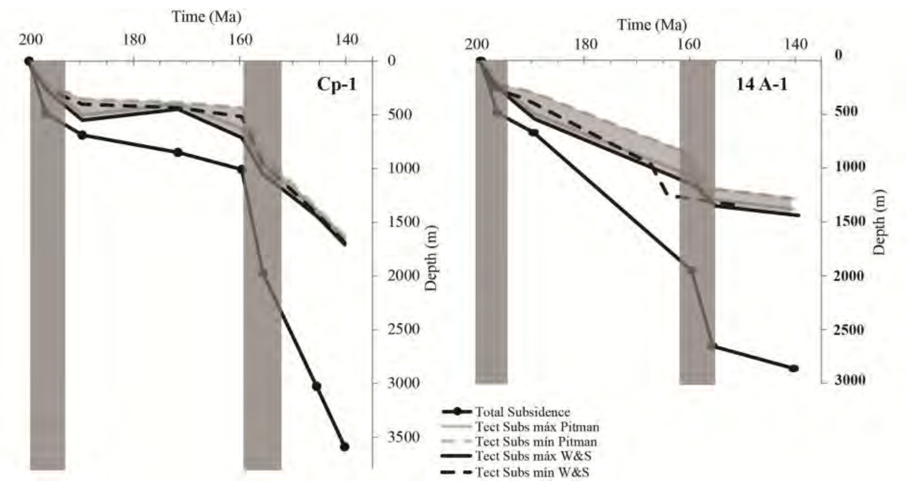
Pena dos Reis, R., Pimentel, N., Garcia, A.J.V., Viana, A. & Bueno, G. 2010. Mesozoic subsidence and uplift history of an exposed Atlantic rifting margin – the Lusitanian basin (Portugal). *II Central & North Atlantic Conjugate Margins, Lisbon 2010, Abstracts Volume, 74.* http://metododirecto.pt/CM2010/index.php/vol/article/view/235

Pereira, R. & Alves, T.M. 2011. Margin segmentation prior to continental breakup: a seismic-stratigraphic record of multiphased rifting in the North Atlantic (Southwest Iberia). *Tectonophysics*, **505**, 17-34.




***Figures 1 a) & b)*** – *Lusitanian Basin location (green) and main structures (in Matos, 2009).*

***Figure 1c*** – *Stretching factors (β) for the studied wells.*




***Figures 2a) & 2b)*** – *Subsidence curves for wells Cp-1 and 14 A-1, with intense subsidence rift phases marked with grey bars.*

# ORPHAN BASIN CRUSTAL STRUCTURE FROM TOMOGRAPHIC INVERSION WITH DENSE RECEIVERS

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## Introduction

Orphan Basin is located offshore north-eastern Newfoundland, between the Bonnavista Platform and Flemish Cap. This basin is characterised by a zone of ultra-stretched continental crust as determined by an earlier refraction study using 15 instruments on a 550-km-long line (Chian *et al.,* 2001). A hypothesis for its formation is a clockwise rotation of Flemish Cap from the north-eastern Newfoundland shelf between the late Triassic and early Cretaceous (Sibuet *et al.,* 2007). Gravity modelling shows that the extended crust might be as thin as 5 km in the thinnest areas of the basin (Welford & Hall, 2007).

The OBWAVE (Orphan Basin Wide-Angle Velocity Experiment) project has acquired a much higher resolution refraction seismic data, than common surveys, using ~100 OBSs (Ocean-Bottom Seismometers) along a 500-km-long profile across the Orphan Basin (Sept.-Oct. 2010). The spacing of the instruments varies from 3 km in the highest resolution part of the profile, where the crust was predicted to be the thinnest, to 5 km on Flemish Cap and in the western part of the basin.

## Method

After relocation of each instrument, we picked first arrivals (~67,000 picks) and PmP reflection arrivals from the Moho discontinuity (~23,000 picks) to obtain a joint tomographic inversion of both sets of arrivals using Tomo2D (Korenaga *et al.,* 2000). The refraction arrival times constrain the velocities in the model, while the PmP arrival times control both the velocities in the crust and also the depth of the Moho interface. The final model was computed following a detailed parametric study to determine the optimal parameters controlling the ray-tracing and the inversion processes. It is normalised, $\chi^2$ is 0.86, which means that the model satisfies the picked arrival times within their uncertainties.

The final model was used as a basis for a checkerboard analysis, allowing us to define its spatial resolution. The finer structures (5 km horizontally and 2.5 km vertically) are well defined where a sufficient number of rays cross at depths of 5 to 10 km in the model. The coarser structures (e.g., 25 km horizontally and 5 km vertically or 50 km horizontally and 25 km vertically) are well defined at depths from 10 to 25 km. An additional tomography test using the picks of one OBS out of 5 – which simulates spacing used in conventional OBS surveys (e.g. the previous survey in the basin from Chian *et al.,* 2001) – does not give as many details as the final model using all the OBSs (i.e. finer structures and crustal thinning are not recovered).

## Results

The final model (Figure 1) shows clear basement highs in the western part (85, 115 and 155 km), in the eastern part (between 310 and 440 km), and a major basin (280 km) consistent with a strong crustal thinning (high velocities and shallow Moho between 260 and 320 km). Two aspects of the model are of particular interest:

1. At 290 km, where the crust is the thinnest, the Moho discontinuity occurs at 16 km depth and the iso-velocity contours show 7.5 km/s at 15 km depth and 8 km/s at approximately 19 km depth. This means that the velocity at the top of the mantle is

about 7.6 km/s. Such a velocity gradient at the top of the mantle might indicate the presence of partially (< 10 %) serpentinised mantle. However, tomographic modelling inherently results in a smoothed version of the crustal structure. In contrast, the strong PmP reflections that we observe in this region suggest that the Moho is a sharp velocity discontinuity, with higher velocities (and thus little or no serpentinisation) in the underlying mantle. Additional layer modelling will be required to better define such velocity discontinuities.

2. The shallowing of the Moho from 160 to 240 km crosses the 7 km/s iso-velocity contour, which is more characteristic of the lower crust. Therefore, it is possible that the PmP picks in this region correspond to lower crust reflectivity (e.g. a lower crustal mafic intrusion) that might prevent us from identifying the true Moho reflection.

This study shows that dense regional OBS deployments within extensional basins have the potential to image crustal structures with details that are greatly improved over studies using coarser OBS deployments, such as those used previously for regional crustal investigations of rifting. For the Orphan Basin study, increased image resolution was particularly useful to delineate the tilted blocks and capture the extreme thinning of the continental crust.

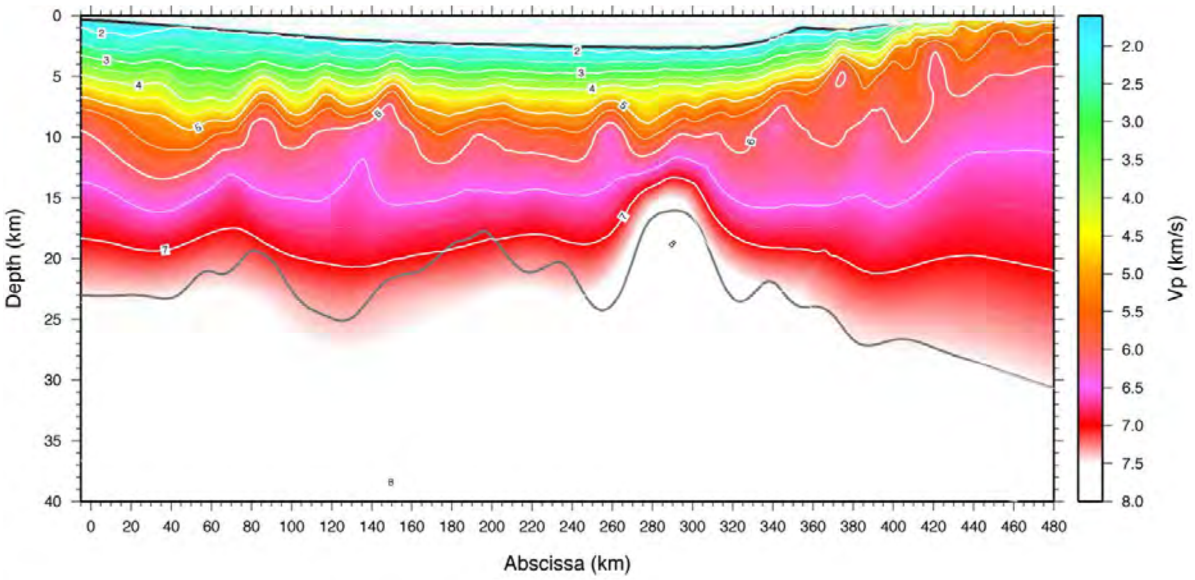


***Figure 1**: Final velocity model. Colours correspond to the modelled P-wave velocities; colour scale is presented on the right. White lines are iso-velocity contours every 0.5 km/s; the thick iso-contours are shown every 1 km/s. The thick black line represents the seafloor and the thick grey line corresponds to the modelled Mohorovičić discontinuity.*

**References**

Chian, D., Reid I.D. & Jackson, H.R. 2001. Crustal structure beneath Orphan Basin and implications for non-volcanic continental rifting, *Journal of Geophysical Research*, **106**(B6), 10,923-10,940, doi:10.1029/2000JB900422.

Korenaga, J., Holbrook, W.S., Kent, G.M., Kelemen, P.B., Detrick, R.S., Larsen, H.-C., Hopper J.R. & Dahl-Jensen T. 2000. Crustal structure of the southeast Greenland margin from joint refraction and reflection seismic tomography, *Journal of Geophysical Research*, **105**(B9), 21,591-21,614, doi:10.1029/2000JB900188.

Sibuet, J.-C., Srivastava, S.P., Enachescu M. & Karner G.D. 2007. Early Cretaceous motion of Flemish Cap with respect to North America: implications on the formation of Orphan Basin and SE Flemish Cap – Galicia Bank conjugate margins. *In:* Karner G.D., Manatschal, G. & Pinheiro, L.M. (eds). *Imaging, Mapping and Modelling Continental Lithosphere Extension and Breakup.* Geological Society London, Special Publications, **282**, 63-76, doi:10.1144/SP282.4.

Welford, J.K. & Hall J. 2007. Crustal structure of the Newfoundland rifted continental margin from constrained 3-D gravity inversion, *Geophysical Journal International*, **171**(2), 890-908, doi:10.1111/j.1365-246X.2007.03549.x.

## LITHOSPHERIC DENSITY VARIATIONS AND MOHO STRUCTURE OF THE LABRADOR SEA AND ITS MARGINS FROM CONSTRAINED 3-D GRAVITY INVERSION

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A 3-D density anomaly model of the Labrador Sea and its margins was generated from a regional inversion of the free air gravity data constrained by bathymetric and sediment thickness information. The model results are compared against available velocity models from crustal-scale wide-angle reflection/refraction surveys and multichannel seismic reflection sections. Using the inverted model, a regional map of Moho structure generally agrees well with seismically constrained Moho depths. Using the regional density anomaly model, we track variations in sediment thickness and crustal thickness to estimate stretching factors across the study area. Our results complement existing seismic studies and provide a more complete regional view of the crustal structure of the Labrador Sea and its margins which will hopefully allow for a more thorough understanding of their tectonic evolution and provide constraints for future palaeoreconstructions.

## A Regional Stratigraphic and Structural Interpretation of the Newfoundland and Ireland Conjugate Margins

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A regional seismic grid has been interpreted on the Newfoundland margin using a combination of modern industry data, and seismic data from government and academia (Figure 1). On the Newfoundland margin, seismic data made available to the project included modern (2002), high-resolution seismic data in the Orphan Basin (courtesy of TGS-Nopec). The interpreted results provided input to *A New Kinematic Plate Reconstruction of the North Atlantic between Ireland and Canada* (Ady & Whittaker, this conference).

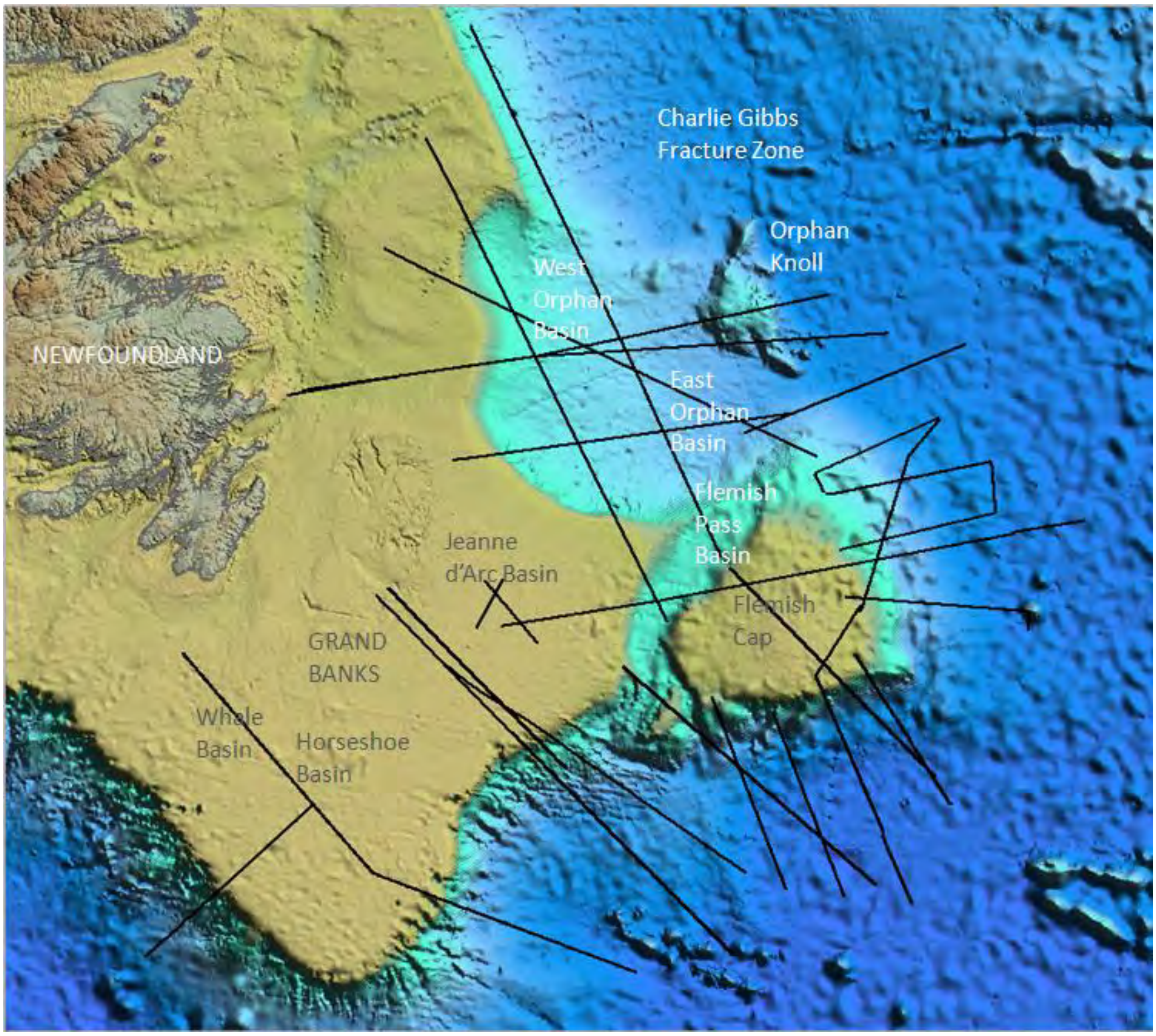


***Figure 1**: Bathymetry map showing the regional seismic database for the Newfoundland margin used in the project.*

Major tectonostratigraphic sequences defined from seismic interpretation around the margin were mapped and seismic stratigraphic correlations (Wheeler Diagrams) were constructed along selected 2D seismic lines in the East Orphan and West Orphan basins. These correlations image spatial variations of sedimentary facies and depositional environments. Fault restoration software has also been used to model the structural development of the conjugate margins. Fault restoration has enabled us to evaluate the structural history of the margin and both differentiate and measure the relative magnitude of the various tectonic events that have affected the area.

The most prominent regional unconformity is the Base Cretaceous which in the east Orphan and Flemish Pass basins is overlain by Lower Cretaceous sediments deposited in restricted basins. In addition, the Wheeler Diagrams show several intra-Cretaceous unconformities, notably an Albian unconformity that is interpreted to be related to a continental breakup at the Flemish Cap - Goban Spur margin. Complementary regional seismic stratigraphic sections were interpreted on the conjugate margin of Ireland (Štolfová *et al.,* this conference) and it is possible to correlate the Albian unconformity between the East Orphan and the Porcupine basins which were juxtaposed prior to breakup.

In the East Orphan Basin a Late Cretaceous unconformity is also interpreted. The exact age of this unconformity is unclear but it is possibly related to tectonic events associated with the progressive breakup of the Irish-Newfoundland margin northwards from the Flemish Cap between Albian and Santonian times. In the central part of the East Orphan Basin the unconformity is overlain by a high amplitude sheet-like deposit, interpreted as a turbidite. The base of the Cenozoic is marked by the regionally extensive unconformity which occurred post-breakup in this area. Late Cretaceous volcanics are interpreted to be present along the outer Newfoundland margin at the outer edge of the Orphan Knoll and West Orphan Basin, to the south of the Charlie Gibbs Fracture Zone. An Early Eocene unconformity has also been recorded in the western Jeanne d'Arc Basin related to basin margin uplift.

The structural and stratigraphic development of the Newfoundland and Irish margins is linked due to the relative movements of the N. American, Eurasian, Greenland and Iberian plates. Fully understanding the kinematic plate model is vital for the analysis of basin development in this area. The interpretation of regional seismic data from the margins of Newfoundland and Ireland has enabled a comparison of both margins and has also resulted in an improved understanding of the evolution of the conjugate passive margins of Canada and NW Europe in general. The stratigraphic study has led to a more thorough evaluation of potential Cretaceous and younger source and reservoir intervals along the margin.

### References

Ady, B.E. & Whittaker, R.C. 2012. A New Kinematic Plate Reconstruction of the North Atlantic between Ireland and Canada. Abstract, *Central Atlantic Conjugate Margins Conference, Dublin, 2012*.

Štolfová, K., Whittaker, R.C. & Shannon, P.M. 2012. New insights into the regional Mesozoic and Cenozoic evolution of the Irish offshore continental margin. Abstract, *Central Atlantic Conjugate Margins Conference Dublin*, 2012.

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# NOTES

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