# II CENTRAL & NORTH ATLANTIC CONJUGATE MARGINS CONFERENCE

## LISBON 2010

# *Rediscovering the Atlantic:*
# *New Ideas for an old sea…*

**EXTENDED ABSTRACTS**


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## Extended Abstracts

# Salt Structures and the petroleum potential of the continental margins in Western Iberia, Newfoundland and South Atlantic

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*ABSTRACT*

*As widely known in the geological community, sedimentary basins showing marked salt tectonics comprise main target areas for hydrocarbon exploration. They can form competent structural and stratigraphic traps, at the same time promoting the flow of fluids in regions adjacent to salt diapir flanks. A comprehensive set of (2D) seismic-reflection profiles, tied to borehole data, allowed the mapping of deep-offshore regions of West Iberia where salt structures are evident. Their geometry, age and importance in the tectono-stratigraphic record of offshore basins are compared with their counterparts in Newfoundland and South Atlantic (Espirito Santo Basin, Brazil and Angolan Margin, West Africa).*

*In essence, developed salt structures not strictly related to Cenozoic inversion are only observed north of $39^0$ 15'N on the proximal region of the western Iberian margin. They comprise Late Triassic-early Jurassic evaporites and shales that were not deposited uniformly north of the latter parallel. Onshore, salt pillows predominated in a structural style resembling that of the Jeanne D'Arc Basin, also in a proximal position on the Canadian margin. Direct comparisons with basins in Newfoundland show salt structures to be more developed at the bass of the continental slope. Thus, the structural styles observed in deep-offshore basins offshore Iberia are similar to those recorded in deep-offshore basins in the Scotian Shelf and in the Salar Basin, to cite two examples.*

*This analysis proposes: a) the presence of salt in depth to contribute to form structural traps in deep-offshore basins and, b) renewed salt tectonics being associated with the inversion of older halokinetic structures. As demonstrated for the shallow-offshore region (Lusitanian Basin), Newfoundland Basins and South Atlantic, the petroleum potential of such structures will depend on: a) timing of tectonic inversion, b) relative thickness of overburden sediment above the salt. Considering the existence of a significant tectonic activity in west Iberia during the Late Cenozoic, deep-rooted inversion structures covered by thick overburden units will present the largest potential for hydrocarbon accumulation.*

*KEYWORDS: Salt tectonics, North Atlantic, South Atlantic, structural traps.*

## 1. Introduction

North Atlantic passive margins are characterised by the presence of Triassic-early Jurassic evaporites at depth, with significant variations in the evaporite layer thickness controlling the structural style of overburden units (Jansa et al., 1979; Alves et al, 2003). In contrast, Aptian salt layers in the South Atlantic effectively divide syn-rift from post-rift units, comprising at the same time an effective detachment layer to gravitationally-unstable continental slope units (Vendeville et al., 1987; Nohriak et al., 2004; Davison, 2005; Mohriak et al., 2008). This work presents an overview of the structural styles of deep-offshore basins of Brazil, West Africa and North Atlantic. The role of deep-rooted evaporite units in the formation of structural traps in the Atlantic is summarised in this presentation. Direct comparisons with deep-offshore basins in west Iberia reveal that salt tectonics is an important factor in controlling the structural evolution of syn- and post-rift units north of $39^0$ 15'N.

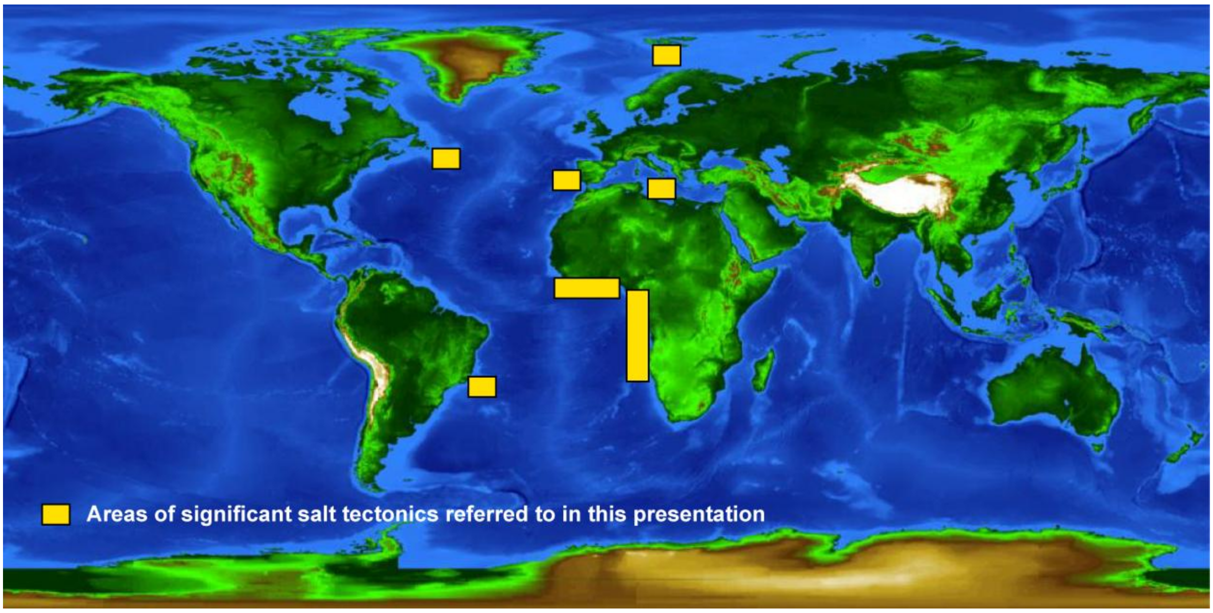


FIG.1 – Seismic data sets currently in use in the 3D Seismic Lab highlighting regions of significant salt and shale tectonics.

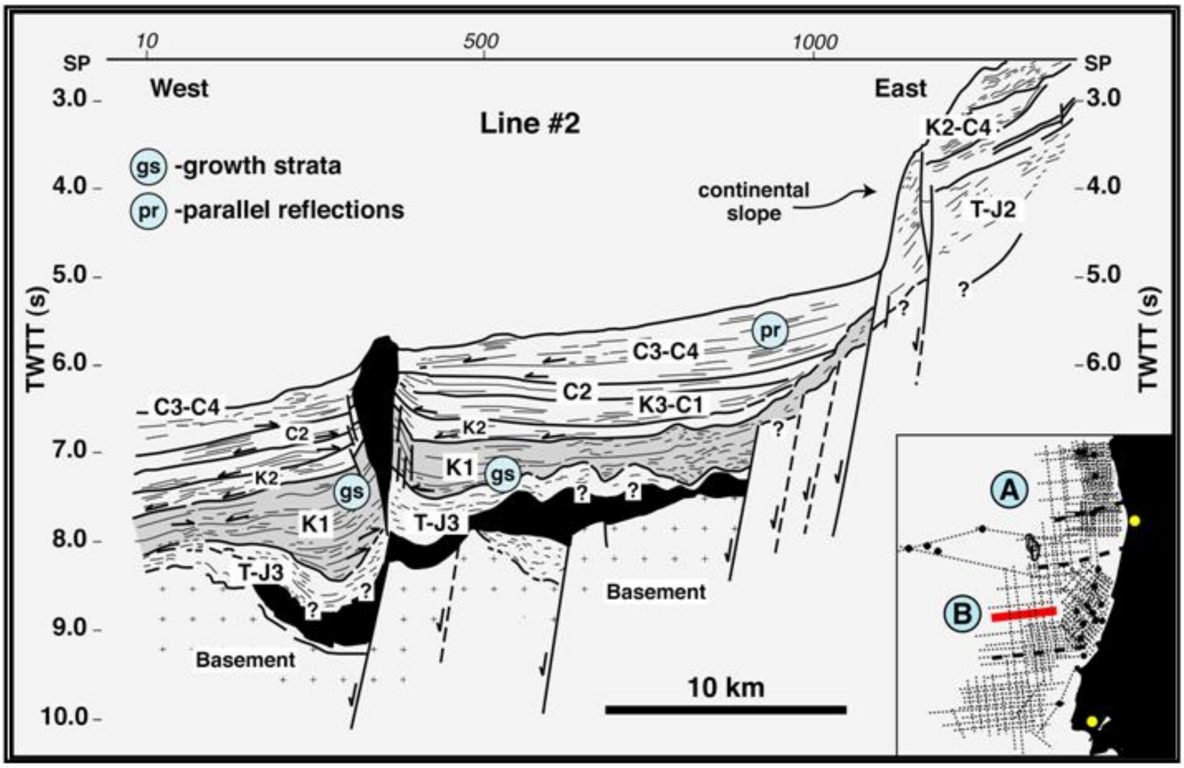


FIG. 2 – Seismic line from offshore Central Portugal depicting a developed salt structure piercing Mesozoic and Cenozoic units.

## 2. Salt structures: Fracture patterns and fluid flow on 3D seismic data

The South Atlantic is characterised by extensional tectonics in upper slope regions, changing into diapir and compressional regions towards the base of the continental slope (Brun and Fort, 2004; Mohriak et al., 2004). Pre- and post-salt reservoirs are affected by several fault families that promote fluid flow from syn-rift to post-rift reservoirs. Data from a 3D seismic block from the Espírito Santo Basin, Brazil, is used to illustrate the complex geometry of the different sets of faults that cut the post-salt overburden (Alves et al., 2009). The preservation of pre-salt oil is in great part a function of how effective faults are in promoting fluid migration onto shallow (post-salt) reservoirs. A similar setting is observed in West Africa, with several fault-bounded compressional structures comprising fluid-flow paths from pre-evaporite source units. Post-shortening either formed large structural traps and/or lead to vertical stacking of reservoir units in adjacent synclines.

In West Iberia, a similar setting to the South Atlantic is observed in areas of thick Triassic-early Jurassic evaporites. However, it is proposed that in West Iberia the thickness of pre-salt units is not fully resolved on seismic data, with speculative Triassic (and older?) source units potentially leading to the formation of petroleum plays that are unknown in the proximal margin. Subsequent phases of basin inversion are always more evident in salt-rich areas of the margin, and led to the formation of regional traps (Rasmussen et al., 1998; Uphoff et al., 2002).

## 3. Conclusions

Main conclusions are:

- Offshore west Iberia, thick strata occur below Triassic-early Jurassic evaporites, thus increasing the petroleum potential of such regions
- In salt-rich parts of west Iberia, the post-salt overburden is apparently deformed similarly as key regions in the South Atlantic. If reservoir units similar to those in the South Atlantic are to exist in West Iberia, there is a strong potential for fault-controlled fluid migration from pre-salt and post-salt source rocks to occur around main salt structures.

*Acknowledgements*

*We acknowledge the scientific support - and authorization for publishing this abstract - granted by T. Abecasis, DGEG-DPEP and TGS-Nopec Geophysical Company ASA. CGG-Veritas are acknowledged for the 3D seismic data presented here and published in various works.*

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# Faulting of salt-withdrawal basins during early halokinesis: Structural controls on reservoir distribution in South Atlantic Conjugate Margins

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*ABSTRACT*

*Three-dimensional (3D) seismic-reflection data were used in the analysis of submarine channel systems in the Espírito Santo Basin, Brazil. In the study area, pervasive normal faulting of pre-Oligocene strata was triggered during early halokinesis (Stage A) but initially hardly controlled the evolution of a channel system (RDCS) which, at the time, incised the continental slope axially within a salt withdrawal basin. In a second stage (Stage B) crestal/radial faults controlled erosion over growing salt structures, while synclinal and channel-margin fault sets dissected overbank strata to the RDCS. In the later part of Stage B, channel sinuosity decreased sharply in response to fault activity and associated seafloor destabilization. Vertical propagation of blind faults was triggered in a third stage (Stage C) - in association with crestal collapse of buried salt anticlines and regional diapirism.*

*We have assessed the importance of faulting during early halokinesis on the 4D development of the RDCS. Statistical analyses of observed fault sets show that synclinal faults are in average 2.3 times longer than the crestal/radial types but record 60% of the throw (average 83 m) experienced by the latter. Significantly, the analysed axial fault sets are shown to have contributed to local cannibalisation of the seafloor, to vertical stacking of channel-fill strata and to structural and depositional compartmentalisation of potential reservoir successions. As a result, channel systems show marked differences in mean values for sinuosity, height and width in relation to five (5) main phases of channel development.*

*The structural setting in the study area differs from productive areas offshore Espírito Santo (e.g. Golfinho field), West Africa and Gulf of Mexico. It reveals - in distal parts of the Brazilian margin - the existence of local controls on submarine-channel architecture and structural compartmentalisation prior to the principal stages of diapirism, which are dated as Miocene to Holocene.*

*KEYWORDS: South Atlantic, salt diapirs, submarine channels, faults.*

## 1. Introduction

Strata adjacent to salt diapirs potentially contain significant oil and gas accumulations, particularly on Atlantic-type continental margins (e.g. Gulf of Mexico, West Africa, Brazil, Norway) where they constitute one of the most challenging settings for field development (e.g. Rowan et al., 1999; Tari et al., 2003; Mohriak et al., 2004; Yin and Groshong Jr., 2007). Fault patterns associated with the development of salt structures: a) pose significant difficulties during borehole drilling (Haskell et al., 1999; Koupriantchik et al., 2005), b) increase local risks in terms of local slope stability (Brun and Fort, 2003); c) may generate fluid-migration paths, potentially contributing to the escape of hydrocarbons in evolving reservoir units to growing diapirs (Weissenburger and Borbas, 2004). The aim of this presentation is to analyse a very common facet of the geology of sedimentary basins, this being the movement of salt (halokinesis), the role this movement has in the development of normal faults and how these faults subsequently affect deepwater channel development. We focus on a major submarine channel complex using high quality 3D seismic reflection data from a salt-rich continental slope basin in the South Atlantic (Espírito Santo Basin, Fig. 1a). Thus, we introduce the: a) effects of (early) halokinesis on the compartmentalisation of reservoir units; b) implications of the interpreted tectono-sedimentary model for other salt-rich continental slope basins.

## 2. Statistical analyses of fault families offshore Brazil

Several examples of syn-sedimentary faulting in adjacent areas to submarine channels in the Espírito Santo Basin (FIG.1) were studied in order to quantify the geometry of the distinct sets of faults cutting post-Aptian overburden strata, and the way they relate to: a) the incision of submarine channels within the studied sub-area; b) thin-skinned tectonics and associated diapir growth. Graph 1 confirms synclinal faults as having greater lengths than the crestal/radial faults (FIG.2). Length values for synclinal faults average 3,150 m against 1,480 m for the crestal/radial types. Also in FIG.2, graph 2 indicates that faults with larger lengths exhibit the smaller throw values, i.e. the longer synclinal faults have smaller throws than the shorter crestal/radial types, the opposite relationship to that normally recorded in extensional settings (e.g. Cowie and Scholz, 1992). Synclinal faults exhibit a maximum throw of 124 m, contrasting with the 205 m observed in crestal/radial faults. Such discrepancy between T/Z (fault throw versus depth) values most likely derives from the reactivation of crestal/radial faults during the Late Cenozoic (Baudon and Cartwright, 2008).

Based on the studied data set, we propose that overburden faulting contributed to the vertical stacking and limited lateral migration of channel systems, when compared with their counterparts in West Africa, a character achieved by combined rim syncline subsidence, structural segmentation, and relative growth of adjacent salt anticlines during the principal phases of channel development. Such character, not recorded in the Golfinho Field (Fiduk et al., 2004) is significant in more distal areas of the Espírito Santo Basin – including parts of the study area - in which a greater compartmentalization of Cenozoic units is recorded on the continental slope.

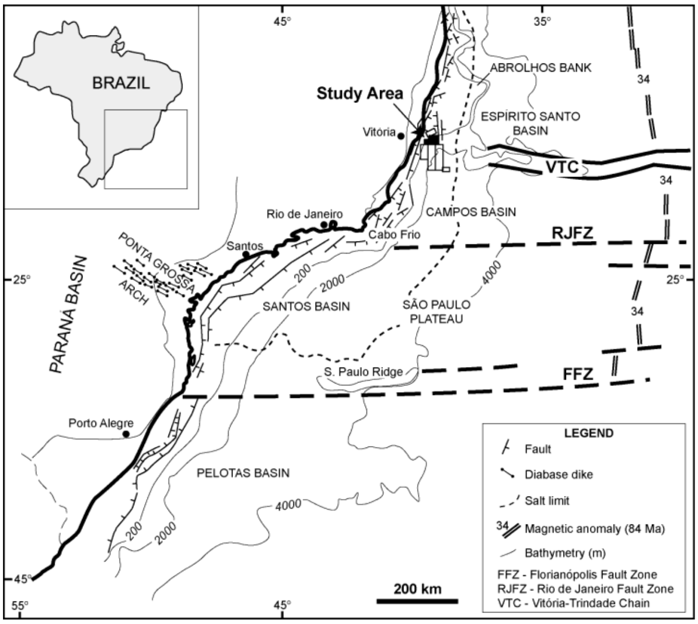


FIG.1 – Regional map showing the location of the study area. Modified from Alves et al. (2009).

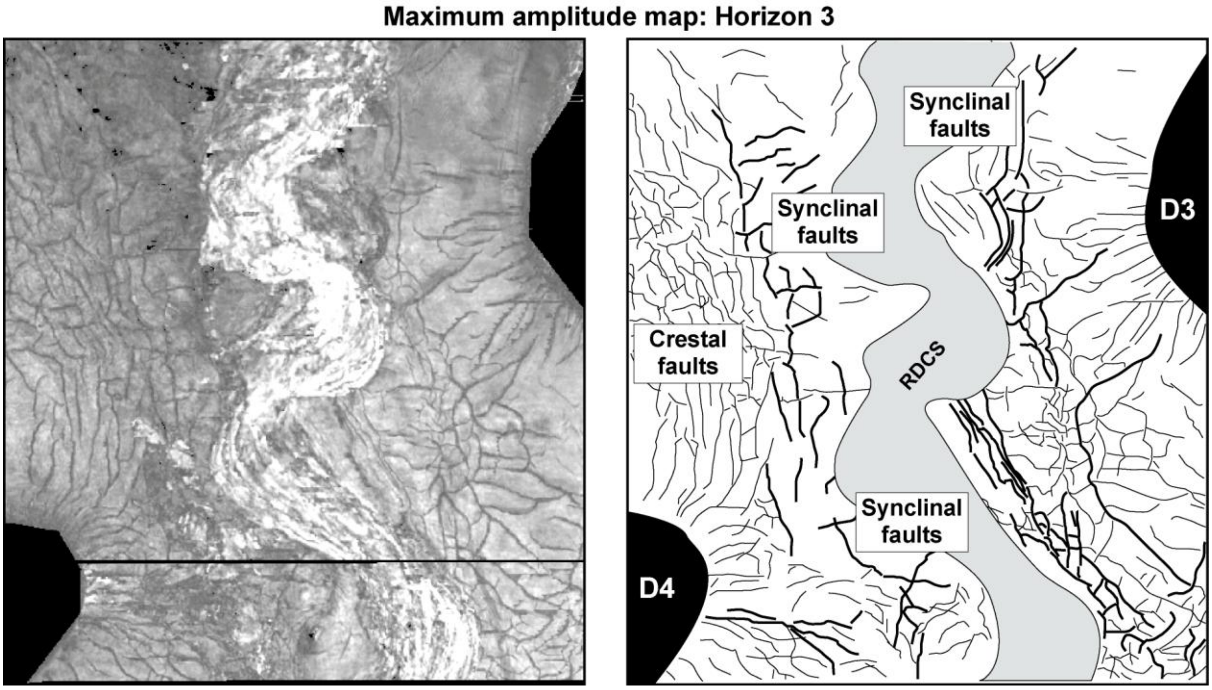


FIG. 2 – Amplitude maps evidencing the geometry of overburden faults mapped in the Espírito Santo Basin. Modified from Alves et al. (2009).

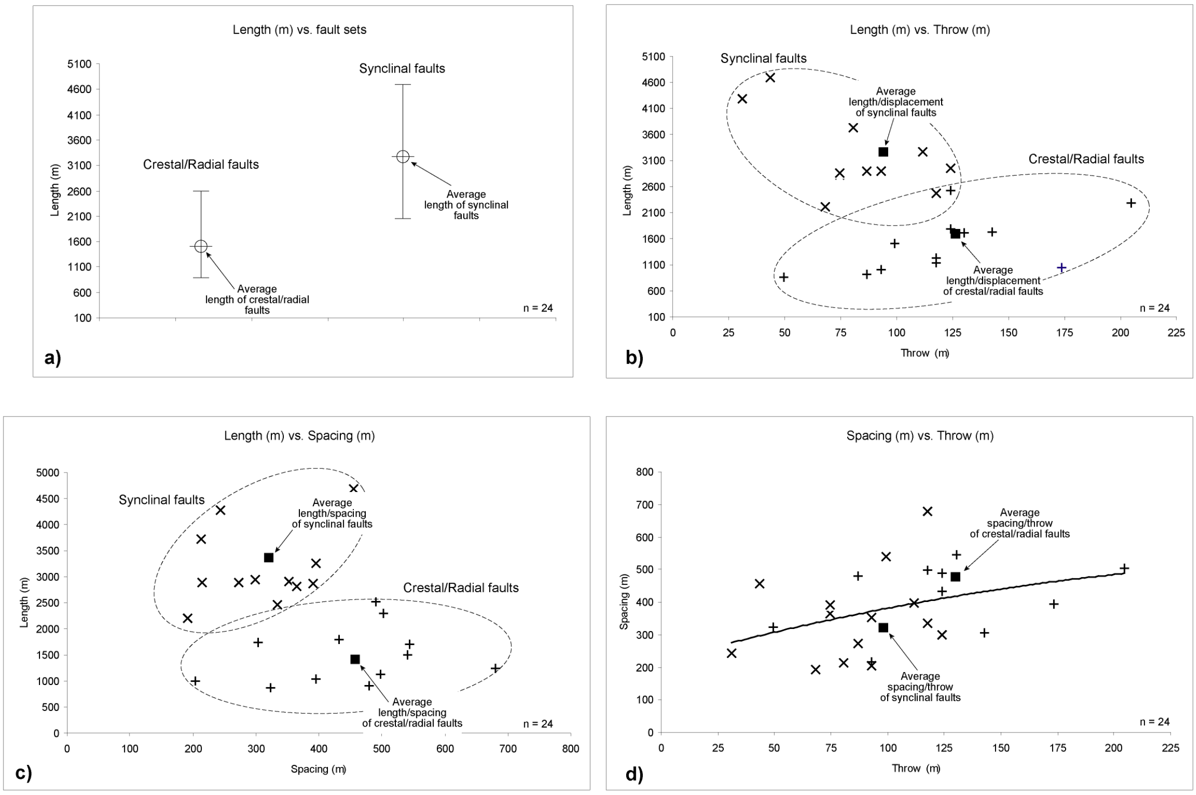


FIG. 3 – Statistical data for the different fault families (synclinal and crestal/radial) observed in the study area offshore Espírito Santo, southeast Brazil. From Alves et al.(2009).

## 3. Contrasting styles to West Africa and Conclusions

The seismic and statistical analyses in this study provide important clues to understand the geometry of fault systems in salt withdrawal basins and their importance in the compartmentalisation of reservoir units. By documenting the geometry of synclinal, and crestal/radial faults sets on a salt withdrawal basin we prove that significant faulting of salt withdrawal basins can occur during the early halokinesis. In particular, synclinal fault systems on the continental slope can be responsible for: a) the capture of slope channels by increasing local rates of subsidence during salt withdrawal; b) structural segmentation of local highs (and sub-basins) on salt withdrawal basins, leading to the formation of small-scale depocentres on the margins of evolving channel-levee systems; c) the generation of structural paths for the vertical migration of hydrocarbons or, instead, contributing to hydrocarbon entrapment by forming stratigraphic and structural compartments in salt withdrawal basins.

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*We acknowledge the scientific support and data granted by CGG-Veritas.*

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# Structural Evolution and Timing of Continental Rifting in the Northeast Atlantic (West Iberian Margin)

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*ABSTRACT*

*Regional (2D) seismic-reflection profiles, outcrop and borehole data are used to indicate that the bulk of Late Jurassic-earliest Cretaceous subsidence occurred in the present-day continental slope area. Five (5) principal regressive events (and their correlative basal unconformities) reflecting tectonic uplift and relative emersion in proximal basins are correlated with major rift-related tectonic events on the deeper margin. A significant portion of the west Iberian lower-plate margin was uplifted and eroded during the last stages of continental rifting. Such process was repeated at different times (and in different areas) as the locus of rifting and continental break-up migrated along the future passive margin. As a result, in west Iberia two distinct rift axes are recognised, a first axis extending from the Porto Basin to the Alentejo Basin and a second axis located on the outer proximal margin north of 38⁰ 30'N. We propose the late-rifting phases of tectonic quiescence, widespread erosion and sediment progradation on the inner proximal margin as marking the abandonment of extensional basins east of a major Slope Fault System (SFS), and the subsequent onset of syn-rift extension on the outer proximal margin. However, rift-related units of Triassic (and older?) to Middle Jurassic age are well represented on the outer proximal margin. This fact indicates that crustal extension on continental slope basins of west Iberia consisted of a prolonged process in which the last rifting episode is structurally imprinted over older – but not less important – rift episodes.*

KEYWORDS: *North Atlantic, continental slope, tectonic subsidence, West Iberia.*

## 1. Introduction

Variations in the geometry of rift basins are observed across distinct crustal segments separated by transfer faults (Driscoll et al., 1995; Tucholke et al, 2007). However, the timings of continental rifting, the relative locations of continental break-up and the significance of syn-rift and post-rift tectonics in the Northeast Atlantic are issues not yet fully addressed. This abstract presents regional (2D) seismic-reflection profiles, outcrop and borehole data that indicate the bulk of Late Jurassic-earliest Cretaceous subsidence to have occurred in the present-day continental slope area. Five (5) principal regressive events (and their correlative basal unconformities) reflect tectonic uplift and relative emersion in proximal basins. These events are correlated with major rift-related tectonic events occurring on the deeper margin. Direct comparisons with the Peniche Basin of northwest Iberia reveal that a significant portion of lower-plate margins is uplifted and eroded during the last stages of continental rifting. This process was repeated at different times (and in different areas) as the locus of rifting and continental break-up migrated along the future passive margin.

## 2. Tectono-stratigraphic evolution of the west Iberian margin

A key aspect revealed on seismic data is the marginal position of the inner proximal margin during continental rifting, with a Slope Fault System (SFS) separating the inner proximal margin from highly-extended tilt-blocks in the deep-offshore (FIG. 1).

At the onset of Late Jurassic-earliest Cretaceous extension (Rift 3), Oxfordian-Early Kimmeridgian rift basins were formed at the inner and outer proximal margins, whilst tilt-blocks at the outer proximal margin evolved as highly-subsident sub-basins during the Advanced Rifting Stage. Examples of highly-segmented rift margins of the ancient Tethis Ocean are exposed in the Alps (Froitzheim and Manatschal, 1996). In order to illustrate the evolution of southwest-central Iberia, the Ligurian Basin is compared with the interpreted evolution of the southwest Iberian margin during the Triassic-Early Cretaceous in FIG.2.

In this work, we propose the subsequent phases of tectonic quiescence, widespread erosion and sediment progradation on the inner proximal margin as marking the abandonment of extensional basins east of the SFS, and the onset of syn-rift extension on the outer proximal margin.

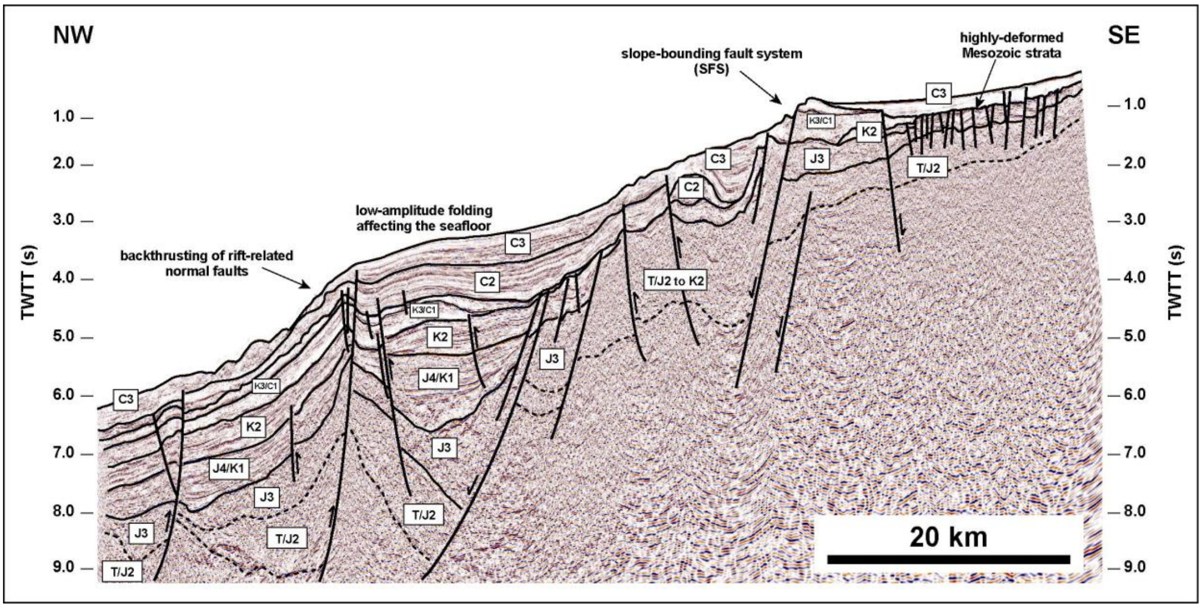


FIG.1 – Interpreted seismic line showing the geometry of deep-offshore rift basins. The SFS separated the developed deep-offshore graben/half-graben basins from proximal basins on the continental shelf. From Alves et al. (2009).

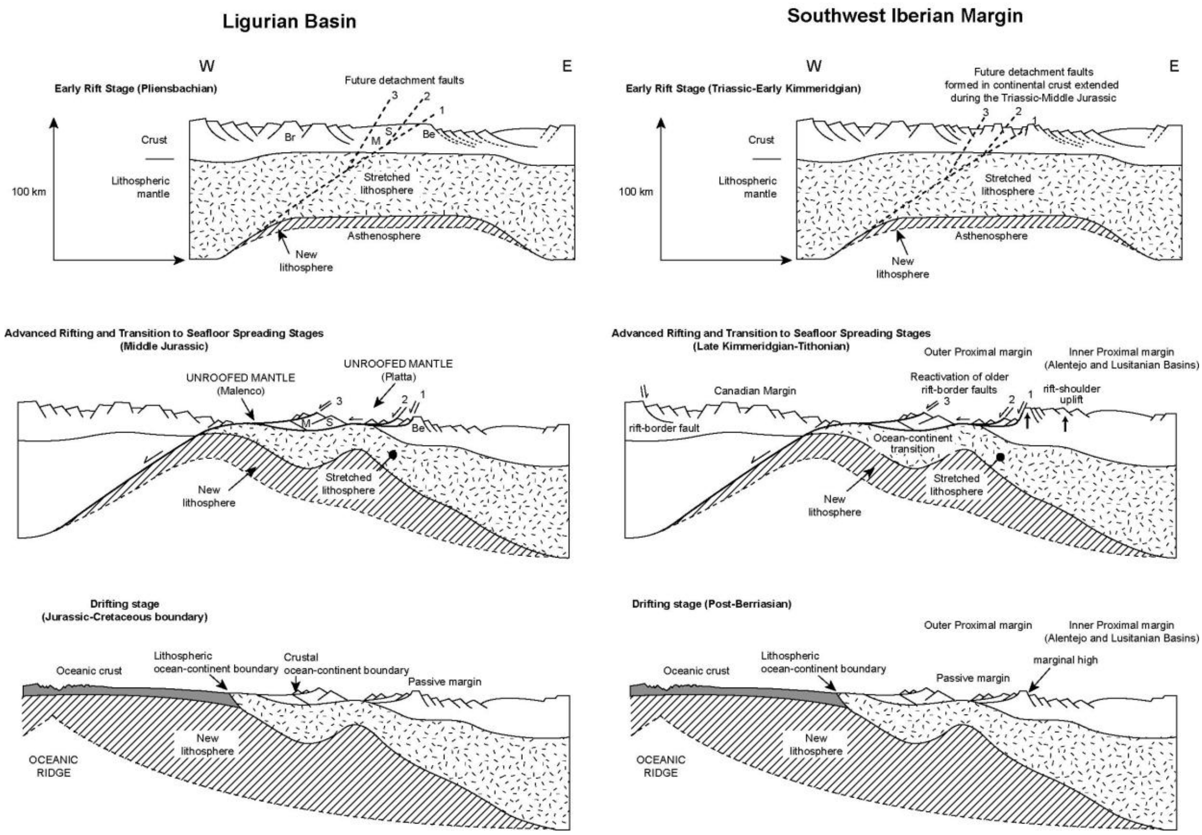


FIG.2 – Diagram comparing the kinematic evolutions of passive margins in the Tethyan Ocean (Ligurian Basin) and southwest Iberia.'Stretched lithosphere' is pre-rift continental lithosphere; 'new lithosphere' is syn- or post-rift lithosphere derived from cooling asthenosphere. Be, Bernina; Br, Briançonnais; M, Margna; S, Sella. Modified from Froitzheim and Manatschal (1996).

## 3. Conclusions

Main conclusions of this work are, as follows:

- Principal depocentres in deep-offshore basins are separated from proximal basins by a slope-bounding fault system (SFS).
- Five regression episodes (S1 to S5) should reflect major tectonic events occurring on the deeper margin. They sign the development of two principal Oxfordian-Aptian axes of rifting in west Iberia. Separating these two axes is a marginal horst west of the Lusitanian Basin (Berlengas Horst and its continuation towards the Aveiro High, Alves et al, 2006), and an inferred northwest-trending lineament marking the edge of continental-slope basins southwest of Lisbon and Estremadura. Consequently, continental rifting west of the Lusitanian Basin may have progressed during the latest Jurassic (Late Kimmeridgian-Tithonian).

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# Passive Margin and Continental Basin: the necessity of the Holistic approach.

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*ABSTRACT*

*The formation of the sedimentary basins and continental passive margins have long been explained by numerous physical models, usually built on only one passive margin considered as the reference. However, passive continental margins are so diverse that the existence of a unique thinning process must be re-considered and discussed. However, the recurrence of some general features (abrupt thinning, large transitional domain, whatever the nature of the crust oceanic, continental or mixed) pleads in favour of general rules.*

*No margin presents all the features needed to support a general model, but each margin supplies pieces of the jigsaw. Understanding the thinning process can therefore only be reached using a holistic approach, comparing many different margins. The main, and most difficult, trick is to distinguish and to decipher local (as probably the presence or absence of a sag basin) and general characteristics (the abrupt thinning for instance). The thinning of passive continental margins is usually explained by models using pure stretching or simple shear, with or without depth-dependent thinning process. These models imply hypothetical extensional structures and large horizontal movements between the two conjugate margins. The holistic approach implies to combine geometrical description with precise plate kinematic reconstructions. This approach allows us to propose some general rules for the early thinning process, among which a high position of the system, throughout the entire process of thinning and a lost of lower continental crust are the most important. The diversity of the final structural morphologies observed seems to be a matter of tectonic heritage, geodynamic context and probably mantle heat segmentation.*

*KEYWORDS: Margins Genesis, South and Central Atlantic, Mediterranean Sea, Basins.*

## 1. Introduction

Passive continental margins are so diverse (FIG.1) that the existence of a unique thinning process must be considered for discussion. Nevertheless, the recurrence of some general features (abrupt thinning, large transitional domain, whether oceanic, continental or mixed) pleads in favor of general rules.

Because of this diversity, two approaches can be used in order to try to understand the continental thinning process: the one-way approach and the holistic approach.

## 2. The one-way approach.

This approach is the most commonly used approach and consists in working on one specific margin (and its conjugate), and increasing the amount of new data on this system, and then in producing a hypothesis or a concept, which is one of the possible hypothesis among others (some margins were explained with completely contrary hypothesis, with the same kind of data, see Aslanian *et al.*, 2009, for an example). This concept can become a model, which can be strengthened by numerical or analogic modeling that produces images reproducing the actual morphology of the margin, and the concept, in great details (even if they start with oversimplified flat and homogenous layers – whereas almost all breakups occurred on old sutures with complex morphologies).

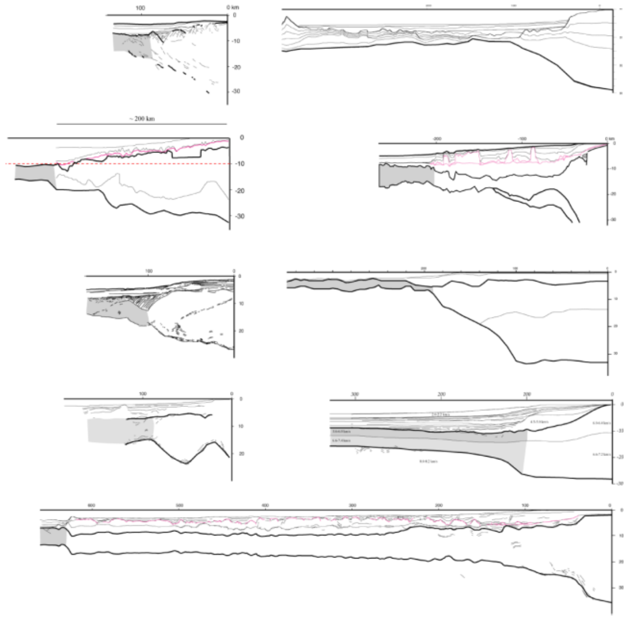

FIG.1 – Some examples of continental passive margin, all around the Atlantic margin, from Spitzerbg to Argentina, in order to demonstrate the variability of the crustal geometries. All profiles are at the same horizontal and vertical scales (in km). Some of them are reversed in order to place the oceanic crust to the left of the picture.

There is an enormous amount of researches with this kind of approach, especially between Iberia and Newfoundland or between Brazil and Africa margins. No margin presents all the features needed to support a general model, but each margin supplies pieces of the jigsaw; we therefore need this kind of detailed studies. The problem comes when we want to apply this model (singular statement: this is a model of for this margin) to other margins (general statement: this model is valid for all margins). Not to mention the fact that it is deductively invalid (Karl Popper, *The Logic of Scientific Discovery,* 1968), this « jump » has a certain number of epistemic problems:

1) The first hypothesis is that the studied system is a typical system without any anomalies (which allows us to produce a very detailed model).

2) When some discrepancies are observed, they are usually related to a different tectonic setting or heritage of the « other » margins. Nevertheless, the model will not be changed: observations on other margins will not be taken into account to modify the previous model. The model will therefore become a paradigm as defined by Thomas Kuhn (*The structure of scientific revolution*, 1962) and we will work within conceptual paradigms that strongly influence the way in which they see data (model dependent interpretation, see Unternehr *et al.*, 2010, for an example).

As we already wrote (Aslanian et al., 2009), following the principle of falsification of Karl Popper (1968): «Quantitative modeling provides predictions that should be tested against observations. If sound agreement is found between observations and predictions, the initial hypothesis is still possible. If not, the hypothesis is not valid.»

Therefore we must strive to question, for falsification, our hypotheses instead of proving them; the more they resist, the more they become reliable. The one-way approach, which is a closed system as defined by Karl Popper (1968), does not allow this to be done (FIG.2). As Thomas Kuhn (1962) wrote: « *Scientists will go to great* *length to defend their paradigm against falsification, by the addition of ad hoc hypotheses to existing theories* ».

**2. The holistic approach.**

The purpose of the holistic approach is to re-build the jigsaw ~~in~~ by taking into account all the pieces of all the studied margins (at least as much as possible). The main, and most difficult, trick is to decipher between local (as probably the presence or absence of a sag basin) and general characteristics (the abrupt thinning for instance) and this could be done by comparing different margins. However, local characteristics may also hide and prevent the observation of major general characteristics. The building-up

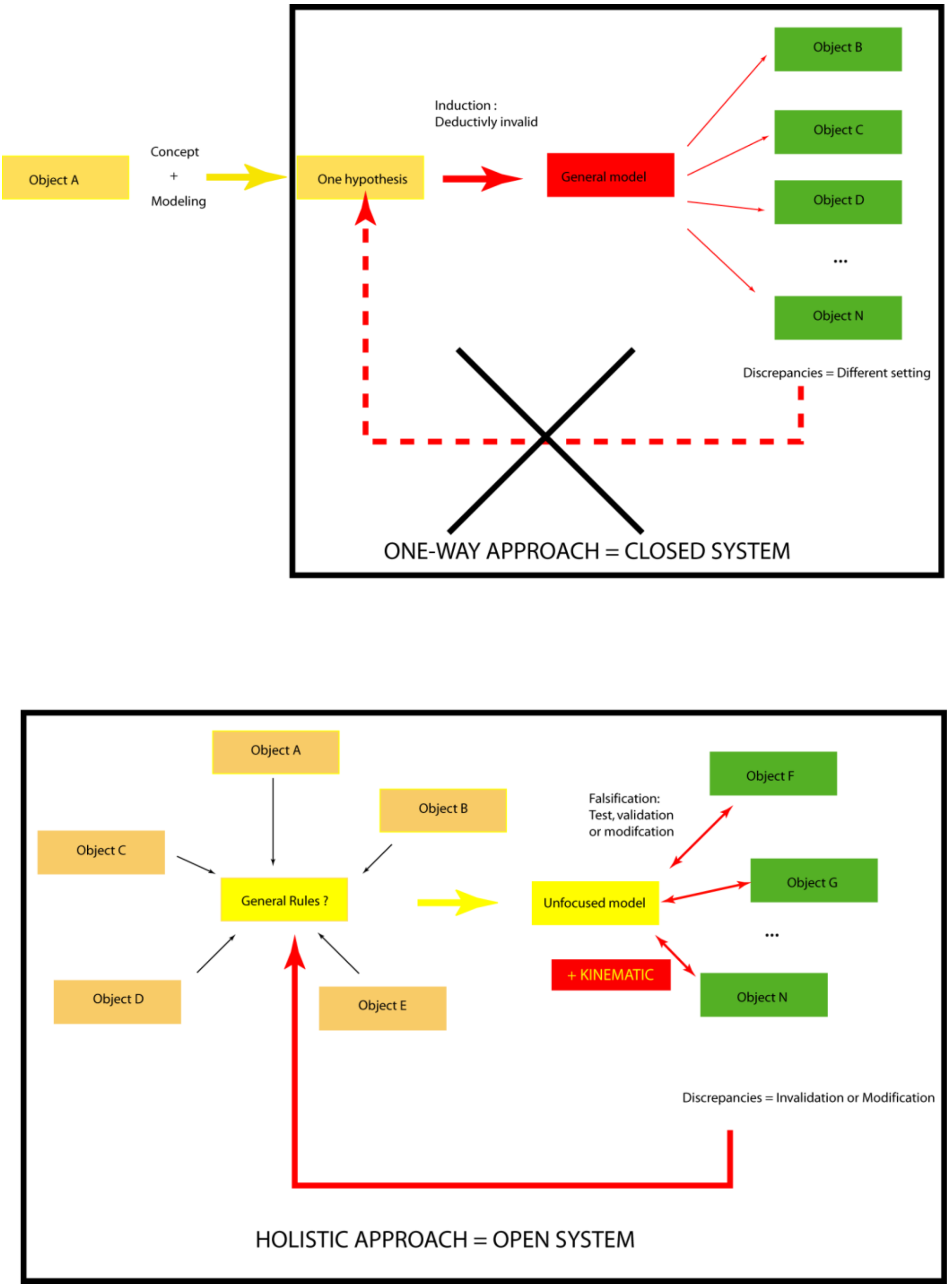


FIG.2 – Sketch showing the differences between the two approaches

will therefore start slowly and produce an unfocused image. This image needs then to be tested on all margins and to be improved by others observations as an open system as defined by Karl Popper (1968).

Then, because conservative models intrinsically imply important horizontal movement whose consequences will have to be observed in the field, we must put this model in a precise paleogeographic evolution. The horizontal movement is not usually constrained in models whilst it is one of the main parameters to be considered, especially for conservative models (pure stretching, simple shear, multiple shears and all their combinations…), which imply hypothetical extensional structures and large horizontal movements between the two conjugate margins (for example more than 250 km for the Brazilian and Angolan Margins, Aslanian et al., 2009; Moulin et al., 2010).

We already showed that plate tectonics does not only « *provide a useful framework for description of margins* » (Keen & Beaumont, 1990) but is also a powerful constraint to understand the genesis of passive margins, and we proposed a first unfocused model of margins evolution for the Central segment of the South Atlantic Ocean. We will show now the result of using this kind of holistic-kinematic approach in comparing the main features of three distinct regions, with three distinct tectonic contexts, located in Central Atlantic Ocean, South Atlantic Ocean and Mediterranean Sea. From the unfocused image produced by this comparison, we will deduce some general rules for the early thinning process, which has to be tested in future works:

Abrupt thinning, large transitional domain, whatever the nature of the crust oceanic, continental or mixed, high position throughout the entire thinning process as described already by Moulin et al. in 2005, and Bache et al., 2010, middle/lower crust disappearance. This last point urges us to reconsider conservative models as being the sole thinning process. McKenzie *et al.* (2000) show that a thick continental crust (equal or greater than about 30km) and magmatic activity can reduce the lower crustal viscosity to a level at which flow is possible. Therefore, it can either “flow” in the first accreting process, as earlier suggested by Bott (1971), for the volcanic margin, and/or flow laterally along different margin segments. It can also be involved in exhumation processes to create the first “proto-oceanic crust” (like the “Type III” crust), or even mixed with the upper mantle underneath. These points are far from being inconceivable if we keep in mind that continental break-up nearly always occurs inside previous orogenic belts and that the material involved in the process is therefore highly heterogeneous. Last, following Aslanian *et al*., 2009, we can describe the thinning process in three main phases. These three phases correspond also to the three stages described by Montenat et al. (1988, 1998) in the Red Sea: the tilted block stage, the horst and graben stage and the flexuration stage.

*Acknowledgements*

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# The Combined Effect of Sedimentation Rate and Salt Tectonics on the Angolan margin

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*ABSTRACT*

*The Angolan margin is an excellent example of a passive margin affected by salt tectonics. Both the Lower Congo and Kwanza basins are heavily influenced by salt movement. The interaction between salt movement and sediment deposition leads to extensional and structural domains characterized by salt diapirs, faults and folds. In this study, laboratory experiments are used to examine the effect of sedimentation rate on the development of extensional and compressional salt tectonic features. The experiments were done using sand and silicone to simulate respectively the brittle behaviour of the sedimentary layers and the ductile behaviour of the salt layer.*

*The results show that sedimentation rate has an effect on the extent of the extensional and compressional domains. Low sedimentation rates result in a wider extensional domain than high sedimentation rates. Structural styles within each domain also depend on the sedimentation rate. Diapirs and rollovers are abundant in models with low sedimentation rates, whereas trust faulting is primarily seen in models with high sedimentation rates. Experiments with high, low, increasing and decreasing sedimentation rates have been performed and the structural styles are analyzed and compared with each other.*

*The laboratory models are compared with the sedimentary history and seismic data from the Lower Congo and Kwanza Basins and important similarities can be correlateted.*

*KEYWORDS: Angolan margin, Salt tectonics, Congo basin, Kwanza basin, Sedimentation rate.*

## 1. Introduction

This study focuses on salt tectonics in passive margin basins offshore Angola, namely the Lower Congo and the Kwanza basins. Research on salt tectonics has been the focus of wide interest from petroleum industry and strong debate among geoscientists for the past 20 years because of its importance not only for basin analysis and structural studies, but also for its association with sedimentary basins with proved petroleum systems. This study applies the technique of salt tectonics physical modelling through laboratory experiments by using sand and silicone. The study has the purpose to analyze the effect of different sedimentation rates on sedimentary basins affected by salt tectonics and its impact on structural domains as well as the qualitative and quantitative analysis of geological structures observed on different sedimentation rates. To examine this effect, five laboratory experiments were conducted at the experimental laboratory at Statoil in Luanda.

**2. The Angolan Basins**

The Angolan Lower Congo and Kwanza basin are the main targets of this work. The basins are located between 5º S and 10º S in the South Atlantic region in the West Africa margin (FIG.1).

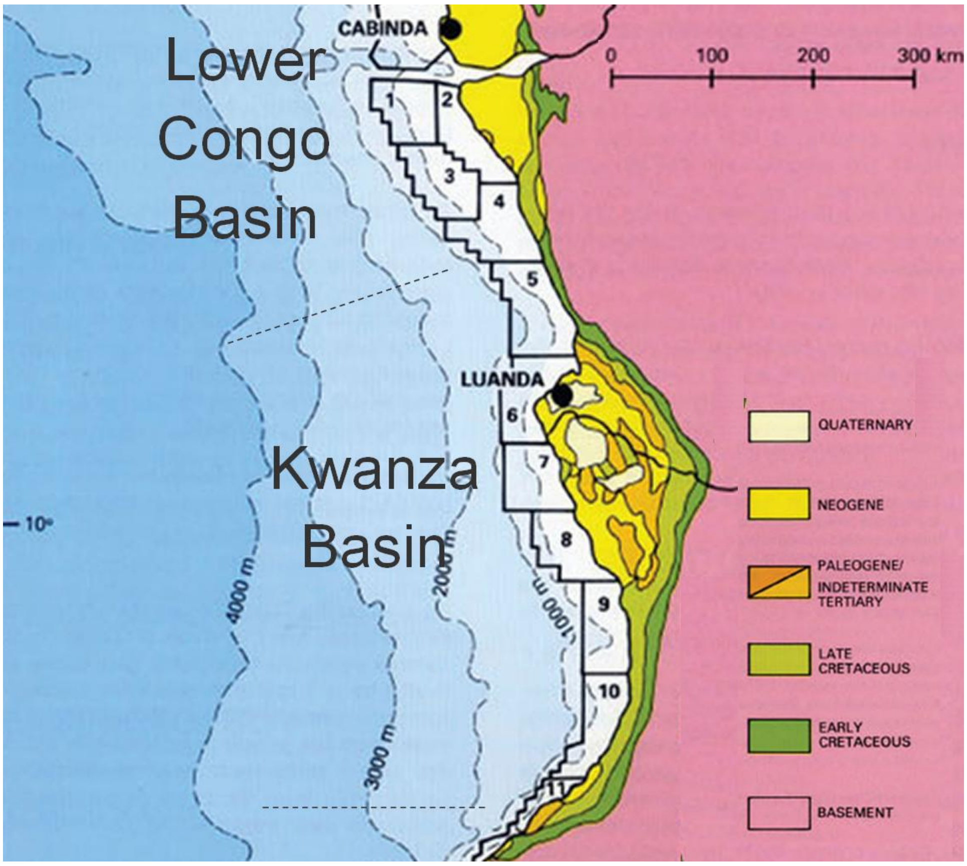


FIG.1- Location map of the study area in the South Atlantic (modified from Stark et al., 1991).

The Angolan basins were formed during the opening of South Atlantic Ocean (Brognon & Verrier, 1966; Marton et al., 2000; Rosendahl et al., 2005). They belong to a Mesozoic series of basins that developed during the late Jurassic and Neocomian times on the conjugated margins of Africa and Brazil. The rifting of the Angolan margin started around 144 – 140 Ma and continued with the separation of the continents by 127 – 117 Ma. The tectonic periods can be divided into prerift, synrift, transitional, early drift and late drift units. The prerift lithology consists mainly of siliciclastics sandstones, fluvio-lacustrine and some volcanics. Synrift lacustrine deposits with organic-matter rich shales of Neocomian to Barremian times lie unconformably on top of Precambrian fault blocks (Brice et al, 1982; Fort et al, 2004). The boundary between prerift and synrift is marked by a breakup unconformity followed by a thick and widespread sag basin formed at the end of the active rifting episode, by Late Barremian to Early Aptian (Karner et al., 1997; Fort et al., 2004; Karner & Gamboa, 2007). During Aptian times restricted marine conditions led to the precipitation of evaporites and consequently the deposition of massive salt formation consisting of halite and other soluble evaporites with high potassium content. Following salt deposition, oceanic circulation increased leading to the deposition of Albian carbonates (Hudec & Jackson, 2002) of the Pinda Group followed by sedimentation dominated by marls and clays (Brogon & Verrier, 1966; Fort et al., 2004). By the end of the Early drift period, which is characterized by transgressive sequences, until the Late drift period, which is markedly characterized by regressive sequences, huge amounts of sediments were deposited on the Angolan margin due to the uplift and westward tilting of the African craton, sea level changes and increased river runoff (Kola et al, 2001). During Oligocene times, large amounts of sediments were transported into the Lower Congo Basin as a consequence of Late Tertiary uplift and formation of the Congo River, which resulted in the development of the Congo Fan by Late Tertiary time (Kola et al., 2001; Fort et al., 2004; Hudec & Jackson, 2004). Structurally the Angolan margin displays a proximal domain of extension with tilted blocks, rollovers, listric faults and salt diapirs, whereas the compressional domain is characterized by growth folds, diapirs and thrusts, similar to the Eastern Brazilian margin (Mohriak, 2005).

## 3. Experiments and Results

In accordance with the situations observed in seismic profiles along the Angolan margin, similar conditions are provided by laboratory experiments that aim at simulating the structural and stratigraphic parameters. The five experiments conducted during this study consist of physical models using silicone to represent salt and dry sand layers do represent sediments. A short explanation for some of the parameters used in the models is summarized in Table 1 below. A tilt of three degrees was done to simulate the subsidence. The sedimentation was done by the deposition of sands through a funnel travelling on the model and each experiment was conducted during 70 hours.

| Type of experiment | Description of sedimentation | Variation in time |
|---|---|---|
| **Normal** | 100% sedimentation( deposition travel forth and back on model ) | constant |
| **Low** | 50% sedimentation( one travel forth on model ) | constant |
| **High** | The double of 100% sedimentation (four travels ) | constant |
| **Increasing with time** | 50% (first 20 hours); 100% (during the following 25 hours); High sedimentation (during the last 15 hours). | Variable at three times |
| **Decreasing with time** | High sedimentation (first 20 hours); 100% (during the following 25 hours); 50% (during the last 20 hours). | Variable at three times |

Table 1– Summary of all experiments done in the laboratory.

The cross sections and top views (FIG.2) clearly show an extensional domain upslope subdivided by sealed tilted blocks, growth fault/rollovers and extensional diapirs. Further downslope the domain of compression is subdivided by squeezed diapirs, growth folding, thick salt plateau and thrusts. Moreover, the low sedimentation rate experiment favoured a strong development of listric normal faults in the extensional domain, with the creation of a large number of diapirs and roll-overs, whereas the high sedimentation rate favoured the development of a compressional domain associated with strong folding and a large number of thrust and reverse faults. On the other hand, in the experiment with increasing sedimentation rate with time a large number of folds was observed in the compressional domain, whereas a smaller number of tilted blocks and growth faults/rollovers were observed in the extensional domain. Hence, the weak development of diapirs in these models can be linked to the increase in sedimentation rate. Finally, the model with decreasing sedimentation rate with the time showed a high quantity of tilted blocks, growth fault/rollovers and strong development of diapirs in the extensional domain.

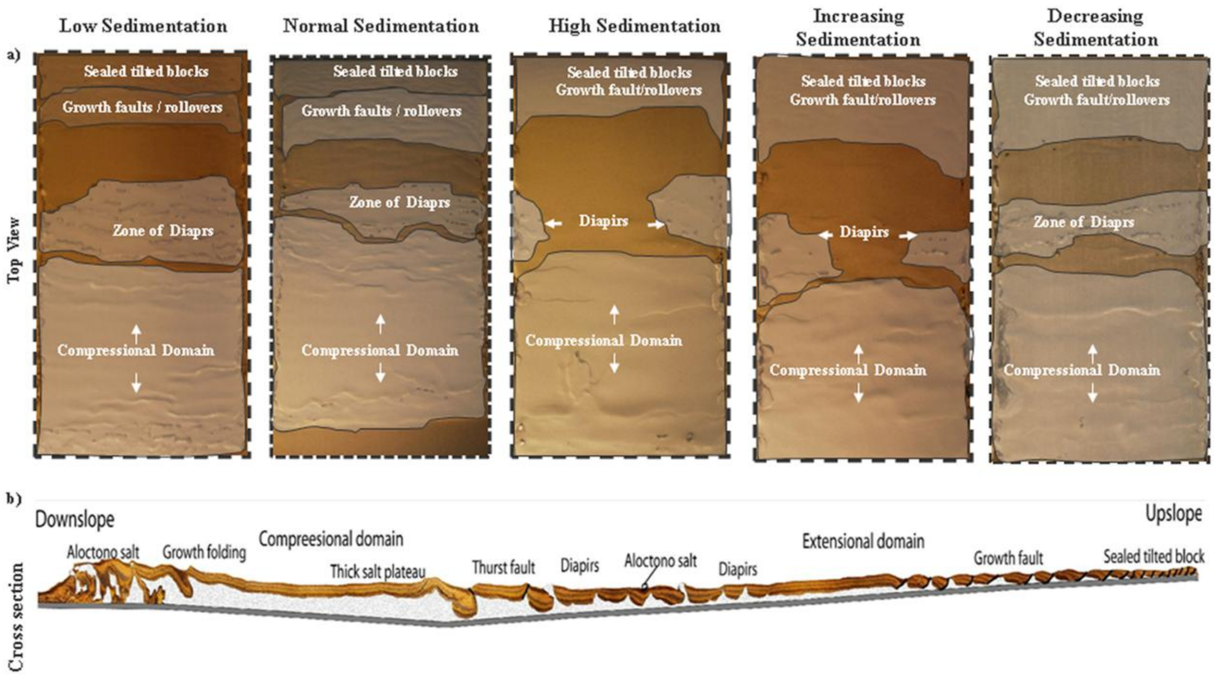


FIG.2- Above: FIG.2-a (top) shows the top view of the sandbox experiments with variable sedimentation rates; Figure 2-b (bottom) shows a longitudinal cross section for a low sedimentation rate experiment.

Comparisons of the model cross sections with a seismic section across the Angolan margin can be made in order to clarify the different domains of deformation stated above. The domains of extension and compression can be observed, similar to what is present in the cross sections from the models, underlining the similarity between laboratory experiments and the seismic data. On the other hand, comparison between the experiment results and well data near Kiame Field offshore Angola through a burial diagram (FIG.3) is made to examine the effect of different sedimentation rates.

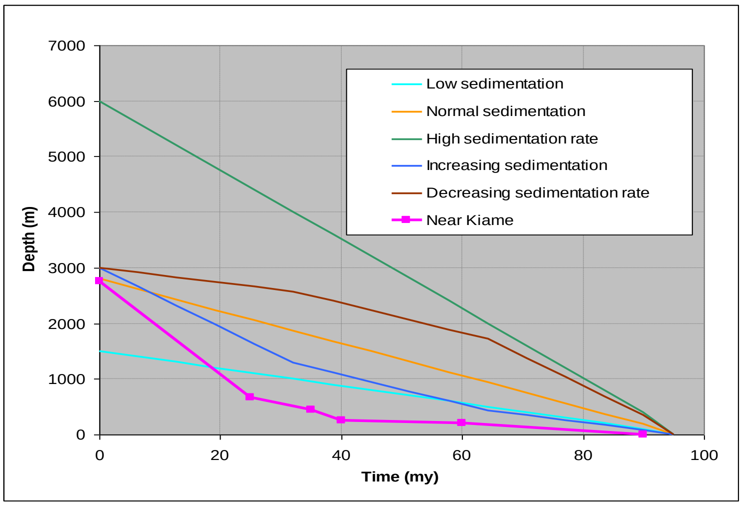


FIG.3 - Burial diagram showing the rate of sedimentation through time. The sediment thickness from the models scaled up to match the real thickness in metres.

The experiment that has the best approximation to the real situation could be the model based on the experiment with sedimentation rate increasing with time (blue colour) since the burial curve from the well data (pink colour on the diagram) also varies with time and they have almost the same trend.

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# Triassic salt tectonics in the High-Atlas (Morocco)

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*ABSTRACT*
*The Triassic terrestrial deposits et the north edge of the High Atlas of Marrakech are represented in the majority of outcrops by thick sequences of massive layered red sandstone topped by a formation of silt and pink brown clay containing large deposits of evaporites, mainly rock salt and gypsum. The silt and clay formations contains a set of dome structures, marked by the gypsiferousinjections and disharmonic folds outlined by fine sandstone beds, as well as isolated anticlines on a metric scale. The structural study of these structures shows that their directions do not show any relationship to the major directions of the Atlas Mountains chain uplift, but are strongly linked to the depositions of rock salt and gypsum in the Upper Triassic High Atlas of Marrakech. Same phenomeon is observed in the atlantic passive margins west morocco.*
*KEYWORDS: Upper Triassic evaporites, salt tectonics, High Atlas of Marrakech, Morocco.*

## 1. Lithostratigraphy

The terrestrial Triassic formations at the northern edge of the High Atlas of Marrakech, are the most proéminant features forming the landscape, with thicknesses that can easily reach 400m. They consist essentially of two formations F5 (the Oukaïmeden sandstone) and F6 (the Superiors Silts) corresponding to the uppermost part of the Triassic litho-stratigraphic column orignally defined in the Ourika valley by Biron (1982). The first formation is a thick (400m) range of detrital red beds formed by multi-metric red sandstones with fine to medium-sized diamond-shaped sedimentary bodies with metric HF, interbedded with centimetric to metric beds composed of red clay brown silts and red. This ensemble is overlain by the second formation (50 to 90m thick) consisting of red silts, clays and brown argillites with significant deposits including evaporites, rock salt and gypsum. These two formations are attributed to the Late Triassic. Formation F5 is dated as Carnian (Benaouiss *et al*., 1996), while formation F6 is attributed to the passage Carnian-Norian in the passage of Argana (Tourani *et al*., 2000).

## 2. Tectonic Structures

At the northern side of the High Atlas of Marrakech, the upper silt formation is marked by large deposits of rock salt and gypsum. The movements of these evaporitic masses consists of a set of dome structures, folded sandstone beds and isolated small anticlines.

2.1. Domes (Ait Ourir) : These are structures formed by beds of red siltstone and brown claystone with cores of alternations of salt and / or different types of gypsum in the form of massive slabs of some tens of centimeters thickness. The size of these structures is decametric-metric. In places, the internal structure of the domes in formation F6 is designed by creeping of gypsiferous levels (FIG.1).

2.2. Disharmonic folds (Tighadwyine) ; In some localities, the Upper Triassic red silts show levels with patches of fine to medium sandstone with a thickness of some tens of centimeters, which are folded in all directions at the sheer scale of an outcrop. Sometimes on the first glance, these structures can be confused with slumps that reflect synsedimentary tectonic instability.

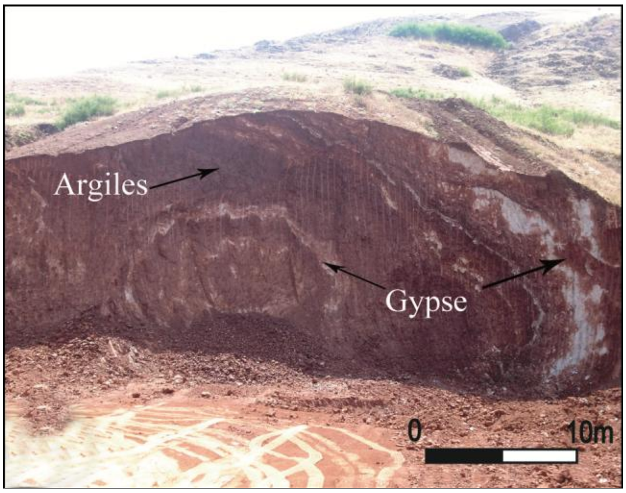


FIG.1- Internal structure of the dome formation, with silt above.

2.3. Isolated anticlines : In some localities, sandstone intercalated with fine silt red evaporites, form metric anticlines of multi-lateral extension, whose heart is filled with silts and clays to evaporites (gypsum). This gypsum is present, sometimes in the form of scattered whitish centimetric to metric stains. The anticlines are spaced apart and are not separated by synclinal structures, they are isolated.

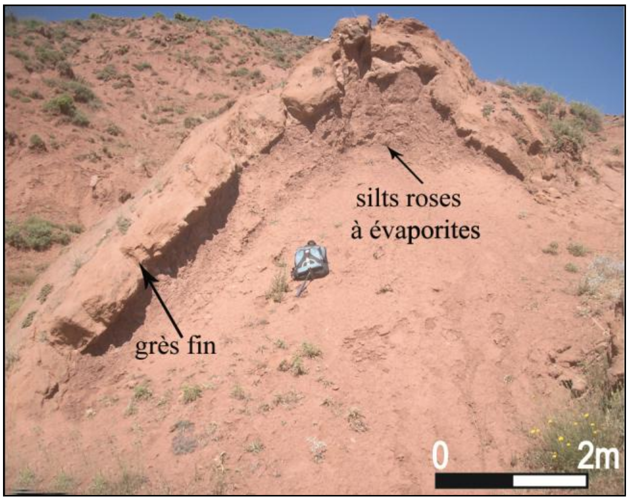


FIG.2 - Structure of a folded form in an isolated anticline.

## 3. Discussion

The stereographic analysis of the different directions of axes measured on all of these structures shows that they do not show any preferential direction. This can be seen even at the scale of a single structure. Folding disharmonious for example, show very contrasting directions of S0 stratification. Similarly, isolated anticlines have axes that plunge in all directions, with different axial planes. Regionally, all these structures are in the area of cups of Ait Ourir (Ferrandini & Le Marec 1982). They are synclinal megastructures, originating dishes and ovoid shapes, divided by the ejection of Triassic anticlines (FIG.3), which are always regarded as aquifers that have slipped from the axial zone of the High Atlas chain in South at uplift. These structures also show very different directions of their axes, so one does not find obvious markers that reflect their shift.

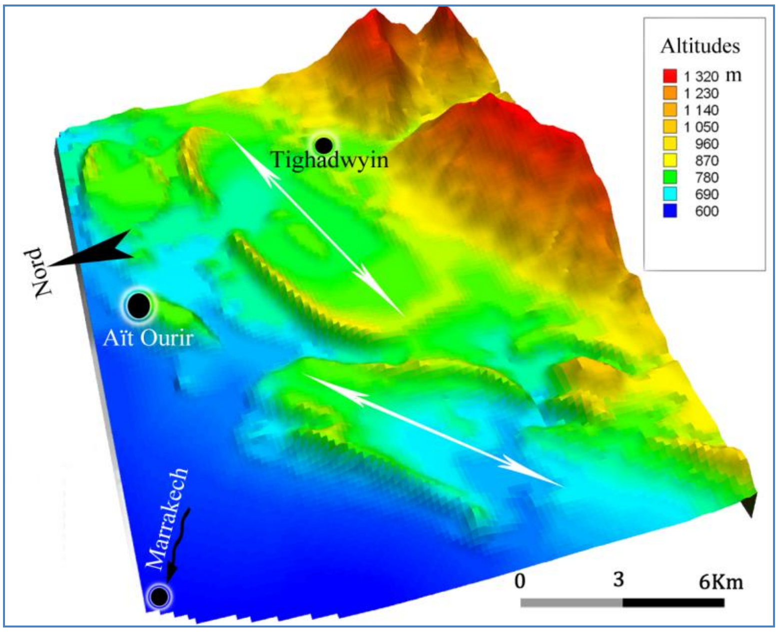


Fig.3 - 3Dmodeling of the area of "bowls" at Ait Ourir

**4.Conclusion and interpretation**

Massive deposits of evaporites (halite and gypsum) in Triassic F6 facies at the northern edge of the High Atlas of Marrakech, are responsible for the genesis of a set of dome structures, disharmonic folding of sandstone beds, and isolated anticlines. These structures are the result of the response at depth of these enormous masses of salt and gypsum to the lithostratigraphic pressure load applied by the thick sedimentary overburden. This salt tectonics is not justified by the consistency of fold axes with the major directions of the phase responsible for the Alpine uplift of the Atlas range. Thus, these new data suggest a new vision to interpret the establishment of these bowl structures at Ourir Ait. This phenomenon is also reported in halokinetic level of seismic profiles in the Essaouira Basin, west of Marrakech (Hafid *et al.* 2006) (FIG.4).

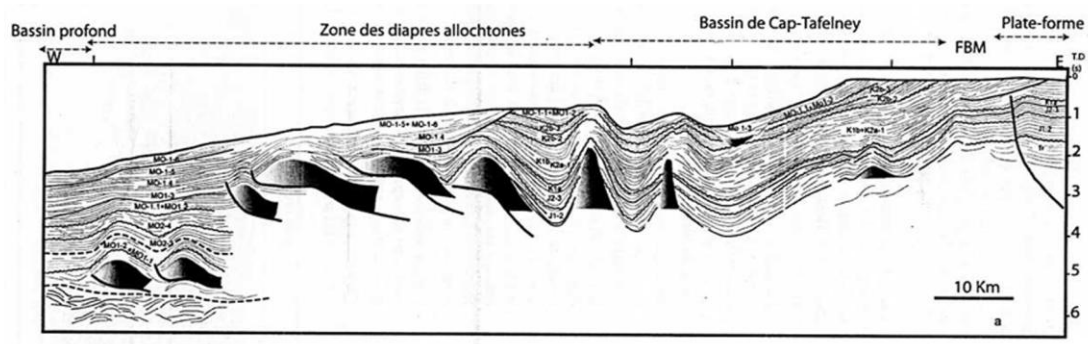


FIG.4 - EW seismic section located offshore between Cape Sim and Essaouira (Hafid et al., 2006)

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# Early seafloor spreading in the South Atlantic Ocean: M-series isochrons north of the Rio Grande Fracture Zone?

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*ABSTRACT*

*South of the Rio Grande Fracture Zone (RGFZ), which intersects the South American and African continents at the northern limits of the respective Rio Grande Rise and Walvis Ridge hotspot tracks, Mesozoic magnetic isochrons (M-series), M11 to M0 (~136 to ~125 Ma), have been identified and mapped by several workers since 1979. We examined new magnetic data, acquired in tandem with long-offset, long record seismic reflection data by ION-GXT, and correlated similar anomaly features north of the RGFZ, offshore Brazil. Integrating these results with earlier work, that utilized open-file magnetic anomaly data offshore South America and Africa, we interpret and map magnetochrons M4, M2 and M0 (~130, ~128 and ~125 Ma) north of the RGFZ, offshore Brazil and Angola.*

*Recent tectonic reconstructions of the South Atlantic between Africa and South America have partitioned the ocean basin into Equatorial, Central, and Austral segments, with the RGFZ being the boundary between Central and Austral segments. Diachronous opening of the South Atlantic has been proposed: 1) seafloor spreading in the Austral segment was facilitated by an intraplate boundary in South America that extended southeastward from the Andean Cochabamba – Santa Cruz bend to the RGFZ, followed by 2) sea floor spreading north of the RGFZ after M0 (~125 Ma). Unpublished evidence for this boundary is interpreted from remote sensing data, however the Parana flood basalts obscures much of the hypothesized boundary. Our results are inconsistent with recent tectonic interpretations for the earliest opening of the South Atlantic and suggest that, although the ocean basin may have opened from south to north, seafloor spreading may also have begun earlier north of the RGFZ.*

*KEYWORDS: South Atlantic, seafloor spreading, magnetics.*

## 1. Introduction

Opening of the South Atlantic began in the southernmost part of the ocean basin around M11 time (~136 Ma) (Rabinowitz & Labreque, 1979) and progressed northward over time. In the central part of the basin, just south of the Rio Grande Fracture Zone (RGFZ), M4 is the oldest identified geomagnetic isochron ("Chron") and it is thought that seafloor spreading north of RGFZ began after M0 (~125 Ma) (Moulin et al., 2009; Eagles, 2007). However, Jackson et al. (2000) report that both M4 and M0 have been mapped north of RGFZ on the African side, offshore Angola. Unfortunately, sparse coverage of open-file magnetic data has made it difficult to identify conjugate anomalies over offshore Brazil. Recently, however, new marine magnetic data acquired by ION-GXT in 2008 (FIG.1 & FIG.2), have made it possible to carry out a more detailed analysis of anomalies over the Brazilian margin, We have examined these data and have been able to correlate linear magnetic anomalies that we identify as Mesozoic Chrons.

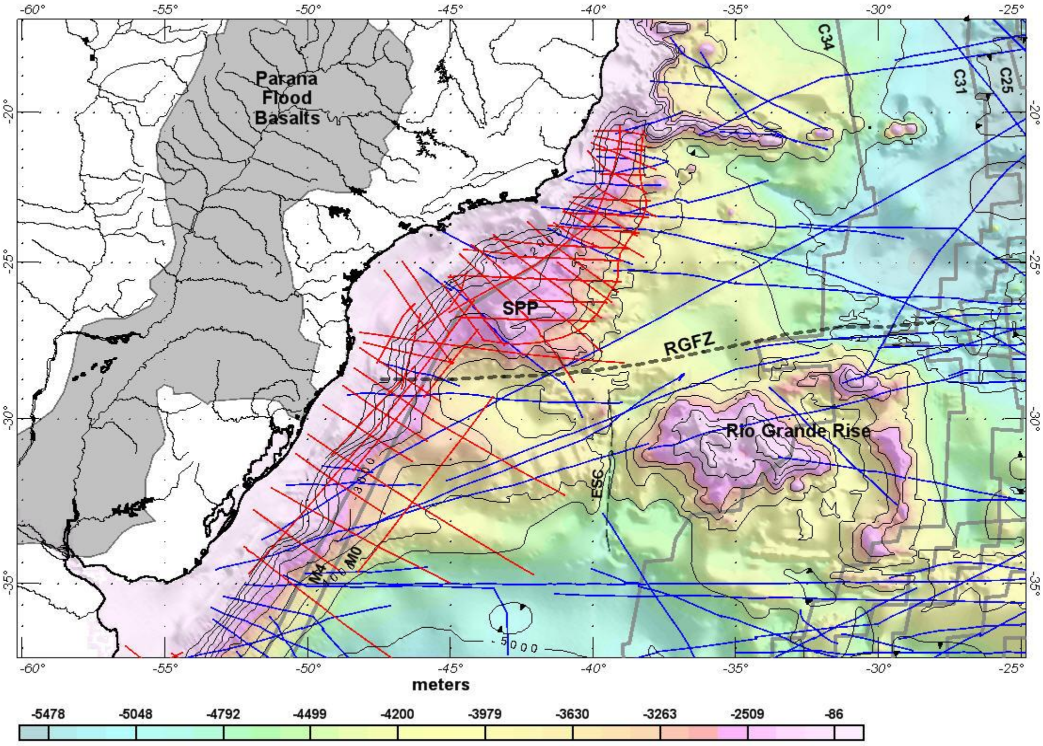


FIG.1 – Central South Atlantic topography, offshore Brazil. ION-GXT shiptracks (red lines), open-file shiptracks (blue lines), geomagnetic isochrons (thick gray lines, after Muller et al., 1997), Rio Grande Fracture Zone (RGFZ, dashed thick black line), Extinct Spreading Center (ESC, thin dashed black line), Sao Paulo Plateau (SPP), and isochrons (ages after Gradstein et al., 2004): M4 (~130 Ma), M0 (~125 Ma), C34 (~84 Ma), C31(~68 Ma), and C25 (~57 Ma). Contour interval is 500 m.

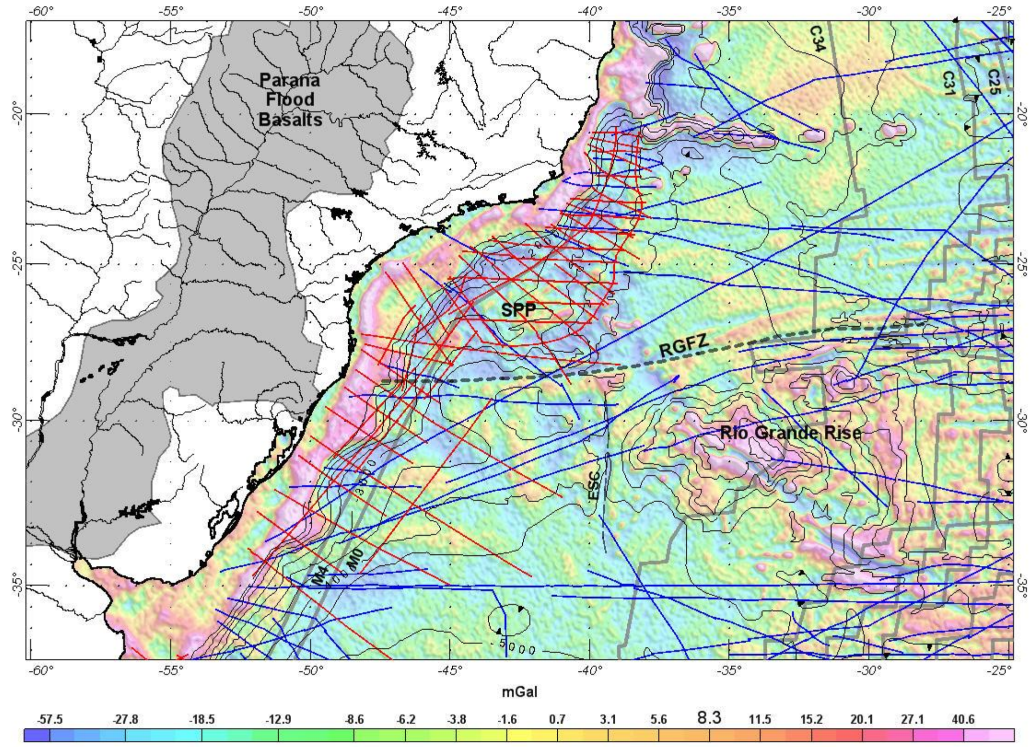


FIG.2 – Satellite-derived free air gravity anomalies over central South Atlantic, offshore Brazil. See FIG.1 caption for details.

## 2. Results

We use new marine magnetic anomaly data, and integrate it with open-file marine magnetic anomaly data, to identify and map, line-by-line, Mesozoic Chrons north of the RGFZ, offshore Brazil. Several prominent magnetic features with amplitudes of ~ 250 – 300 nT can be successfully correlated along the margin (FIG.3A). Seafloor spreading models show that these prominent features correlate well with those associated with M4, M2 and M0 (FIG 3B)

## 3. Discussion & Conclusion

We are able to trace the subtle expression of unnamed oceanic fracture zones from free air gravity anomalies, just south of Martin Vaz Fracture Zone (north of RGFZ), eastward from the Mid-Atlantic Ridge to anomalies we identify as M0, about 250 km offshore Angola. We are also able to trace the same fracture zones westward from the Mid-Atlantic Ridge to about 200 km east of the Sao Paulo Plateau. The extent of these fracture zones on either side of the ridge indicate that seafloor spreading was both coeval and approximately symmetric on either side of the basin, and that if Mesozoic Chrons are observed on the African side, then they must also be present on the South American side.

In their thorough review of South Atlantic kinematics, Moulin et al. (2009) tabulated finite rotations for the earliest opening of the ocean basin from several workers ranging from Bullard et al. in 1965 to Eagles in 2006. We calculated South Atlantic finite rotation poles for C5 through M4 (Hall & Bird, 2007; Bird & Hall, 2009; Bird & Hall, 2010). Diachronous seafloor spreading models (Moulin et al., 2009; Torsvik et al., 2009; De Wit et al., 2008; Eagles, 2007; Nurnberg & Muller, R. D., 1991; Unternehr et al., 1988) rely upon limited evidence of seafloor spreading anomalies north of the RGFZ and some propose that as much as 150 km of dextral shear occurred along a continental transform fault that extended southeastward from the Andean Cochabamba – Santa Cruz bend to the RGFZ. Reported geological evidence for this transform is from an, "… interpretation of remote sensing data (F. Bénard, pers. Commun., 1986)", but notes that extensive basalt flows make, "direct field evidence extremely difficult to obtain" (Unternehr et al., 1988, p. 175). Our results are inconsistent with this diachronous spreading model, but instead indicate that seafloor spreading north of RGFZ was roughly coeval with seafloor spreading south of RGFZ.

*Acknowledgement*

*We thank ION-GXT for allowing us to analyse magnetic data acquired with their BrazilSPAN™ and PelotasSPAN™ long-offset, long record reflection seismic programs.*

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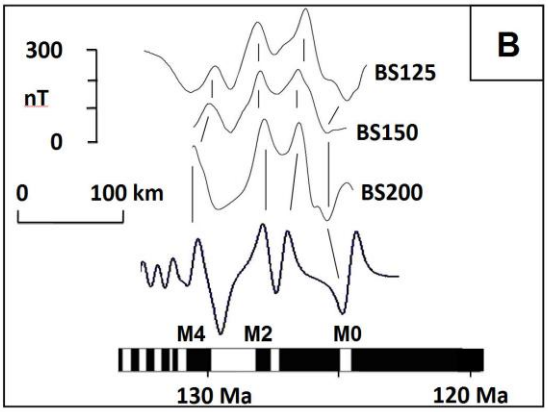
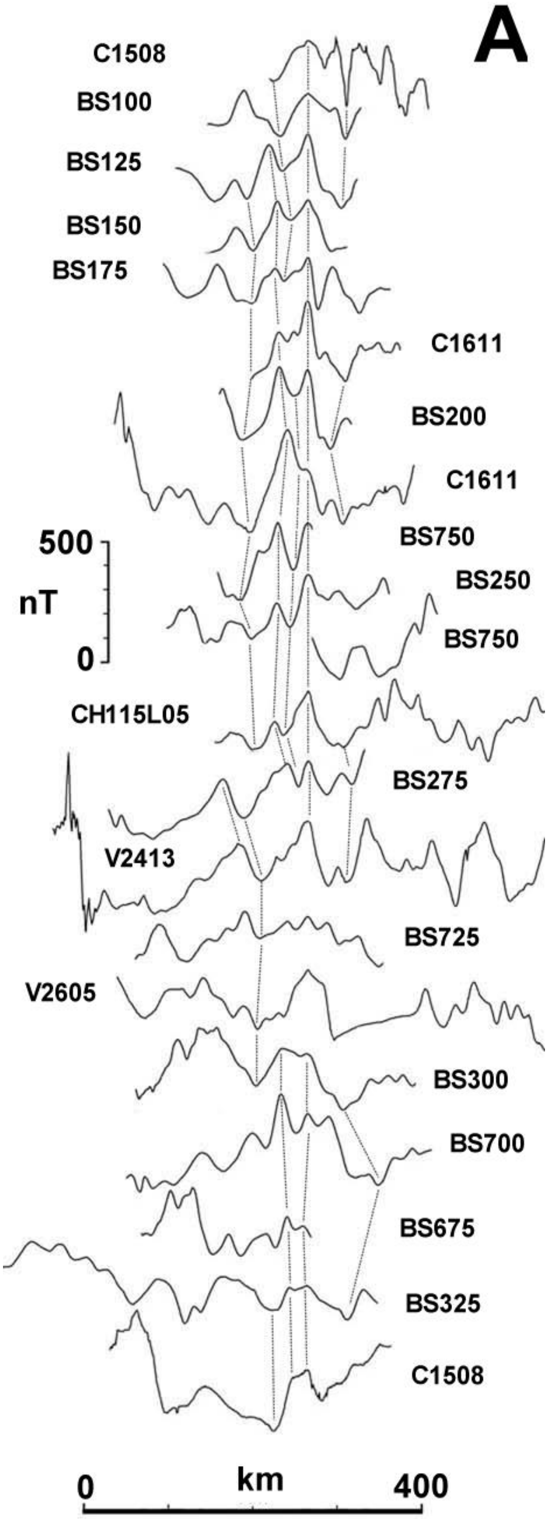
FIG.3 – **A**. Magnetic anomaly profiles over the Brazilian margin aligned so as to display line-to-line correlations of several prominent features identified as M4, M2 and M0. Profiles include ION-GXT BrazilSPAN™ ("BS") lines, Lamont-Doherty Earth Observatory cruises ("C" and "V"), and Woods Hole Oceanographic Institute cruise ("CH"). **B.** Seafloor spreading model showing a comparison between anomalies calculated for a spreading rate of 25 mm/yr with several magnetic anomaly profiles from the newly acquired magnetic data. The model is 2 km thick from a depth of 7 km.



# Middle-Upper Jurassic palynology of the Sagres region and the Carrapateira Outlier, southern Portugal

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*ABSTRACT*

*The palynology of the Middle-Upper Jurassic fill of the Sagres region (Algarve Basin) and the Carrapateira outlier, southern Portugal was investigated. Samples were collected from Mareta beach, Cilheta beach and the Carrapateira outlier. Dinoflagellate cysts are confined to the Upper Bajocian to Upper Callovian sedimentary rocks exposed at Mareta and Cilheta beaches and the Lower Kimmeridgian strata of the Carrapateira outlier. The palynostratigraphical study of the Jurassic successions has yielded new biostratigraphical data based on dinoflagellate cysts and miospores. The results confirm, and in some cases refine, the existing macrofaunal age determinations of these successions.*

*KEYWORDS: Portugal, Algarve Basin, Carrapateira outlier, Biostratigraphy, Dinoflagellate cysts, Jurassic.*

## 1. Introduction

The Algarve Basin corresponds to the southernmost geological province of mainland Portugal. It has an E-W strike and is represented onshore from Cape São Vicente to the Guadiana River on the Portuguese-Spanish border (Fig. 1). More than 3000 m of essentially marine sediments accumulated during Mesozoic-Cenozoic times in the Algarve Basin (Mannupella, 1992).

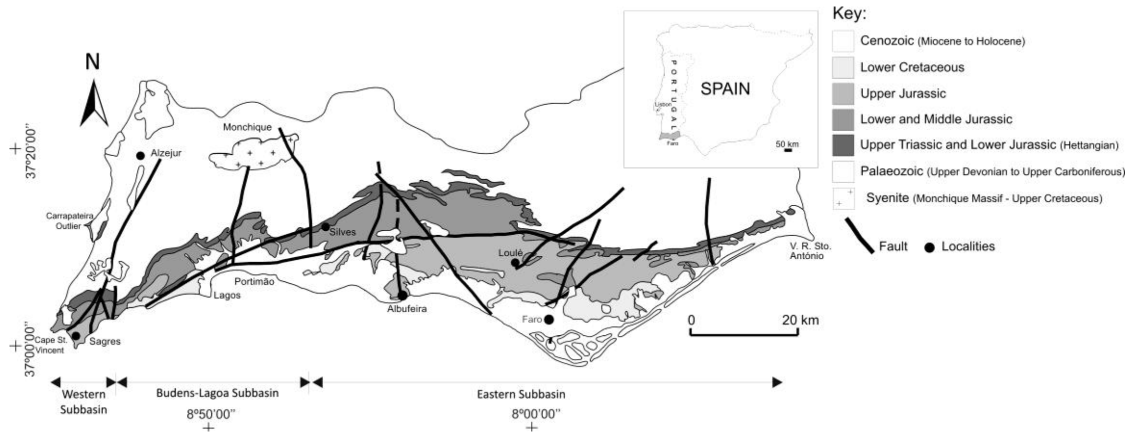


FIG.1 – The location and geology of the Algarve Basin and the Carrapateira outlier, illustrating the areas studied herein (adapted from Manuppella, 1992).

The Sagres Region is the reference area for the Mesozoic fill of the Western sub-basin where the Middle-Upper Jurassic strata outcrop in the cliffs between Mareta and Cilheta Beach.

The Mareta beach represent an important reference section for the Middle and Upper Jurassic of the Algarve Basin. A composite section is exposed, which is a 140 m thick succession of grey marls that grade into marly limestones, assigned to the late Bajocian to early Kimmeridgian. The coastal exposures at the Cilheta beach comprise 40 m thick succession of marly limestones, of the Callovian to Kimmeridgian interval (Rocha, 1976).

The Carrapateira outlier is located on the coast around 20 km north of the main Algarve Basin, west of Carrapateira village and consists of basic volcanics, dolomites, limestones, marls, and sandstones of Late Triassic to Late Jurassic age, that exhibit marked lithostratigraphical and macropalaeontological similarities with the succession in the Sagres Region. The most complete exposures are the coastal outcrops of Upper Jurassic carbonates which have been partially dolomitised. An Early Kimmeridgian age for this section has been invoked based on corals (Ramalho and Ribeiro, 1985).

The palynology of the Jurassic fill of the Algarve Basin and the Carrapateira outlier, southern Portugal was investigated. Samples were collected from Mareta beach, Cilheta beach and the Carrapateira outlier. The present contribution is a initial account of the Upper Bajocian to Lower Kimmeridgian of the Sagres Region and in the Carrapateira outlier.

## 2. Methodology

Samples were collected from outcrops at Mareta beach, Cilheta Beach and Carrapateira outlier. They were prepared following standard palynological processing techniques involving mineral acid digestion with HCI and HF to remove the carbonates and the silicates, respectively (Wood et al., 1996). The organic residue was sieved using a 15 µm mesh sieve and mounted on microscope slides using Entellan® resin. The microscope slides were studied and light photomicrographs were taken, with an Olympus CX 41 optical microscope equipped with a SC 20 digital camera.

All organic residues and microscope slides are housed in the collections of the LGM/LNEG, S. Mamede Infesta, Portugal.

## 3. Palynology

The palynological study of the Mareta, Cilheta and Carrapateira successions has yielded new biostratigraphical data based on dinoflagellate cysts and miospores.

The organic residues are abundant and comprise well-preserved palynomorphs and phytoclasts. Pollen and spores are the dominant palynomorphs however, marine microplankton (i.e. acritarchs, dinoflagellate cysts, foraminiferal test linings) are also present in significant proportions. The miospores comprise bisaccate pollen, *Classopollis classoides*, *Callialasporites dampieri*, *Callialasporites turbatus*, *Callialasporites* spp., *Cyathidites* spp., *Ischyosporites variegatus*, *Leptolepidites* spp., *Perinopollenites elatoides*, *Sestrosporites pseudoalveolatus*, and *Todisporites* spp.

The dinoflagellate cysts, from the grey marls, present in the lower part of the Mareta succession are indicative of the Bathonian stage, mainly based on the occurrence of *Ctenidodinium* spp., *Ellipsoidictyum/Valensiella* group, *Korystocysta* spp. and *Valensiella ovulum* (Riding et al., 1985). The species *Impletosphaeridium varispinosum*, *Ctenidodinium cornigerum*, *Ctenidodinium sellwoodii*, *Gonyaulacysta jurassica* subsp. *adecta*, *Korystocysta gochtii* and *Meiourogonyaulax caytonensis*, present in the middle part of the succession, assigned to the Macrocephalus Zone (Rocha, 1976), are characteristic of the early Callovian.

The uppermost strata of this succession corresponds to the Cilheta outcrop and yielded *G. jurassica* subsp. *adecta, Korystocysta* spp., *M. caytonensis, Mendicodinium groenlandicum*, *Tubotuberella dangeardii* and *Wanaea acollaris* and are assigned to the Callovian Stage (Riding, 2005).

The dinoflagellate cyst associations from the Carrapateira outlier are indicative of an Early Kimmeridgian age due to the occurrence of species such as *Amphorula* sp *Gonyaulacysta jurassica* subsp. *jurassica*, *Histiophora ornate* and *Tubotuberella dangeardii* (Riding, 2005).

## 4. Conclusions

The biostratigraphical data based on dinoflagellate cysts confirm the previously existing macrofaunal age of these successions. The dinoflagellate cyst assemblages from the Upper Bajocian, Bathonian and Callovian of Mareta and Cilheta beaches and the Lower Kimmeridgian of the Carrapateira outlier proved to be consistently significantly less diverse than coeval assemblages from northwest Europe. The partially enclosed nature of this part of the Algarve Basin and the Carrapateira outlier seems to have prevented the free migration of dinoflagellates between southern Portugal and elsewhere in Europe. However, this conclusions are preliminary because more palynostratigraphical research in the Algarve Basin and Carrapateira outlier is currently still in progress.

*Acknowledgements*

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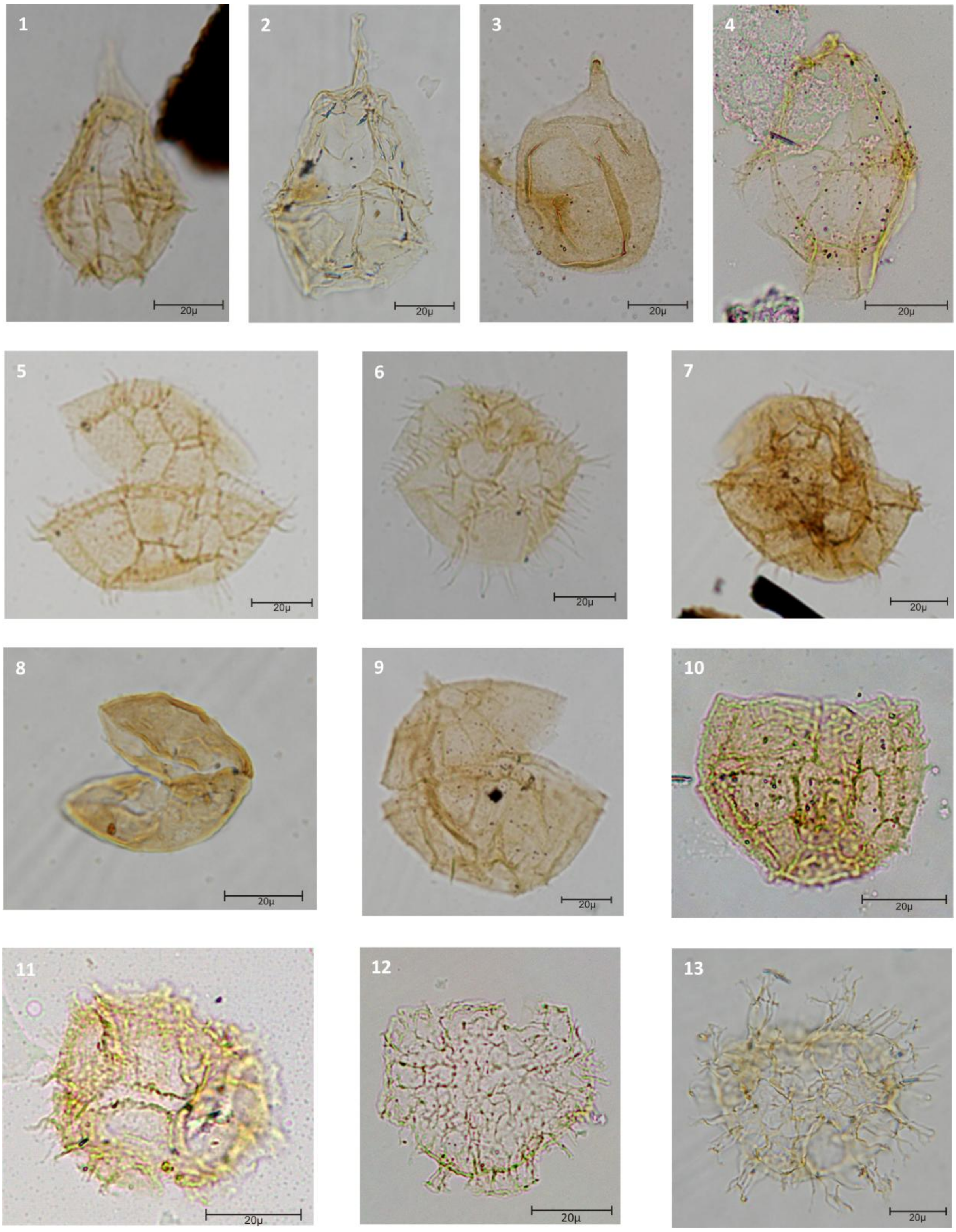
**PLATE 1** – Selected dinoflagellate cysts from the Mareta beach section and Carrapateira outlier. The sample, slide and England Finder coordinates are provided.

**1.** *Gonyaulacysta jurassica* (Deflandre 1939) Norris & Sarjeant 1965 subsp. *adecta* Sarjeant 1982. Mareta Beach section, Sample M27; N47
**2.** *Gonyaulacysta jurassica* (Deflandre 1939) Norris and Sarjeant 1965 subsp. *jurassica* (autonym). Carrapateira outlier, Sample C47; R12/4
**3.** *Pareodinia ceratophora* Deflandre 1947. Mareta Beach section, Sample M28; L38-2
**4.** *Tubotuberella dangeardii* (Sarjeant 1968) Stover & Evitt 1978. Mareta Beach section, Sample M45; P18
**5.** *Ctenidodinium sellwoodii* (Sarjeant 1975) Stover & Evitt 1978. Mareta Beach section, Sample M2; W53

**6.** *Ctenidodinium cornigerum* (Valensi 1947) Jan du Chêne et al. 1985. Mareta Beach section, Sample M25; N3
**7.** *Ctenidodinium* spp. Carrapateira outlier, Sample C12; G34/4
**8.** *Mendicodinium groenlandicum* (Pocock & Sarjeant 1972) Davey 1979. Mareta Beach section, Sample M27; Q30/1
**9.** *Korystocysta gochtii* (Sarjeant 1976) Woollam 1983. Mareta Beach section, Sample M28; M63
**10.** *Meiourogonyaulax caytonensis* (Sarjeant 1959) Sarjeant 1969. Mareta Beach section, Sample M3; O18/3
**11.** *Histiophora ornata* Klement 1960. Carrapateira outlier, Sample C35; R36
**12.** *Ellipsoidictyum/Valensiella* group. Mareta Beach section, Sample M4; M12/3
**13.** *Systematophora areolata* Klement 1960. Carrapateira outlier, Sample C4; U36V30/2

PLATE 1



# Erosional Unconformities, Megaslumps and Giant Mud Waves: Insights into passive margin evolution from the continental slope off Nova Scotia

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*ABSTRACT*

*Understanding of the Cenozoic geological history of offshore Nova Scotia, Canada, is provided through interpretation of high quality seismic reflection data tied to exploration wells. A seismic stratigraphic framework devised for the study area allows regional correlation of depositional elements. Channel incision was severe in the Eocene and Quaternary, but also occurred during the Oligocene and Miocene. Large mass-wasting events occurred in the Late Miocene and Pliocene and contributed to the formation of sub-regional unconformities, transferring sediment to the continental rise. Bottom currents eroded regional unconformities in the Oligocene, Miocene and Pliocene and constructed sediment drifts. Sediment drift growth was greatest during the Late Miocene and Pliocene. Drifts, together with large mass transport deposits, form the dominant constructional features on the lower slope and rise.*

*KEYWORDS: Nova Scotia, continental margin, Cenozoic, unconformity, mass transport deposit, sediment drift*

## 1. Introduction

The deepwater Cenozoic geological history off Nova Scotia (FIG.1) is understudied, both in terms of understanding passive continental margin evolution and hydrocarbon potential. Interpretation of seismic reflection data and sparse hydrocarbon exploration well data reveals regional seismic stratigraphic units that correlate to the well-studied U.S. Atlantic margin and North American Basin (FIG.2). Whereas U.S. margin studies benefit from numerous scientific drilling program wells, the present study of the Scotian margin benefits from superior high-quality seismic reflection data coverage which provides insight into deposition patterns and seismic geomorphology not previously attainable.

Published studies of the Cenozoic geological history offshore Nova Scotia focus on the central Scotian margin, in the vicinity of Sable Island, where past exploration effort was greatest (e.g. Swift 1987; Wade et al. 1995; MacDonald 2006; Fensome et al. 2008). In general, sediment accumulation appears to have been broadly controlled by changes in relative sea level; however, local sediment distribution patterns were strongly influenced by local variations in sediment supply, slope morphology, erosion by bottom currents, and salt tectonics. The present study focuses on the western Scotian margin, the location of a Cenozoic depo-centre (Swift 1987) and the only portion of the margin where Paleogene and Neogene deposits were targeted by exploration drilling.

## 2. Stratigraphic Framework

The global greenhouse to icehouse transition that occurred during the middle Cenozoic marked a major shift in geological and oceanographic conditions in the northwest Atlantic Ocean. During this transition, strong contour currents developed and sediment input to the North American Basin increased. These events were coeval with development of regional unconformities within the basin and along the basin margins. In many cases, however, the relationships between abyssal plain and continental margin unconformities and associated depositional elements are unclear (e.g. Mountain and Tucholke 1985; Wade et al. 1995). In this study, a revised seismic stratigraphic framework is presented for the Scotian margin and is correlated to the well-established North American Basin stratigraphy (Tucholke and Mountain 1979; Mountain and Tucholke 1985) (FIG.2). Seismic reflection data density in this study area is adequate to decipher the complexities of margin erosion history, either due to along-slope or down-slope processes, and provide insight into depositional elements and processes.

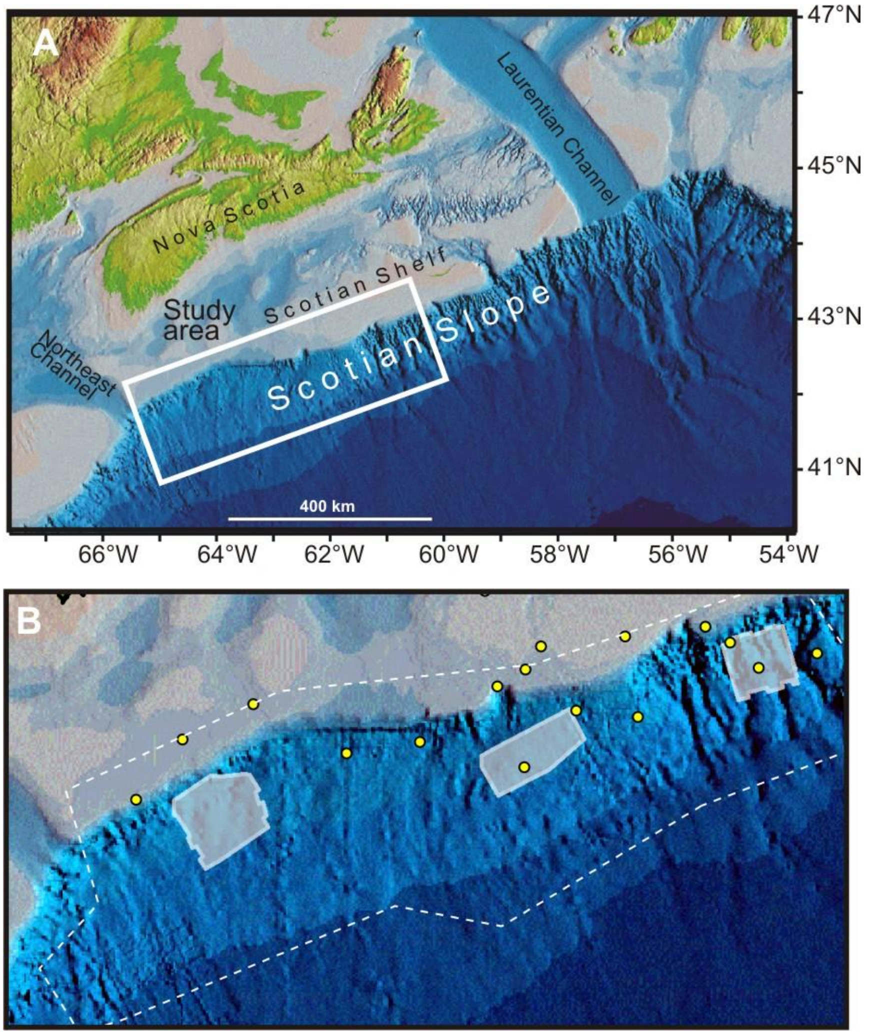


FIG 1- A) Location map of the continental margin off Nova Scotia. B) Detailed map of study area. Yellow circles indicate locations of exploration wells, greyed polygons show the extent of 3D seismic reflection data, dashed polygon shows extent of 2D seismic reflection data coverage (8 x 8 km grid). Bathymetric background from Shaw and Courtney (2004).

### 3. Results and Discussion

Regional channel erosion was widespread in the study area during the Middle Eocene and Quaternary, but is also recognized during the Oligocene to Middle Miocene and Late Miocene. Most canyons extend beyond the seaward limit of data coverage, implying sediment transport across the slope and upper rise to the deep basin. Exceptions are observed where gravity flows were trapped by pre-existing topography, such as terraces and small basins formed by erosion, drift construction, or salt tectonics. Mass transport deposits, among the largest reported anywhere in the world in the literature, appear to initiate on the steep foresets of shelf margin clinoforms, or along the lower slope in the vicinity of salt diapirs. Very large mass wasting events were more common during the Late Miocene and Pliocene than other periods in the Cenozoic and contributed to the formation of regional and sub-regional

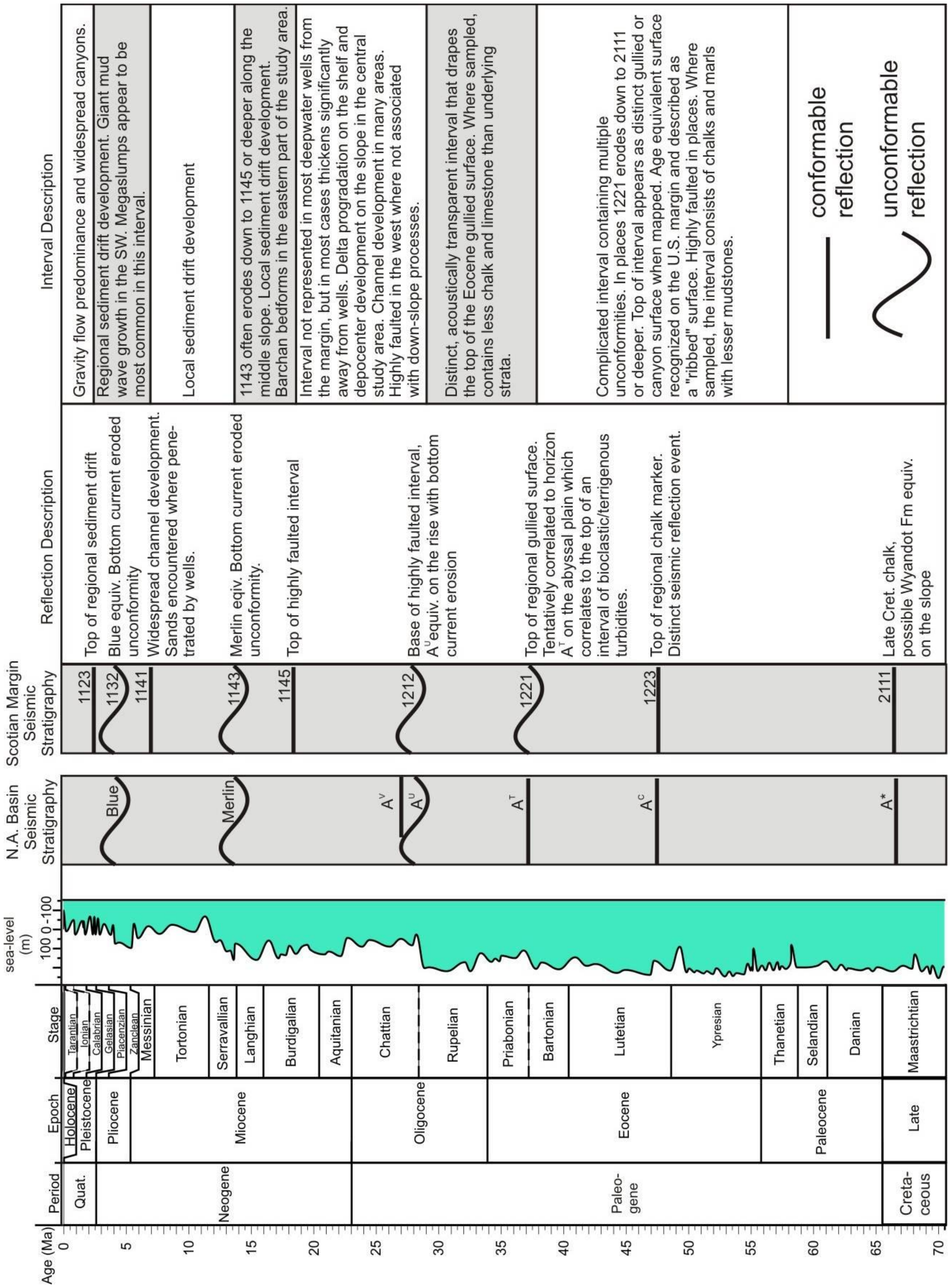


FIG. 2- Seismic stratigraphy of the North American Basin and Scotian margin. North American Basin seismic stratigraphy from Tucholke and Mountain (1979) and Mountain and Tucholke (1985). Scotian margin seismic stratigraphy modified from Shimeld and Wade (2005). Biostratigraphic control from Fensome et al. (2008). Time scale and sea-level curve from Time Scale Creator (www.tscreator.com, accessed July 12, 2010).

unconformities, and moving significant amounts of sediment onto the lower continental slope and rise.

Margin erosion by bottom currents is recognized on the continental rise during the Oligocene and on the continental slope and rise during the Middle Miocene and Pliocene. This erosion is interpreted to represent a changing circulation regime in the Northwest Atlantic, with primarily deep Antarctic Bottom Water contributing to the Western Boundary Undercurrent in the Oligocene, followed by increased contribution from Norwegian Sea and Labrador Sea water masses in the Neogene. Previous studies suggested Neogene sediment drifts did not exist off Nova Scotia (McCave and Tucholke 1986), or were of limited geographical extent (Swift 1987; MacDonald 2006). The present study shows that large sediment drifts were constructed during the Miocene and Pliocene and form stacked sequences of giant sediment waves, or elongate mounded drifts. Scotian margin drifts are contemporaneous and morphologically similar to the Hatteras and Chesapeake drifts on the U.S. Atlantic margin (Mountain and Tucholke 1985). Drift location, style, and evolution appear linked to the morphology of the underlying surface. In many cases, the unique morphology of sediment drifts aided in trapping gravity flows that otherwise would transit to the continental rise and abyssal plain. Sediment drifts, together with large mass transport deposits, form the dominant constructional features on the lower slope and rise, a result not previously recognized.

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# Foraminifera from the Lower-Middle Jurassic of the Lusitanian Basin (Portugal) – biostratigraphic and palaeocological significance

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*ABSTRACT*

*The detailed study of benthic foraminifera of four reference sections from the Lower-Middle Jurassic of the Lusitanian Basin has allowed the recognition of the biozonal scale based on foraminifera, established in the North Hemisphere (Dorbignyi Biozone). The analysis of abundances of the recorded taxa points out palaeoecological preferences, at the species level, among apparently homogeneous assemblages corresponding to different depositional environments in the basin. Determination of richness and dominance indexes supports the recognition of two palaeoecological different intervals along the Lower-Middle Jurassic transition, ranging from unstable to more stable conditions for the development of benthic foraminiferal communities. This kind of detailed studies, based on this microfossil group, seems to be a good proxy for age determination, North Atlantic correlations and palaeoenvironmental interpretations.*

*KEYWORDS: Foraminifers, Lower-Middle Jurassic boundary, Lusitanian Basin, Portugal.*

## 1. Introduction

In this work a detailed study of benthic foraminifera of four reference sections from the Lower-Middle Jurassic transition of the Lusitanian Basin (Central Portugal) is presented. Data refer to Murtinheira (Canales *et al*., 2000; Canales & Henriques, 2008; Henriques *et al*., 2008), S. Gião (Magno, 2010) and Maria Pares (Guterres, 2010) sections, which are located in the Northern Lusitanian Basin; and to Zambujal de Alcaria (Figueiredo, 2009; Figueiredo *et al.*, 2010) section, located in the Central Lusitanian Basin (FIG.1).

The four sections represent different facies of the *sag* interval which follows the Late Triassic rifting episode of the basin (Henriques *et al.*, 2008), corresponding to distal external marine ramp (Murtinheira; Cape Mondego), transitional zones of the platform (S.Gião and Maria Pares), and proximal internal marine ramp (Zambujal de Alcaria; Maciço Calcário Estremenho), clearly differentiated in Bajocian-Calovian times through the litholofacies record (Azerêdo *et al.*, 2003), now reinforced through the foraminiferal record.

## 2. Composition of the foraminiferal assemblages

A total of 73 samples have been collected from the Upper Toarcian (Mactra and Aalensis Subzones; Aalensis Biozone), Lower Aalenian (Opalinum and Comptum

Subzones; Opalinum Biozones) and Middle Aalenian (Bradfordensis Subzone; Bradfordensis Biozone) marly limestones, based on a previous biostratigraphic framework, well calibrated through the rich and diversified ammonite record (Henriques, 1992, 1995, 2000). More than 31,700 specimens of benthic foraminifera have been obtained (5,291 from Zambujal de Alcaria; 15,273 from Maria Pares; 8,764 from S. Gião; 2,375 from Murtinheira), which have allowed the study of the assemblages´ composition and the analysis of its evolution throughout this time interval.

The studied assemblages are abundant and diverse. Specimens are well preserved and no significant taphonomic processes seem to have affected the recorded assemblages, which are composed by typical taxa of the Boreal Realm. Most of the assemblages are dominated by Lagenina Suborder, Vaginulinidae Family and *Lenticulina* Genus. However, differences in the spatial distribution of the species have been recognized, reflecting paleoenvironmental preferences.

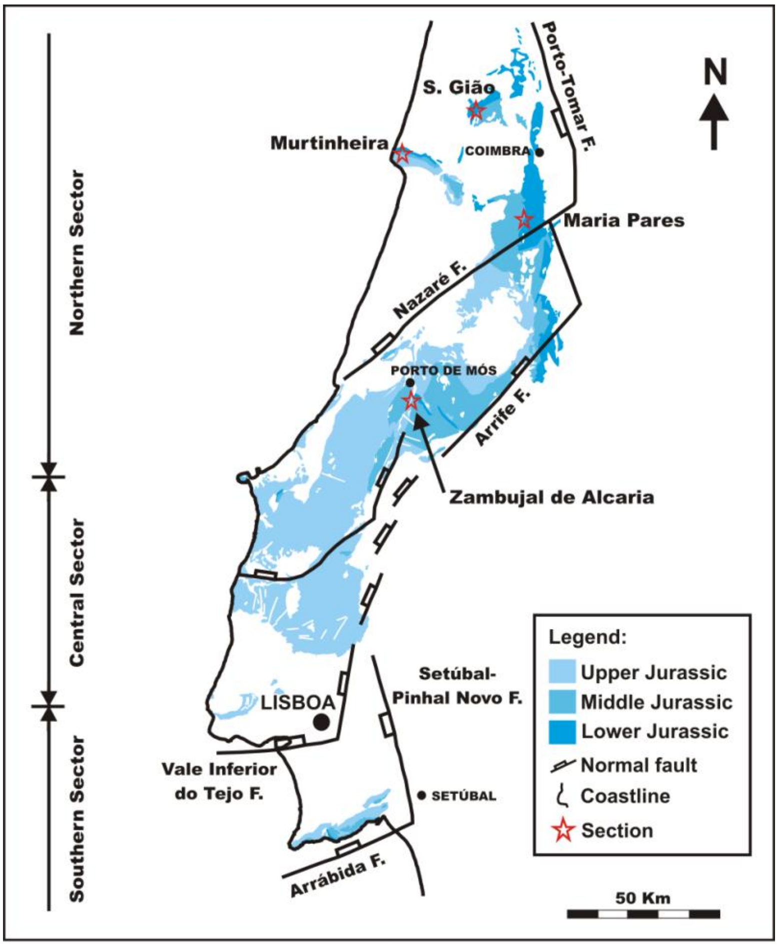


FIG.1 – Location of the Murtinheira, S. Gião and Maria Pares sections (North Lusitanian Basin) and Zambujal de Alcaria (Central Lusitanian Basin).

## 3. Biostratigraphical and palaeoecological implications

The recognition of *Astacolus dorbignyi* (Roemer) as index species for the studied stratigraphic interval, in the four studied sections, allows accurate correlations with other North European basins.

Taxonomical composition of the recorded assemblages is apparently homogenous due to the presence of the almost the same species in the four studied sections. However, the analysis of the abundances of the taxa, in each section, points out that the distribution of some species is spatially differentiated, allowing the recognition of three types of assemblages (FIG.2):

- Assemblages developed in distal facies of shelfal basin environment, where *Ammobaculites fontinensis* (Terquem), *Spirillina numismalis* Terquem & Berthelin, *Spirillina orbicula* Terquem & Berthelin, *Prodentalina pseudocommunis* (Franke), *Planularia protracta* (Bornemann) and *Eoguttulina liassica* (Strickland) show the highest values of abundances of the four sections (Murtinheira);
- Assemblages developed in transitional facies from internal to distal facies of shelfal basin environment (S. Gião, Maria Pares), being the most abundant and diverse of the four sections. Here, the Miliolina Suborder representatives and the species *Falsopalmula jurensis* (Franke), *Nodosaria liassica* Barnard, *Nodosaria pseudoregularis* Canales, *Pseudonodosaria vulgata* (Bornemann), *Lenticulina helios* (Terquem), *Citharina colliezi* (Terquem) and *Planularia cordiformis* (Terquem) show the highest abundance values.
- Assemblages developed in internal facies of shelfal environment, where *Ammobaculites coprolithiformis* (Schwager), *Ammobaculites vetustus* (Terquem & Berthelin), *Nodosaria pulchra* (Franke) and *Lenticulina toarcense* (Payard) show the higher abundance values of the four sections (Zambujal de Alcaria).

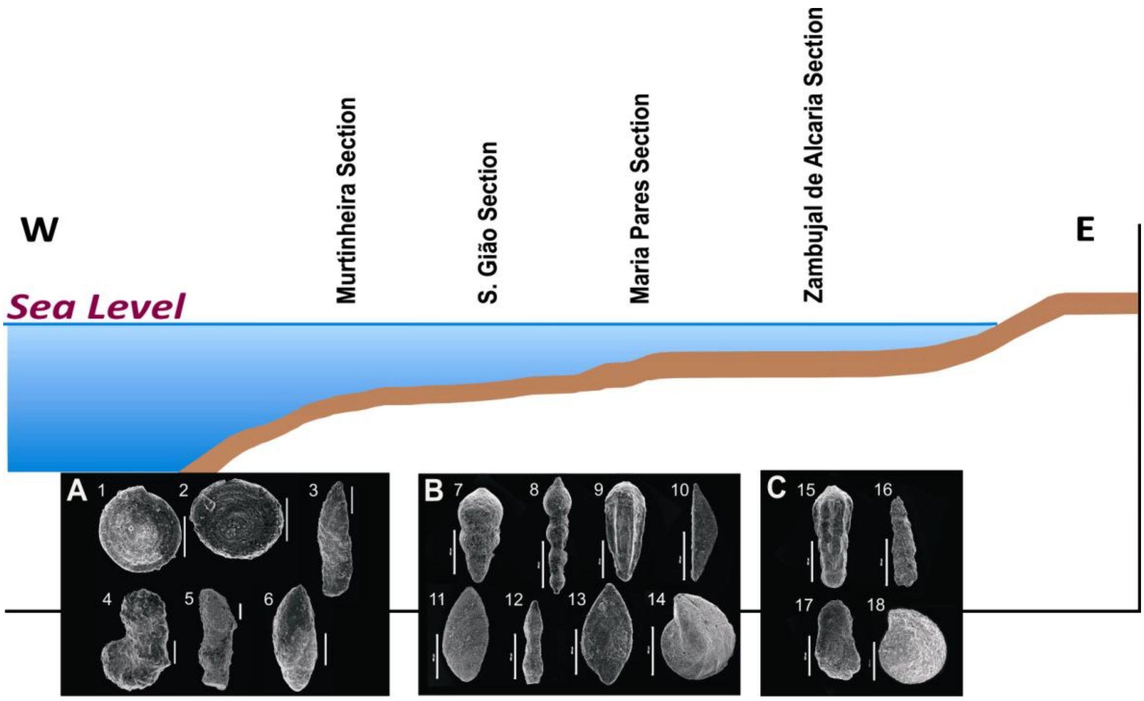


FIG.2 – Spatial distribution of some foraminiferal species in the Lusitanian Basin for the Lower-Middle Jurassic transition. A) Selected species showing a significant high abundance in distal facies of shelfal basin environment (Murtinheira section): 1. *Spirillina numismalis*

Terquem & Berthelin; 2. *Spirillina orbicula* Terquem & Berthelin; 3. *Planularia protracta* (Bornemann); 4. *Ammobaculites fontinensis* (Terquem); 5. *Prodentalina pseudocommunis* (Franke); 6. *Eoguttulina liassica* (Strickland). B) Selected species showing a significant high abundance in transitional facies from internal to distal facies of shelfal basin environment (São Gião and Maria Pares sections): 7. *Pseudonodosaria vulgata* (Bornemann); 8. *Nodosaria pseudoregularis* Canales; 9. *Nodosaria liassica* Barnard; 10. *Citharina colliezi* (Terquem); 11. *Planularia cordiformis* (Terquem); 12. Specimen of the Miliolina Suborder; 13. *Falsopalmula jurensis* (Franke); 14. *Lenticulina helios* (Terquem). C) Selected species showing a significant high abundance in internal facies of shelfal environment (Zambujal de Alcaria section): 15. *Nodosaria pulchra* (Franke); 16. *Ammobaculites vetustus* (Terquem & Berthelin); 17. *Ammobaculites coprolithiformis* (Schwager); 18. *Lenticulina toarcense* Payard..

Richness indexes (Fischer´s α and Margalef) and diversity indexes (Simpson, Berger-Parker, Shannon-Wiener and Equitability) have been calculated for each studied sample. Analysis of the resulting data, as well as comparison of data of the four sections, allows distinguishing two intervals along the Lower-Middle Jurassic transition. First interval ranges from the Mactra Subzone (Aalensis Biozone, Upper Toarcian) to the lower part of the Comptum Subzone (Opalinum Biozone, Lower Aalenian). There, the indexes show regular values, indicating unstable environmental conditions. Second interval ranges from the lower part of the Comptum Subzone (Opalinum Biozone, Lower Aalenian) to the lower part of the Bradfordensis Subzone (Bradfordensis Biozone, Middle Aalenian). Along this interval, indexes values are higher than in the previous interval, and homogeneous, reflecting more stable and favourable environmental conditions for the development of foraminiferal assemblages.

The biostratigraphic and palaeoecological data resulting from this approach can represent a proxy to determinate both age and depositional environments assigned to core samples analysis from the Lower-Middle Jurassic boundary of the Lusitanian Basin.

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# Tectono-stratigraphic relationships in the Palestina Graben, Araripe Basin, NE Brazil

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*ABSTRACT*
*The Palestina Graben is one of the NE-trending asymmetric grabens of the Araripe Basin. It is part of the Interior Basins province of Northeastern Brazil, being related to the fragmentation of the Gondwana supercontinent and the opening of the South Atlantic Ocean. Stratigraphically the graben is composed of four tectonosequences, Paleozoic, Jurassic, Rift and Post-rift; the latter does not occur in the present study area.*
*KEYWORDS: Araripe Basin, Neocomian rift, tectonosequences, NE Brazil*

## 1. Introduction

The breakup of Western Gondwana, leading to the opening of the South Atlantic Ocean, migrated northwards and reached NE Brazil by the end of the late Jurassic period (Ponte *et al.* 1991; Matos 1992; Assine 2007). Along the continental margins, the first stages of this event are underlain by a thick cover of the main rift stage (Hauterivian to early Aptian), followed by younger deposits of late rifting and the drift stages. The Interior Basins province, in northeastern Brazil, samples the initial to the climax stages of the Neocomian rift along an aborted branch called the *Cariri-Potiguar* Trend (Matos 1992, 1999; Jardim de Sá *et al.* 2007). The Araripe Basin (FIG. 1), well known by its well preserved post-rift, Aptian fossil records, rests on the Neoproterozoic terrains of the Transversal Zone, Borborema Province, immediately to the South of the Patos strike-slip shear zone. This basin consists of a series of NE-trending asymmetric grabens and horsts filled with neocomian deposits (hereafter designed as the Rift Tectonosequence) overlying Jurassic and early Paleozoic pre-rift tectonosequences.

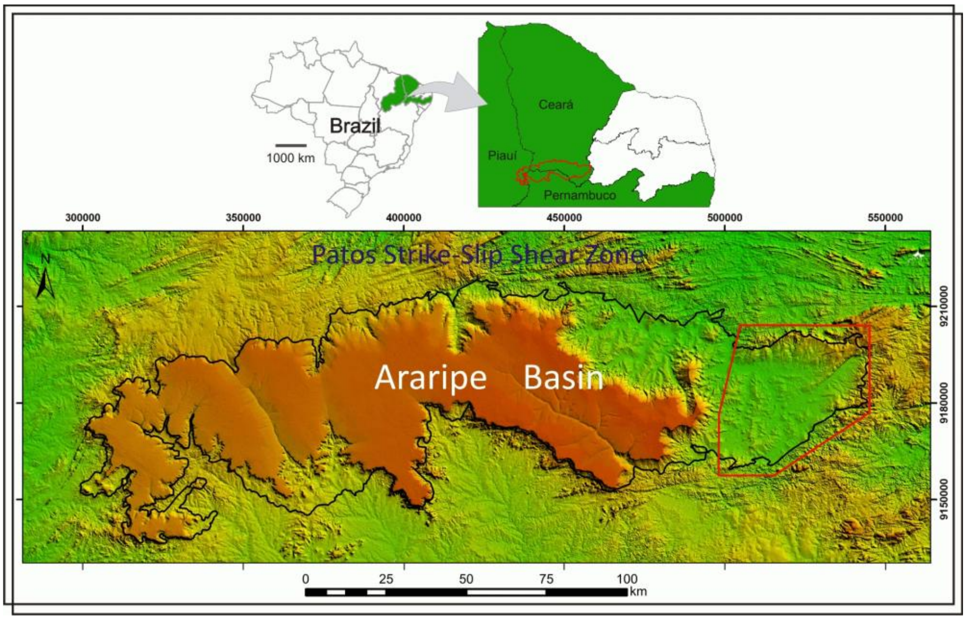


FIG.1 – Location of the study area in the Araripe Basin, Northeast Brazil, bounded by the red polygon. The black line delimits the area occupied by sedimentary rocks. STRM image obtained from Global Land Cover Facility - University of Maryland.

## 2. Structural and Stratigraphic Interpretation

The Palestina graben, located in the eastern portion of the Araripe Basin (FIG. 2), presents a half-graben geometry controlled by the NW-trending extensional eocretaceous strain. Its SE border behaves as a flexural margin, where the sedimentary pile is affected by normal faults with small displacements. The eopaleozoic Mauriti Formation sandstones unconformably rests upon the Precambrian crystalline basement (FIG. 2 and 3). The tectonic setting of the Jurassic sequence, the Brejo Santo Formation, is still debatable, either as a pre-rift or the beginning stage of the Neocomian rift. Its correlation with a pre-rift environment is suggested by radiometric dates ca. 198 Ma in intrusive basic dykes in pelites of the Lavras da Mangabeira basin, immediately to the north of the present area. These dikes, which can be associated with the Central Atlantic Magmatic Province (CAMP) at 200±4 Ma (Marzoli *et al.*, 1999), are preserved across four continents. The Brejo Santo Formation originated in a distal floodplain related to ephemeral drainages; its deposits extend from inside to outside the neocomian grabens at the Araripe Basin.

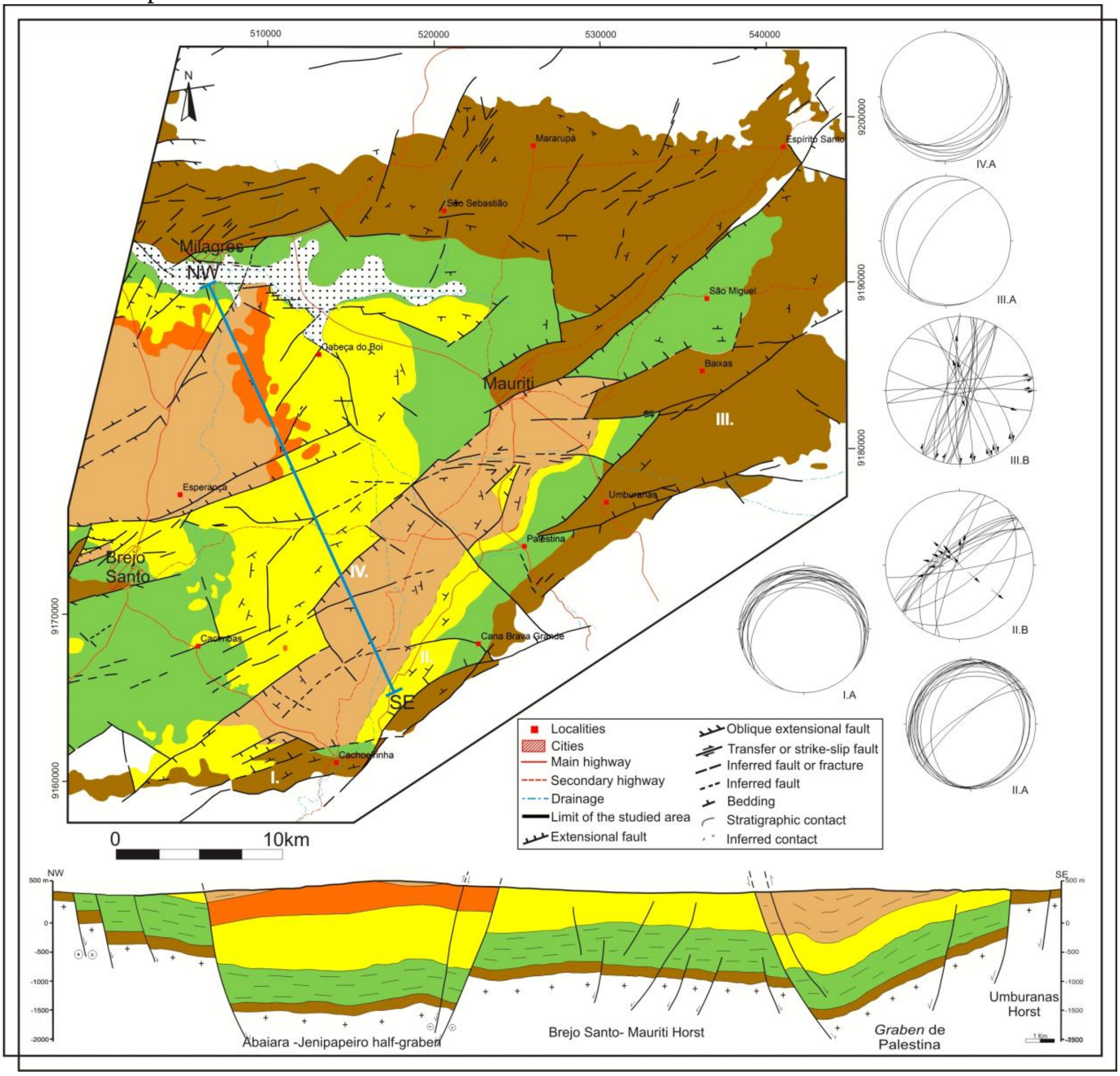


FIG. 2 - Geological map of the study area with a geological profile drawn along a seismic line with NW-SE direction. Stereograms illustrate bedding (A) and fault structures (B).

The Rift sequence starts with the Missão Velha Formation (FIG. 2 and 3), whose lower section is related to a braided to meandering fluvial system. Previously and still regarded by many authors as a pre-rift unit, its paleocurrent system was controlled by the rift compartments, and the tectonic signature of synlithification deformation bands leads to assign it to an Initial Rift Tectonic Systems Tract. The upper section of the Missão Velha Formation is separated from the underlying section by a major unconformity; this younger interval was originated by a braided fluvial system. Finally, the younger Abaiara Formation represents a deltaic system fed by a meandering fluvial system. The latter two units correspond to the Rift Climax Tectonic Systems Tract (FIG. 3).

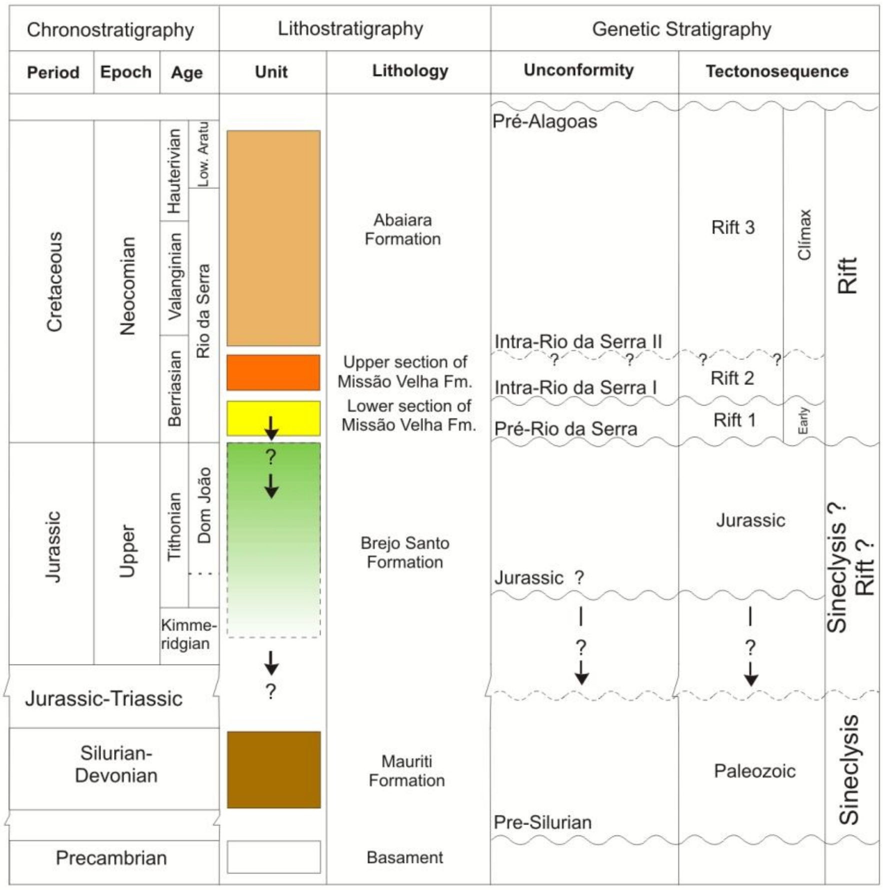


FIG.3 - Simplified stratigraphic column, showing the lithostratigraphic units, unconformities and tectonosequences recognized in the study area.

The NW border of the graben is marked by normal faults with major displacements, which control the overall tilting of the layers to the NW. The interpretation of gravity data and a seismic line indicates that the main fault has a variable dip slip component, defining two deeper portions within the graben, in which the sedimentary column can reach thicknesses of up to 2 km (FIG.2). The NE-trending normal faults define an arrangement with penecontemporaneous E-W-trending strike-slip faults with sinistral shear sense. Both systems are controlled by the trend of the Precambrian shear zones in the basement. A bulk NW extensional regime of the rifting event was locally combined with transtensional deformation along the E-W faults.

In the map of Figure 4, and taking into account the significant erosion (on the order of at least 1-2 km) and a larger original area occupied by the basin, it is observed that the Rift Climax Tectonic Systems Tract reaches greatest thicknesses along the Palestina and Abaiara-Jenipapeiro grabens, including a strike ramp in the eastern border of the latter. Besides their occurrences flooring the depocenters, the pre-rift tectonosequences (Paleozoic and Jurassic syneclises) outcrops in the horsts, what suggests their independence from the Neocomian structure. The usual absence of coarse, proximal facies at the base of the Jurassic Tectonosequence suggests that its source areas were far away from the rift structural highs, additionally supporting the assumed pre-rift setting. The Initial Rift Tectonic Systems Tract behaves intermediately between these two extremes, pointing to an initial period of sag style subsidence covering a wider area, with progressive accumulation of the thicker sedimentary piles along the axis of the grabens, with coarser siliciclastic facies related to proximal sources occurring at the base of this systems tract.

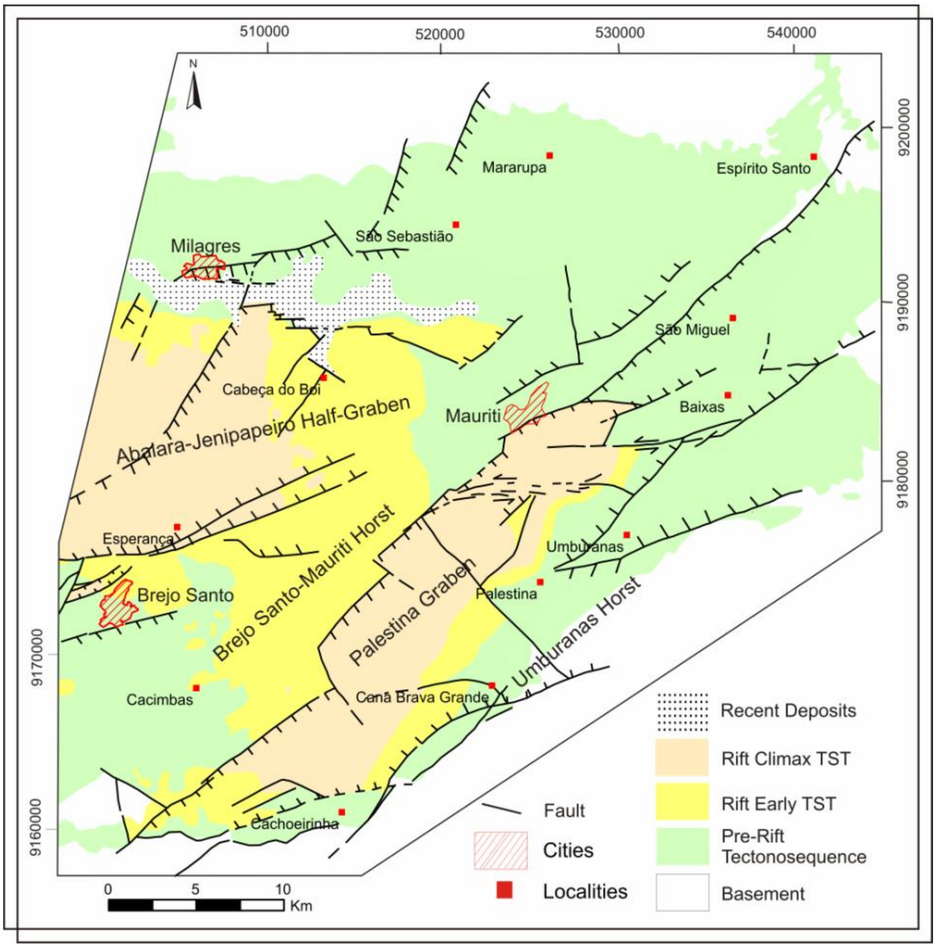


FIG.4. Simplified sketch of the geometry of grabens and horsts in the study area and their relationships with the recognized tectonosequences.

## 3. Conclusions

Within this framework of the Palestina Graben, eastern Araripe Basin, classical models with orthogonal extension or pull-apart styles deserve some caution in their application. The Palestina Graben is not bounded, at its extremities, by E-W transcurrent zones, as it should be in the case of the pull-apart geometry. The dominant NE-trending normal faults point to a setting of orthogonal opening of the graben. This picture is modified by the coeval the strike-slip/transtensional faults. The Abaiara-Jenipapeiro half-graben is bordered by oblique normal faults. All these structures share a common subhorizontal NW-trending extension (X) axis; basement structures (foliations and shear zones) with different trends influence on the style at the shallower crustal levels.

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# The thermal history and hydrocarbon source rock potential of the mid Carboniferous Quebradas Formation in SW Portugal and its correlatives in eastern Atlantic offshore basins

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*ABSTRACT*

*The mid Carboniferous Quebradas Formation of the 'South Portuguese Zone' (SPZ) comprises 80m of post-mature black mudrocks with a mean TOC of 2.5%. Lithostratigraphic units of similar facies and age such as the Holywell Shale, the Edale Shale and the Bowland Shale are important HC source rocks in the UK, having sourced a considerable proportion of the hydrocarbons in the East Irish Sea, East Midlands and Formby oilfields respectively. The kerogen content of the Quebradas Formation is mixed but slightly more oil-prone in its lower part. At outcrop, it is strongly post-mature with vitrinite reflectance ($R_r$) ca. 4%. Illite crystallinity results from the Quebradas Formation and associated units suggest lower maturity than vitrinite reflectance. Analysis of the optic fabric of very thin coal lenses within the Brejeira Formation which overlies the Quebradas Formation suggests that peak temperatures were attained before the Variscan (late Carboniferous – early Permian) deformation. Triassic rocks unconformably overlying the Carboniferous sequence are much less mature, with $R_r$ ca. 1.2%. Although the the Quebradas Fm has no HC source potential onshore due to its high maturity, Carboniferous rocks offshore may not have experienced the same extreme thermal history as the SPZ.*

*KEYWORDS: Portugal, Quebradas Formation, Carboniferous, Maturity, Thermal history.*

## 1. Introduction

The mid Carboniferous Quebradas Formation of the 'South Portuguese Zone' (SPZ) comprises 80m of post-mature black mudrocks with a mean TOC of 2.5% (based on 65 analyses). The TOC of this unit when within the oil window is estimated to have been *ca.* 3 – 4%. Lithostratigraphic units of similar facies and age such as the Holywell Shale, the Edale Shale and the Bowland Shale are important HC source rocks in the UK, having sourced a considerable proportion of the hydrocarbons in the East Irish Sea, East Midlands and Formby oilfields, respectively. Palynofacies analysis of samples from the Quebradas Formation indicates a mixed kerogen content but slightly more oil-prone in its lower part.

## 2. Thermal History

At outcrop near Murração, the Quebradas Formation is strongly post-mature with vitrinite reflectance ($R_r$) *ca.* 4%, as it presumably also is throughout the SW part of the SPZ, where it is overlain by a thick sequence of post mature late Carboniferous turbidites, principally of the Lower – Middle Pennsylvanian Brejeira Formation. Several lines of independent evidence shed light on the thermal history of the southern part of the SPZ:

1) Vitrinite reflectance ($R_r$) is uniformly high throughout the thick Upper Palaeozoic sequence in the SPZ, with no apparent correlation between stratigraphic position and VR (McCormack, 1998, McCormack *et al*., 2007). A poorly-constrained trend of decrease in maturity from N to S exists.

2) Illite crystallinity (Kübler Index) results from Upper Palaeozoic mudrocks throughout the SPZ indicate a position spanning the Deep Diagenetic Clay Maturity Zone and Low Anchizone Clay Maturity Zone of Merriman (2005), suggesting lower maturity than the vitrinite reflectance and palynomorph colour data.

3) Analysis of the optical fabric (*sensu* Levine and Davis, 1984 and 1989) of very thin coal lenses within the Brejeira Formation at Arrifana (figure 1) suggests that peak temperatures were attained before the Variscan (late Carboniferous – early Permian) deformation that has strongly affected the Carboniferous succession throughout the region. These results do not preclude a subsequent thermal event raising temperatures close to, but not exceeding those attained during the first event.

4) No Permian sediments are preserved in the region but Triassic rocks unconformably overlying the Carboniferous sequence are much less mature, with $R_r$ *ca.* 1.2%.

An interpretation of Palaeozoic thermal history consistent with the evidence outlined above entails an intense but short-lived late Carboniferous heating event prior to the main phase of Variscan deformation. This timing is supported by the optical fabric results and the short duration of this event is supported by the mis-match in maturity between the illite crystallinity and VR results. Post-tectonic heating during the latest Carboniferous elevated temperatures in the Upper Palaeozoic rocks currently at or near surface to temperatures close to, but not exceeding, those attained during the earlier thermal event. This did not result in the 'overprinting' of the optical fabric of the coals.

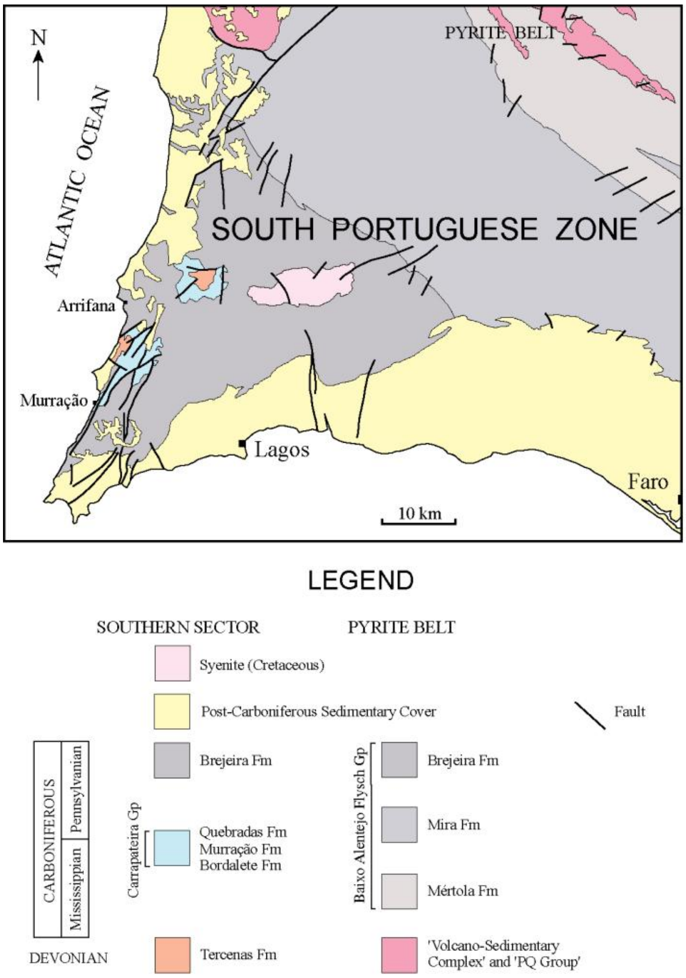


FIG. 1 - Outline geology of the 'South Portuguese Zone' with locations of the Arrifana and Murração sections shown (after McCormack *et al*. 2007).

## 3. Hydrocarbon source rock potential

Although the Quebradas Formation has no HC source potential onshore due to its high maturity, Carboniferous rocks offshore may not have experienced the same extreme thermal history as the SPZ. The widespread distribution of mid-Carboniferous black mudrocks throughout Western Europe suggests that these may be present in many offshore basins where Carboniferous rocks have been preserved.

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# Seismic stratigraphy and numerical basin modeling of the southern Brazilian margin (Campos, Santos, and Pelotas basins)

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*ABSTRACT*

*An integrated approach of sequence stratigraphy, inverse-basin and forward stratigraphic modeling have been carried out on three seismic reflection profiles (~320 km each) in the Campos (CB), Santos (SB) and Pelotas (PB) basins, offshore Brazil. Twenty-one calibration wells provided lithologic, bio-/chronostratigraphic ties, and paleobathymetry for the Barremian-Holocene basin fill. Between twelve and fourteen seismo-stratigraphic units have been identified in each basin; they show distinct stacking patterns and geometries, which reflect the evolution of accommodation space and sedimentation. Inverse modeling allows to quantitatively analyze major controls on the basin architecture: subsidence, eustacy and sediment supply. Six subsidence trends (ST1 to ST6) controlled the Barremian-Holocene basin development. These are directly related to the tectonic stages of basin development. From syn-rift to the early drift configuration (ST1-ST3) thermo-tectonic subsidence led creation of accommodation space. However, the syn-rift to post-rift transition occurred diachronously from the PB to the CB, during northward propagation of continental break-up (Moulin et al., 2010). As result, different architectures characterized each of the basin investigated: Aptian lacustrine environments with uniform paleobathymetry in the CB and SB allowed widespread deposition of salt; in the PB, the time-equivalent succession is composed of marine siliciclastics deposits, and salt is absent. As the flexural isostatic sediment loading progressively increased, Late Cretaceous-Tertiary basin-specific variations in subsidence and changes in accommodation are directly related to the sediment supply. Forward stratigraphic modeling indicates that different interrelated variables, with specific degree of implication for each of the studied basins, have controlled the syn-rift to drift development. The most significant factors include: (i) in the PB, sediment flux, and erosion-downslope deposition feedback processes related to second order eustatic sea-level fluctuations; (ii) in the SB and CB, syn-rift basin sagging, far-field intraplate deformation affecting sediment flux, sand/shale ratio and depositional gradients, combined to generate long-term salt remobilization and to increase the hydrocarbon potential.*

*KEYWORDS: southern Brazilian rifted margin, seismic stratigraphy, integrated numerical basin modeling, basin development.*

## Introduction

The southern Brazilian Campos (CB), Santos (SB) and Pelotas (PB) basins are investigated in terms of 2D seismo-stratigraphy, numerical inverse-basin and forward stratigraphic modeling (Nadin and Kusznir, 1996). Our study is based on one 2D seismic line for each basin covering 300-340 km from the shelf top to the continental rise and twenty-one calibration wells (FIG. 1). Between twelve and fourteen second order depositional units (3-50 m.y.) within the Barremian-Holocene basin fill (130-0 Ma) define the resolution of the seismic stratigraphy investigated in each basin (FIG. 2).

Inverse-basin modeling quantitatively analyzes and restores the basin architecture. The stratigraphic simulator Phil/Basim$^{TM}$ (Bowman and Vail, 1999) allows 2D flexural backstripping of cross-sections. Input variables comprise: present-day thicknesses, lithology, porosity, paleobathymetry, eustatic sea-level and crustal parameters (i.e.

effective elastic thickness, taper limit and mantle density). Main results include: rates of total subsidence and its genetic components, i.e., thermo-tectonic, flexural, compaction-induced subsidence; (ii) sediment flux; (iii) accommodation space evolution. Forward stratigraphic modeling aims to simulate the basin development and quantify the primary factors controlling deposition. Calculated thermo-tectonic subsidence and sediment supply rates are incorporated. In addition, a set of sedimentation and deformation algorithms (e.g. depositional gradients, dispersion distance, carbonate productivity, erosion) can be sensitivity analyzed during the model development. It allows to test and visualize independently the response of each process and its contribution to basin formation.


FIG. 1 – Location of the seismic reflection profiles (red lines) and correlation wells (red points)

2a) Campos Basin (CB)

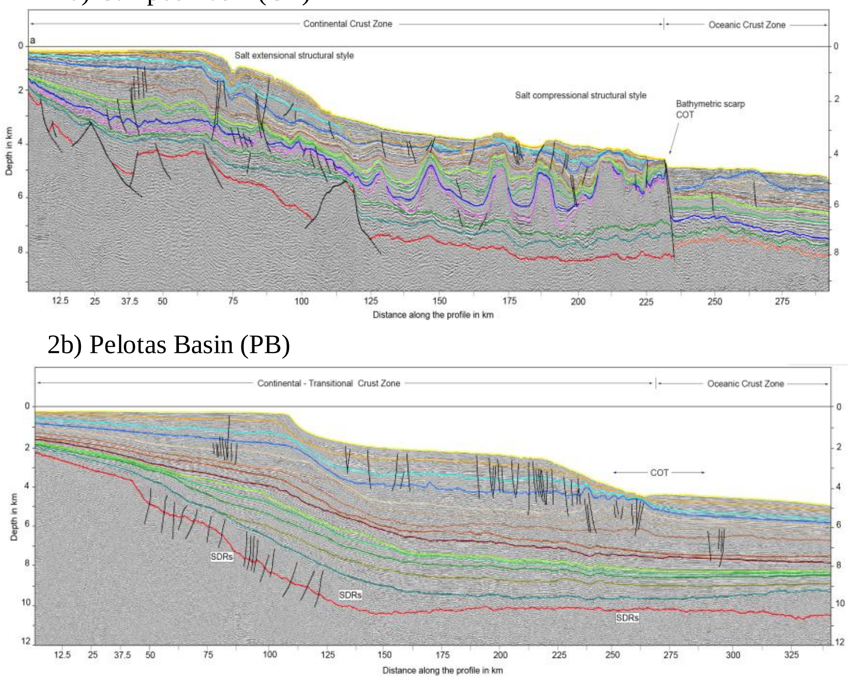


FIG. 2 – Interpreted regional seismic reflection profiles of the Campos (CB) and Pelotas (PB) basins in depth domain.

## Structural framework and basin fill

The CB and SB show similar tectono-stratigraphic features, whereas the PB differs considerably. In the latter basin, elongated reflectors only disrupted by Barremian and Tertiary high-angle extensional faults and Paleogene shale diapirs are characteristic. Syn-rift half-grabens were not recognized, and Aptian salt is absent. In the CB and SB, the following structural features are recognized: (i) Barremian-Aptian listric and high-angle extensional faults; (ii) salt domes; (iii) salt-induced listric and inverse faults; (iv) a fault zone associated to a bathymetric scarp at the lower slope, interpreted as the transition to oceanic crust (COT).

The Barremian succession records the terminal rift extension prior to continental break-up. Half-grabens on the shelf to upper slope resulted from a major extensional phase between Hauterivian and late Barremian times. These depocenters were rapidly filled by volcanic series intercalated with alluvial and fluvial-deltaic sediments. In the PB, widespread seaward dipping reflectors (SDRs) indicate the volcanic nature of this margin-segment. Reflector geometries and subsidence analysis suggest that SDRs evolved to submarine sea-floor spreading in the early Aptian (~122 Ma). Unfaulted subparallel reflectors of late Barremian-middle Aptian age cap syn-rift depocenters and indicate (only in the CB and SB) the transition from fault-controlled brittle deformation to depth-dependent lithosphere thinning (Kusznir and Karner, 2007). Thus, late Barremian-middle Aptian fluvial-deltaic to lacustrine sediments represent the sag basin fill. By the latest Aptian (112?-115 Ma). up to 2,500 m of evaporites accumulated in preceding sag wide lakes. In the PB, time-equivalent conglomerates and sandstones graded to marine shales in bathyal environments.

Lower-middle Albian carbonate progradation-aggradation marks the transition to the post-rift stage in the CB and SB. In the PB, transgression, shallow-water carbonates to marine shales record the transition to the drift stage. Since the late Albian, open-marine environments developed in the three basins. Late Cenomanian-Turonian anoxia caused the deposition of organic-rich shales and marls. From Coniacian to Maastrichtian tectonic uplift and erosion in the hinterland caused basin-specific depositional patterns: (i) high sediment supply to the SB caused progradation; (ii) in the CB and PB, eustatic sea-level rise and low sediment supply resulted in transgression. A late Paleocene unconformity marks the base of the Tertiary basin fill. During the Eocene, depositional systems were reversed: late Eocene-Oligocene progradation in the CB, contrast with transgression in the SB. In the PB, increasing sediment flux and progradation resulted from the Incaic and Quechua phases of Andean orogeny. Neogene stacking patterns are highly variable between basins. They were controlled by sediment input rates, overprinted by eustatic sea-level fluctuation and inherited basin architecture.

## Numerical inverse-basin modeling

The Barremian to Holocene subsidence development shows significant differences between the CB, SB and PB. Six major trends of subsidence were established (ST1-ST6). These are not only related to the structural framework (thermo-tectonic component), but also to the effects of source areas and sediment input (flexural, compaction-induced subsidence). In the CB and SB, there is an initial rapid decrease in subsidence from Barremian (trend ST1) to middle Aptian. This pattern has been correlated with the offset of syn-rift faulting. In the PB, a gentler subsidence decrease, high sediment flux and rising bathymetry suggest the transition to the post-rift stage during the early Aptian. From middle Aptian to early Albian (ST2) subsidence continued to decrease in the CB and SB shelf areas, whereas constant subsidence rates characterized the slope to deep basin margin. Thus, significant depositional gradients did not exist and differential subsidence was largely absent (basin sagging). From the early Albian to Maastrichtian, trend ST3 indicates long-term subsidence decrease in three basins. Margin development was now controlled by lithosphere thermal contraction (early drift stage; 110-65.5 Ma). During the Tertiary, basin-specific intervals of uplift and subsidence exist (ST4-ST6). Other than in the Cretaceous, subsidence variations are closely related to changes in sediment flux (FIG. 3) and resulting accommodation space.

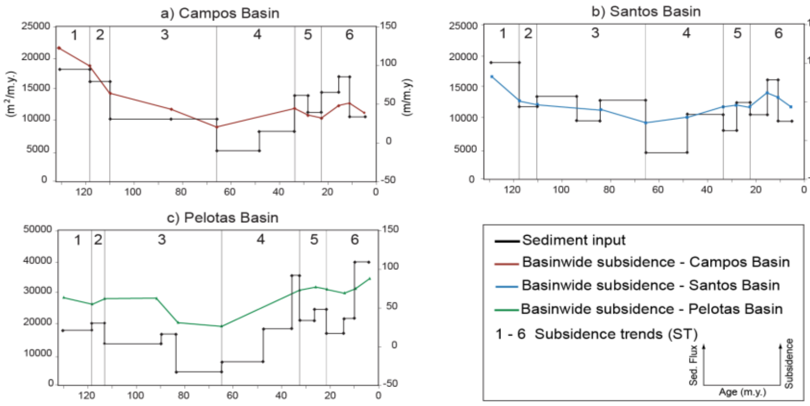


FIG. 3 – Basinwide subsidence development and sediment flux from Barremian to recent times. During ST1-ST3, thermo-tectonic subsidence dominated and fluctuations in the sediment flux had minor influence. Trends ST4-ST6 are highly influenced by sediment loading and flexural response of the crust.

## Forward stratigraphic modeling

Results indicate that although the initial rift development of the three basins is very similar, basin architecture, sedimentary infill and lithofacies distribution differ considerably since the Aptian sag to post-rift basin stages. Different geological variables, which are interrelated, have controlled the distinct basin architectures:

Syn-rift lithosphere deformation: sensitivity analysis of the effective elastic thickness (Te) indicates temporal changes in the thickness competent crust. Best-fit models have been achieved by Te values of 12 km in the CB and SB (sag depocenters), and 20 km in the PB (widespread volcanic SDRs).

Late Cretaceous-Tertiary far-field intraplate deformation triggering rift shoulder uplift, shelfal erosion and downslope sediment transport had strong implications for sediment supply and differential subsidence: in the SB during the Santonian-Maastrichtian, the CB during the Middle Eocene-Miocene, and in the PB during the Eocene-Holocene. Besides, salt remobilization, sediment distribution in the CB and SB were highly affected (FIG. 4).

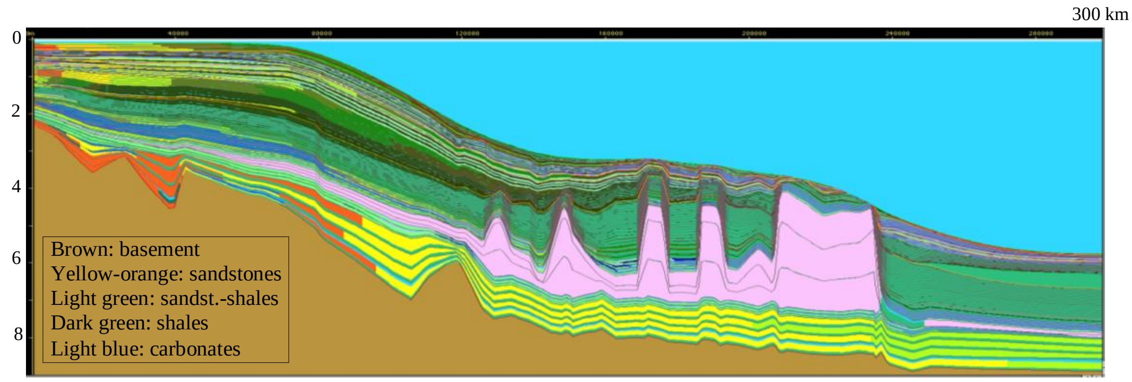


FIG. 4 – Modeled cross-section in the Campos Basin showing the predicted Barremian-Holocene (130-0 Ma) lithofacies distribution (compare with FIG. 2a). Distance: 300 km; Depth: 9 km.

## Conclusions

Subsidence/uplift changes exerted the primary control on the evolution of accommodation space and second order depositional sequences. Structural reconfigurations of hinterland source areas considerably influenced the sediment input rates, the margin architecture and development of HC systems: (i) Barremian-middle Aptian and Cenomanian-Turonian rapid subsidence in combination with anoxic conditions resulted in deposition of organic-rich shales; (ii) decreased clastic supply for the Aptian sag CB and SB allowed carbonate precipitation around structural highs, partially exposed during eustatic sea-level falls, which represent major reservoirs; (iii) Late Cretaceous accommodation space overbalanced by major sediment supply caused prograding delta sandstones and turbidite reservoirs in the SB; (iv) Eocene-Miocene subsidence combined with eustatic sea-level rise created the necessary space for deposition of sand-rich reservoirs in the CB; (v) after the Late Cretaceous, abundant space was available in the PB: this enabled the sedimentation of thick prograding wedges, which contain sandstones within probable basin floor fans, encased in impermeable shales, where bottom simulating reflectors (BSR) have been recognized.

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# Diagenesis and Provenance of the Sandstones of the Rift Tectonosequence of Araripe and Rio do Peixe basins, NE Brazil

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*ABSTRACT*

*Rio do Peixe and Araripe basins are part of the set of interior basins of northeastern Brazil. They are aligned along the Trend-Cariri Potiguar and are genetically related to Early Cretaceous rifting. With respect to the lithostratigraphy, the studied interval corresponds to Antenor Navarro, Sousa and Rio Piranhas formations, in the Rio do Peixe Basin, and Missão Velha and Abaiara formations in Araripe Basin, that outcropping in the central-west of Cariri Valley. The diagenetic and provenance studies of sandstones belonging to the Rift Tectonosequence allowed associating the studied formations in each basin, the specific phases of evolution of the rift stage.*

*KEYWORDS: Diagenesis, Provenance, Araripe Basin, Rio do Peixe Basin*

## 1. Introduction

Rio do Peixe and Araripe basins, along with the other basins that comprise the set of interior basins of northeastern Brazil (Iguatu, Ico, Lavras da Mangabeira, and others) are a series of sedimentary basins of small to medium size (Castro *et al*., 1999), which are aligned along the Trend-Cariri Potiguar (Matos 1992, 1999).

The origin of these intracratonic basins is directly linked to tectonic forces associated with the rifting that shaped the current continental margin as a result of the separation of the South America and Africa continents during Early Cretaceous. Matos (1992), using a simple model, suggests that the tectonic evolution to the basins of the Cariri Rift Valley was a result of NW-SE distension that reactivated a sigmoidal shear zone of neoproterozoic age. This same author states that, in a generical way, these basins are made of half-grabens with variable geometry, with dips towards SE. Françolin *et al*. (1994) propose a more complex tectonic evolution. For these authors, the basins of the Cariri Rift Valley suffered a lateral E-W displacement along the Malta Fault. As such, its shape, location and stratigraphic stacking would be strongly controlled by pre-existing regional lineaments of Precambrian basement (Matos 1992, 1999), in the Borborema Province.

## 2. Rio do Peixe and Araripe Basins

Rio do Peixe Basin is located at the northwest boundary of the Paraíba State with the Ceará State, encompassing the towns of Sousa, Uiraúna, Poço, Brejo das Freiras, Triunfo, Santa Helena and Pombal, more precisely between 37 º 47 ' 00" and 38 º 50 '00" west longitude meridians, and between 06 º 25' 00" and 06 º 50 '00" south latitude parallels (Córdoba, 2008; Nunes da Silva, 2009; Srivastava & Carvalho , 2004). This basin is divided into four minor basins that correspond to half-grabens of Pombal, Sousa, Brejo das Freiras and Icozinho, separated by highs of crystalline basement. Its main faults are controlled by shear zones of Portalegre (NE-SW) and Patos (EW). Theses half-grabens comprise an area of about 1,250 $km^2$, and the largest Sousa half-graben, with 675 $km^2$.

Araripe Basin is the largest of the interior basins of Northeast Brazil, with the following geographic coordinates: 38 ° 30 and '40 ° 55' west longitude, and 7 º 07 and '7 ° 49' south latitude (Ponte & Ponte Filho, 1996). Its occurrence area extends from the Araripe Plateou to the Cariri Valley, with a total area of 9,000 km$^2$ (Assine, 1992).

The Araripe Plateau is the geomorphological feature that most stands out in the region, providing an extensive tabular surface located among the states of Ceará, Pernambuco and Piaui. This basin presents a length of 160 km from east to west (major axis) and about 50 km from north to south (Kellner, 2002), and is bordered by steep erosional scarps (Assine, 2007).

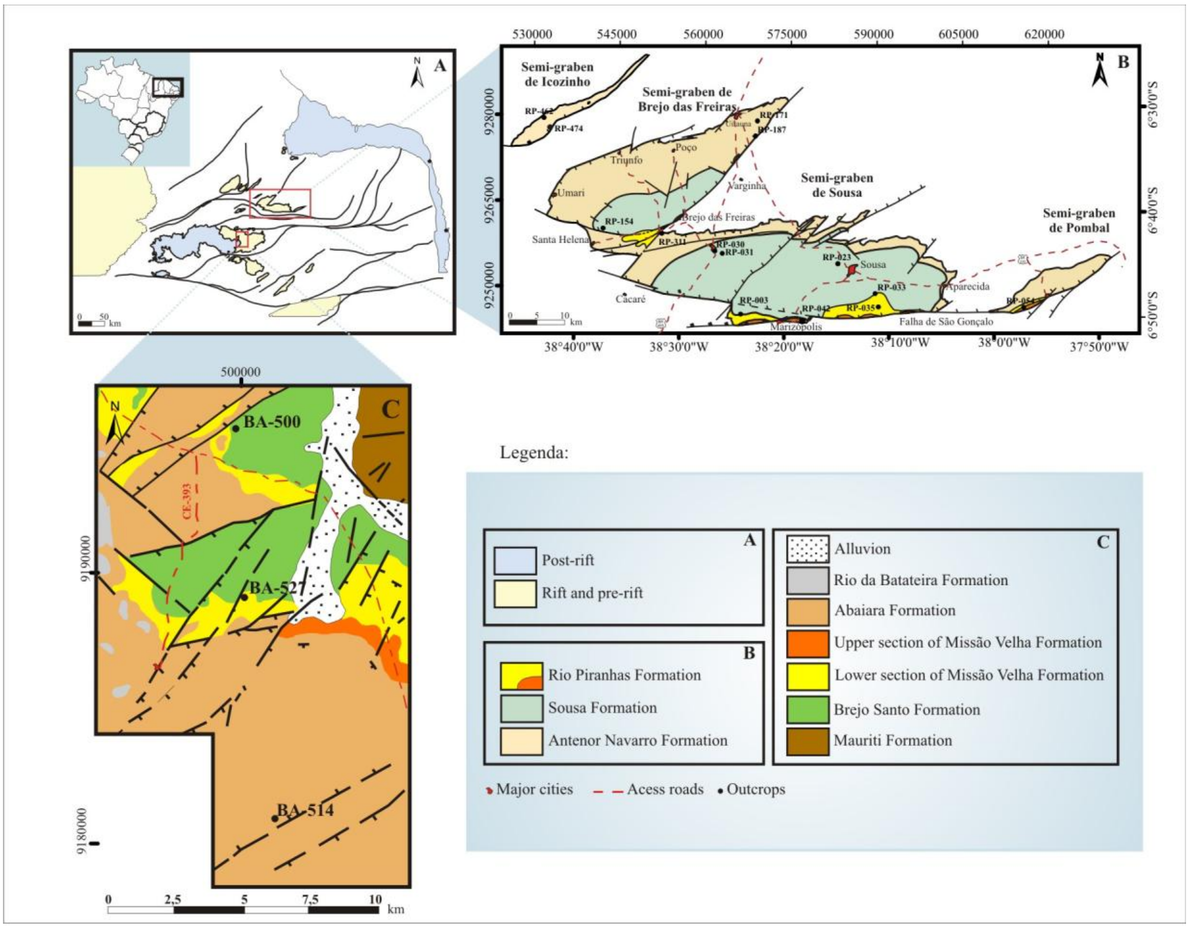


FIG.1 – Location and geological maps of the study area: A) Location map of the basins of the Rio do Peixe and Araripe in the context of Northeast Brazil, (B) Geological map with location of studied outcrops in the Rio do Peixe Basin (Nunes da Silva, 2009), and C) Geological map with the location of outcrops studied in the central-western Araripe Basin (Modified Projeto Bacias Interiores; Aquino, 2009).

## 3. Rift Tectonosequence: Facies and Deposicional Systems

The facies analysis of the studied sandstones in the Rio do Peixe Basin identified nine distinct facies, with one composed by conglomerates, four by sandstones and four by pelites. Associations of these facies allowed interpreting that the depositional setting established during the deposition of Antenor Navarro and Sousa formations was represented by fluvial distributary systems. These systems were laterally associated with alluvial fans providing from the failed margin, represented by facies of Rio Piranhas

Formation. The studied sandstones of Araripe Basin, in turn, consist of ten facies of which one is composed by conglomerates, seven by sandstones, and two by pelites. The facies analysis allowed to interpret that the lower section of Missão Velha Formation represents meandering to braided fluvial systems, that the upper section of Missão Velha Formation consists of braided fluvial systems, and that Abaiara Formation represents deltaic systems that evolve at the end of this unit to meandering fluvial systems.

## 4. Petrographic and Diagenetic Analysis

In terms of petrography, the studied sandstones in both basins exhibit grains with variable mineralogical composition with the predominance of quartz, feldspar and rock fragments. In all studied sandstones, muscovite, biotite, chlorite, tourmaline, zircon and titanite are present, but in minor quantities. Particularly in sandstones of Araripe Basin also occur staurolite, garnet and epidote. The matrix identified in all studied rocks is formed by infiltrated clay. Cements evidenced in the rocks of all formations of Rio do Peixe Basin are represented by ferruginous and carbonate cements, and quartz overgrowths. In Araripe Basin, the rocks of Missão Velha Formation exhibit ferruginous cements, as well as quartz and feldspar overgrowths. The rocks of Abaiara Formation, in turn, contain besides quartz overgrowths, ferruginous cements and clay minerals. The modal analysis allowed classifying the studied lithotypes, in both basins, as Quartzarenites.

Based on the diagenetic analysis of studied rocks, it was possible to identify nine distinct processes that were grouped in eo, meso and telodiagenetic stages. The eodiagenetic stage is marked by mechanical infiltration of clays and the beginning of mechanical compaction. These processes, mainly the mechanical infiltration of clays, acted with more intensity in sandstones belonging to Rio do Peixe Basin. The mesodiagenetic stage is characterized by the continuity of mechanical compaction and the beginning of chemical compaction, quartz and feldspar overgrowths, generation of authigenic kaolinite, alteration of the grains to chlorite and illite, and finally, precipitation of opaque minerals processes. These diagenetic events have acted differently on the rocks of studied basins. Mesodiagenetic processes that have acted more significantly in the sandstones of Rio do Peixe Basin, were the precipitation of mosaics of calcite in the interstitial spaces and the alteration of the grains and the matrix to chlorite and illite. In Araripe Basin, in turn, the sandstones were mainly subjected to quartz and feldspar overgrowths and to dissolution of feldspars with the generation of secondary porosity, which explains the higher values obtained for the porosity in this basin. The telodiagenetic stage is represented by the partial oxidation of grains, matrix and cement; this stage is quite evident in the Rio do Peixe Basin.

## 5. Provenance Studies

The provenance studies using QtFL and QmFLt diagrams (Dickinson & Suczek, 1979) revealed that the studied rocks show continental origin, with most of them indicating the interior craton provenance. The application of these diagrams also allowed highlighting those rocks with greater mineralogical maturity and chemical stability, which focus on Sousa and Rio Piranhas formations, in Rio do Peixe Basin, and in the lower section of Missão Velha Formation and in the Abaiara Formation in Araripe Basin. The rocks of Antenor Navarro Formation in Rio do Peixe Basin, and those of the upper section of Missão Velha Formation in Araripe Basin were whose samples showed comparatively lower mineralogical maturity and chemical stability.

The shortest mineralogical maturity and chemical stability found in sandstones of Antenor Navarro Formation can be explained by the fact that they represent the proximal portions of a distributary fluvial system, areas adjacent to sources composed of rocks rich in feldspar. For the rocks of Sousa Formation, higher values may be explained by the greater distance of sediment transport. In the case of sandstones of Rio Piranhas Formation, that characterize a alluvial fan systems providing from failed margins, the higher values of mineralogical maturity and chemical stability can be explain by the fact of the source rocks are poor in feldspar. In Araripe Basin, the interpretation of the results was mainly based on depositional systems since the geology of source area has not proved to be a conclusive factor. The sandstones of the lower section of Mission Velha Formation represent sandy meandering fluvial systems; the ones of upper section of Missão Velha Formation characterize sandy and gravelly braided fluvial systems, and the sandstones and pelites of Abaiara Formation represent sandy meandering fluvial and deltaic systems. The lowest mineralogical maturity and chemical stability shown in the upper section of Missão Velha Formation can be explained by the fact that this system be related to more proximal compared with other formations. The results based on values of mineralogical maturity and chemical stability allowed associating the studied formations to each specific phase of the Rift Stage. Thus it was possible to relate the lower section of Missão Velha Formation in Araripe Basin to the Rift Initiation Phase, the upper section of Missão Velha Formation in Araripe Basin and Antenor Navarro Formation in Rio do Peixe Basin to Rift Climax Phase, and the Sousa and Rio Piranhas formations in Rio do Peixe Basin and Abaiara Formation in Araripe Basin, to a Filling Rift Phase.

## 6. Conclusions

Diagenetic and petrographic studies of sandstones belonging to the Rift Tectonosequence of Rio do Peixe and Araripe basins allowed understanding that these rocks were buried to depths related to mesodiagenetic zone, since they were affected by processes such as chemical compaction and quartz and feldspar overgrowths. These studies also showed similarities and differences between the processes that acted in the sandstones of the different studied basins. The provenance studies, in turn, made it possible to associate the studied formations in each of the basins to specific stages of Stage Rift evolution.

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# Morphostructure of the S. Vicente Canyon, Marquês de Pombal Fault and Pereira de Sousa Fault (SW Iberia margin)

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*ABSTRACT*

*The S. Vicent Canyon (SVC), Marquês de Pombal Fault (MPF) and Pereira de Sousa Fault (PSF) are located along the SW Iberian margin. The SVC appears to be controlled by the S. Vicent Fault (SVF), a steep NE-SW striking fault that outcrops along the southeast flank of the canyon.*

*To better understand the SVC, MPF and PSF structures and the Meso-Cenozoic morphostructural evolution of this sector it is important to identify the main tectonic phases from the Mesozoic up to Plio-Quaternary. To attain this objective, the main regional structures were mapped using 2D seismic lines and multibeam swath bathymetry data, allowing the mapping of the northern prolongation of PSF and the identification of faults that do not reach the sea floor.*

*KEYWORDS: Portugal, SW Iberian Margin, morphostructure, Alentejo Basin.*

## 1. Introduction

The S. Vicent Canyon (SVC), Marquês de Pombal Fault (MPF) and Pereira de Sousa Fault (PSF) are located along the SW Iberian margin, northwards of the Africa-Eurasian plate boundary comprised of the Gloria Fault and Strait of Gibraltar, which is described as a diffuse boundary by Sartori et al. (1994). This tectonic setting is particularly important to understand which structures are still accommodating the present day tectonic deformation.

The NNE-SSW trending MPF and the N-S trending PSF acted both as extensional faults during the Triassic-Early Cretaceous tectonic rifting phases in West Iberia. During the Late Cretaceous-Palaeogene and the Neogene, this margin underwent two tectonic inversion events related to the Alpine orogeny (e.g. Terrinha, 1998). During that time the MPF was inverted as a thrust-fault, whereas the PSF continued to act as a normal fault until the Recent (Terrinha et al., 2003; Zitellini et al., 2004).

The SVC appears to be controlled by the S. Vicent Fault (SVF), a steep NE-SW striking fault that outcrops along the southeast flank of the canyon (Valadares et al., 2009), and possibly is the submarine prolongation of the 600 km long Odemira-Ávila Fault.

The objective of this work is to better understand the tectonic control of the SVC, the structure of the MPF and PSF regarding their geometry and the kinematic control during the Plio-Quaternary . Furthermore the study also aims to investigate why the PSF remained a normal fault during the Meso-Cenozoic. The interpretation of multibeam bathymetry SWIM data (Zitellini et al., 2009) together with good quality multichannel

2D seismic data allowed to: i) characterise the fault distributions in depth ; ii) better define the northern termination of the PSF; iii) recognize new structures that could help explain the reason why this fault remained a normal fault after the basin inversion during the Meso-Cenozoic.

## 2. Data and methods

The work integrated two different datasets, the SWIM multibeam bathymetry (Zitellini et al., 2009) and the information obtained through the interpretation of 2D seismic data. The SWIM bathymetry resulted from the compilation of 19 surveys, acquired between 2000 and 2006 funded by the ESF EuroMargins SWIM project. The 2D seismic data was acquired between 2000 and 2002 with a record length of 12 seconds.. The acquisition was carried out in perpendicular directions, NW-SE and SW-NE defining a grid of 10 km by 5 km.

The SWIM bathymetry and the seismic dataset have different resolutions and spatial coverage, being both complementary to each other. The merge of the bathymetric data obtained from seismic (tracking the sea floor on seismic), with the existing SWIM bathymetry, allows to extend the bathymetry to the east. Additionally, the 2D seismic data provides a view of the subsurface over areas covered by this data.

First the sea floor horizon was mapped ("seismic bathymetry") on seismc and the main fault segments correlated on each of the 2D seismic lines. Thereafter fault polygons were derived for the sea floor horizon. Since the seismic data is in two-way time the sea floor horizon had to be converted to depth before being integrated with the SWIM bathymetry. Following a data quality check the sets were merged in a GIS system into a common grid representing a single bathymetric map

The final map was obtained by complementing the fault polygon interpretation in areas with no seismic coverage through analysis of the SWIM bathymetry itself.

## 3. Results

The joint interpretation of both sets, 2D seismic data and bathymetric data, allowed the identification of the main structures that deformed the Plio-Quaternary sediments and the seafloor. The main morphostructures are the MPF, PSF, SVC, a set of thrust-faults recognized in the Príncipe de Avis Plateau and a set of N-S normal faults in the proximal margin of the Alentejo Basin and the Sagres Plateau.

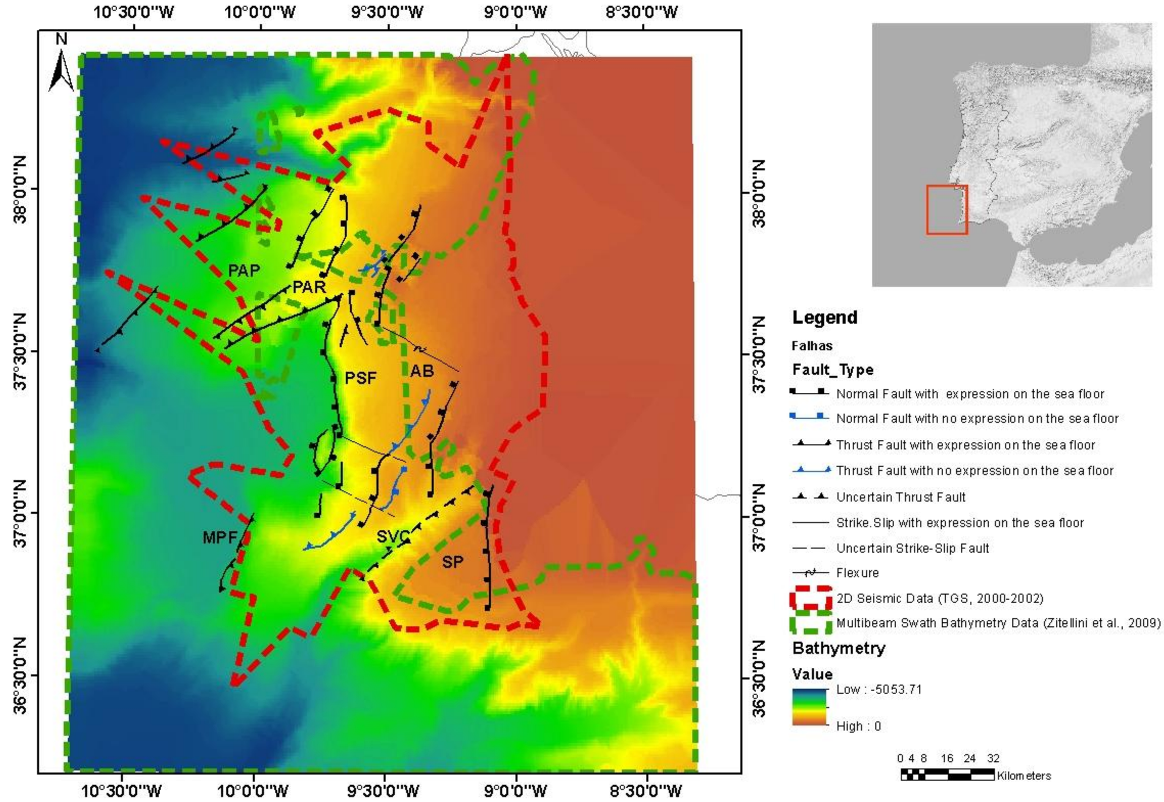


FIG.1 – Structural map of the SW Iberia Margin: **PAP** – Principe de Avis Plateau; **PAR** – Príncipe de Avis Ridge; PSF – Pereira de Sousa Fault; **MPF** – Marques de Pombal Fault; **SVC** – S. Vicent Canyon; **AB** – Alentejo Basin; **SP** - Sagres Plateau.

Clearly identifiable thrust faults with sea floor expression appear to be restricted to the west of the PSF alignment, normal faults are located in the Sagres Plateau which forms the proximal margin of the Alentejo Basin (sensu Alves et al., 2009) and in the NE end of Príncipe de Avis Plateau.

The MPF is a NNE-SSW thrust-fault dipping SE that offsets the seafloor producing a scarp about 1 km high. This fault acted as an extensional fault during the Mesozoic rifting phase related to the opening of the North Atlantic Ocean. During the Alpine compression phases at Palaeogene and Neogene, the MPF was inverted as a thrust-fault, showing evidences of Plio-Quaternary activity.

The PSF and Príncipe de Avis Plateau are relevant to better understand where the deformation is being accommodated since the Paleogene (FIG.1).

The PSF is an N-S trending steep normal-fault about 50 km long, cutting from the basement until the seafloor and forming an 1800 m high scarp. This fault is related to the Mesozoic rifting, creating accommodation space to Meso-Cenozoic sediments that reaches about 2600 m thickness in the footwall, against 3000 m in the hanging wall and there are evidences that it remained active until Plio-Quaternary.

The Príncipe de Avis Plateau is cut by a set of NNE-SSW to ENE-WSW thrust faults showing opposite vergence; these thrust faults have associated a group of minor blind faults, with the dominant vergence being NW. (FIG.1).

One of the main morphostructures identified in the Príncipe de Avis Plateau is the ENE-WSW Príncipe de Avis Ridge, a pop-up structure bounded by two opposite-dipping ENE-WSW thrust-faults. The southern thrust-fault intersects the northern culmination of the PSF. Considering the ENE-WSW trend shown by these faults, they could be ancient transfer-faults associated with the Mesozoic rifting.

The SVC seems to be controlled by a NE-SW fault which is probably a thrust.

There is a further group of thrust faults in the proximal margin of the Alentejo Basin which do not show any morphological expression, since their movements occurred until the beginning of Paleogene.

The set of N-S normal faults in Sagres Plateau and proximal margin of the Alentejo Basin were active until the beginning of the Paleogene.

## 4. Discussion and conclusion

Comparing the structural model propose in this work and the one presented by Terrinha et al. (2003) for this area, several remarks can be made: i) it is confirmed that the PSF is a normal-fault, probably still active, that consist of a Mesozoic extensional fault related to the rifting of the West Iberia Margin and was not reactivated as a thrust-fault during the Cenozoic; ii) there is no evidence in the seismic data of the WNW-ESE sinistral strike-slip faults that offset the PSF, as suggested by Terrinha et al. (2003). The possible existence of these faults could be suggested by the bathymetric data and the lack of continuity between the N-S normal faults in the southern end of this fault; iii) the thrust-faults that bound the pop-up structure, named Príncipe de Avis Ridge in this work, could be correlated with the TTR-10 and F1 faults mapped by Terrinha et al. (2003).

The N-S orientation and the deep and steep fault plane geometry that characterized the PSF probably prevent its reactivation as reverse-fault during the Cenozoic Alpine phases. The TTR-10 fault intercepts the PSF fault and is probably the reason why this fault ends abruptly. Conversely, the nearby MPF, also a Mesozoic normal rift fault, was reactivated as a reverse fault during the Cenozoic.

In the Príncipe de Avis Plateau area the Neogene compressive deformation seems to be accommodated by a succession of NNE-SSW to ENE-WSW blind thrust-faults.

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# Mechanisms for Asymmetric Lithospheric Extension and Implications for the West Iberia-Newfoundland Conjugate Margins: A New Perspective from a Self-Consistent Asthenosphere-Lithosphere Numerical Model

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*ABSTRACT*

*We use a finite-difference based, combined Lagrangian-Eulerian, thermo-mechanical numerical modelling approach to investigate some general conditions under which passive (rift or Atlantic-type) continental margins asymmetries may develop, and model the geodynamic evolution of the West Iberia-Newfoundland conjugate margins. In contrast to previous models of rifting, the present model maintains a self-consistent thermo-mechanical coupling between the "rigid" lithosphere and the convecting sub-lithospheric mantle during rifting. This is particularly relevant when modelling the long-term evolution of rift margins (10's to 100's of m.y.), and we address its implications for the long-standing "upper plate paradox" and the thermal structure of rift margins.*

*KEYWORDS: Passive margins, Asymmetries, Detachment faulting, Numerical modelling.*

## 1. Introduction

Passive margins develop by thinning of the continental lithosphere, followed by continental break-up and the formation of new oceanic basins. A feature of the rifting process is that it can be highly asymmetric, and pairs of conjugate margins often exhibit important variations in the width of the stretched continental lithosphere and Ocean-Continent Transition (OCT), the distribution of faulting along the continental slope and rise, the extension and thickness of the sedimentary basins, and in the amount of syn- and post-rift subsidence (Ruppel, 1995; Ziegler and Cloetingh, 2004 and references therein).

Kinematic models which have been proposed to explain the observed asymmetries systematically invoke shearing along low-angle normal faults or detachment zones (see Rosenbaum et al., 2008 for a review on previous studies and models), associated with differential crustal and lithospheric mantle stretching across a rift system composed of an upper and a lower plate margin. It has been noted, however, that the detachment or "simple-shear" model of rifting and continental break-up may be insufficient to explain the complexity of the observations. First, because in some margins detachment faults have only been seismically imaged oceanwards of the continental slope, under thin and/or transitional-type crust (< 10 km thick; Reston et al., 1996), and thus cannot explain the general large-scale asymmetry. Second, the structure of conjugate margins remains paradoxical, as the amount of extension measured from faulting (horizontal extension) appears to be much smaller than that measured from crustal thinning (vertical thinning), generating an apparent mass deficit at the rift centre (Davis and Kusznir, 2004). This phenomena is commonly referred to as the "upper plate" paradox (Dirscoll and Karner, 1998).

## 2. Numerical Modelling: Setup and Results

The numerical model employs the finite-difference based, Lagrangian-Eulerian numerical modelling approach of Gerya and Yuen (2003), which we have applied to model extensional settings. Being based on a dense distribution of Lagrangian particles, the method allows arbitrarily large strain, enabling the simultaneous representation of mantle convection and localized deformation (faults and shear zones) in the mantle lithosphere, crust and sediments.

Fig. 1 upper panel shows a snapshot of the quasi-steady state lithosphere-upper mantle system prior to rifting. We assume a uniform, 40 km thick crustal layer composed of a 20 km thick wet quartzite upper crust, and an equal thickness plagioclase lower crust (Ranalli, 1995). For the mantle we assume a dry Olivine rheology and consider both the effects of dislocation and diffusion creep (Karato and Wu, 1993). In the frictional-plastic regime all materials yield according to a Mohr-Coulomb, pressure dependent, criterion. Initially, the angle of friction is 36 $^0$ and reduced to $0^0$ with increasing plastic strain (i.e. strain softening). During extension this results in localization of strain and the generation of initially steep shear zones that resemble normal faults.

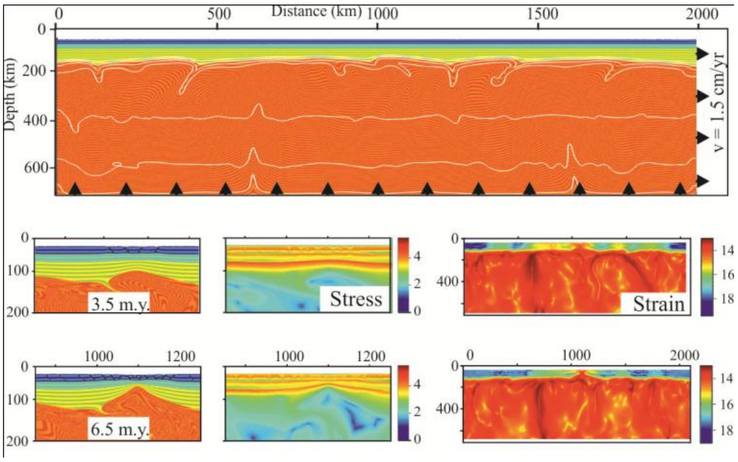


FIG.1 - **Upper panel** is a snapshot of the quasi-steady state between the lithosphere and the convecting asthenosphere prior to rifting. **Middle and Lower panels** are snapshots of lithology (left), effective stress, $\sigma_{II}$, (centre), and strain rate (right; logarithmic scale), after approximately 3.5 and 6.5 m.y of extension at a constant rifting velocity of 1.5 cm $yr^{-1}$. In the left panels the colours represent: dark blue – upper crust; light blue – lower crust; green – lithospheric mantle; orange – Asthenosphere. Vertical and horizontal scales are in km*100

The lower panels in FIG.1 are snapshots of (left to right) geometry, effective stress, and strain rate after approximately 3.5 and 6.5 m.y. into a rifting experiment, respectively. This reference extension model reproduces the standard features of continental rifting, namely: i) brittle deformation in the upper crust; ii) crustal thinning and isostatic Moho upwards; iii) the sub-lithospheric mantle is displaced upwards; and iv) the base lithosphere topography is affected by Buck (1986) convection, driven by the relatively large horizontal temperature differences in the mantle. In the centre of the rift, after ~100 km of extension (lower left panel), the stretching factor, β, increases with depth from ~1.5 in the upper brittle crust, to ~2.5 in the ductile lower crust, to ~10 in the lithospheric mantle.

Two approaches have been successfully applied to generate regional-scale asymmetries during rifting: (1) a variable rift velocity (or multi-stage continental rifting) in a laterally uniform lithosphere (pure-shear model; left panels in FIG.2); and (2) a pre-existing, weak detaching, dipping layer (simple-shear model, sensu Wernicke 1985; right panels in FIG.2). The models predict, however, a distinct structural framework and tectonic evolution.

The multi-stage, pure-shear model predicts an approximately symetric rift during the early stages of extension, followed by large-scale asymmetric extension of a cooled, strengthened lithosphere (e.g. Bassi, 1993). We show, however, that the polarity, as well as the skewness of the asymmetry is largely unpredictable (2 lower panels), since it results from the complex interaction between small-scale convection in the asthenosphere and the continuously deforming lithosphere. Similar results have been verified in other experiments for different rift velocities, crust and lithospheric structures. The models also show that, although depth-dependent stretching is pervasive across the entire rift system, its effect is much more pronounced in one of the conjugate margins. This has implications for the thermal history, patterns of post-rift subsidence and, hence, sedimentation.

The lithospheric-scale detachment (simple shear) model presented here (right panels in FIG.2) assumes a constant stretching rate of 1.5 cm $yr^{-1}$. The model is better described in three stages and, despite its simplicity and limited duration, it explains the first-order regional asymmetries between the West Iberia and Newfoundland conjugates as well as a number of distinct features in the margins. A snapshot of a high resolution, interpreted detachment model is presented in FIG.3 for clearness.

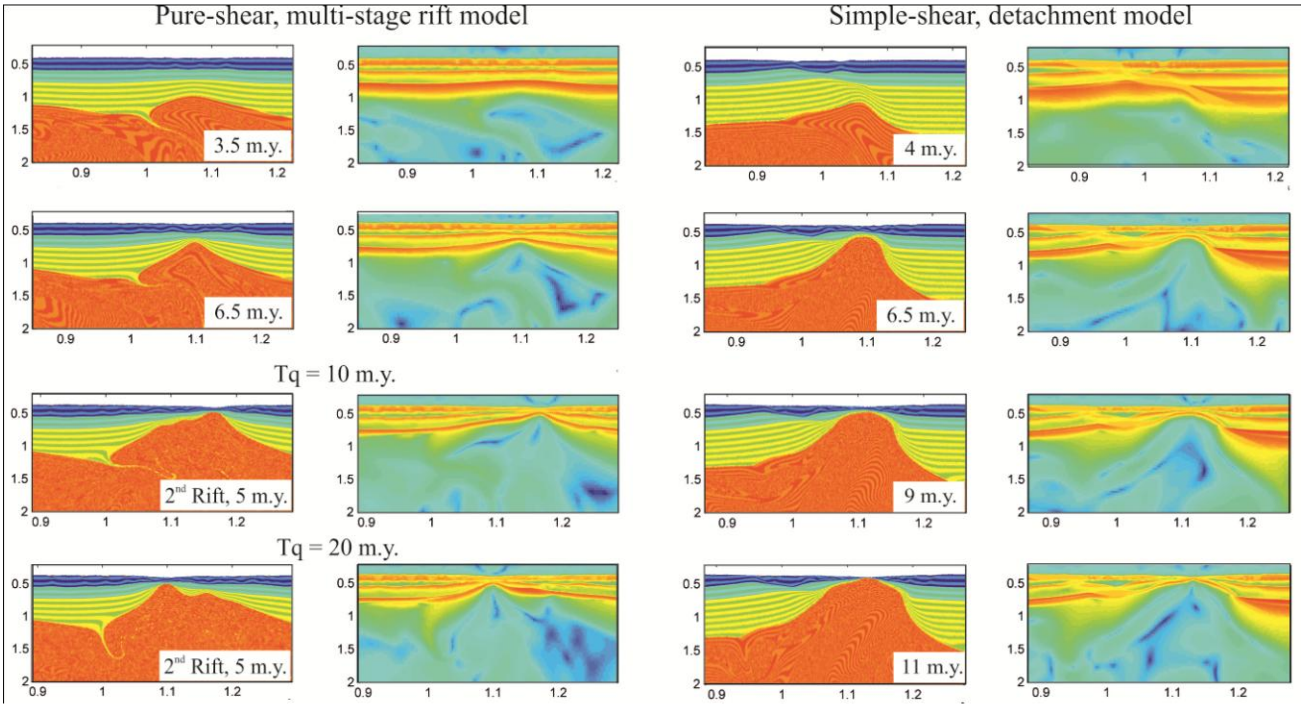


FIG.2 - Snapshots of lithology and effective stress for pure-shear (left) and simple-shear (right) models of rifting. The pure-shear model is a 2-stage rift model assuming a tectonic quiescent period (Tq) of 10 m.y. or 20 m.y between the two rift events (2 lower panels). The simple-shear model assumes a predefined weak zone at an angle of $20^0$ and initial strength of 20 Mpa.

As extension initiates, until ~4 m.y., strain focus mostly around the detachment surface, laterally offsetting the location of maximum extensional deformation in the crust and lithospheric mantle. In the proximal, lower plate margin, a large depression forms, limited by the gently dipping detachment and, on the opposite side, by a series of tilted faulted blocks. An intermediate stage in the rifting process can be then defined between 4 and 6.5 m.y., characterized by faulting in the distal, upper plate margin, ductile boudinage in the lower crust, which eventually disrupts the original detachment, and intense stretching of the mantle lithosphere within a narrow zone (<100 km). Depth-dependent stretching is pronounced throughout this period. By the end of this intermediate stage, relics of the original detachment surface are observed in the effective stress plots (FIG.2) at lithopsheric depths in the distal upper plate margin, and near the base of the crust, dipping away from the rift centre, in the proximal, lower plate margin.

From about 6.5 m.y. onwards, rifting becomes broadly symmetric, and an approximately 50 km wide area of stretched upper crust forms over extremely thinned lower crust and lithospheric mantle. Faults within the upper crust become listric with depth, possibly soling onto a shear zone. The result is a relatively symmetric deep "offshore" margin separating two shallow-intermediate margins which are strongly asymmetric, in contrast to that predicted by the multi-stage continental rifting, pure-shear model.

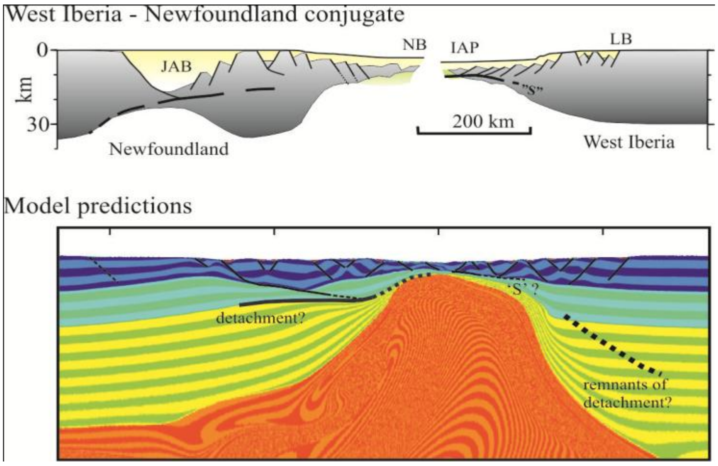


FIG.3 - Comparison between the West Iberia (WI)-Newfoundland (NF) conjugate margin system (top) and the simple-shear model predictions (bottom). The schematic representation of the WI-NF margins crustal structure is based on numerous seismic and well data (e.g. Tankard and Welsink, 1987; Reston et al., 1996; Shillington et al., 2006;) Acronyms: IAP, Iberia Abyssal Plain; JAB, Jeanne d'Arc Basin; LB, Lusitanian Basin; NB, Newfoundland Basin.

Importantly, the results presented in FIG.2 show that, regardless of the conceptual model of lithospheric extension, depth-dependent stretching is pervasive and highly variable across the margins strike. Small-scale convection in the asthenosphere is the main mechanism controlling margin-scale depth-dependent stretching, which introduces a new perspective into study of the rifting processes and questions the essence the "upper plate paradox".

## 3. Main Conclusions

1 - The introduction of convection in the rift models, with ongoing mass exchange in the thermal boundary layer at the base of the lithosphere, introduces randomness in the rifting process.

2 – Prominent conjugate margin asymmetries, associated with both lateral and vertical variations in the amount of crust and lithospheric thinning (i.e. depth-dependent stretching), may develop without an intervening major detachment surface. This could explain, for example, why margins switch from upper-plate to lower-plate

characteristics across transfer faults, as observed along strike the North Africa-East Coast U.S conjugates (Lister et al., 1986).

3 – Large-scale detachment faults or decóllements control the way strain is distributed during distinct stages of the margins evolution. We believe such a model explains the first-order asymmetries observed between the West Iberia and Newfoundland conjugate margins.

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# Salt Tectonics and Sub-salt Exploration Plays in the Essaouira Basin, Morocco

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*ABSTRACT*

*The Essaouira Basin forms part of the main Moroccan Salt Basin of the Central Atlantic Province. The salt is interpreted to have been deposited during rifting at ca. 200 Ma, as there are CAMP volcanics above and below the salt. The salt was particularly mobile in this basin, with large allocththonous sheets extruded, which are 1-2 km in thickness, and extrude up to 20 km away from vertical feeders. Sheet extrusion mainly occurred in the early Upper Cretaceous ca. 85 to 95 Ma. The salt canopy itself is interpreted to be folded on a wavelength of 10 km and amplitude of 700m, with a sediment cover of approximately 1.5 km of growth strata above the salt. This folding phase took place from late Oligocene? to Miocene times, and through to present day. The sea bed is folded, but is also undergoing extensional collapse where the sea floor has oversteepened. The recent folding has blown a lot of the shallow anticlinal traps and pre-salt targets are particularly attractive where the top seal will have remained intact.*

*There is a perceived lack of reservoir potential in the deep salt basin, after two recent dry holes. However, new seismic data has been acquired with a 10 km long streamer length and this has enabled very good imaging below the complex allocththonous salt sheets. We have identified several important channel input points which contain pre-Santonian sandstones. These reservoirs have undergone later folding below the allocththonous salt sheet. Numerous truncation and sub-salt anticlinal traps have been identified, and the basin is considered to have good potential for a working Jurassic (oil)-Early Cretaceous(reservoir) petroleum system. We will present new high quality seismic data of the Lower Cretaceous pre-salt play, which has yet to be tested.*

## 1. Introduction

This paper will present the results of a recently acquired 2D seismic data shot by Canamens Energy as part of their exploration effort in the Central Essaouira Basin where they operate 4 offshore blocks (FIG.1).

## 2. Stratigraphy

The Essaouira Basin is part of the main Moroccan salt Basin with the main rifting phase occurring from Carnian though to early Jurassic times, with salt deposited very rapidly within a 1 M yr time period around 200Ma at the same time as CAMP basalts were extruded. The original salt is interpreted to be up to 2 km in thickness in the Essaouira Basin, and was deposited rapidly into pre-existing rifted basins. Carbonates were deposited on the shelf throughtout the Hrassic up until Early Cretaceous times then the basin became inundated by clastic sedimentation due to uplift of the NW African margin. Deep water turbidite sandstones are expected in the Essaouira area, and channelized faceis are clearly recognised in the seismic data.

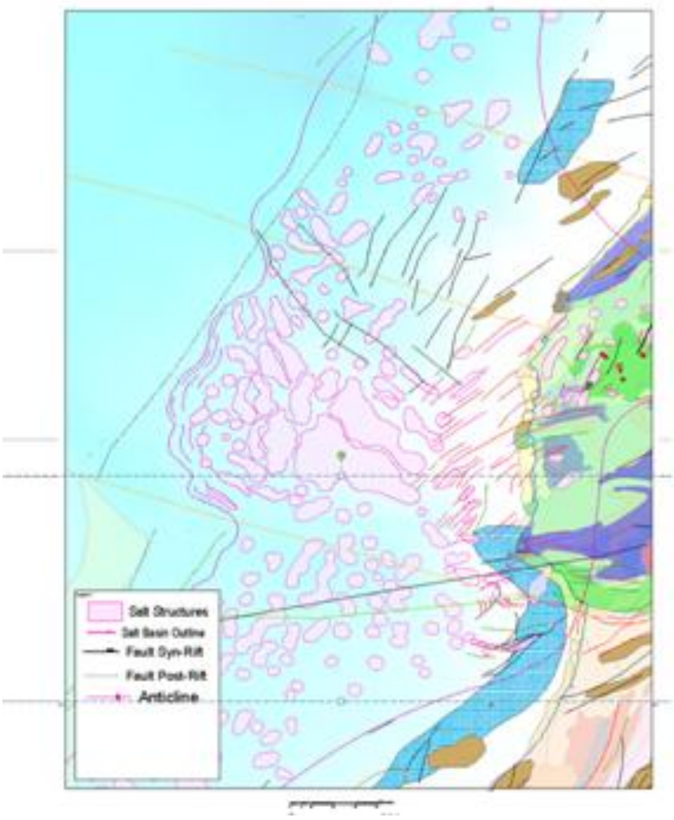


FIG.1 – Map of the Essaouira Basin showing shallow salt structures and Alpine age fold trends

## 3. Salt Tectonics

Triassic-Early Jurassic salt reaches its maximum thickness in this area, and large diapirs and allochthonous salt sheets have been imaged in the deepwater, and the diapirs extend onshore (Tari et al. 2000). Allochthonous salt canopies are present over large sections of the offshore salt basin, reaching up to 50 km in width and 2 km in thickness (FIG.1 and 2; Tari et al. 2000, Haddou and Tari 2007). The main phase of extrusion of the allocththonous sheets is timed to have initiated close to the timing of the Santonian unconformity when the basin underwent a phase of compression which squeezed the diapirs up to the surface.

## 4. Hydrocarbon Prospectivity

Jurassic source rocks can be expected in the basin, and these are probably situated within the oil window. Seismic data suggest the presence of channelized facies in the deepwater areas below the salt, and the structuring of the traps has continued through until the Miocene once oil migration has taken place. Anticlinal folds and truncation traps with a salt top seal can be expected. Hence, all the main ingredients of the hydrocarbon system are present. However the mapping of sub-salt structuring and reservoir presence is very difficult and the next phase of exploration will require 3D seismic imaging to define drillable prospects.

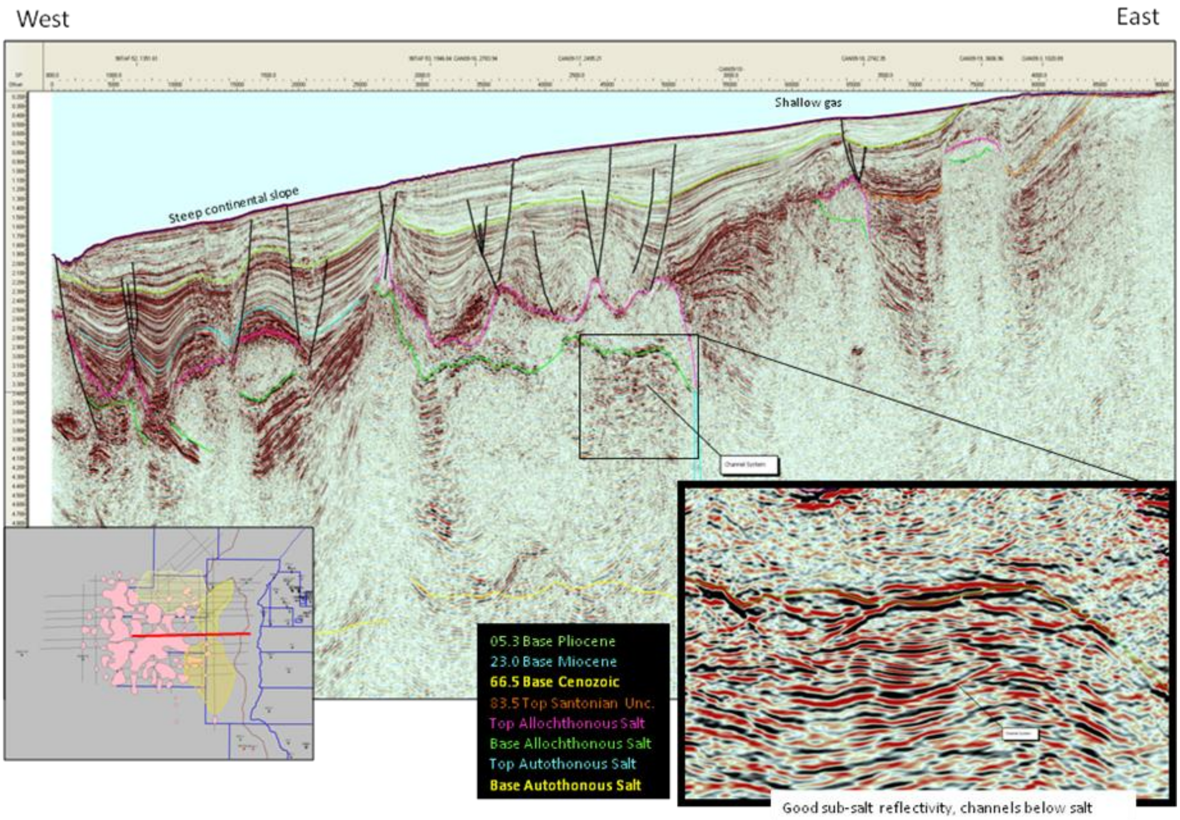


FIG.2 – Regional seismic section across the central Essaouira Basin. The detailed seismic inset indicates that sand-filled channels may be present below the allocththonous sheets, and the channels and salt sheets have subsequently been folded by later compression. Location of the study in the inset map showing the location of shallow structures in pink and possible early Cretaceous channel complexes in yellow.

*Acknowledgements*
*We would like to thank Canamens Energy Ltd. and ONHYM for permission to publish this work.*

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# Initial rifting and break-up between Nova Scotia and Morocco: An examination of new geophysical data and models

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*ABSTRACT*

*The continental margins off Nova Scotia and Morocco formed during the early Mesozoic separation of Africa from North America. The Nova Scotia margin is today characterized by a thick sedimentary basin overlying continental crust that thinned from 40 km original thickness to less than 5 km in places. The southern part of the margin is identified as volcanic, consistent with the US Atlantic margin, whereas the central and northern margins are interpreted as non-volcanic. The nature of the transition from volcanic to non-volcanic, and its recognition in various geophysical data sets on both sides of the Atlantic, have been the subject of numerous studies in previous years. This study focuses on the magnetic anomalies associated with the conjugate margins to establish the presence and extent of rift-related volcanism along the margin and explore other possible sources of the ECMA and their links to variations in rifting character along the margins.*

*KEYWORDS: Nova Scotia, Morocco, rifting, magnetics.*

## 1. Introduction

The margins off Nova Scotia and Morocco began forming during Late Triassic rifting and Middle Jurassic separation of the North American and African plates. Initial rifting formed small rift basins bounded by long, sinuous faults. Thick salt deposits accumulated in these early rift basins, later deforming younger sequences as the margins evolved. Images of deeper crustal structure show that faulting style and basin geometry vary along the margin, and beneath the central and northeastern Scotian margin the continental crust was thinned by up to 50% over 150 to 200 km distance prior to breakup and initiation of sea floor spreading. Thermal subsidence of the Scotian margin was also greater to the northeast, resulting in a thick (in excess of 10 km) post-rift succession and numerous salt structures that obscure basement and deeper structure.

Determining the nature and timing of rifting between Morocco and Nova Scotia has proved challenging. The margin to the south of Nova Scotia has clearly recognized 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 (FIG.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 most of the Scotian margin, and the magnetic anomalies on the Nova Scotia and Moroccan margins change character and fade in amplitude midway along the margins. Understanding the nature of the ECMA and WACMA is regarded as being critical to understanding the nature of rifting.

## 2. Magnetic Data and Profiles

The East Coast Magnetic Anomaly (ECMA) can easily be followed along the US Atlantic margin and much of the Nova Scotia margin. The anomaly varies in character along the margin, with several areas where offsets are noted, such as the vicinity of the New England Seamounts near 40°N (FIG.1). The changes are more notable offshore Nova Scotia, where both the trend and the character of the anomaly change. The anomaly becomes more difficult to follow to the northeast, and appears to break into two parallel components, one of which terminates near Sable Island at 60°W. The outermost branch continues until at least 58°W. It is difficult to determine the trend of the anomaly east of this location on the regional compilation of magnetic data, which was compiled and processed by the Geological Survey of Canada (GSC) from a variety of sources including aeromagnetic grids and marine surveys (Oakey and Dehler, 2004). A grid of high resolution magnetic data, acquired by Fugro in 1999 through 2001, covers the northeastern end of the margin where GSC coverage is sparse. This grid was processed and merged into the regional GSC grid for this study to allow examination of the eastern end of the ECMA. On the merged map the ECMA appears to continue until at least 57°W (FIG.2).

This study is focusing on the nature of the magnetic anomaly. Seaward dipping reflectors are seen only at the southwestern end of the Scotian margin, and there is no evidence of related volcanics further to the north or on the conjugate Moroccan margin. Interpretations of the primary seismic refraction lines in the region support this observation, with the central and eastern segments of the margin interpreted as non-volcanic (Funck et al. 2004; Wu et al., 2006). It is clear that at least part of the ECMA is related to the rift-related volcanic extrusives present along the US and southwestern Scotian margin. However, the source of the anomaly along the central and eastern part of the Scotian margin may not be related to this event, or may have been disrupted by additional tectonism during or following rifting. Various models are being developed to evaluate the range of possible source types and magnetic properties, with constraints provided by other geophysical and geological evidence.

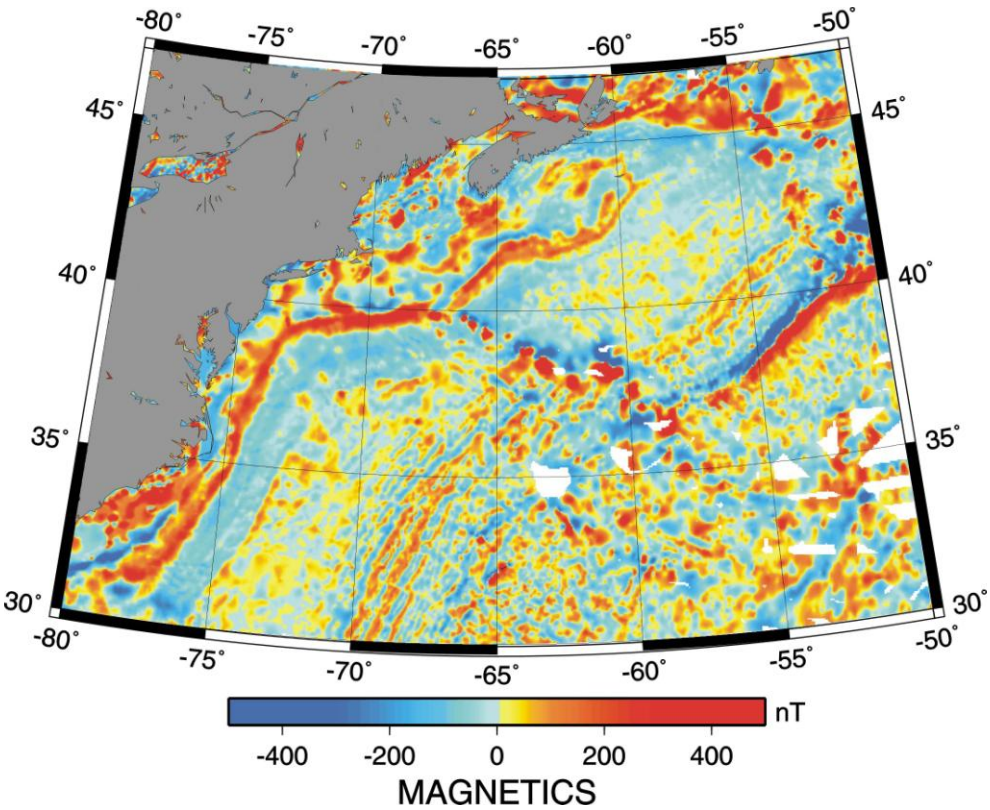


FIG. 1 – Magnetic anomalies along the US and Canadian (Nova Scotia) continental margins and adjacent ocean. The ECMA is a prominent positive anomaly along much of the margin.

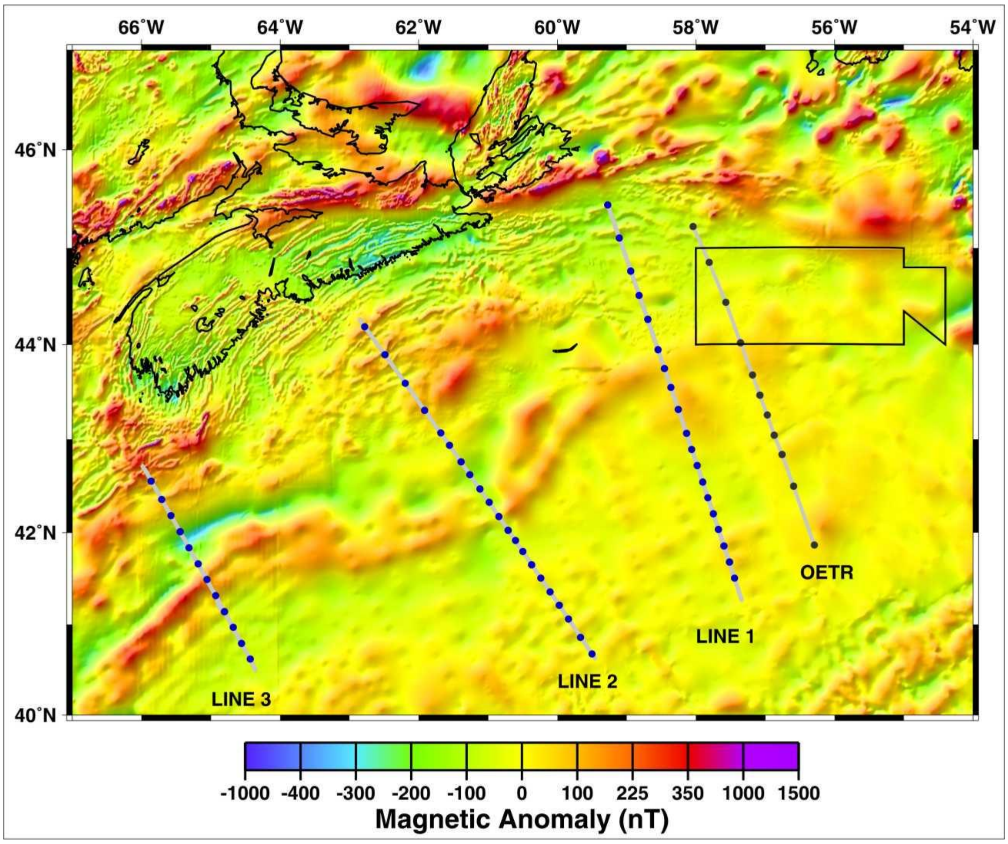


FIG. 2 – Magnetic anomalies along the Scotian margin, showing variations in trend and amplitude of the ECMA. Data from Geological Survey of Canada (Oakey and Dehler, 2004), except outlined area where data are courtesy of Fugro and Offshore Energy Technical Research Association, Nova Scotia. Lines with labels indicate locations of seismic refraction profiles.

## 3. Initial Results

Profile data, extracted along the primary seismic refraction lines in the area, show the variations in width and amplitude of the magnetic anomaly along the Scotian margin (FIG.3). Comparison with the coincident refraction models shows correlation between the crustal transition zone, characterized by high velocity material, and the position of the ECMA. However, on line 3 the ECMA also correlates with SDRs on the flank of the thinned continental crust, and this may explain the much greater amplitude of the anomaly at this location. Modelling is underway to test whether the ECMA on the other lines can be explained by a similar source body, with reduced volume or increased burial depth, or whether a distinct and separate source is associated with the anomaly.

Other evidence, ranging from geophysical (gravity, magnetics, reflection and refraction studies) to geological (volcanic age dating, salt deposition, and Triassic/Jurassic stratigraphy) is also being evaluated to garner insight into the early stages of rifting and break-up. The new interpretations and supporting evidence are being used to develop revised models for the early rifting between Nova Scotia and Morocco in order to provide a better framework for predicting palaeo environments and heat flow during the rifting process, both critical to understanding the hydrocarbon prospectivity.

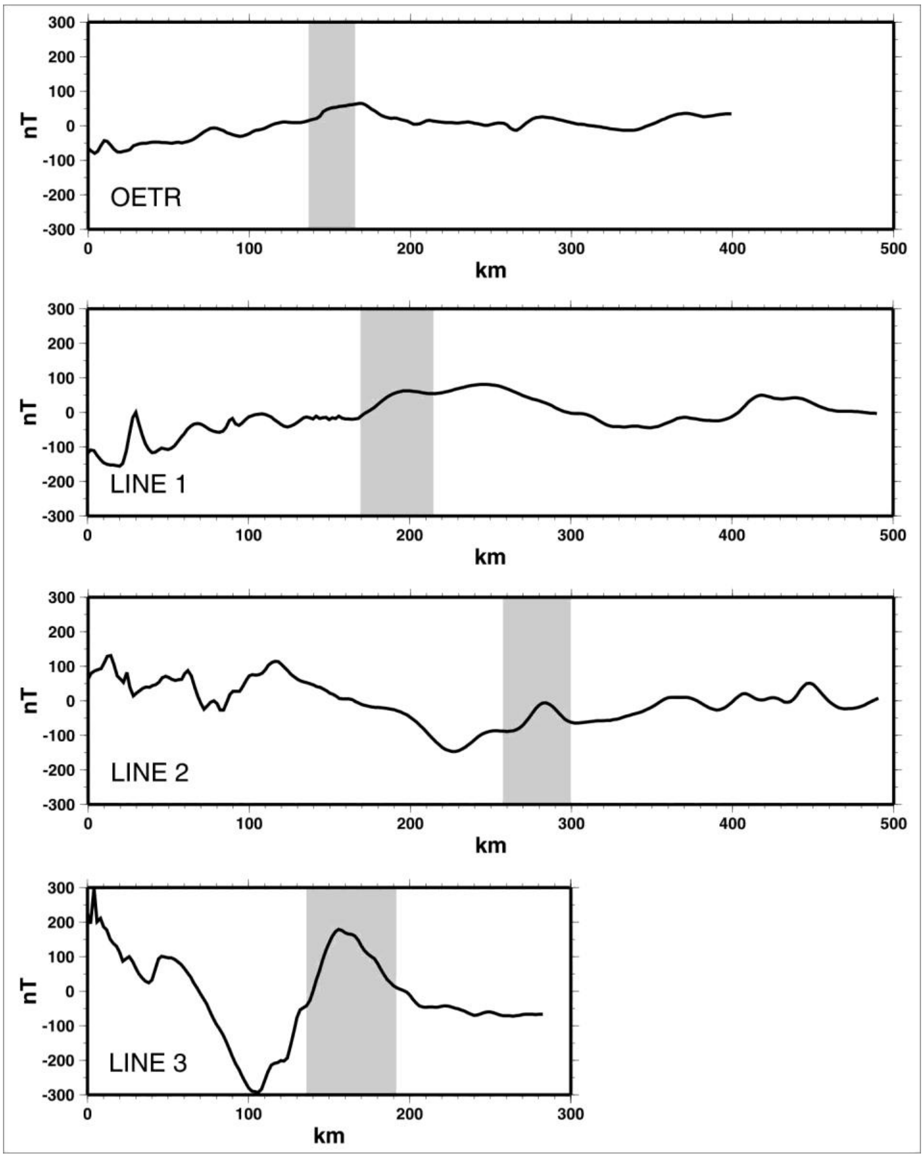


FIG.3 – Magnetic profiles along the main seismic refraction corridors shown in FIG.2 (profiles shown northwest to southeast orientation). The positive anomaly identified as the ECMA is indicated on the profiles (shaded areas).

*Acknowledgements*
*The author thanks the Offshore Energy Technical Research (OETR) Association and Fugro Gravity and Magnetic Services for permission to use the Fugro magnetic data in this study. This work is supported by Natural Resources Canada, Earth Sciences Sector, through the Offshore Geoscience program.*

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# Waveform tomography applied to long streamer MCS data from the Scotian Slope, offshore Eastern Canada

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*ABSTRACT*

*Conventional seismic imaging of complex margin structures such as salt diapirs, mass transport deposits and sequence boundaries at the edge of the shelf is often challenging even using the most advanced techniques. Determining the nature of sediment reflectors is also of great importance for exploration purposes and requires imaging beyond reflection. Waveform tomography is a method that can produce high resolution velocity fields. Modern marine acquisition with long streamers now offers the ability to record far offset arriving refracted waves. We use 2D MCS data acquired with a 9-km-long streamer over the Nova Scotia Slope. Using a frequency domain acoustic code over frequencies from 8-24 Hz, we detail how the refracted waves can constrain the shallow velocity field and image velocity inversions corresponding to weak bottom simulating reflectors.*

*KEYWORDS: Nova Scotia, seismic, tomography, inversion, hydrates*

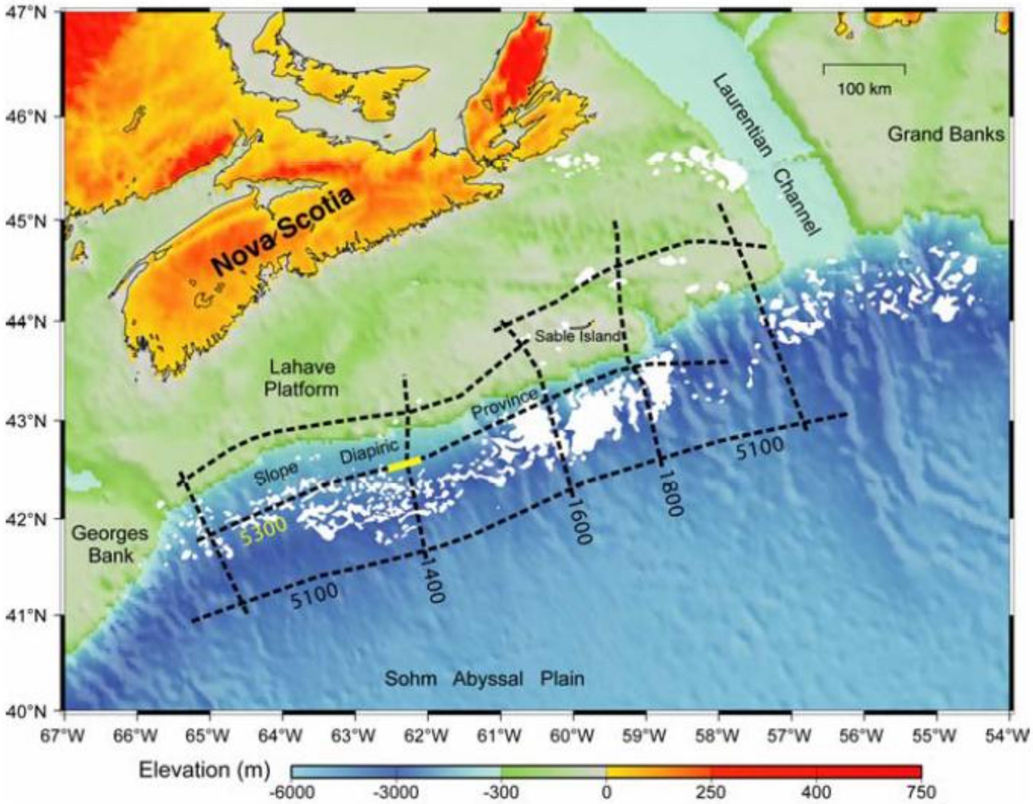


FIG.1 - Location of the Novaspan 2D lines acquired by GXT in 2003 on the Scotian slope using a 9-km-long streamer (dashed lines). The yellow section of line 5300 is used in this study. White areas represent salt.

## 1. Introduction

In this paper, we apply 2D waveform tomography inversion in frequency domain using a long streamer MCS dataset. The 9-km-long streamer 2D MCS data acquired on the Scotian Slope (FIG.1) and used in this study include refracted waves arriving earlier than the seafloor reflection and later than the direct wave (FIG.2). These waves constrain the background velocity field above their turning depth. The simple, slowly varying sedimentary environment (FIG.3) minimizes the limitation with the acoustic approximation. We first present the dataset, then describe the preconditioning and inversion strategy, and finally discuss the results in terms of possible targets of MCS waveform tomography and additional information it can provide when compared to a prestack depth migration image.

## 2. Data preconditioning

We present the Novaspan profile 5300 (FIG.1) acquired by Ion-GXT in 2003. The streamer is composed of 360 receiver groups with 25 m spacing. The shot spacing is 50 m. For the investigated 44 km-long section of Line 5300, we use 231 shots spaced every 150 m (every third shot) and all receivers.

These data are equivalent to 83,160 individual seismic traces. Because of feathering and streamer bending, the receiver positions should be defined in 3D but it is possible to find an approximate 2D geometry where fixed receiver positions can be used by different shots. Thus for line 5300, the 83,160 independent receiver positions are reduced to 1768 fixed receivers with a reduced (24.5 m) spacing due to streamer bending.

Amplitude corrections, must be applied, since the observed data are acquired with a point source, corresponding to a 3D geometrical spreading of the acoustic energy, while the acoustic forward modeling code is 2D and assumes a line source with cylindrical spreading. A simple solution is to apply an offset dependent cylindrical amplitude correction (Ursin, 1990) $(V_{rms}(t)*(t^2+x^2/V_{rms}(t)^2)^{1/4}$ where x is the offset) after NMO adjustment to normal incidence traveltime followed by reverse NMO.

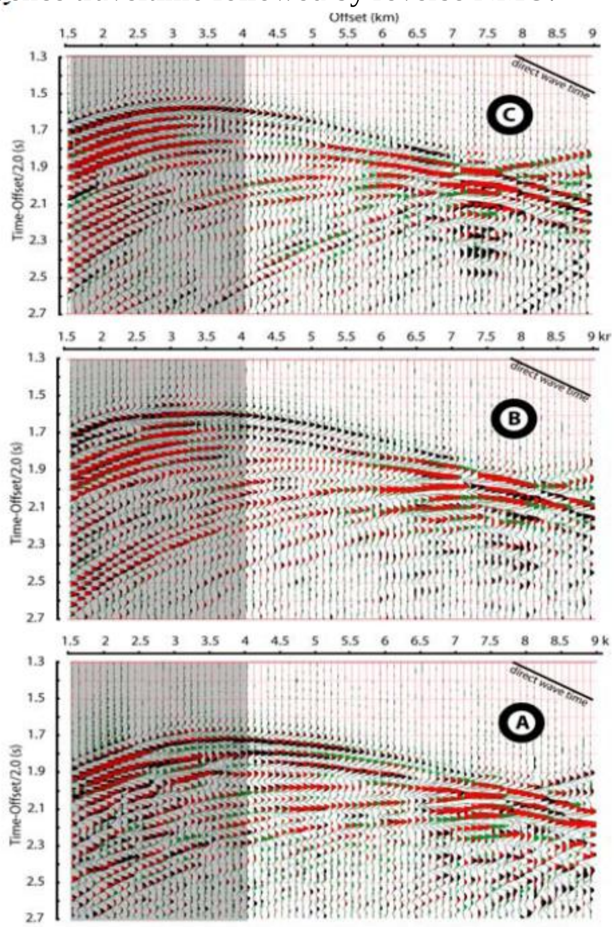


FIG. 2 - Observed (black) and modeled (green) shot gathers (f=8-25 Hz). The refracted waves on these shot gathers turn approximately at positions A, B and C of FIG.3. Area where the model and the data agree is shown in red. The wavefields are displayed with a 2 km/s reduced velocity. Shaded receivers for nearest offsets (0-4 km) are not used in the inversion. Only every 4th trace is displayed.

**3. Inversion strategy**

We use the frequency domain waveform tomography approach of Pratt and Worthington (1990) and Pratt (1999). This method is computationally efficient as the data are manipulated in frequency domain and are utilized progressively from lower to higher frequencies. This incremental frequency strategy also helps overcome the non-linearity of the wavefield inversion. For the inversion to run within a reasonable computing time (i.e. <24 hours), we limit our velocity grid size to a 3020x333 dimension, which corresponds to a 15 m spacing (45 km x 5 km) and a 25 Hz maximum frequency. Because structures are seen through different incident angles, one frequency illuminates a range of spatial wavenumbers (Sirgue and Pratt, 2004), which means that a small number of frequencies cover a continuous range of spatial wavenumbers. In our case, 9 frequencies are used from 8 to 24 Hz with a 2 Hz step.

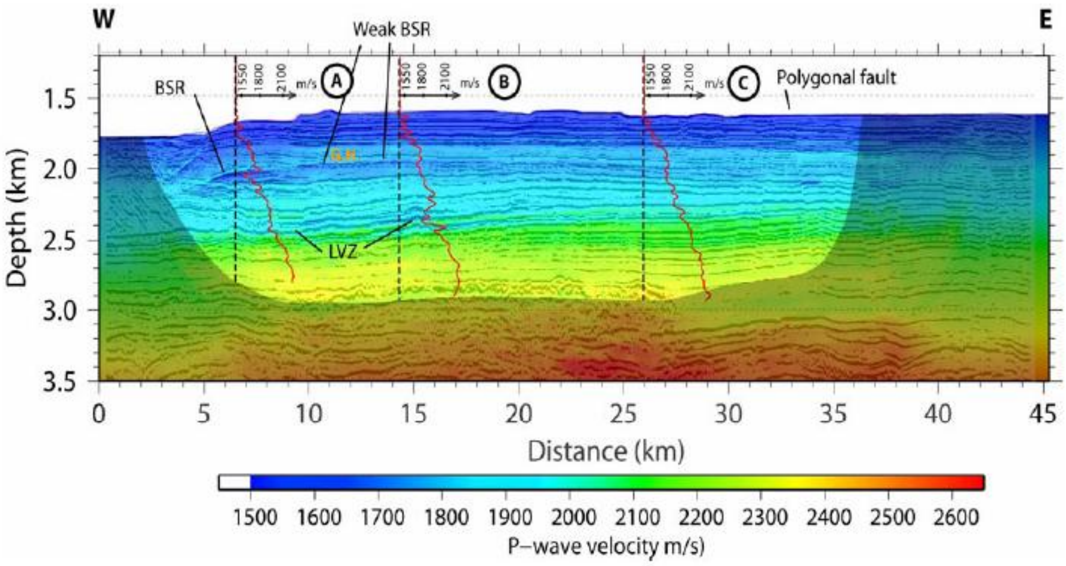


FIG. 3 - Waveform tomography velocity model for GXT line 5300 using 9 frequencies (range 8-24 Hz; step 2 Hz) superimposed on the prestack depth migrated reflection image. The BSR reflector is visible at 2 km depth between distances of 5-8 km. Red curves show velocity versus depth at three specific locations (A,B,C). These positions are also where the shot gathers on FIG.2 are located. Shaded areas are not covered by the refracted rays recorded on the 9 km-long streamer. G.H. are gas hydrates.

**4. Results**

Figure 3 shows the result of our inversion for line 5300 derived using 9 frequencies and 18 iterations. Several significant features are now derived that did not exist in the initial, smooth velocity model from traveltime tomography. First, as expected, a low velocity appears below a BSR reflector imaged on the prestack depth image (velocity profile A). Of particular interest is that this low velocity layer continues eastward where the reflection image does not show a clear BSR (FIG.3). A high velocity is also present above the low velocity layer, which is consistent with a gas hydrate layer (LeBlanc et al., 2007). The contrast between those two velocity zones gradually decreases towards the east (compare velocity profiles A,B,C in FIG.3), but it is still detected by the waveform tomography image. Deeper information can also be extracted from this new velocity field. The gently dipping reflector around 2.4 km depth acts as the ~2000 m/s limit. This dipping reflector has a strong amplitude in the western half of the profile. In the waveform tomography image, it corresponds to a low velocity zone above it (see velocity profile B, LVZ). On both modeled and field shot gathers (FIG.2), this lateral evolution is visible with a clear, long refraction event for the eastern shot gathers (profile C) and a later refraction event for the western shot gathers (profiles B and A). Lower amplitudes on shot gather B seem to correspond to the low velocity just above the 2.4 km deep reflector.

## 5. Conclusions

Waveform tomography applied to MCS data is a promising imaging method when used in a suitable environment. The relatively high starting frequency (8 Hz) and the limited weight of the refractions in the dataset make the starting velocity model a crucial element for a successful inversion. Our simple margin environment also ensures the validity of the acoustic approximation. In this simple case, the use of MCS waveform tomography appears to be adapted best to studies of shallow sediment particularly including the characterization of gas hydrate structures. The high resolution background velocity field helps to interpret a low amplitude reflector as the continuation of a strong and well defined BSR. It also associates the main sedimentary units to characteristic velocities and detects velocity inversions down to the depth limit of the turning waves.

*Acknowledgements*
*The authors thank Ion-GXT for use of the NovaSPAN seismic dataset. David Mosher (Geological Survey of Canada, Atlantic Division) kindly allowed us to use the Gundalf© source modeling software.*

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# The 'slope detachment zone' on the western Scotian Slope, offshore Nova Scotia: structural style, timing, and implications for margin evolution

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*ABSTRACT*

*The 'slope detachment zone' (SDZ) is a region of raft tectonics developed above a variably thick autochthonous salt layer on the western Scotian Slope. Detachment of cover strata was likely initiated in the Early to Middle Jurassic and is probably coincident with the development of the margins hinge zone, across which basement depth plunges abruptly. Associated thin-skinned faulting and folding continued above the autochthonous salt layer or its primary weld until the mid to Late Cretaceous. Decoupling of the deformation styles in the basement and cover strata in some cases resulted in reversals in the polarity of extensional faults above and below salt. Deformation of cover strata and the patterns of salt withdrawal were strongly influenced by basement topography, but it is not yet clear to what extent thick-skinned extension influenced the structural evolution of the SDZ.*

*KEYWORDS: Nova Scotia, Salt, Raft Tectonics, Thin-skinned Deformation, Autochthonous Salt*

## 1. Introduction – Slope Detachment Zone

Regional 2D and 3D seismic mapping efforts reveal a *ca.* 350 km long and *ca.* 15 to 55 km wide structurally distinct region covering more than 13 000 $km^2$ on the central and western parts of the Scotian Slope, offshore Nova Scotia. This region, referred to here as the 'Slope Detachment Zone' (SDZ), runs parallel to, and outboard of, the Jurassic carbonate bank and is characterized by the distinct scarcity of allochthonous salt diapirs in present day water depths that are generally between 500 to 2500 m (Fig. 1). It encompasses roughly 30% of the total area of the Scotian Slope in water shallower than 2500 m, and as such it is of significant economic and academic interest (in terms of understanding deep water petroleum systems and margin configuration and evolution). Because there are few overhangs associated with allochthonous salt diapirs in the SDZ, crustal seismic markers and faults, the autochthonous salt layer, and cover strata are locally well imaged on reflection seismic profiles. The landward edge of the SDZ closely corresponds to the structural hinge zone that parallels the Upper Jurassic carbonate bank. It separates a relatively stable platform with localized rift basins to the north, from heavily faulted and significantly thinned continental crust to the south. Its distal limit, as defined here, corresponds to the landward edge of the 'slope diapiric province' (Wade and MacLean, 1990) comprised dominantly of allochthonous salt diapirs and walls (Fig. 1). This short paper provides an introduction to the dominant structural styles in the SDZ, and provides some preliminary constraints on timing and significance.

## 2. Basement structure

Within the SDZ, strong decoupling is recognized between the structural styles above and below a seismically amorphous interval interpreted as an autochthonous salt layer corresponding to the Upper Triassic to Lower Jurassic Argo Formation (Fig. 2).

The basement morphology below the autochthonous salt layer (or its associated primary weld) is commonly rugose, with abrupt offsets believed to have been produced by a complex arrangement of horsts and grabens or half-grabens that developed during rifting (note that in this paper the term 'basement' refers to any rocks below the autochthonous salt layer or its primary weld, and the term "autochthonous salt" refers to salt that is still attached to its original depositional surface, and although the layer may be variably deformed it is still situated in its original stratigraphic position). The absolute relief of basement structures is highly variable across the SDZ, but locally exceeds 1 s two-way time. Using velocities derived from refraction seismic (Wu et al., 2006), the present-day graben-to-horst relief thus can be in excess of 2.5 km (using upper crust velocities of 5 to 6 km/s).

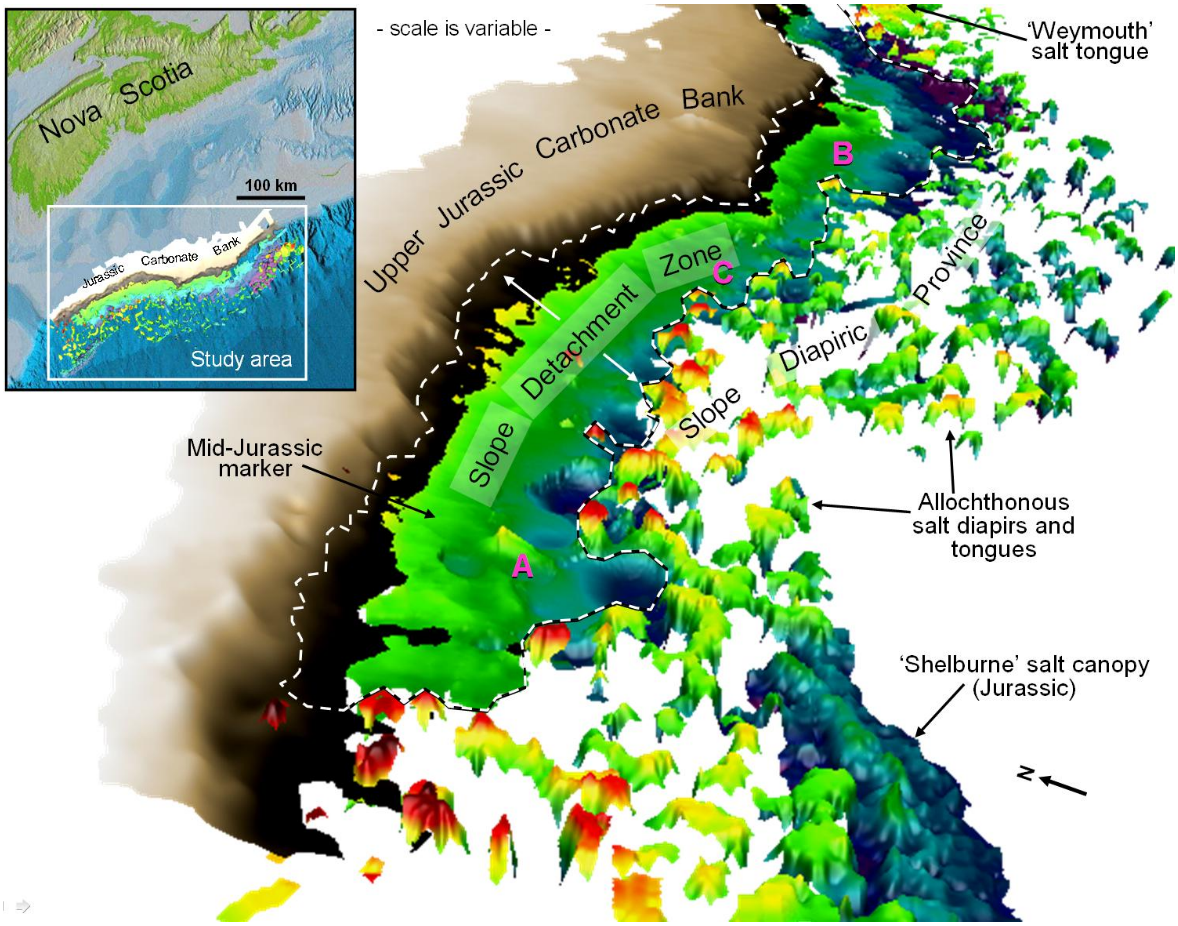


FIG.1 – Perspective view from the southwest showing the relationship between the carbonate bank edge, slope detachment zone, and allochthonous salt bodies (collectively referred to as the 'slope diapiric province' by Wade and MacLean, 1990) on the SW Scotian Margin. The 'slope detachment zone', located between the seaward edge of the Jurassic carbonate bank and the landward edge of the slope diapiric province (dashed boundary), is characterized by the distinct absence of allochthonous salt diapirs. It is an area dominated by raft tectonics above a thin autochthonous salt layer. Location of the study area is shown in the inset. "A" identifies the location of figures 2, 4, and 5 and "B" identifies the location of figure 3. "C" identifies region of thicker autochthonous salt in the central parts of SDZ.

In area "A" (Fig. 1) extensional basement faults dip towards the NW and bound *ca.* 1 to 4 km wide basement blocks with NE trending long axes that can be followed along strike for up to 20 km. In area "B" basement faults are more difficult to map but two NE trending basement highs are believed to correspond to horsts or the rotated hanging walls of half-grabens that can be followed along strike for > 25 km. In general, these positive-relief basement structures appear to have focused salt expulsion from negative-relief grabens or half-grabens (Figs. 2-3). The orientation of these basement lineaments is consistent with the orientation of a series of synrift horsts and grabens or half-grabens north of the SDZ below the carbonate bank (Emerald, Naskapi, Mohican, and Mohawk basins and ridges of Welsink et al., 1989).

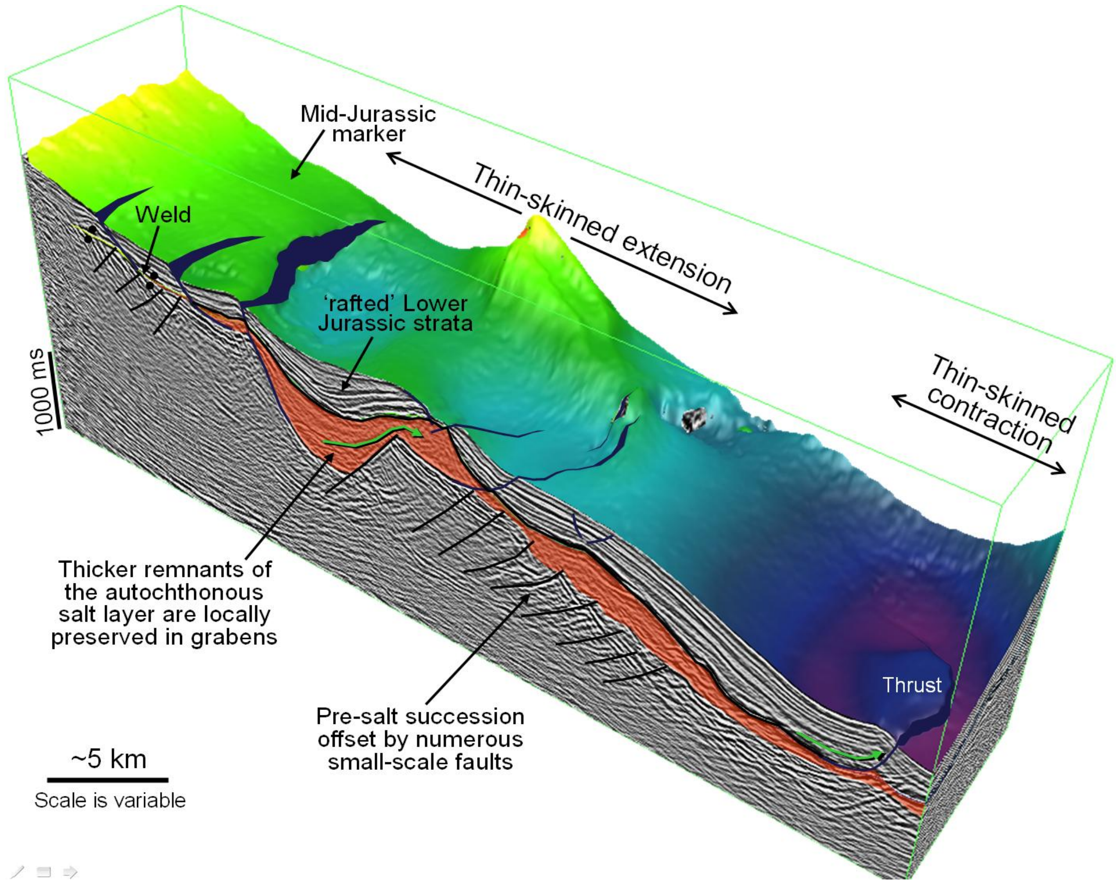


FIG.2 – Perspective view 3D seismic image across the SDZ showing both thin-skinned extension (upslope) and contraction (down-slope) of Lower Jurassic strata above the autochthonous salt layer. Thicker remnants of the autochthonous salt layer are locally preserved within grabens, and the edges of faulted basement blocks commonly localize diapirism. See figure 1 for location (A)

## 3. Deformation in Jurassic cover strata

The deformation style within the Lower to Middle Jurassic cover strata above the autochthonous salt layer (or its primary weld) is dominated by thin-skinned detachment and associated raft tectonics. Both extensional and contractional structures are recognized (Fig. 2). Jurassic strata are commonly offset along listric growth faults that sole out in the autochthonous salt layer. These faults define the headward parts of detached 'slabs' of Jurassic strata, and are commonly composed of a series of shorter arcuate fault traces that link-up across relay ramps in the cover strata to produce longer detachment trends extending along strike for > 60 km. Detachment above the autochthonous salt layer appears widespread across the SDZ and Jurassic cover strata are commonly offset at very low angles. Rafts of pre-kinematic Lower Jurassic strata can be offset horizontally by > 8 km across these faults, but more typically have translated < 2 km relative to the most proximal listric fault. Arcuate salt rollers (plan view) within the autochthonous salt layer are common, with some rollers forming linear salt highs that coincide with the sheared margins of rafted slabs. The headscarps of some detached slabs coincide with the steep flanks of underlying basement fault blocks, presumably because of the increased propensity for gravity sliding (detachment) in such areas (e.g. Fig. 3). Where the autochthonous salt basin extends northward below the Jurassic carbonate bank, parts of the outer bank foundered in a similar manner, with rotated limestone dominated blocks as thick as 1.2 s (twt) detaching above the autochthonous salt layer.

In general, slab detachment is normal to the Jurassic carbonate bank, however, the orientation of positive-relief basement blocks locally alters the detachment trajectory (e.g. on the left side of Fig. 3, a NE trending basement horst diverts the detached cover strata toward the SW). Rotation on some steeply dipping raft blocks raised their down-dip parts above regional grade, producing local angular discordances where rafted Jurassic strata abruptly terminate (e.g. Fig. 2) and are draped by Cretaceous strata. In most cases these angular discordances were generated by fault offsets in the cover strata, but in some instances they could be the product of erosion. Inflated salt or high relief basement blocks may underlie these highly rotated rafts. Locally, detachment appears to be antithetic (faults dipping towards the hinge zone), particularly in the central parts of the SDZ (area “C” in Fig. 1) where a thicker interval of autochthonous salt appears to be preserved below cover strata (compared to the NE and SW parts of the SDZ).

In the southern parts of the SDZ, there is an increased tendency toward contractional structures, including detachment folds, fault propagation folds, reverse faults and thrust faults. The down-slope contractional response in some areas is quite complex, producing squeezed salt stocks, folds with variably oriented axes, and reverse/thrust faults with variable vergence. Fold axes commonly vary abruptly (by as much as 90º) over short distances (Deptuck et al., 2009). In some instances down-building strata within grabens were buttressed against the flank of a basement block, and equivalent strata deposited above the adjacent horst were partially overthrust above the graben, producing repeated sections. Contractional structures continue into the slope diapiric province where diapirs and minibasins are commonly squeezed (Shimeld, 2004).

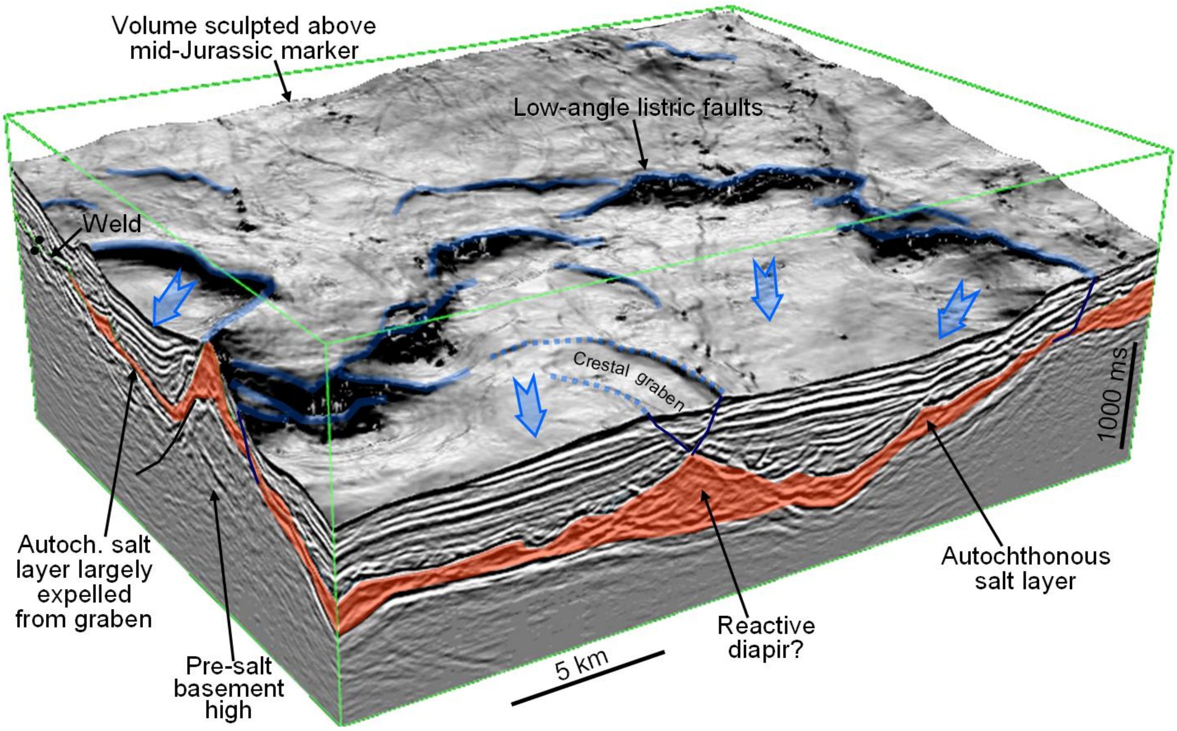


FIG.3 – Perspective view 3D seismic image across the SDZ illustrating the dominant style of slope detachment, with low-angle listric faults that sole out in the autochthonous salt layer. Blue arrows show direction of slab detachment. Note the preferential expulsion of salt along the edge of the pre-salt basement high. See figure 1 for location (B).

## 4. Timing of thin-skinned detachment

The timing of onset of slope detachment is difficult to determine because few wells are available to calibrate the age of seismically defined stratigraphic intervals above the autochthonous salt layer. The earliest deposits above the autochthonous salt layer also show evidence of thinning and thickening that are associated with a period of passive down-building into autochthonous salt and the minibasins that developed appear to predate the onset of raft tectonics. It can be difficult to distinguish these thickness variations from synkinematic growth strata associated with the raft tectonics and gravity gliding. Still, some general constraints are available. Strata of probable Early Jurassic age are characterised by a combination of prekinematic rafts and potentially synkinematic growth strata, and hence development of the SDZ could have started as early as the Early Jurassic. Most Middle to Upper Jurassic stratigraphic intervals show growth across the listric faults along the headward parts of rafts, making it clear that detachment was underway by this period. However, it is also clear that detachment of rafts was a diachronous process. For example, foundering pre-kinematic Upper Jurassic strata on the outer carbonate bank clearly took place in the latest Jurassic or earliest Cretaceous, long after the onset of rafting in, for example, area “B”. Detachment of thick carbonate blocks on the outer margin of the bank probably represents a younger retrogressive response along the margin hinge zone, across which the slope steepens abruptly.

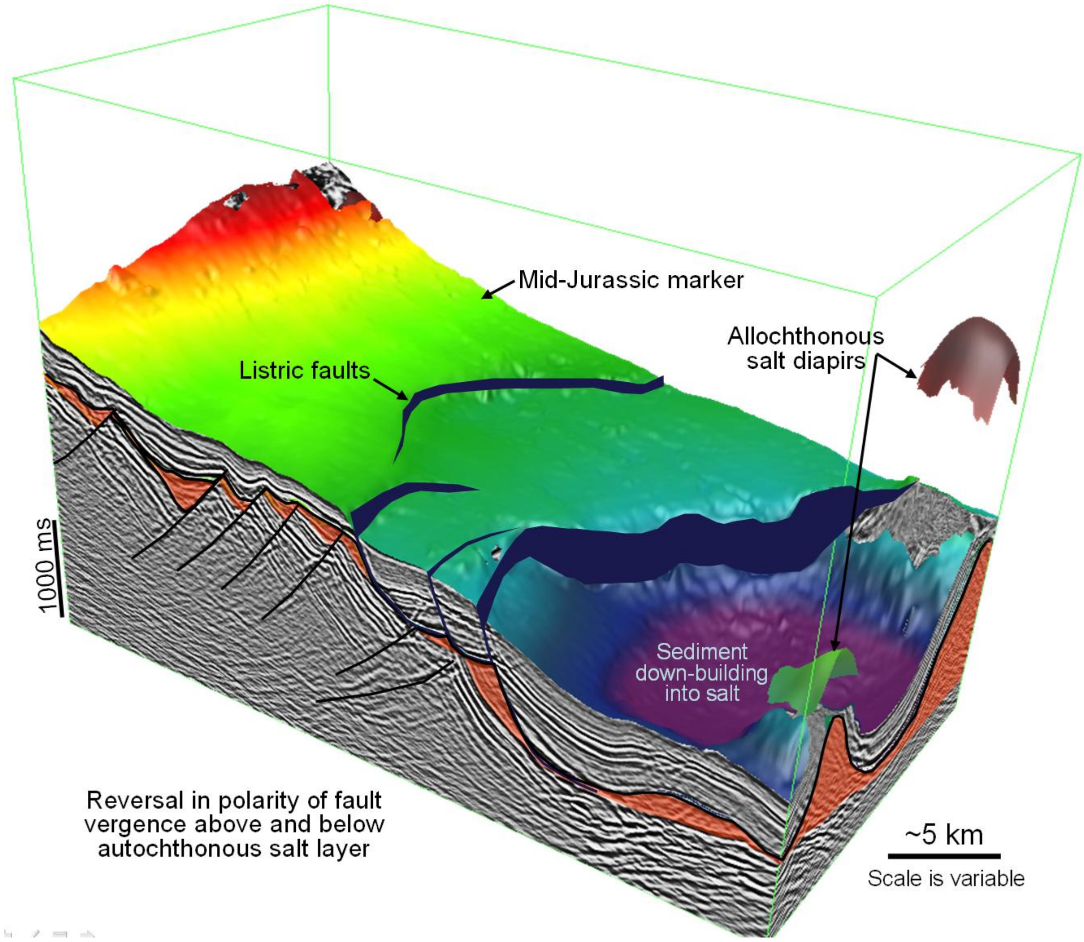


FIG.4 – Perspective view 3D seismic image showing a series of landward-dipping extensional basement faults forming a series of small half-grabens overlain by a thin interval of autochthonous salt. Lower Jurassic cover strata detach above the salt with faults dipping in the opposite direction. Right side of image transitions into the slope diapiric province with allochthonous salt diapirs.

Some listric faults continued to offset strata as young as Late Cretaceous. Likewise, fold development associated with detachment in the autochthonous salt layer in some cases also continued to deform strata as young as Late Cretaceous. As such, the onset of slope detachment may have started as early as the Early Jurassic, but was almost certainly in full swing by the Middle to Late Jurassic, and appears to have continued in a more subtle way into the mid to Late Cretaceous.

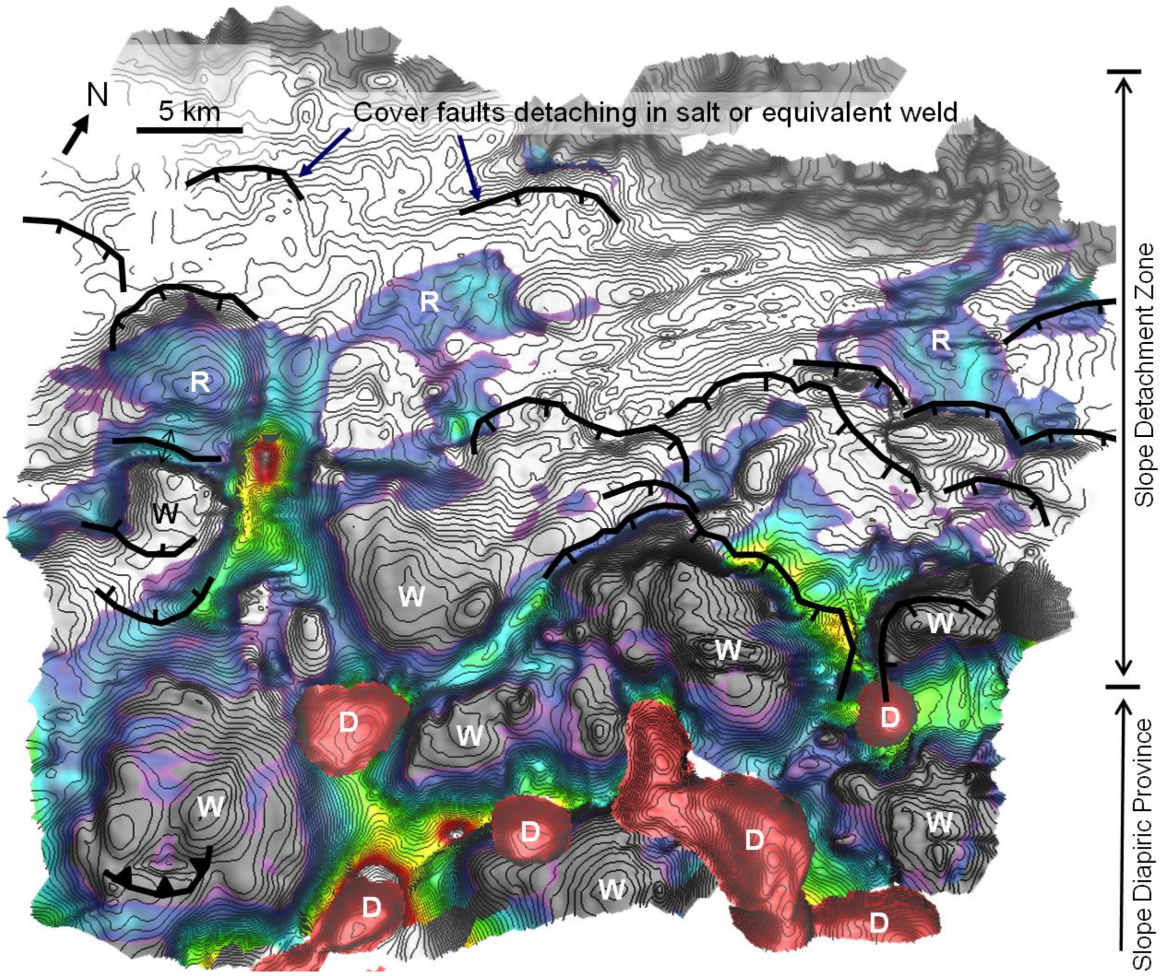


FIG.5 – Autochthonous salt time-thickness map draped on the top autochthonous salt structure map in area "A". Also shown are the faults in the cover strata that detach in the autochthonous salt layer. Red = areas where salt is greater than 1500 ms thick. Using 4400 m/s (see Shimeld, 2004), this corresponds to salt that is thicker than 3.3 km. Areas not coloured show salt that is below 100 ms (twt) or 220 m thick; R = remnants of salt preserved in grabens or half grabens (see Fig. 2); W = welded minibasins haloed by rims of inflated autochthonous salt; D = allochthonous salt diapirs on landward edge of slope diapiric province.

## 5. Why so few allochthonous salt diapirs in the SDZ?

The lack of allochthonous diapirs over much of the SDZ is believed to reflect regional variations in the original depositional thickness of autochthonous salt layer, with more salt originally accumulating in the slope diapiric province. A 3D seismic volume from area "A" (Fig. 1) spans the width of the SDZ, extending from the margin hinge zone to the landward edge of the slope diapiric province. It provides insight into the complex transition from areas of the Lahave Platform with no salt, to deepwater areas with a high density of allochthonous salt bodies. A salt thickness map from area "A" shows a proximal to distal transition from thin or absent salt, to locally preserved (and partially expelled) intervals of thicker salt within grabens and half-grabens (R) (e.g. Fig. 2). These pass down-slope into sub-circular minibasins rimmed by halos of inflated autochthonous salt (W) (e.g. Fig. 4). Most salt was expelled from the centers of these basins, the seaward margins of which marks the first occurrence of allochthonous salt diapirs and the transition into the slope diapiric province (Fig. 5). Further seaward still (to the SE), most minibasins are flanked on all sides by expelled allochthonous salt bodies. In area "A" and elsewhere along the SDZ, there is little evidence to suggest that much salt moved more than a few km seaward from the source bed during sediment loading and detachment. Instead, significant Jurassic and Cretaceous sediment down-building took place primarily along a chain of sub-circular minibasins similar to the ones shown in Fig. 5. These minibasins parallel the seaward boundary of the SDZ, with down-building accommodated by salt expulsion focused along the landward edge of the slope diapiric province (e.g. Fig. 4). Some of these minibasins developed into turtle structures. A few salt diapirs lean seaward, but salt climbs no more than a few km across time-equivalent stratigraphic intervals. Likewise, expulsion rollovers are not observed and sediment down-building dominates the slope diapiric province seaward of the SDZ (Shimeld, 2004).

The northwestern part of Fig. 5 (left side of Fig. 2) is interpreted to approximate the depositional edge of the original autochthonous salt basin in area "A". Although local areas of increased salt thickness are found in basement grabens and half-grabens, the general transition from thin or no salt above an irregular, tightly faulted basement terrain, to sub-circular depressions rimmed by swelled autochthonous salt, is interpreted to correspond to an overall increase of salt thickness towards the primary salt basin (Fig. 5). The chain of minibasins along the leading edge of the slope diapiric province probably defines the approximate boundary across which autochthonous salt was more widely deposited and consistently thick. A significant downward step in basement elevation commonly takes place across a complex series of faulted basement blocks below these minibasins (e.g. Fig. 4), and may have provided more accommodation space for salt to accumulate.

The development of extensional and contractional structures in the cover strata is believed to have been prompted by tilting of the generally tapered margin of the primary salt basin (i.e. the SDZ) during Jurassic thermal or mechanical subsidence after continental break-up. As such, the onset of raft tectonics is inferred to coincide with the initial development of the margins hinge zone, an Early Jurassic feature that overprinted pre-existing rift basins (Wade and MacLean, 1990). Landward of the hinge zone, localized fault-bounded salt accumulations below the carbonate bank (e.g. Mohican Graben complex, see Wade and MacLean, 1990) were unaffected by tilting and show little evidence for gravity gliding. The reversal in polarity of thin-skinned extensional faults above the autochthonous salt layer in the SDZ, on the other hand, provides direct evidence for an abrupt change in subsidence seaward of the margin hinge zone initiated some time after sediment down-building onto the autochthonous salt layer had already begun

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# Morphologies and emplacement mechanisms of the lava flows of the Central Atlantic Magmatic Province (CAMP) of Morocco

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*ABSTRACT*

*The morphology and emplacement mechanisms of the Central Atlantic Magmatic Province (CAMP) lava flows of Morocco are presented. Four Lava Flow Fields, emplaced in subaerial environment, are separated by sedimentary levels and paleosols representing minor periods of volcanic inactivity:* the *Lower, Intermediate, Upper and Recurrent Formations. The lava flows are either compound pahoehoe flows or simple flows. The former are almost exclusively confined to the older formations, while the later dominate in the younger formations. The CAMP lava flows of Morocco show clear evidence of endogenous growth or "inflation".The comparison of the Moroccan CAMP with other regions like the Fundy basin in Canada and the Algarve in southern Portugal indicate that the CAMP do not have a simple "layer-cake stratigraphy", but that it displays complex internal and external architectures governed by the volume of individual eruptions, the location and abundance of volcanic centres, and the evolution of the centres through time.*

*KEYWORDS: Morocco, Central Atlantic Magmatic Province (CAMP), Physical volcanology, Emplacement mechanisms.*

## 1. Introduction

The Central Atlantic Magmatic Province (CAMP), is one of the largest Continental Flood Basalt (CFB) provinces in the world, formed at about 200 Ma on four continents preceding the disruption of Pangea and the opening of the Central Atlantic and coinciding with the Triassic–Jurassic boundary and mass extinction. Voluminous data regarding the CAMP were published in the last years (e.g., Knight et al., 2004, Marzoli et al., 2004, Nomade et al., 2007; Verati et al., 2007) but the physical volcanology of the extrusive products remains sparsely investigated (e.g., Martins et al., 2008; Kontak, 2008). There is therefore considerable scope for physical volcanological studies focusing on the morphology and internal structure of lava flows and their emplacement mechanisms.

The main objectives of this study are: (i) to describe the morphology and internal structures of the CAMP lava flows of Morocco, (ii) to define lava flow emplacement mechanisms, and (iii) to discuss implications on the evolution of CAMP and other Large Igneous Provinces.

## 2. Geological setting

The Triassic-Jurassic series of Morocco are formed by two lithologic sequences overlying the Hercynian basement. Carnian sandstones and polygenic conglomerates are covered by a sequence of evaporites and pelites (e.g., Youbi et al., 2003) deposited during Norian to Rhaetian-Sinemurian (e.g., Marzoli et al., 2004). This sequence includes the CAMP volcanic pile that corresponds approximately to the Triassic-Jurassic boundary ($^{40}Ar/^{39}Ar$ ages of 196 to 200 Ma; Verati et al., 2007).

The CAMP lava flows can be found in all structural domains in Morocco except in the Anti-Atlas where this magmatism is represented by an important dyke swarm. In most basins, the total thickness of the lava pile is 100 to 200m. However, it may reach 350m or be as thin as 8 to 50m in the inter-basin areas.

**3. Results**

For the description of the morphology and internal structures of the CAMP lava flows, we followed the terminology and methodology proposed by Self et al. (1997).

The thickest lava flow sequences of the Moroccan CAMP and best preserved and most complete basaltic lava piles are exposed in the Central High Atlas (FIG.1). Four Lava Flow Fields, emplaced in subaerial environment, are recognized: Lower, Intermediate, Upper and Recurrent Formations. The Lower Fm. is a 55 - 173 m thick succession of 2 to 9 individual flows. The Intermediate Fm. (up to 130 m) is composed of 2 to 9 individual flows. The Upper Fm. (15 - 76 m thick) is formed of one or two lava flow units. The Recurrent Fm. is formed of one 5 - 50 m thick flow. These formations are separated by thin sedimentary units (siltstones, sandstones, stromatolitic limestones) and paleosols that represent minor periods of volcanic inactivity. Compound pahoehoe flows are almost exclusively present in the Lower and Intermediate Fms., while simple flows dominate the Upper and Recurrent Fms. The larger lobes forming the compound pahoehoe flows display a characteristic three-tiered structure with a thin “basal lava crust”, a dense “lava core”, and an “upper lava crust”. The later may present “tumuli”, “squeeze up” and horizontal “squeeze” structures, whereas the lava core displays segregation structures such as vesicle cylinders, spherical vesicles and vesicle sheets.

The simple flows are simple cooling units and can be traced over large distances. They also display a three-tiered structure with a thin basal zone, a dense central zone, and a thick vesicular crust. Segregation structures are rare in the central zone of simple flows.

Pillow lavas, displaying radial jointing and glassy rinds are occasionally found in the base of the Intermediate Fm. or in the Upper Fm. The pillows represent subaerial flows that entered small lakes occupying depressions on the volcanic topography. Their occurrence does not imply a generalized subaqueous environment at the time.

**4. Interpretation: emplacement mechanisms of the CAMP basaltic flows of Morocco**

The CAMP basalt flows of Morocco show clear evidence of endogenous growth or inflation (e.g. Self et al., 1997). They are similar to the inflated pahoehoe flows in Hawaii (Hon et al., 1994), the Columbia River Basalt Province (e.g. Self et al., 1997), and the Deccan Traps (Bondre et al., 2004). The features indicating endogenous growth are: (i) the three-tiered structural division of the flows; (ii) the presence of break-outs, tumuli, and associated structures (squeeze-ups and horizontal squeezes); (iii) a vertical distribution of vesicles with the presence of segregation structures.

**5. Comparison with the CAMP lavas of other regions and conclusions.**

In Moroccan CAMP, “compound pahoehoe flows” are found almost exclusively at the bottom of the volcanic pile (Lower and Intermediate Fms), while “simple flows” dominate the Upper and Recurrent Fms. Compound flows are characteristic of near-vent settings in active basaltic systems and, by analogy, are likely to represent vent proximity when found in a prehistoric succession. In contrast, simple flows, where each individual thick a'a or pahoehoe flow represents an eruptive event, are commonly found at distal locations (Lesher et al., 1999).

The volcanic products of the Algarve CAMP (southern Portugal) include subaerial lava flows, pyroclastic deposits and peperites, and contemporaneous sedimentation is dominated by mudstones and conglomerates, often containing volcanic fragments (Martins et al., 2008). The thickness of the preserved volcano-sedimentary pile is 30 and 50 m. Five to eight pahoehoe lava flows are present in the most complete sections. In terms of the terminology of Walker (1971), the CAMP lava flows of the Algarve basin are simple flows.

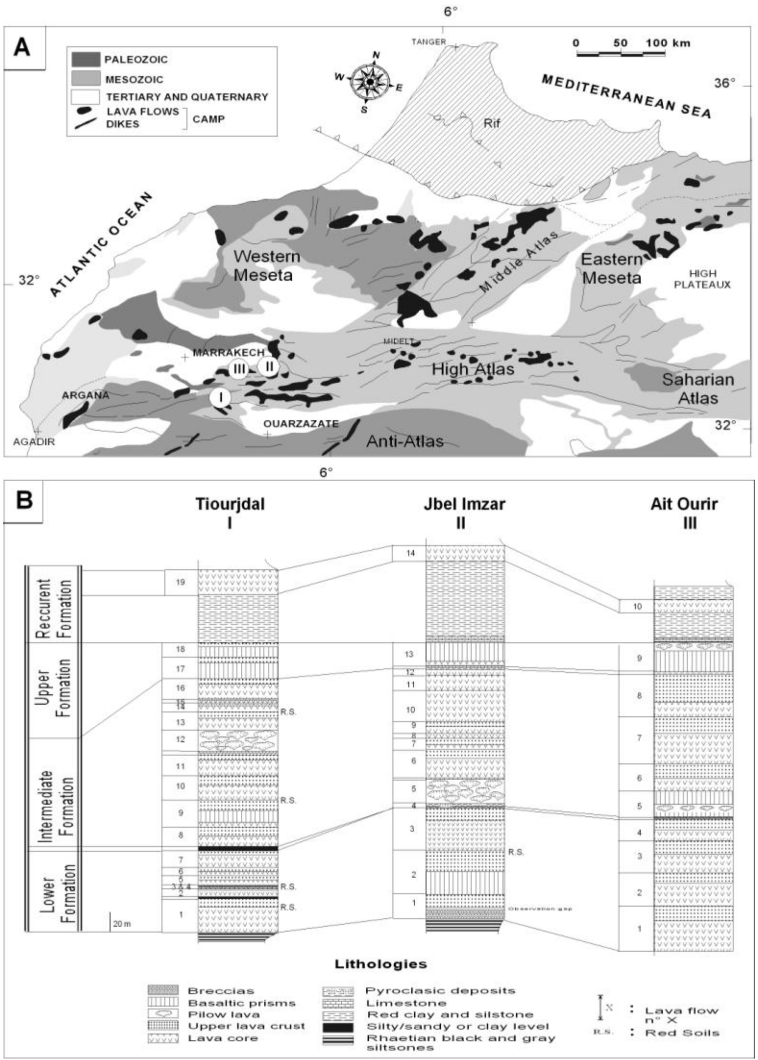


FIG.1 – (A) Simplified geological map of Northern Morocco showing the main structural domains, CAMP outcrops and the location of the representative sections the CAMP volcanic pile; (B) Lithostratigraphic columns across the CAMP volcanic complex of the Central High Atlas.

In the North Mountain Basalt Fm (CAMP of the Bay of Fundy, Canada) three lava members were defined (Kontak, 2008): (i) East Ferry; (ii) Margaretsville; and (iii)

Brier Island. The lower and upper members are massive flows with pervasive joint development on varying scales; the most notable difference between the two is the presence of pegmatite layering in the East Ferry member, whereas segregation pipes are locally present in the Brier Island member. Although neither of these flows contain internal features like the sheet lobe flows of the Margaretsville member, they are nevertheless considered to reflect products of inflation. These large flows are the products of single sustained effusive events, while numerous shorter duration effusive events are reflected in the thinner sheet lobe flows of the Margaretsville member. Thus, in terms of the terminology of Walker (1971), the East Ferry and Brier Island members are simple flows, whereas the Margaretsville member is a compound flow.

Studies on the physical volcanology of Continental Flood Basalt (CFB) provinces indicate that they do not have a simple “layer-cake stratigraphy”, but that they display complex internal and external architectures governed by the volume of individual eruptions, the location and abundance of volcanic centres, and the evolution of the centres through time (e.g., Jerram & Widdowson, 2005). In general, the architecture of most, if not all, the CFB provinces reveals that, like in Morroco CAMP, compound pahoehoe flows were followed in time by flows with a simple sheet-like geometry, indicating a fundamental temporal change in the emplacement of flows (e.g. Jerram & Widdowson, 2005). It appears that flood basalt volcanism initially starts out at relatively low effusion rate, low-volume eruptions that gradually accelerate to high effusion rate, high volume eruptions. This must reflect the common gradual increase of magma production rates pointing to similar magma genetic processes associated to the origin of CFB throughout the world.

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# Regional Setting of the Late Jurassic Deep Panuke Field, offshore Nova Scotia, Canada II: Part 2 - cuttings-based synthesis of a reef margin gas pool set within the lateral changes of a platform adjacent to a delta – a unique(?) hydrocarbon system and play type

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*ABSTRACT*

*This hydrothermally-dolomitized reef margin gas field is alone on the northwest Atlantic offshore. Its setting in the Abenaki carbonate platform as affected by the nearby large Sable paleodelta results in systematic lateral changes in carbonate slope-margin depositional properties and reef/mound types. These early settings and events in turn set it up to become a unique play type when reservoir was enhanced by burial diagenesis.*

*KEYWORDS: Jurassic reefs, sponge mounds, thrombolitic-microbial mound and slopes, Abenaki Formation, Nova Scotia shelf, carbonate play type*

Published studies (Weissenberger et al., 2006; Wierzbicki et al., 2005, 2006; EnCana 2006) give details on the hydrothermally-dolomitized reef margin gas field discovered below a depleted oil pool in 1998 and starting production in 2011. Expanding on those studies using cuttings and core data in over 25 Abenaki Formation wells, Panuke is placed in a larger context between the northeast contemporaneous major Sable Island paleodelta prograding ramp shelf and the southwest thick aggrading carbonate platform. Wells can be grouped based on geometry and position relative to the shelf margin as follows (FIG.1A & B): prograding ramp margin (only a few of the numerous wells in the Sable Island paleodelta are included), margin slope, margin with full shoaling sequence, margin with paleohighs and encased pinnacles (typical of Deep Panuke area) developed between an inner and outer margin flexure, margin inboard flexure with oolite shoals, interior platform oolitic shoals and shaly lagoon-'moat' and near-shore siliciclastic-rich ridge. The large-scale (second order?) vertical full-shoaling stratigraphic sequence is seen in nearly all margin wells (FIG.2). It comprises a basal transgressive oolite usually, then forereef with thrombolitic mud mounds, then shallow coral-coralline sponge reefs, then oolites and two types of capping beds – either oolites or lithistid sponge-rich beds. Laterally there is a curious pattern to the argillaceous sponge-rich cap beds in being flanked by wells with oolite caps both nearer the delta with sandstone interbeds and south-westward of the Panuke area wells but lacking sandstone (FIG.2 & 3 section). The older proximal oolite was buried in shallow deltaic siliciclastics while the distal oolite forms younger platform carbonates that continued growing after the intervening platform was drowned. In some cases the southwest platform top has red coated ironstone ('iron oolite') then thin glauconitic sponge-rich beds indicating slow sedimentation (see FIG. 2). There is also a regional trend in the limestone color relative to the Sable Island delta from proximal darker to distal lighter both in oolite and in slope thrombolitic-rich beds (FIG.1 B&C) that even become red and white in the most distal margin well (B-13). In B-13 the upper white oolite is cut by near vertical fractures with very thin red geopetals interpreted as Neptunian dykes fed from eroded capping marine red beds (FIG.2). Some reef types and microsolenid coral occurrences also show lateral changes. Slope thrombolites likely include microbialite ‘mud’ mounds (sometimes with branching corals) and taphonomically-complex hexactinellid sponge reef mounds. As listed and schematically shown on a section (FIG.3), these facies trends relative to the Sable Island delta and the associated early, deep prodeltaic burial are key factors that contributed to Deep Panuke’s possibly unique hydrocarbon system of reservoir (fractured reef with deep burial dolomitization), trap (stratigraphic and structural), seal (cemented oolite, sponge-rich limestone, prodeltaic shale) and charge (gas prone lignitic prodelta shale) properties. Early deltaic burial promoted early cementation of the likely calcitic oolite that then formed updip stratigraphic seals.

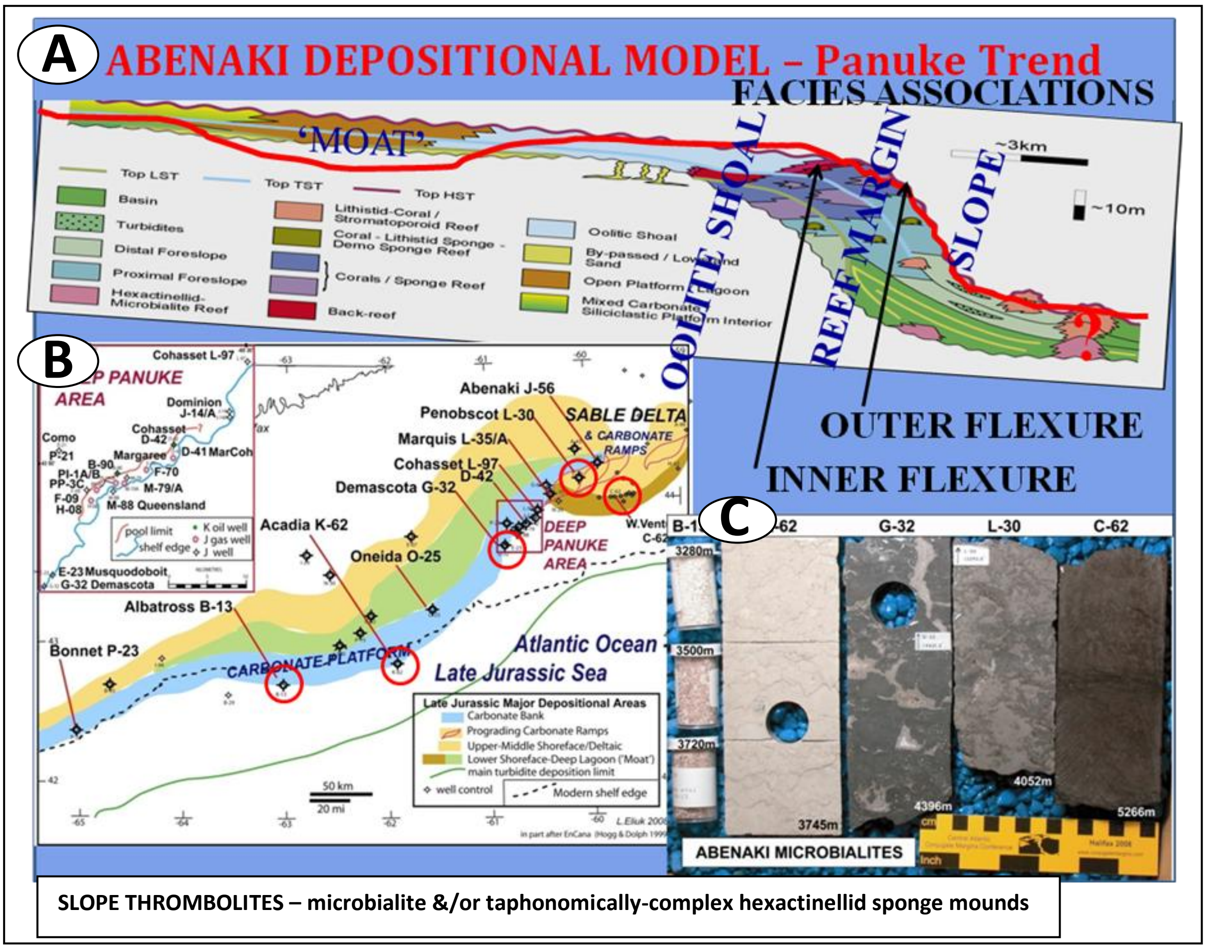



FIG.1**A-** Facies association model (modified from Wierzbicki et al. 2002) with red line showing schematic bathymetry including margin double flexures and deep lagoon/moat that helped isolate nearshore siliciclastics from carbonate platform. Note that thin sandstones helping define sequence breaks eventually are absent southwest of Sable Island paleodelta. **B.** Well location and major facies map with location of illustrated microbialites circled in red. **C.** Systematic color changes in slope thrombolites away from major delta. Note the classic stromatactis in G-32 and the red and white colors that occur cyclically in most distal B-13 indicating (?)highly-oxidizing slow(?) seafloor sedimentation.

FIG.2 - Map of carbonate margin well styles and major capping facies showing the large scale shoaling pattern in most wells after an initial transgressive oolitic limestone above the Misaine Shale Member. Thrombolites are characteristic of the slope everywhere and pass upward into coral reefal beds then oolites. But in the Panuke area and in some interior wells further southwest the Abenaki is capped by thin argillaceous lithistid sponge-rich beds that are younger away from the delta (see FIG.3). These formed in deeper water over a drowned carbonate platform with several instances of iron oolite formation either below sponge beds (P-15) or in the absence of sponge beds (O-25 and P-23). On the western shelf (K-62, B-13, P-23) carbonate sedimentation re-established or continued with an intervening drowned zone to the northeast (shown on FIG.3 section also). This same style is seen in age equivalent carbonates in a dip direction in Baltimore Canyon Trough. Oceanographic-deltaic stresses may be indicated by the oncolitic zone in K-62 (see FIG. 3). In contrast to the capping older (?Late Jurassic) oolite beds that are interbedded with sandstones near the Sable delta, the Western shelf oolite beds are much younger (possibly Barremian which is the age of the O Limestone within the Missisauga Formation Sable deltaic

FIG.2 - **continued.** sediments), lighter-colored to even white and lack sandstones. Near vertical open fractures in uppermost B-13 oolitic limestone with very thin red geopetals are interpreted as neptunian dykes from eroded capping marine red beds. In P-23 the carbonate platform is capped by red iron oolite indicating younger drowning and slow seafloor sedimentation/diagenesis. These relationships can be interpreted to indicate long-continued north-eastward-directed currents that winnow and even erode the carbonate platform after its drowning during at least two different times. Such currents would also keep fine clayey sediment of the Sable delta away from the carbonate platform during its growth. Such an oceanographic or wind-driven flow may help explain the much different style of the Abenaki carbonate shelf northeast of the Sable Delta (shown only on Fig.3 section) where thick sandstones interbed with yet thicker carbonates (Dauntless D-42, Sauk A-57).

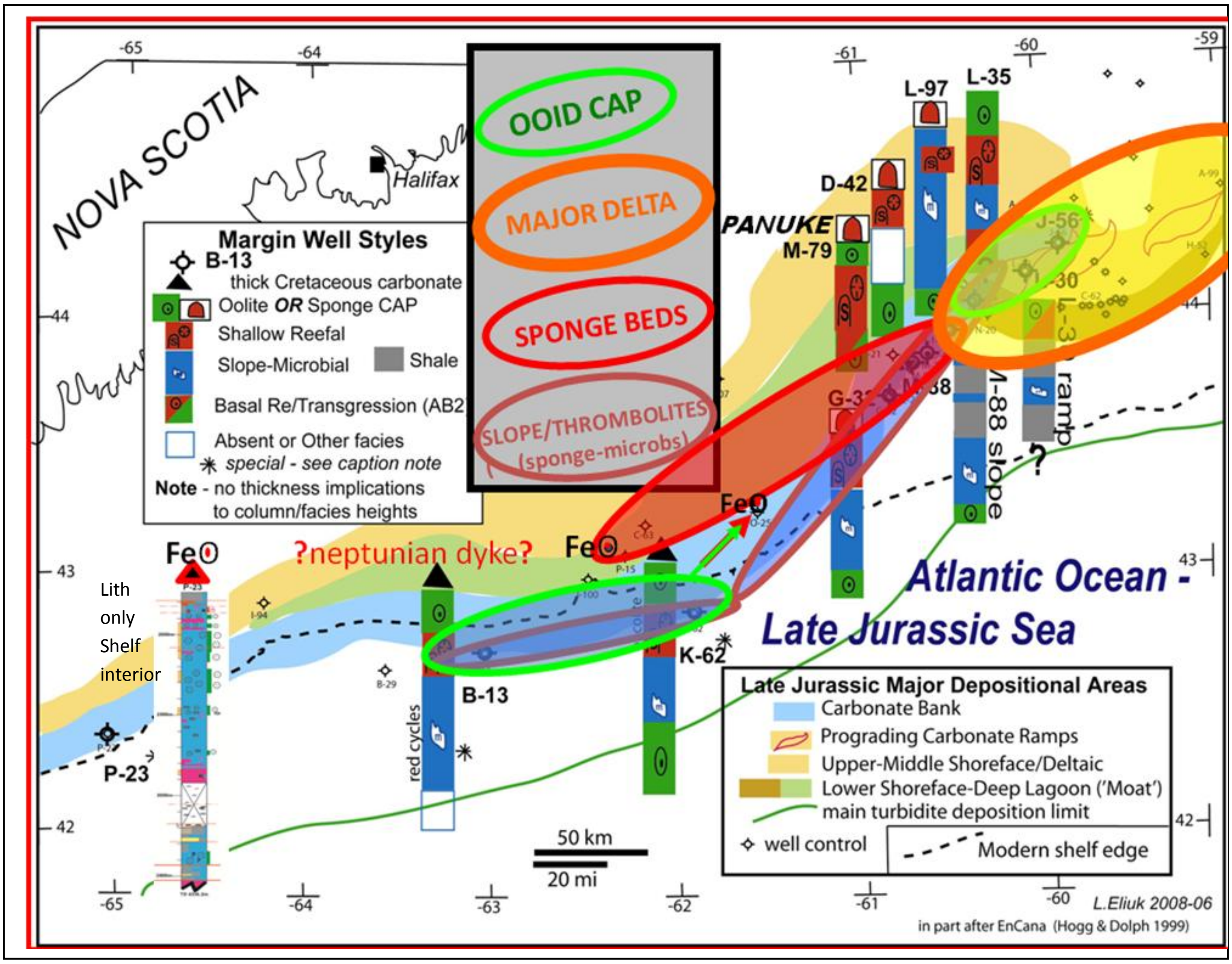
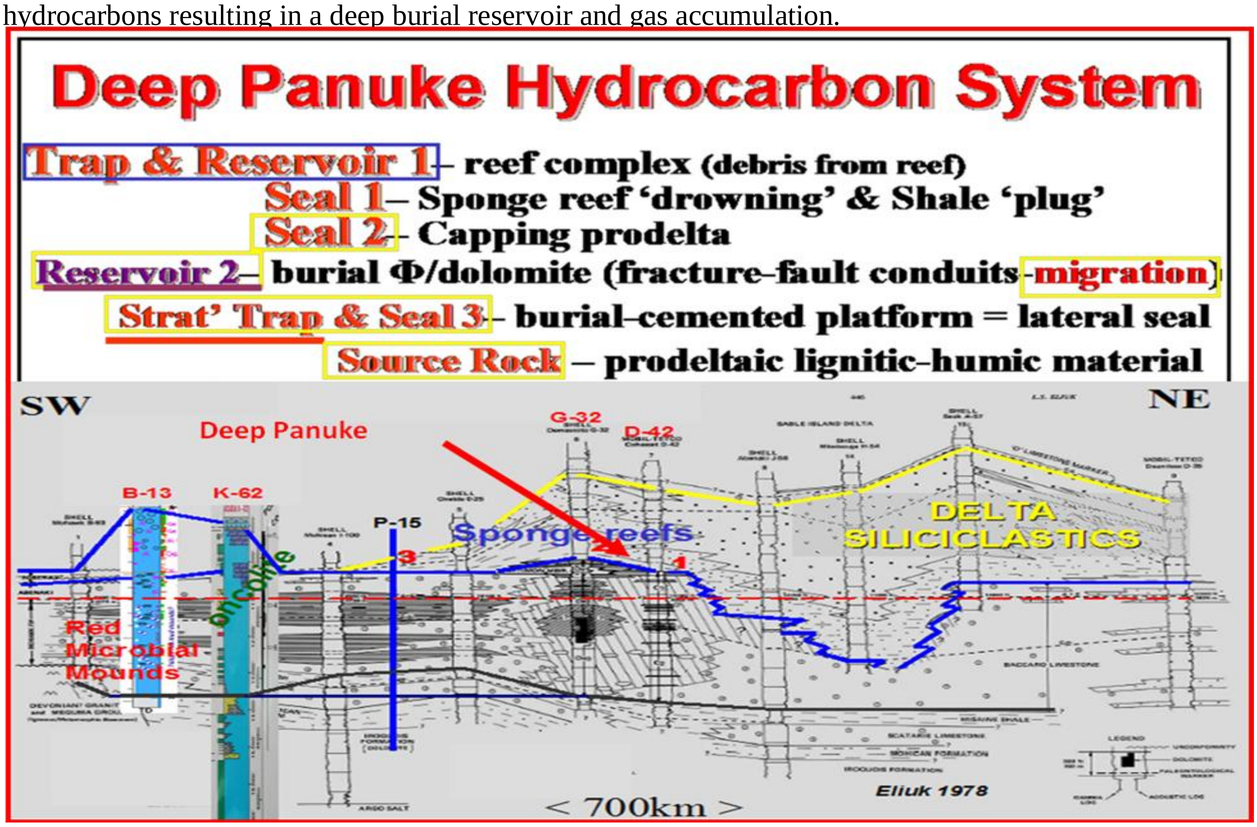



FIG.3 - Deep Panuke hydrocarbon system summary and regional dip section. As indicated by the section, Deep Panuke is possibly uniquely situated in a kilometre thick attached platform of continuous carbonate that is adjacent to a large delta apparently without intervening bathymetric or tectonic lows that typically act as siliciclastic sinks to prevent burial or environmental deterioration of the carbonate. Overtime the delta does bury some of the Abenaki platform and proximally burial seems to occur in shallow water where oolite occurred. But in the Deep Panuke area there is an intervening zone of capping sponge reefal beds that grew in deeper water adjacent to prodeltaic shales- #1 oldest to #3 youngest. In the most distal settings the platform drowned prior to onset of sponge-rich sediments or even in their absence as indicated by red coated ironstone ('Fe-oolite') beds. On the Western Shelf far from the delta, carbonates continued growing even if temporarily drowned or exposed and finally were long exposed on the seafloor before eventual burial in much younger shales. The consequence of this setting and history is a hydrocarbon history that has aspects of a delta such as capping prodelta beds to give lignitic-humic source rock and seal. But the reservoir and trap is the carbonate reef margin itself. But perhaps due to

FIG.3 - **continued.** early cementation in the highly saturated late Mesozoic calcite seas and burial cementation from the rapid and deep burial in deltaic sediments; the adjacent updip platform limestone, even the oolite, is non-porous. So it acts as a lateral seal giving a partial stratigraphic trap. Even prior to prodelta shale, the argillaceous sponge reefal beds also gave a top seal. At the Dominion J-14 well, there is an anomalous shale pod in the shelf margin that acts as a lateral 'plug'. Dominion J-14A side-tracked near horizontally from J-14 found shallow reef but no dolomite nor porosity over one kilometre. The shelf margin position localized by probable underlying tectonic paleohighs makes fracturing and faulting both highly likely and highly variable. This provided migration conduits for dolomitizing fluids and later hydrocarbons resulting in a deep burial reservoir and gas accumulation.





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# Regional Setting of the Late Jurassic Deep Panuke Field, offshore Nova Scotia, Canada II: Part 1 - Distant and fractal analogues and possible process controls for a thick carbonate platform flanked by a large delta.

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*ABSTRACT*

*Deep Panuke shelf margin gas field is possibly uniquely situated on a thick carbonate shelf beside the large Sable Island paleodelta. To help assess controls on this rare relationship two analogues are offered – a fractal analogue of the present-day Atlantic continental shelf off North America and a distant analogue of the Neogene (especially Miocene platform) northern Great Barrier Reef as it grades into the Fly River delta in the Gulf of Papua. Controls on these analogues plus Late Jurassic seawater chemistry give insights into likely controls on the Abenki platform-Sable delta relationship.*

*KEYWORDS: Nova Scotia shelf, Abenaki Formation, mixed carbonates-siliciclastics, Late Jurassic reef gas field*

Deep Panuke, discovered in 1998, is the only carbonate gas field in the eastern North America continental shelf. This shelf margin reef complex pool occurs between the northeast contemporaneous Sable Island paleodelta prograding ramp shelf and the southwest aggrading carbonate platform. This juxtaposition of a thick continuous carbonate platform so close to a large delta is extremely rare in the geological record and was thought to be unique. However at least two analogues are possible. The utility of analogues is not exact duplication; rather similar patterns may help infer similar control processes and principles at work. This better understanding aids future exploration and exploitation. From north to south, the Panuke pattern to match in the uppermost Abenaki (Latest Jurassic-early Neocomian age) is a large delta burying the shallow carbonates and passing laterally from prodelta shales to diachronous deeper sponge reefs to starved sediments (coated ironstone = 'iron oolite') on a drowned shelf to continued shallow platform oolite and coral reef growth (Fig. 1A). The fractal analogue (self-similar at different time and space scales) is the North American eastern continental shelf margin itself (Fig. 1B). The Jurassic gigaplatform (Poag 1991) is mostly buried in siliciclastics until the deep Blake Plateau that is thinly covered in starved sediment with major evidence of seafloor diagenesis (and even minor deep-water coral reefs) where shallow carbonates drowned in the Aptian but continue growing off Florida and in the Bahamas. Some relevant process controls are northward plate tectonic drift (paleo-latitude/climate changes), erosive-inhibitory oceanic currents (Gulf Stream), subsidence and eustatic sea-level changes. The distant analogue in both time and space is the Neogene northern Great Barrier reef system in the Gulf of Papua with the large Fly River delta siliciclastics input that buried a drowned Miocene carbonate platform and southward the world's largest barrier reef continues growing (Andre Droxler pers. comm. AAPG short course 2010 & references especially Tcherepanov 2008). For varied time including to the present day, proximal shelf margin reefs and outboard atolls continued growing. One encased in deltaic clastics reservoirs the undeveloped Pandora reef gas pool. Control processes on carbonate platforms involved are (in part based on Davies et al. 1989) in long term – plate motions northward and subsidence; in short term – rifting (pre-existing topography), eustacy, climate (variations through Neogene), oceanography (for instance Miocene phosphate inhibition of reefs and particularly East Australian Current that swept deltaics northward from carbonates), collision (change from passive to active margin of Papua-New Guinea). Both these analogues have lessons to help understand the Abenaki platform-Sable delta juxtaposition. Differing sea-water chemistry of Neogene aragonitic seas versus Jurassic-Cretaceous calcitic seas (much greater oolite) is a key difference.

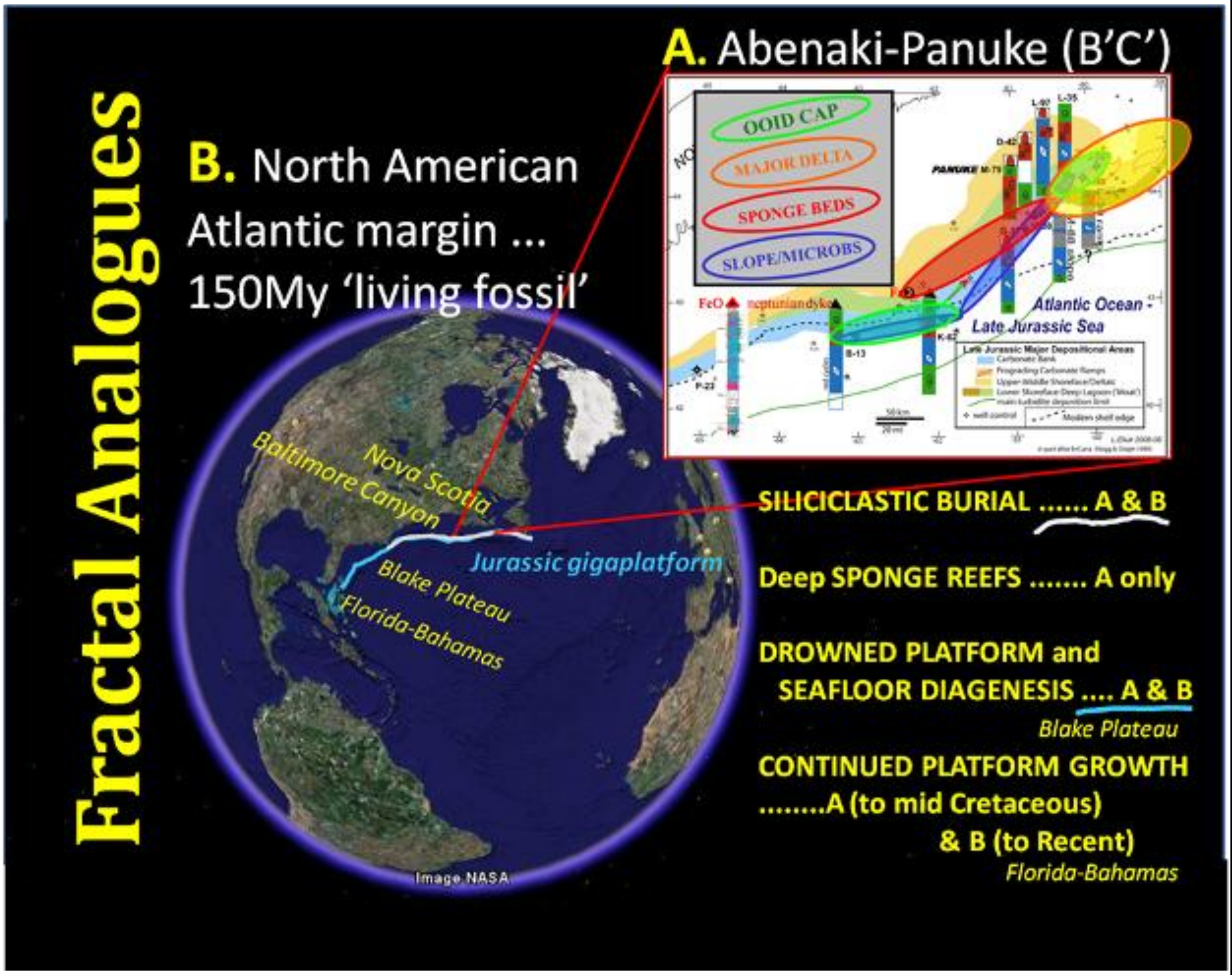


FIG.1 - Fractal analogue comparison. **A.** Abenaki-Panuke (Late Jurassic-early Neocomian) near end of carbonate sedimentation with deltaic burial on NE through deep sponge reefing on drowned platform with iron-ooid starved seafloor diagenesis to continued carbonate growth on SW (see Eliuk 2010 Fig. 2 this conference for details). **B.** Modern North American Atlantic continental margin with Late Jurassic gigaplatform from Grand Banks to Bahamas buried in siliciclastics as far south as Blake Plateau where it is drowned but thinly buried or exposed with seafloor diagenesis but still growing in the Florida-Bahamas as a 150 million year old 'living fossil'. Probably the north-flowing Gulf Stream that winnows and erodes the Blake Escarpment and Plateau had an early equivalent in the Latest Jurassic that aided growth of the Abenaki platform by keeping Sable paleodelta clays-nutrients off the carbonates. This suspect current may also explain the margin profile seaward of Oneida O-25 of a distally-steepened ramp and O-25's abrupt Late Jurassic termination of Abenaki Formation limestone with a red coated ironstone ('iron oolite') cap.

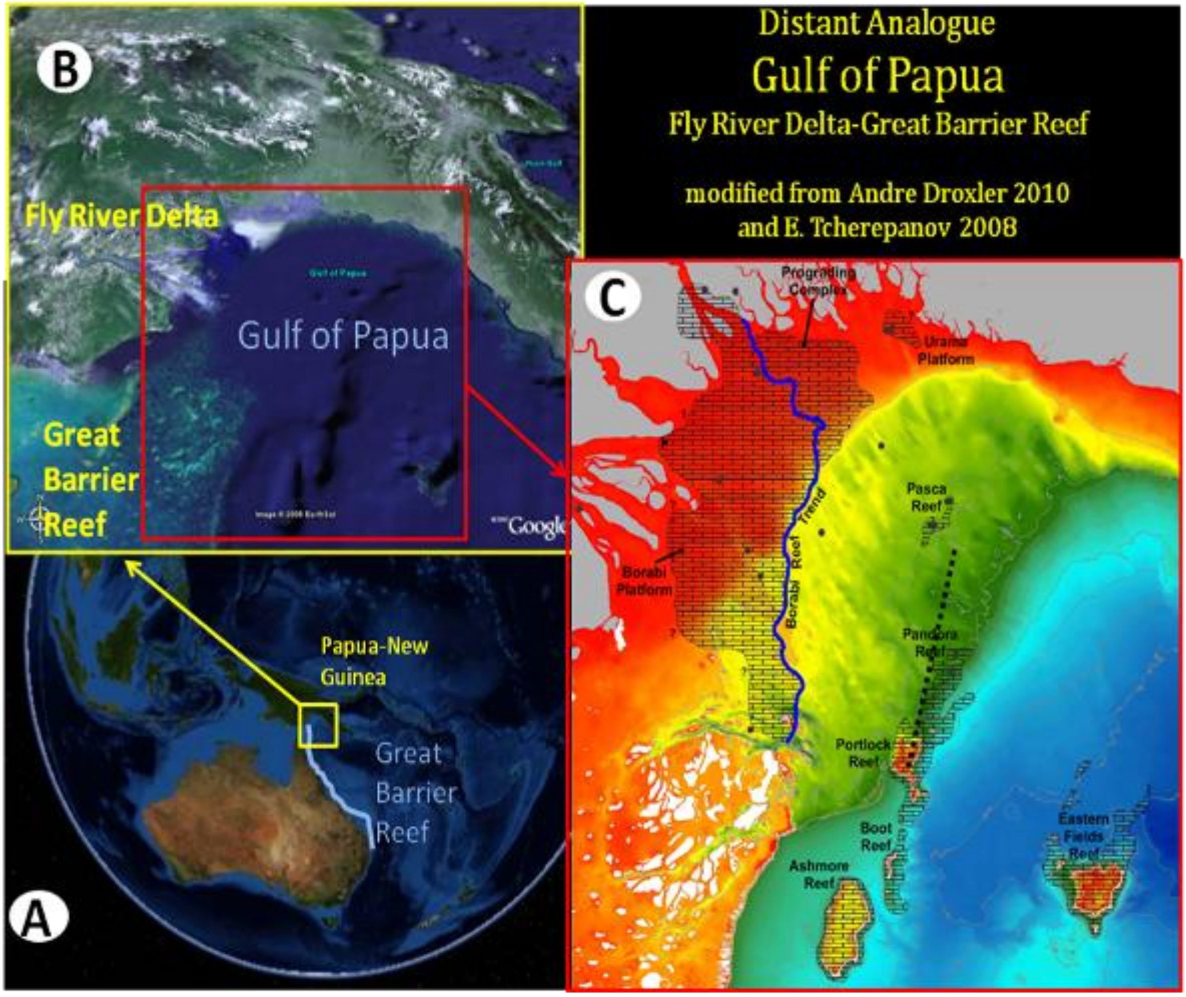


FIG.2 - Distant Analogue - Gulf of Papua. **A.** Southern hemisphere showing Australian Great Barrier Reef that goes north into Gulf of Papua. The equator is just north of Papua-New Guinea. Globe is about the same scale as in Fig. 1 thus showing the Late Jurassic gigaplatform was perhaps twice as long initially. But over geologic time plate tectonic drift northward took the Abenaki out of reef-favourable climates as it took the Great Barrier Reef further into them. **B.** Satellite view of Gulf of Papua showing contemporaneous existence of isolated reef complexes (Portlock, Boot, Ashmore, Eastern Fields mainly growing on earlier Miocene reefs) separated by deep water from the Fly River Delta and also Great Barrier Reef patch reefs on the adjacent shelf. **C.** Map showing drowned Late Miocene platforms in blue block symbol with attached Borabi platform partially buried (red) at a slightly later time by Fly River Delta. Dashed line indicates seismic line going through Pandora reef gas discovery from deltaic foresets south to still growing Portlock Reef that is shown in Fig. 3B.

FIG.2B, 2C and 3B are from Prof. Andre Droxler's 2010 AAPG Short Course. Andre and his student Dr. E. Tcherepanov are heartily thanked for them and for introducing me to a fascinating story that has some extremely enlightening similarities to the Abenaki carbonate platform-Sable Island delta relationship. Interestingly, drowning of the Miocene platform occurred well before burial in the Fly River Delta sediments and is contemporaneous with several other Neogene carbonate platform drownings so that global eustacy and oceanographic changes (not specified) are given as the ultimate causes rather than proximity to a delta. There is no apparent sponge reef facies equivalent associated with the Fly Delta-drowned carbonate platform. Also oolite is much rarer in the Gulf of Papua Neogene limestones than in the Abenaki platform (pers. comm. J. Packard of Talisman).

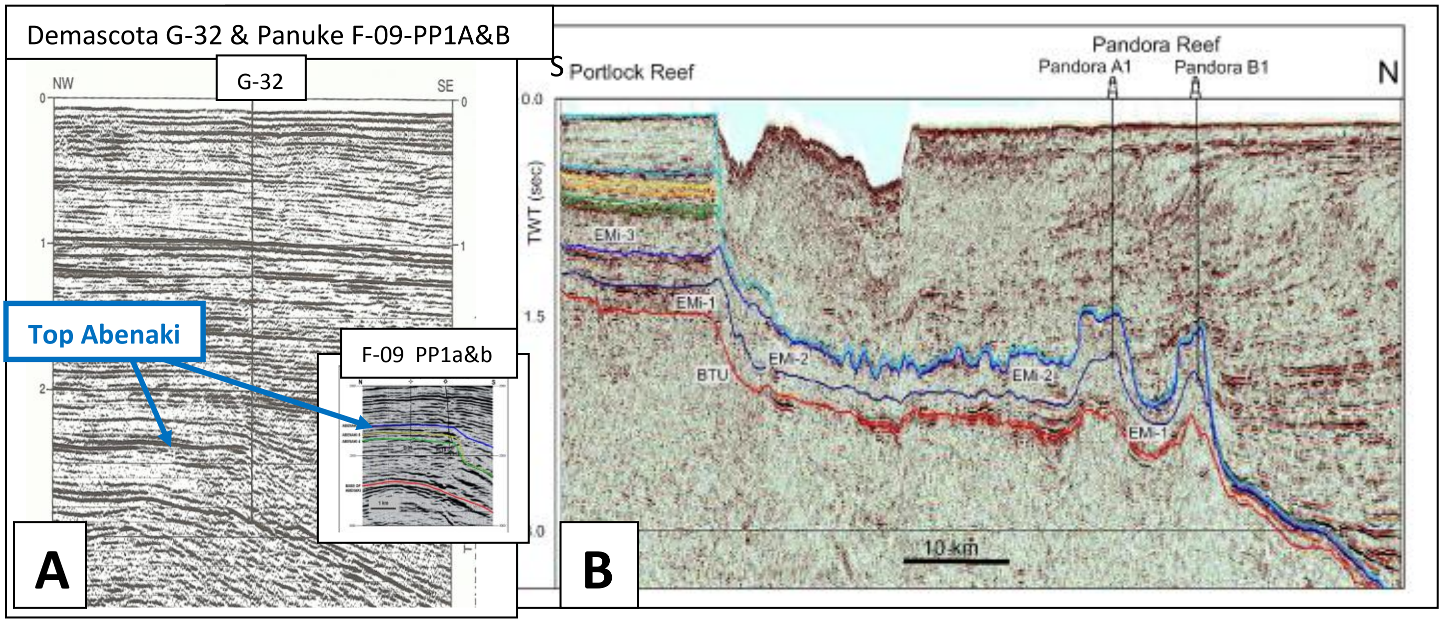


FIG.3 - Seismic sections from sea level down to carbonate platforms/reefs from Panuke trend off Nova Scotia (NS) and Gulf of Papua (GoP) at same vertical time scale. **A.** Dip seismic line just south of Deep Panuke Field (NS) through Demascota G-32, first reef-bearing well drilled, showing greater depth and lower relief than GoP Pandora gas-bearing reef. **Inset** (from Kidston et al. 2005) shows a dip line at Abenaki carbonate level through the bank interior tight oolitic Panuke F-09 to gas-bearing PP-1B that was deviated from PP-1A whose dolomitic porosity was developed below the gas-water level. **B.** South-north GoP line (see Fig. 2c for location) showing still-growing Portlock isolated reef localized by older Miocene reef and buried gas-bearing Miocene Pandora reefs with overlying Fly River prodeltaic clino-forming sediments

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# A re-assessment of the organic maturation and palynostratigraphy of the wells Ruivo-1 and Corvina, offshore Algarve Basin, Portugal

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*ABSTRACT*

*The Algarve Basin is the southernmost geological province of Portugal. The knowledge of its offshore geology is limited to a few hydrocarbon exploration wells and seismic profiles. Two of these wells, Ruivo-1 and Corvina, were studied in order to assess its organic maturation levels and age using the biostratigraphy of dinoflagellate cysts. The well Ruivo-1 intercepted a thick Callovian succession whereas the well Corvina intercepted a thick Oxfordian succession. Both Jurassic successions are within the oil-window.*

*KEYWORDS: Offshore Algarve Basin, Mesozoic, Organic Maturation, Dinoflagellate cysts*

## 1. Introduction

The exploration wells Ruivo-1 and Corvina, located in the offshore Algarve Basin, Portugal (FIG.1), were drilled in the mid 70's. The material (cuttings) available from both wells was studied in order to assess its organic maturation levels and age using the biostratigraphy of dinoflagellate cysts. 31 samples were collected from the wells, 15 from Ruivo-1 and 16 from Corvina. The samples were prepared using standard palynological processing techniques involving acid digestion (Wood et al., 1996). The organic residues obtained were sieved and mounted on microscope slides for palynological, spore colour and fluorescence studies. The organic residues for vitrinite reflectance measurements were mounted using the method described by Hillier & Marshall (1988).

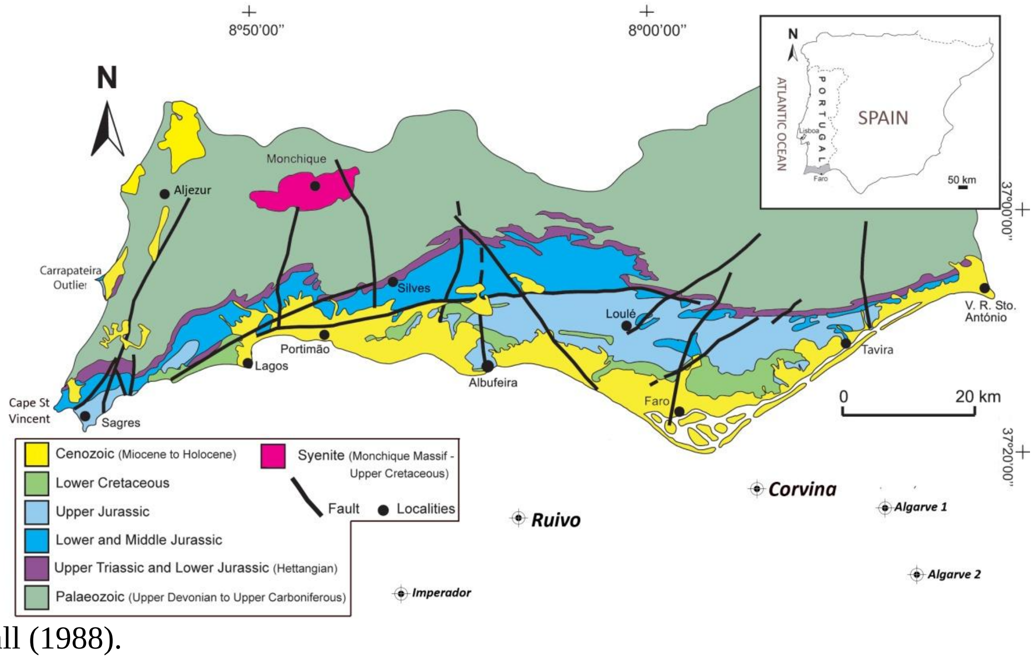


FIG.1 – Location of the wells studied.

## 2. Ruivo-1

This well was a total depth of 2100 m and intercepted lithologies assigned to the Miocene at the top and Upper Triassic at the bottom of the well (FIG.2). Ten samples were collected from marls and marly limestones between 1715 and 2070 m depth, from the interval belonging to the Jurassic. The organic residues from this interval are abundant, and comprise well-preserved palynomorphs, together with plant and wood fragments. The dinoflagellate cysts recorded from samples between 1800 and 2030 m, include *Batiacasphaera* spp., *Ctenidodinium* sp., *Ctenidodinium sellwoodii* Grp., *Ellipsoidictyum gochtii*, *Ellipsoidictyum/Valensiella* grp., *Gonyaulacysta jurassica* subsp. *adecta*, *Impletosphaeridium* spp., *Korystocysta gochtii*, *Meiourogonyaulax caytonensis* Grp., *Pareodinia ceratophora*, *Sentusidinium* spp., *Systematophora areolata*, *Systematophora penicillata*, *Systematophora* spp. and *Tubotuberella dangeardii*. These associations are indicative of the Middle-Late Callovian (Riding, 2005; Riding & Thomas, 1992). From these stratigraphic interval it was also recorded the species *Nannoceratopsis deflandrei* subsp. *deflandrei*, that marks the interval Toarcian-Aalenian, that appeared reworked into the Callovian sediments. Vitrinite reflectance measured from the Callovian sediments are within the oil-window. Ranging between 0.8 and 1.0%Rm. These values are backed up by the colours of TAI, SCI and UV fluorescence colours shown by the spores (FIG.2). The vitrinite reflectance values measured from the Tertiary sediments are also within the oil-window. However, these values were considered from reworked vitrinite particles, since the UV fluorescence colours from autochthonous palynomorphs, that provide the age for this interval, indicates immature kerogen.

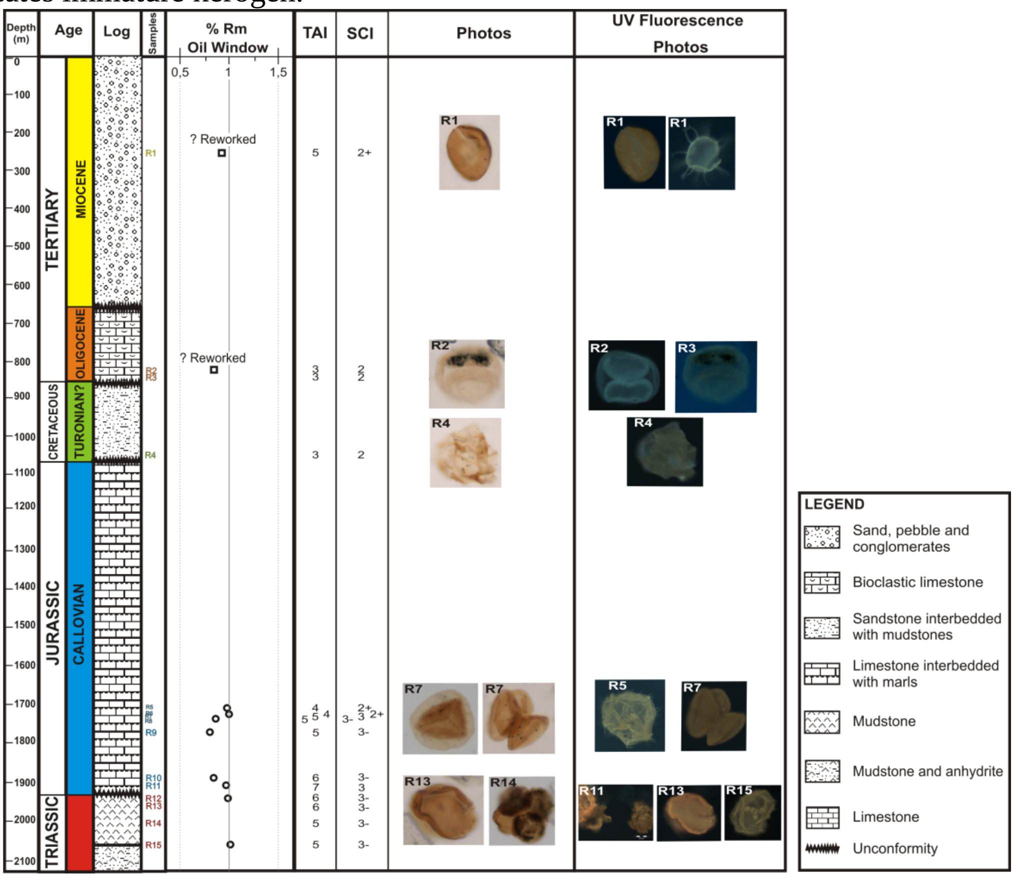

FIG.2 – Stratigraphy and organic maturation indicators of the well Ruivo-1.

## 3. Corvina

This well intercepted a 2700 m depth succession with Miocene sediments at the top and Jurassic sediments at the bottom of the well (FIG.3). The twelve samples collected between 1595 and 2680 m depth, yielded relatively abundant organic residues dominated by dinoflagellate cysts. Miospores observed include bisaccate pollen, *Callialasporites dampieri*, *Callialasporites turbatus*, *Callialasporites* spp., *Classopollis classoides* and *Perinopollenites elatoides*. The dinoflagellate cyst floras from these samples are indicative of ?Early/Middle Oxfordian age due, principally, to the occurrence of *Ctenidodinium ornatum*, *Compositosphaeridium polonicum*, H*ystrichosphaerina orbifera*, *Endoscrinium luridum*, *Gonyaulacysta jurassica* subsp. *jurassica*, *Rigaudella aemula*, *Surculosphaeridium vestitum*, *Stephanelytron redcliffense*, *Systematophora* spp., and *Wanaea acollaris* (Riding, 2005). The vitrinite reflectance values from this thick Oxfordian succession are within the oil-window and range between 0.9 and 1.1%Rm. These values are compatible with the results attained by other thermal maturity indicators, namely TAI, SCI and UV fluorescence (FIG.3). A similar condition to the well Ruivo-1 was also found in the Corvina well, with the Tertiary sediments being immature regarding to the oil-window, but with reworked vitrinite particles.

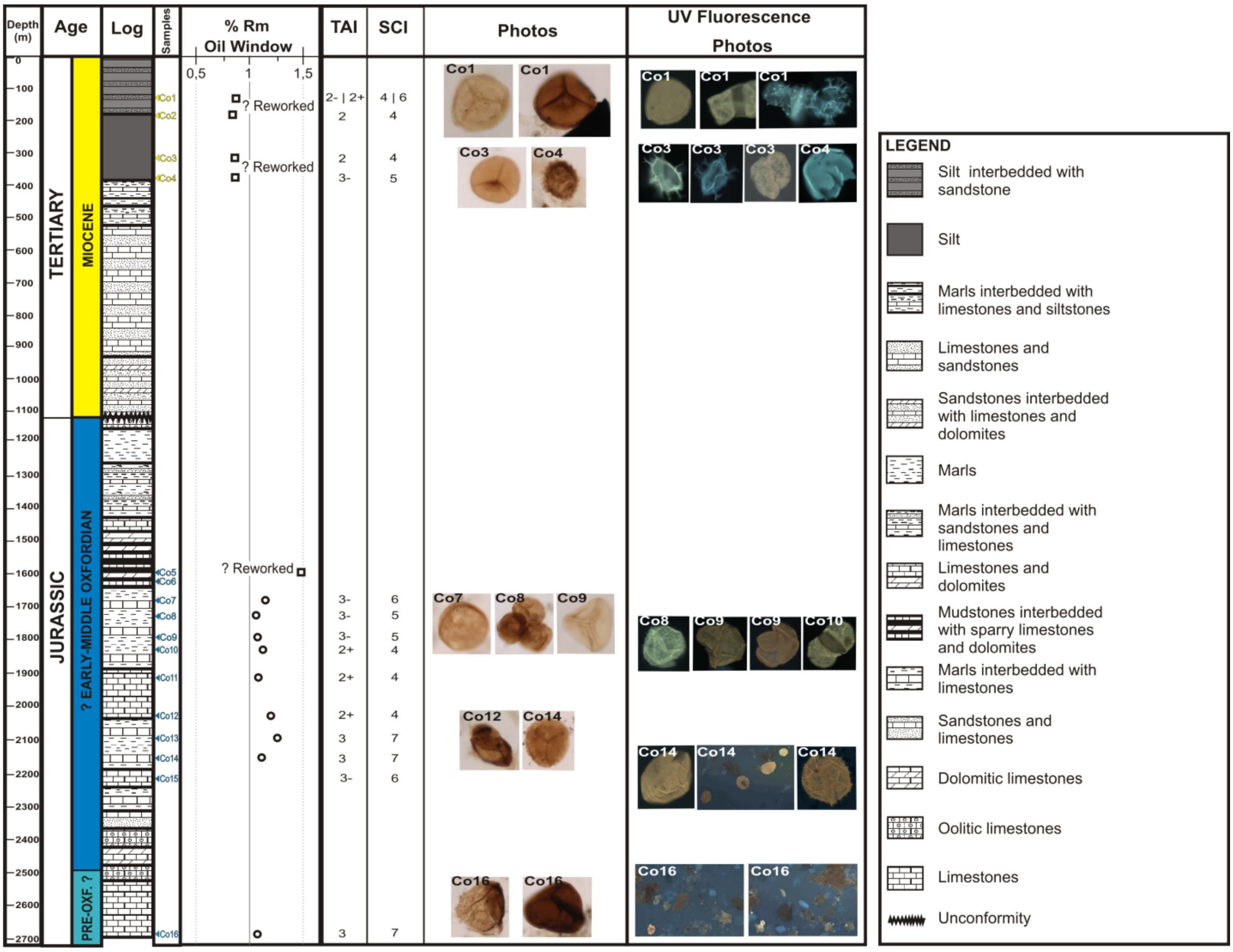

FIG.3 – Stratigraphy and organic maturation indicators of the well Corvina.

*Acknowledgements*

*This work is a contribution to the project 'Hydrocarbon Source-Rock Potential of the Algarve Basin' – Southern Portugal' financed by the Portuguese Foundation for Science and Technology. M. Borges holds* *a PhD scholarship from the Portuguese Foundation for Science and Technology (number SFRH/BD/40428/2007).*

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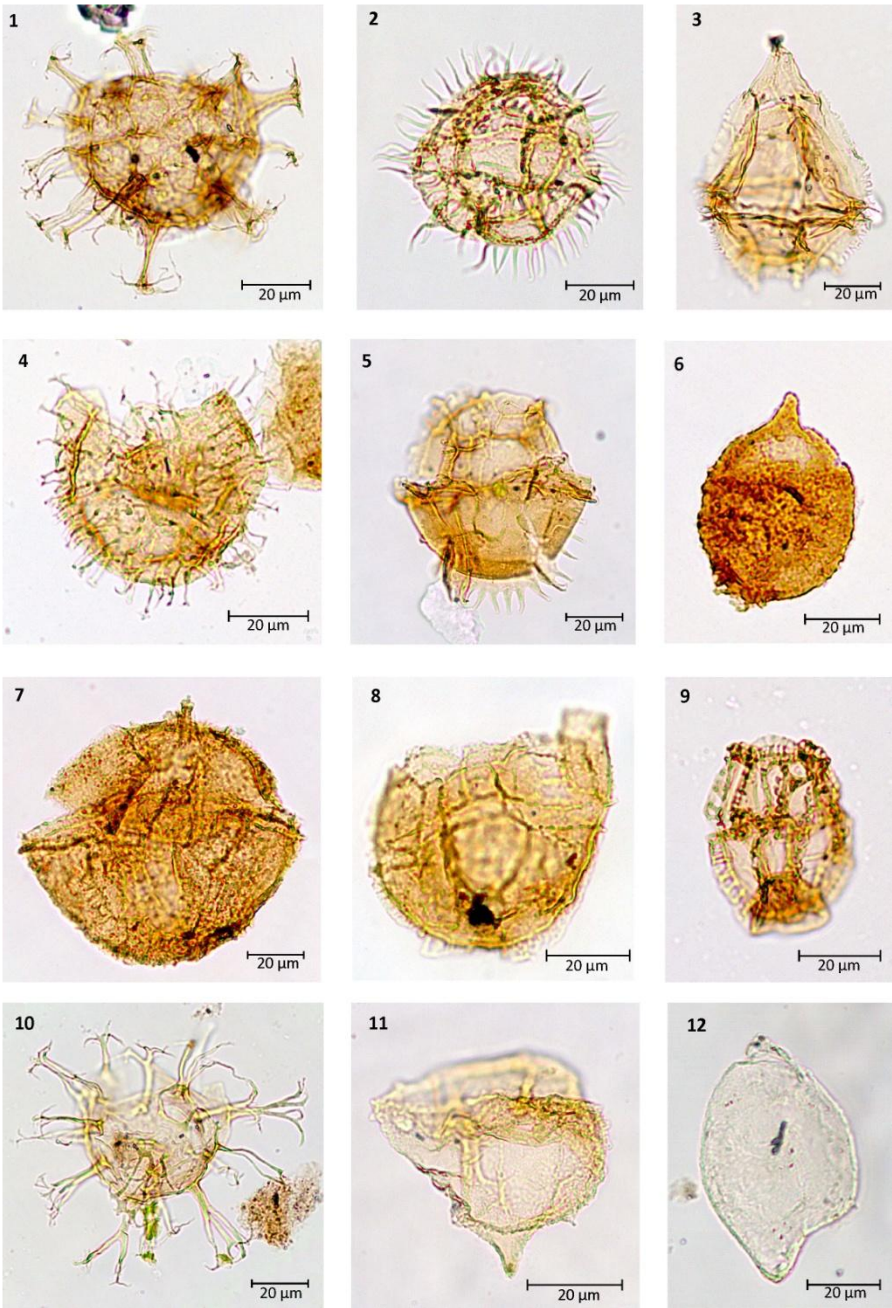
## PLATE 1

Selected dinoflagellate cysts from the Ruivo - 1 and Corvina wells. The sample and England Finder coordinates are provided.

**1.** *Compositosphaeridium polonicum* (Górka 1965) Lentin and Williams 1981. Ruivo-1 well, Sample R8; P11/2
**2.** *Ctenidodinium sellwoodii* (Sarjeant 1975) Stover & Evitt 1978. Corvina well, Sample CO 2235; S33
**3.** *Gonyaulacysta jurassica* (Deflandre 1939) Norris & Sarjeant 1965 subsp. *adecta* Sarjeant 1982. Corvina well, Sample CO 1995; F44/4
**4.** *Impletosphaeridium* spp. Ruivo-1 well, Sample R9; T39/3
**5.** *Ctenidodinium ornatum* (Eisenack 1935) Deflandre 1939. Corvina well, Sample CO 2195; N7/2
**6.** *Pareodinia ceratophora* Deflandre 1947. Ruivo-1 well, Sample R10; K23
**7.** *Korystocysta gochtii* (Sarjeant 1976) Woollam 1983. Corvina well, Sample CO 2235; Q32
**8.** *Meiourogonyaulax caytonensis* (Sarjeant 1959) Sarjeant 1969. Ruivo-1 well, Sample R8; U35
**9.** *Stephanelytron redcliffense* Sarjeant. 1961. emend. Stover *et al.* 1977. Corvina well, Sample CO 1995; J26/1
**10.** *Surculosphaeridium vestitum* (Deflandre 1939) Davey et al. 1966. Corvina well, Sample CO 2195; N21/4
**11.** *Wanaea acollaris* Dodekova 1975. Corvina well, Sample CO 2495; M22/1
**12.** *Nannoceratopsis deflandrei* Evitt 1961 subsp. *deflandrei* (autonym). Ruivo-1 well, Sample R9; Q35/3



# Hydrocarbon generation potential of the Pliensbachian organic-rich series of Peniche (Lusitanian Basin, Portugal): An organopetrographic and thermal maturation assessment integrated analysis.

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*ABSTRACT*

*The purpose of this study is to characterize the hydrocarbon generation potential of the organic-rich facies from Vale das Fontes Formation and the base of Lemede Formation (Pliensbachian) in the Lusitanian Basin reference section of Peniche (Portugal). More than 30 rock samples of marly nature, covering a stratigraphic interval of 47m in outcrop, were analyzed using organopetrographic observation and organic geochemistry, namely Total Organic Carbon (TOC) and selected ratios of molecular organic compounds by CG-qMS techniques, $H_{32}S/(R+S)$ and $H_{30}/M_{30}$. Vitrinite Reflectance and Spore Coloration Index were analyzed in five representative samples spread evenly in the entire studied interval.*

*The organic-rich facies of the Vale das Fontes Formation show an elevated hydrocarbon generation potential in most of the samples analyzed, due to the generally high TOC values and dominance of the type II kerogen, being the part of Lemede Formation analyzed the least hydrocarbon-prone interval of all the members and formations sampled. The thermal maturation indexes fall all in the immature range, observation that is in agreement with previous studies using other methodologies.*

*KEYWORDS: Palynofacies, thermal maturation, Pliensbachian source rock, Lusitanian Basin.*

## 1. Introduction

The Lower Jurassic of the Lusitanian Basin (LB) is characterized by a marly limestone deposition in a marine hemipelagic environment (Duarte & Soares, 2002; Duarte, 2007). The Vale das Fontes Formation (Fm) of Pliensbachian age stands out as one of the most hydrocarbon generation prone intervals of the Lower Jurassic of the LB, due to the organic rich facies of the series (Oliveira *et al*., 2006; Silva *et al*., 2007; Duarte *et al*., 2010). Thus, the aim of this work is to characterize the hydrocarbon generation potential of the Lumpy marls and limestones (LML) and Marly limestones with organic-rich facies (MLOF) members (Mb) of the Vale das Fontes Fm and the base of Lemede Fm, in the reference section of Peniche (FIG.1). The Peniche section shows the most important Pliensbachian succession of the LB, being the type locality of the two formations analysed (e.g. Duarte & Soares, 2002; Duarte *et al*., 2010).

It is presented a simplified kerogen characterization, supported by the use of Palynofacies, and the results of the thermal maturation studies by Vitrinite Reflectance ($R_o$), Spore Coloration Index (SCI) and thermal maturity-related biomarkers. Also, based in the integration of the acquired data, is presented a brief analysis of the hydrocarbon generation potential of the studied lithostratigraphic units.

## 2. Methodologies

Thirty two samples, covering a stratigraphic interval of 47m in outcrop, of generally marly lithotypes were collected in the Peniche section, between the base of the *Ibex* Ammonite Biozone and the base of the *Spinatum* Ammonite Biozone (Mouterde *et al*., 1955). These were analyzed using the Palynofacies technique (following Tyson, 1995; Mendonça Filho, 1999) and organic geochemistry, namely: Total Organic Carbon (TOC) and two thermal maturity-related biomarkers obtained by CG-qMS, the $H_{32}S/(R+S)$ and $H_{30}/M_{30}$ indexes (see Peters et al., 2005).

The $R_o$ and the SCI were analyzed in five representative samples, spread evenly in the entire studied interval.

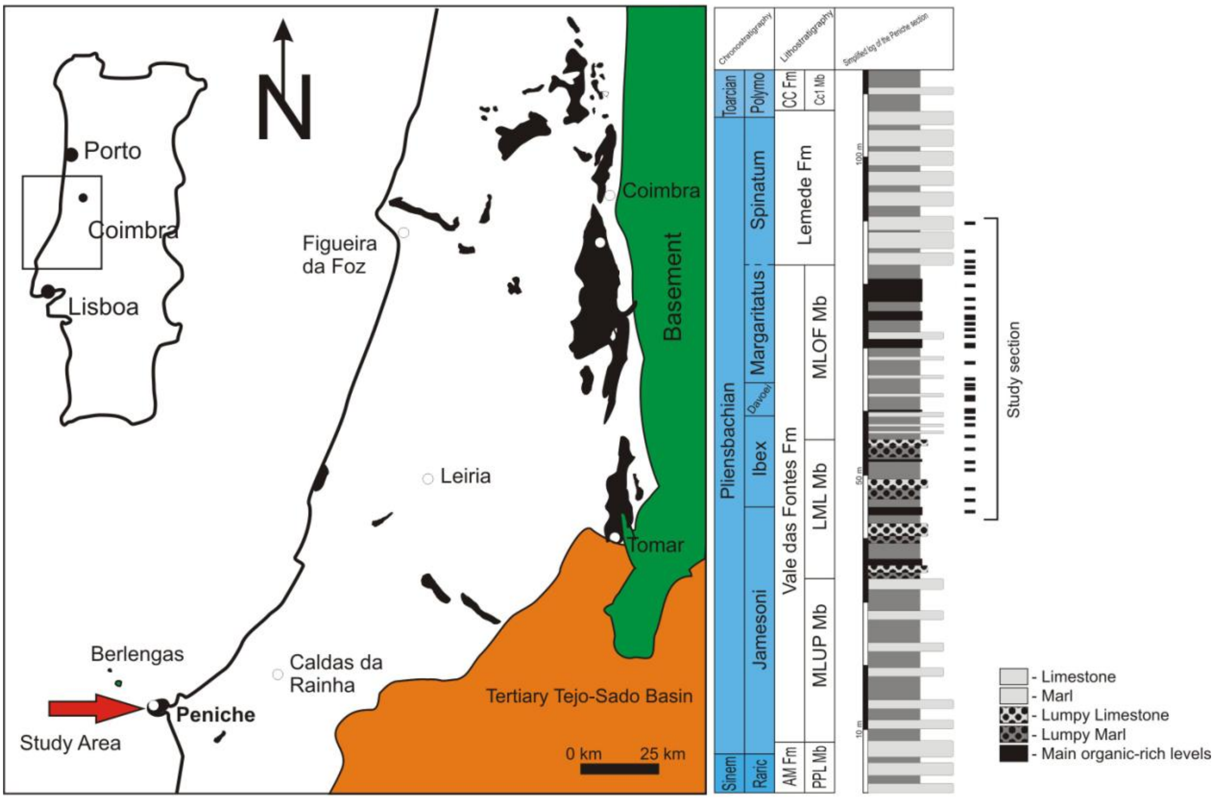


FIG.1– Location of the studied area and the Peniche simplified stratigraphic section. Lithostratigraphic units from Duarte *et al*., 2010.

3. **Results and discussion**

In the Peniche section and for the studied time interval, the TOC content is generally high and these results agree with the TOC data recently presented by Duarte *et al*. (2010) to the Pliensbachian successions of the whole basin.

Clearly, the MLOF Mb is the richest unit in TOC, yielding a average value of 4.73% (n=23), and contrasts with the much lower TOC content determined in Lemede Fm and LML Mb (TAB.1). Both units have TOC average below 1% and the maximum value barely exceeds 1%, which may be considered a boundary limit for characterization of a potential source-rock.

TAB.1 – TOC average, maximum and minimum determined values for the reference section of Peniche.

| Lithostratigraphic unit | TOC (%) | | | |
|---|---|---|---|---|
| | n | Average | Maximum | Minimum |
| Lemede Fm | 3 | 0.74 | 1.00 | 0.34 |
| MLOF Mb | 23 | 4.73 | 26.30 | 0.75 |
| LML Mb | 6 | 0.84 | 1.35 | 0.49 |

n- Number of samples

In terms of palynofacies analysis of the Pliensbachian organic-rich facies of the Peniche section, different assemblages of kerogen are present and are a characteristic feature of each studied unit. Also, it is possible to relate the optically observed palynofacies with the type of kerogen determined by geochemical methods, *sensu* Tissot *et al*. (1974) and later modifications (see Tyson 1995, for an overview).

The LML Mb consists of a mixture of the type II and III kerogens with a variable proportion of marine and terrestrial material. The MLOF Mb is dominated by the type II kerogen, with abundant amorphous organic matter (AOM). According to Peters *et al*. (2005), the AOM material is considered to be highly oil-prone and most likely derived from the degradation of marine material deposited under anoxic conditions. The Lemede Fm is dominated by the type IV kerogen, derived from opaque phytoclasts, although, type III kerogen, derived from non-opaque phytoclasts, is also relevant. From the integration of the obtained data, is possible to infer that many of the samples show an elevated potential for hydrocarbon generation, being the MLOF Mb the most oil prone unit, with a good positive correlation between TOC and AOM content. The LML Mb has a low generation potential (mixed gas/oil) and the Lemede Fm has a marginal gas generation potential (Tyson, 1995; Peters *et al*., 2005 and the references therein).

The $R_o$ and SCI were measured in five evenly spread samples (TAB.2). The average $R_o$ value is 0.48%. The SCI values are presented in the standard "half unit" interval, with values obtained not exceeding 3.5. According to Tissot & Welte (1984), Fisher (1980) and Hunt (1987), retrieved data indicate that the studied section is thermally immature and that have not entered in the oil-window. The average values, discriminated by studied unit (TAB.2), of the thermal maturity-related biomarkers are in good agreement with the determined $R_o$ and SCI, charactering all the samples as immature, $M_{30}/H_{30} < 1$ and $H_{32}S/(R+S) < 0.6$, according to Peters *et al*. (2005) and Seifert & Moldowan (1980).

TAB.2 – $R_o$, SCI and average thermal maturity-related biomarkers determined values for the reference section of Peniche

| lithostratigraphic unit | sample identification | SCI | $R_o$ % | Average $M_{30}/H_{30}$ | Average $H_{32}S/(R+S)$ |
|---|---|---|---|---|---|
| Lemede Fm | 5 | 3 – 3.5 | 0.48 | 0.48 (3 samples average) | 0.14 (3 samples average) |
| MLOF Mb | 4 | 3 – 3.5 | 0.50 | 0.52 (23 samples average) | 0.26 (23 samples average) |
| | 3 | 3 – 3.5 | 0.47 | | |
| | 2 | 3 – 3.5 | 0.45 | | |
| LML Mb | 1 | 3 – 3.5 | 0.48 | 0.54 (6 samples average) | 0.18 (6 samples average) |

## 4. Conclusions

Based in newly acquired data from the reference section of Peniche, is possible to infer that the MLOF Mb of the Vale das Fontes Fm has an elevated hydrocarbon generation potential, due to the presence of high TOC values (average 4.73%) generally related to the presence of an important content of the oil-prone type II kerogen (mainly AOM). However, the conducted thermal maturity studies indicate that the analysed samples are thermally immature. All samples fall in the biogenic gas window, still within the diagenetic phase of thermal development.

Obtained results are in good agreement with the previous studies made in the focus area (Oliveira *et al*., 2006) and with others conducted elsewhere in the LB (e.g., Silva *et al*., 2007, Silva *et al.*, 2010).

*Acknowledgements*

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# Diagenetic Processes and Porosity Evolution Controls in Upper Jurassic Siliciclastic deposits of the Lusitanian Basin (Portugal)

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*ABSTRACT*

*Sandstones and conglomerates of Upper Jurassic intervals of the Lusitanian Basin were studied in the attempt to quantify effects of diagenetic processes on their porosity evolution and reservoir properties. Samples were taken mainly from outcrops and also from wells and represent fluvial and turbidity deposits, related with coastal or transitional siliciclastic and carbonate environments. The framework compositional plots of the Upper Jurassic sandstones reveal considerable variations between different areas in the basin. The framework grains are composed predominantly of plutonic rock fragments (granites, gneisses, schists and philites) common in the coarse proximal deposits. In some sandstones, carbonate rocks fragments (calcilutite and oolitic or bioclastic calcarenites) are present and are interpreted as resulting from intrabasinal erosion of exposed older carbonate platforms. The studied sandstones contain mainly secondary porosity. The average total porosity ranges from 3,35 to 13,7%. Total macroporosity is higher in the non-hybrid sandstones and lower in the hybrid sandstones. Macroporosity resulted from grain dissolution and intergranular secondary pores have also resulted from the partial to pervasive dissolution of carbonate cements.*

*KEYWORDS: Upper Jurassic, Lusitanian Basin, Diageneses, Porosity, Oil Reservoir.*

## 1. Introduction

The paragenetic sequence and porosity evolution pathways of the Upper Jurassic sandstones of the Lusitanian Basin were controlled by multiple factors that include variations in the sedimentary facies, climatic conditions and burial history. Fast burial history resulted in paragenetic sequences with strong compaction processes and important porosity destruction. The more extensive eogenetic carbonate cementation in the slow burial history sectors may have played a role in the preservation of higher porosity and intergranular volumes. Porosity enhancement by carbonate cement dissolution, due to telogenetic meteoric influx into the reservoirs of these sectors, could be significant compared to other sectors.

## 2. Studied Intervals

The studied interval comprise the Abadia, Alcobaça and Lourinhã formations, deposited by siliciclastic influx during the Upper Jurassic rift phase, mainly during the Kimmeridgian and Tithonian ages, in turbiditic, fluvial/deltaic and coastal sedimentary environments.

The depositional setting of these units was extremely influenced and controlled by the tectonic evolution of the basin. According to Alves *et al.* (2003), there were two distinct structural environments that controlled the sedimentary environment of these deposits: (1) transverse footwall-derived sediment fans, predominant in fault-bounded regions, give place to axial southwards-prograding fluvial to shallow-marine units in the diapir-bounded sub-basins; (2) growing salt pillows, absent in the fault-bounded sub-basins, formed barriers to and limited the development of transverse drainage systems.

## 3. Sandstone compositions

The framework compositional plots of the Upper Jurassic sandstones of the Lusitanian Basin reveal considerable variations between different areas in the basin. Dickinson *et.al.* (1983) Provenance Diagrams (Fig. 1) indicate the mainly recycled orogenic to continental transitional source areas to fan-deltaic and turbidite deposits (Fig. 1A, B and C) and cratonic interior source area to fluvial origin sandstones (Fig. 1D).

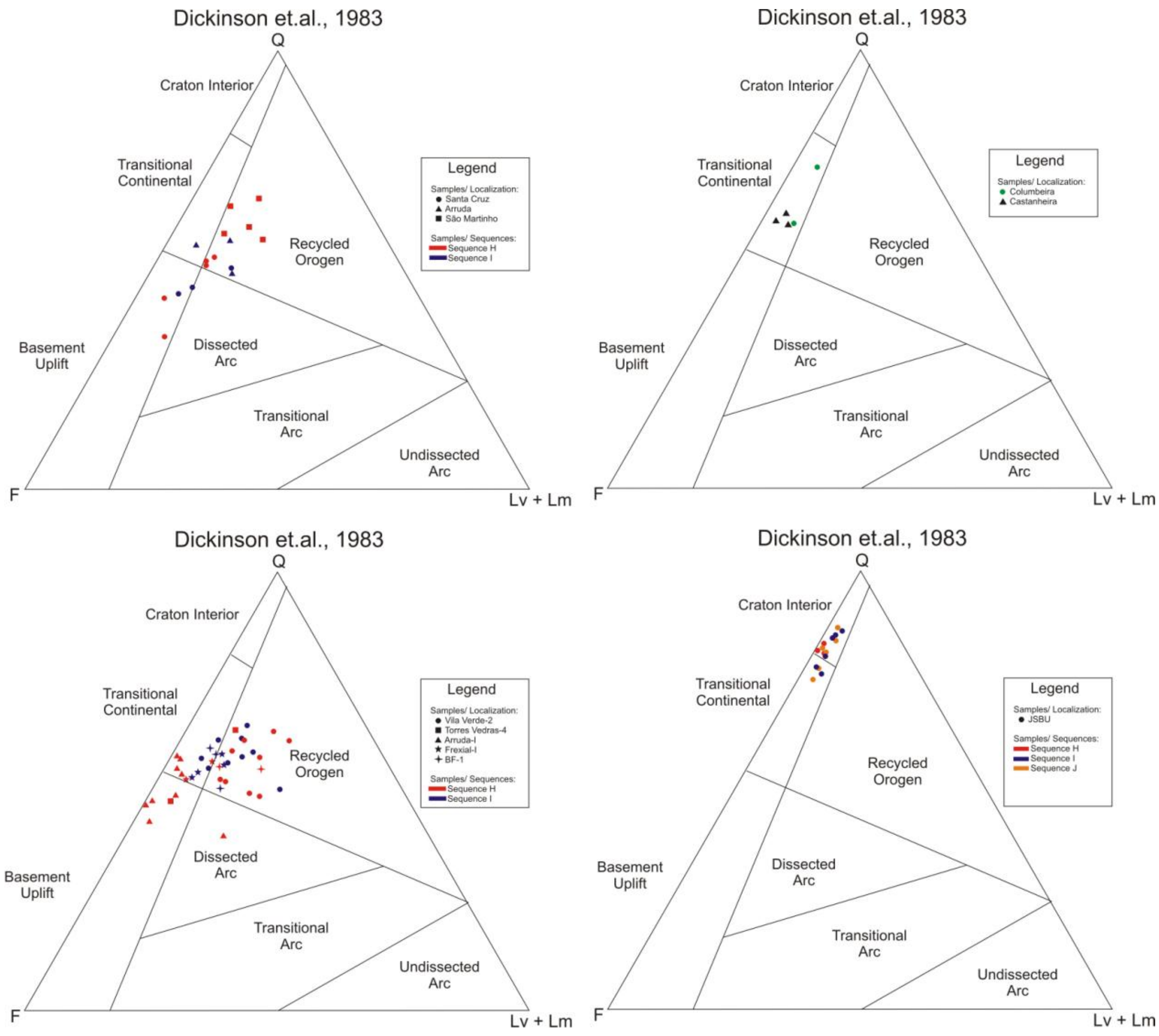


FIG. 1- Sandstone composition plotted in Dickinson *et. al.* (1983) Provenance Diagram. Samples from fan-deltaic and turbiditic deposits of the Abadia Formation from outcrops (Fig. 1A and 1B), from core samples (Fig. 1C) in central area of the Lusitanian Basin and from outcrops in the northern area (Fig. 1D).

## 4. Diagenetic processes and porosity evolution controls

The average intergranular petrographic porosity ranges from 3,35% to 13,7%. Intragranular, mouldic and oversized pores derived from partial to complete dissolution of carbonate cements and detrital feldspar, micas and carbonate fragments (bioclasts, ooids and rock fragments). In addition to framework grain dissolution, intergranular secondary pores have also resulted from the partial to pervasive dissolution of carbonate cements.

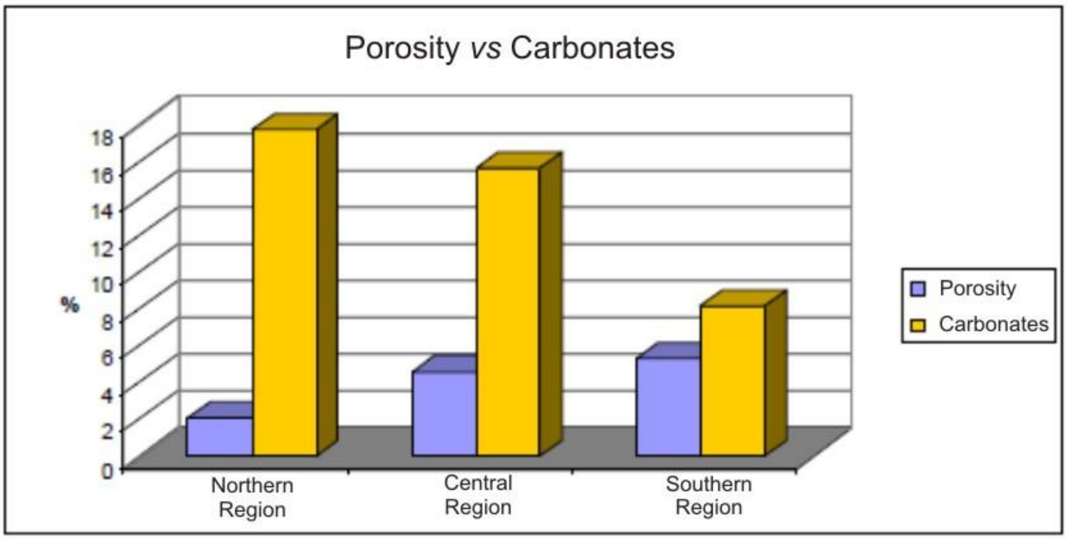


FIG. 2 – Representation of the relationship between porosity and the presence of carbonate cement in samples of north, central and southern areas of the Lusitanian Basin. Secondary porosity increases with the dissolution of carbonate cement.

## 5. Conclusions

Depositional and erosive processes during the Upper Jurassic rift phase produced clastic deposits with framework grains composed predominantly of plutonic rock fragments (granites, gneisses, schists and philites), common in the coarse proximal deposits and in some sandstones, as well carbonate rocks fragments (calcilutite and oolitic or bioclastic calcarenites) interpreted as resulting from intrabasinal erosion of exposed older carbonate platforms.

The compositional and burial history characteristics of each area of the basin resulted in a different paragenetic sequences in more distal and more proximal domains. However, different areas in the same domain were also subjected to different subsidence or uplift intensities.

The patterns of diagenetic evolution recognized in this study allow some discussion of the conditions for optimum porosity preservation and/or enhancement in the Upper Jurassic sandstones as potential oil and gas reservoirs. The best reservoirs of the studied Upper Jurassic siliciclastic rocks occur in non-hybrid sandstones and in slow buried sectors, where porosity was early cemented and enhanced by dissolution of carbonate cement during telogenetic influx of meteoric waters.

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# Spreading evolution of the Norway Basin and implication for the evolution of the Møre rifted margin and its intermediate conjugate system (the Jan Mayen microcontinent)

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*ABSTRACT*

*The Norway Basin is an aborted oceanic basin initiated during the onset of breakup between Norway and the coupled Greenland/Jan Mayen conjugate system in Early Tertiary time (~55 Ma ago). Based on a new aeromagnetic survey, we reevaluate the structure and spreading evolution of the Norway Basin and propose a more complex geodynamic history for the Norwegian-Greenland Sea. The new observations allow us to reevaluate the tectonic calendar of the Norwegian-Greenland Sea and discuss some implications on the syn- and post-breakup development of the surrounding continental margins and the evolution of the Jan Mayen microcontinent, an intermediate conjugate system between the Norwegian and Greenland volcanic rifted margins*

*KEYWORDS: Norway Basin, aeromagnetic survey, volcanic margin, breakup, microcontinent.*

## Introduction and regional setting

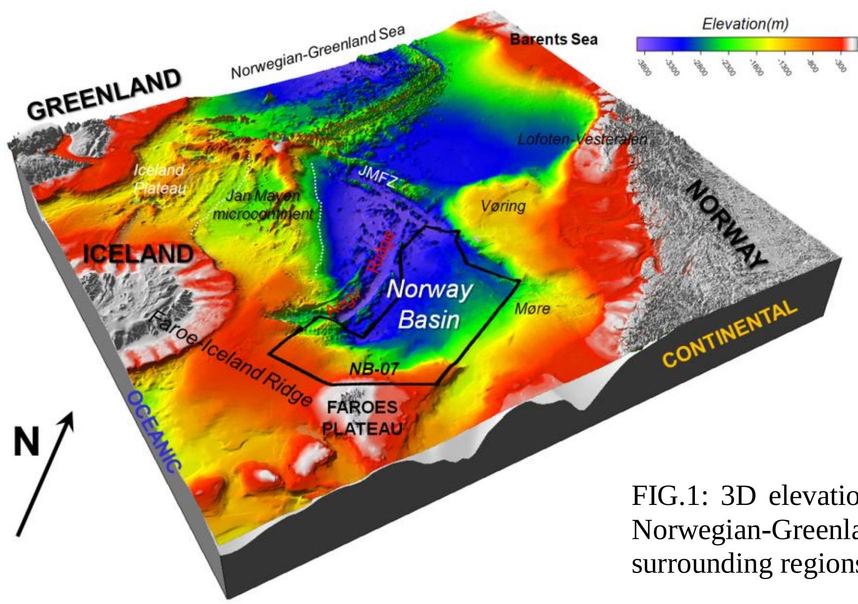


FIG.1: 3D elevation model of the Norwegian-Greenland Sea and surrounding regions

The Norway Basin (NB) is one of the oceanic sub-basins of the Norwegian-Greenland Sea and it represents a key area for investigating detailed seafloor spreading processes and margin segmentation in space and time (FIG.1). The NB developed after a long period of rifting that reached the continental breakup stage in the Early Eocene and ended the seafloor spreading after the extinction of the Ægir Ridge (FIG.1). This region has been the subject of thorough pioneer geophysical investigations in the 60's and 70's (Talwani and Eldholm, 1977; Nunns and Peacock 1983; Skogseid and Eldholm, 1987) that revealed the major outlines of this complex oceanic basin. Subsequently, most of the geophysical studies and research activities focused on the closest conjugate rifted margins, whilst data collection over the oceanic area was sparse. Specific contributions have also illustrated the evolution of the Jan Mayen microcontinent (JMMC) that had been isolated from the continental margins through at least two different episodes of seafloor spreading (Lundin and Doré, 2002; Gaina et al., 2009). However, a detailed model to explain the complex evolution of the Greenland and Norwegian margins and the formation of the JMMC was not achieved due to the sparse data coverage (e.g., Gernigon et al., 2009). Here, we report details of new geophysical data and attempt to develop a comprehensive model for the evolution of the NB and surrounding regions.

**Results of the new aeromagnetic survey NB-07 and spreading evolution of the NB**

The Geological Survey of Norway (NGU) conducted in 2007 a new high-resolution aeromagnetic regional survey on the NB (NB-07 NGU survey) and acquired almost 39,900 km of extra magnetic profiles in that area.

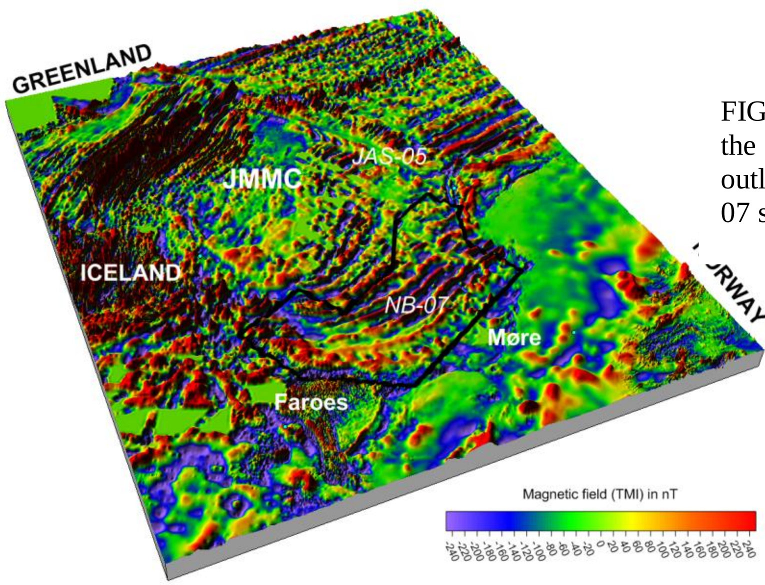


FIG.2: New aeromagnetic compilation of the Norwegian Greenland Sea. The black outline shows the location of the new NB-07 survey

The new aeromagnetic survey that completely covered the eastern NB allowed us to map accurately detailed tectonic features. According to our new survey, the early Cenozoic evolution of the NB developed in 2 distinct stages:

Phase 1 (chron C24 to C21n): Breakup and incipient seafloor spreading initiated in the central part of the Møre Marginal High and propagated regionally from northeast to southwest. In the southwestern part, shearing along the COT is observed and probably coincided with the development of a 'volcanic' shear-margin in the northern part of the Faroes Plateau. During that period, competing oceanic segments have been observed leading to an overlapping system and a 'pseudo-fault' development (the NB Fracture Zone). The new NB-07 survey also suggests the presence of off-axis magmatism and/or an aborted fissure swarm and rift axis, which indicate a local instability of the early spreading system, still influenced by a considerable production of magmatic rocks.

Phase 2 (chron C21n to C10): the spreading centre records an important Mid Eocene seafloor spreading change. This event occurred long before the widely reported Oligocene event that probably led to the extinction of the Ægir Ridge. The Mid. Eocene event has not been documented in the previous literature. Phase 2 is characterised by a clear change of the spreading direction, a decrease in spreading rate and greater fault displacement leading to the initiation of intriguing N-S fracture zones. During this phase, a crude northward-widening, fan-shaped, magnetic anomaly pattern clearly developed along the active Ægir Ridge. The new survey clearly shows that the fan-shaped evolution initiated at C21 (47.9-46.2 Ma) instead of C18-C13 (40.1-33 Ma) or C24 as previously proposed.

**Implication for the formation of the Jan Mayen microcontinent**

The JMMC represents a complex intermediate conjugate system including two sets of conjugate margins. In terms of understanding the tectonic, sedimentary and petroleum setting of the Mid-Norwegian and Faroes-Shetland areas, only a few studies deal in detail with the structure and stratigraphy of the JMMC. Previous interpretations based on ocean-bottom seismographs (OBS) and existing multi-channel reflection-seismic surveys on the JMMC showed that the presumed continental basement is overlain by Palaeozoic to Cenozoic sediments (Kuvaas and Kodaira, 1997). The early history of the JMMC is traditionally associated with the first phase of continental breakup and many studies have considered that the most important tectonic event that influenced the Norwegian-Greenland Sea after the initial rupture occurred in the Late Oligocene. During Oligocene time, the spreading activity along theÆgir Ridge decreased until it became extinct and 'jumped' westwards to initiate the Kolbeinsey Ridge. The relocation of the spreading ridge from the aborted Ægir Ridge to the nascent Kolbeinsey Ridge resulted in the final separation of the JMMC from the Greenland Plate.

Although Müller et al.'s (2001) suggested mechanism for the ridge jump/propagation could be successfully applied to the Norwegian-Greenland Sea (explaining post-10 Ma ridge jumps towards the Iceland hotspot), the amount and timing of extension and magmatic episodes related to the formation of the JMMC is less well constrained. We show that no real 'jump' actually exists but instead there was probably a complex propagating system leading progressively to the second phase of breakup between the JMMC and East Greenland. Complex imbricated and overlapping rift segments suggest a gradual and progressive dislocation of tectonic blocks from north to south within the JMMC (FIG.3). The nature and timing of these events, and the implications for the tectonostratigraphic evolution of the sedimentary basin, have been correlated with a regional kinematic model updated by means of the new aeromagnetic data.

The major phase of extension and dislocation of the JMMC most likely occurred during the onset of phase 2 in the NB (FIG.3). The fan-shapes development of the NB initiated at around 49 Ma (C21r). This is a new and different interpretation compared to previous models. To accommodate the spreading in the NB, extension of the southern JMMC is therefore required at least since the late Early Eocene, i.e. 24 my before the second phase of breakup (west of the JMMC). A comprehensive model of the plate boundary evolution around the JMMC was developed by taking into account the new NB dataset and interpretation and the regional tectonic setting.

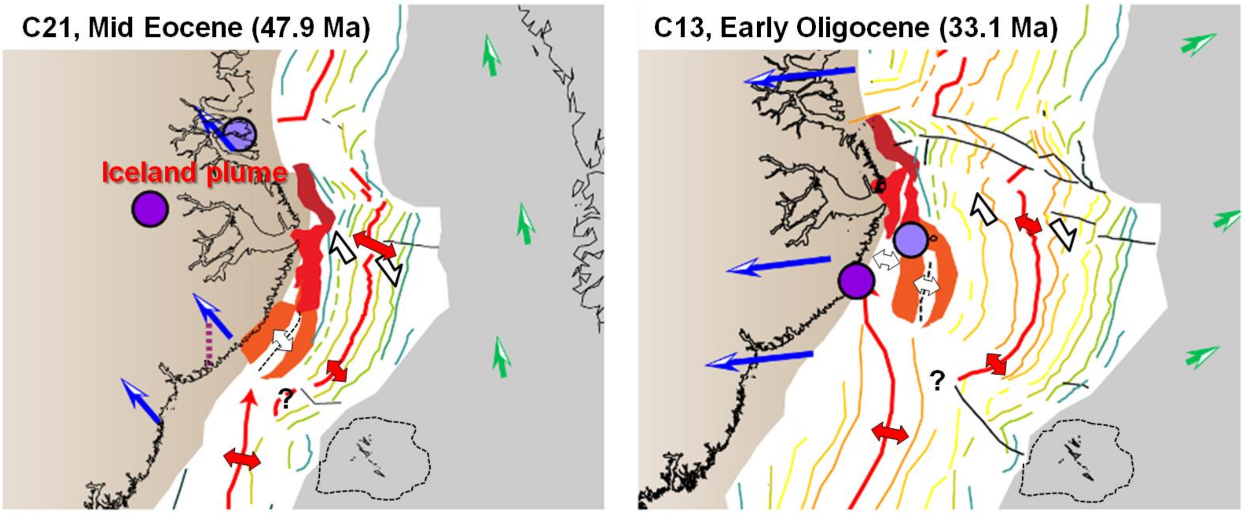


FIG.3 - Mid to Late Eocene reorganisation of the NB seafloor spreading and progressive dislocation of the JMMC. Green and blue arrows represent the relative motion of Eurasia and Greenland relative to a mantle reference frame. A stationary Iceland hotspot is shown by the dark magenta circle; a moving Iceland hotspot (due to mantle advection) is shown by the light magenta circle. Red arrows show the direction of seafloor spreading, thin coloured lines show the positions of different isochrones (and past plate boundaries) of the oceanic crust (modified after Gaina et al., 2009).

*Acknowledgements*
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# The Eocene Salt Canopy of the NW Gulf of Mexico explained by the Mechanism of Squeezed Diapirs – A Numerical Modeling Study

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*ABSTRACT*
*We present a numerical modeling study of canopy evolution through the mechanism of squeezed diapirs. The setting is adapted to the northwestern Gulf of Mexico where a mid-basin canopy formed during the Eocene. The models include a first phase of diapir growth driven only by uneven sedimentation and local isostatic compensation. In the second phase, differential loading by prograding sediments induces gravity spreading. Subsequent shortening leads to squeezing of the diapirs and upward expulsion of salt into a canopy. The resulting structures show a number of similarities to the canopy-related structures of the northwestern Gulf of Mexico.*
*KEYWORDS: Numerical modeling, Salt canopies, Salt diapirs, Gulf of Mexico*

## 1. Introduction

Multiple salt canopies of variable size have developed in the Gulf of Mexico since the Palaeogene, and are now located at several different structural levels. Little is known about their emplacement and early evolution. In some cases, the underlying structures are shielded by salt from seismic imaging. In others, salt has been entirely evacuated from the canopies, and only a salt weld remains. Allochthonous salt structures can have a major influence on the structural evolution of a basin when they act as a detachment layer, and may also affect the sediment deposition patterns and the development of hydrocarbon systems.

This study focuses on the evolution of a salt canopy located in the northwestern Gulf of Mexico (FIG.1). This canopy developed during the Eocene in the center of an up to 350 km wide Mid-Jurassic salt basin. In its later stages, it acted as a detachment surface for large-scale Oligo-Miocene gravity spreading, possibly also involving mobile shale (Peel et al., 1995). By localizing gravitational instabilities at the allochthonous level, the canopy likely postponed gravity-driven deformation above the distal part of the allochthonous salt basin until the late Oligocene, at which time the Perdido Fold Belt began to form here (Rowan et al., 2005).

We investigate the circumstances under which the Eocene canopy could have evolved in the center of a salt basin via the mechanism of squeezed diapirs. During such a process, shortening of a region containing pre-existing diapirs will be absorbed by the salt (the weakest part of the system), which is then expelled upwards to the seafloor.

The evolution of diapirs represents an aspect of salt tectonics that is still incompletely understood. A positive density difference between compacting clastic sediments and salt only develops when sediments are 1.5-3 km thick (Hudec et al., 2009), and their frictional strength hinders the buoyancy driven rise of the salt. Many authors invoke a tensional (Vendeville and Jackson, 1992; Jackson and Vendeville, 1994) or compressional (Ings and Beaumont, 2010) stress regime for the initiation of diapirism. We investigate the evolution of diapirs through local differential sedimentation in a neutral stress regime. No clear evidence for a large regional stress regime has been identified for the late Mesozoic to early Cenozoic Gulf of Mexico. Furthermore, a neutral setting allows us to study the phase of diapir evolution separately from a subsequent phase of canopy evolution in a compressional environment.

## 2. Method

We use 2D finite-element models to study the evolution of diapirs and canopies. The models comprise a viscous salt layer overlain by a frictional-plastic passive margin sedimentary sequence from shelf to deep water, thereby incorporating the dynamical interaction of gravity spreading caused by shelf progradation. Model experiments include sediment compaction, flexural isostasy, loading by the overlying water column, and parametric calculations of the effects of pore-fluid pressures in the frictional-plastic sediments. The models integrate two phases of the basin evolution: Phase 1 in which diapirs develop during sediment aggradation, and Phase 2 in which sediment progradation leads to gravity spreading, shortening (squeezing) of the diapirs, expulsion of salt and the development of a canopy.

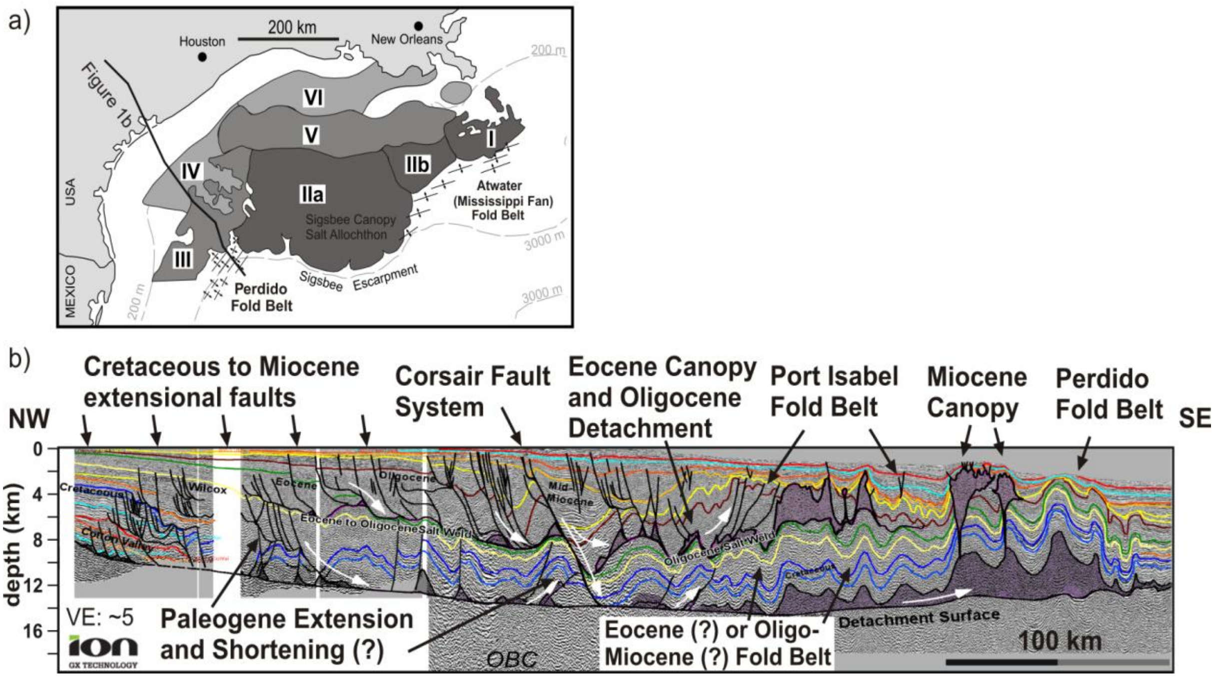


FIG.1 - a) Regional map of northern Gulf of Mexico showing the location of Oligocene (light grey) to Neogene (dark grey) salt canopies and Cenozoic fold belts. Canopy IV is subject of this study (after Peel et al., 1995 and Fiduk et al., 1999). b) Regional NW-SE trending seismic profile from the northwestern Gulf of Mexico extending from onshore into deep water (from Radovich et al., 2007, courtesy of ION-GXT). Large-scale gravity-spreading structures (extensional faults, allochthonous salt, fold belts) are indicated. Location is shown in FIG.1a).

## 3. Results

FIG.2 shows the results of a numerical experiment in which uneven sedimentation above a salt basin drives diapirism. The sedimentation pattern is based on the idea that local bathymetric expressions (such as channel-levee systems or turbidite deposits) can be preserved over certain time scales. These structures need to adjust isostatically relative to the salt layer. In an aggradational environment in which the bathymetric profile is maintained, this local balancing can create sufficient pressure differences to drive diapirism. The success and rate of diapir evolution depend on various factors such as the height and width of the bathymetric features, the sedimentation rate, or the salt and sediment densities.

In the second phase of the model evolution, progradation of a deltaic sediment wedge initiates gravity spreading through the regional differential sediment load (FIG. 3a). Subsequent shortening is localized around the diapirs, and salt is expelled upwards into salt tongues (FIG.3b), which later coalesce into a canopy (FIG.3c). A canopy will not form if too little salt of the pre-existing diapirs is near the seafloor (immature diapirs) or the sediment column is not significantly denser than the underlying salt. The evolving model canopies shows characteristics similar to the Eocene canopy of the northwestern Gulf of Mexico (such as its lateral extent, the structure of the underlying strata, and the postponing of deformation above the distal salt basin). They also share important characteristics with other canopies, for example, an Eocene canopy of the northern Gulf of Mexico.

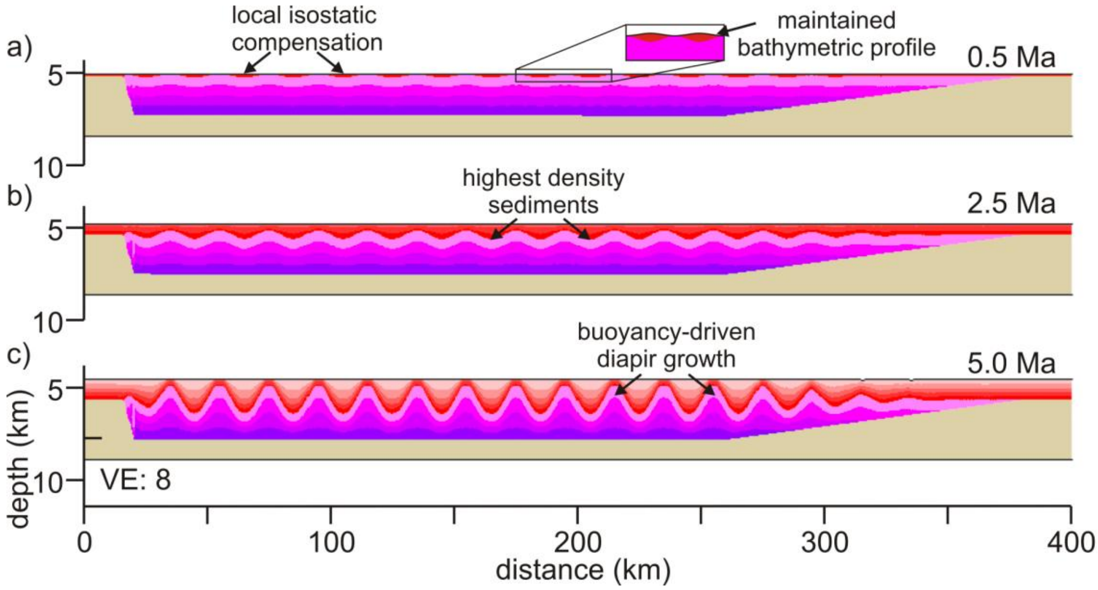


FIG.2 - Results of numerical experiment in which uneven sedimentation above a salt basin drives diapirism. Salt is represented in magenta colors, sediments in red. a) Early local isostatic compensation of sinusoidal sediment mounds. b) Salt-sediment undulations driven by uneven sedimentation and local isostatic balancing. Densities at bottom of sediment column become larger than densities of underlying salt. c) Growing density contrast drives continued diapirism.

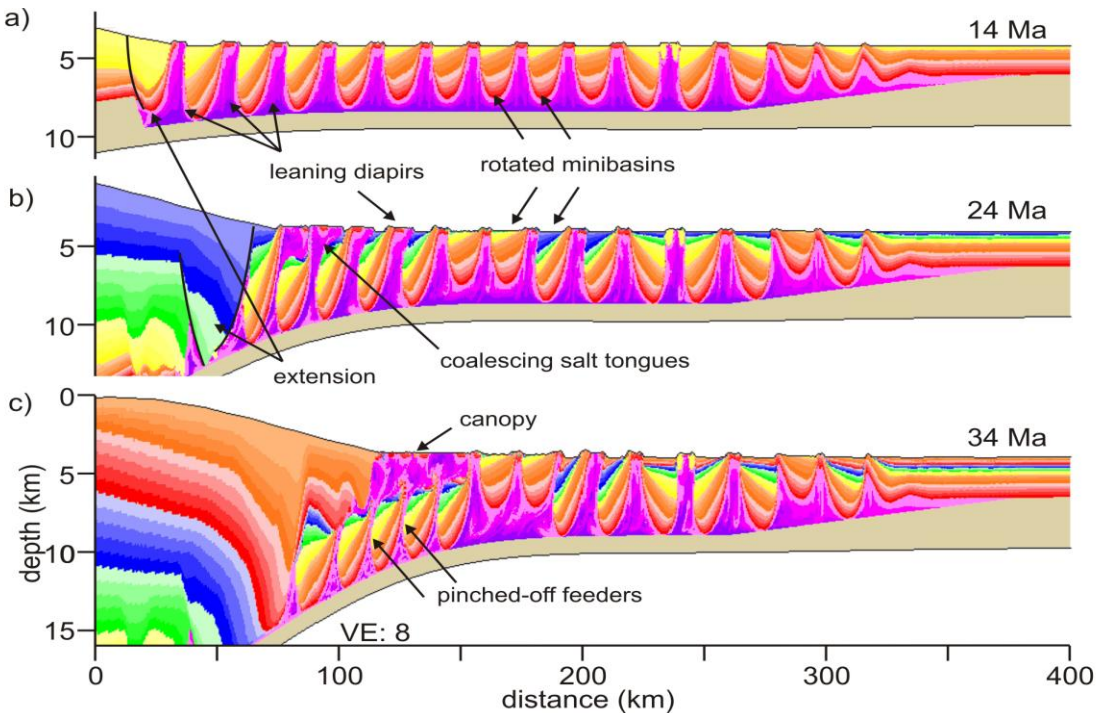


FIG.3 - Result of numerical experiment in which prograding sediment wedge induces gravity spreading and squeezed diapirs form a salt canopy. Salt is represented in magenta colors, sediments in other colors. a) Early gravitational instability tilts diapirs and intermediate minibasins. b) Continued gravity spreading forms coalescing salt tongues. c) Mid-basin canopy develops.

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# From the Solar System to the Reservoir: understanding the influence of Plate Tectonics, Paleogeography, and Paleoclimate on Pre-Salt Petroleum Systems of the South Atlantic

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*ABSTRACT*
*The nature of the break-up between the African and South American plates had a profound influence on petroleum system elements in the South Atlantic Ocean. Scalable earth models and multi-disciplinary basin analysis are critical to determine the fundamental controls on source rock, reservoir distribution and geo-histories of the pre-salt plays. Our workflow integrates mega-regional to pore-scale observations with quantitative modeling to better understand the evolution of the South Atlantic pre-salt petroleum systems.*
*KEYWORDS: South Atlantic, Paleoclimate, Plate Tectonics, Pre-Salt Plays*

## 1. Introduction

The nature of the break-up between the African and South American plates had a profound influence on petroleum system elements in the South Atlantic Ocean. Scalable earth models and multi-disciplinary basin analysis are critical to determine the fundamental controls on source rock, reservoir distribution and geo-histories of the pre-salt plays. Using commercial studies as a base, we have constructed models from the global to reservoir scale to better understand the relationships of plate tectonics to petroleum systems in the South Atlantic.

## 2. Plate Tectonics

We used two different commercially available plate tectonic / paleogeographic models for input to paleoclimate modeling and basin analysis in the South Atlantic. Additionally, we have studied three public domain plate models. Some general conclusions are consistent, regardless of the model used. Plate tectonic reconstructions for the conjugate margins of the Central South Atlantic demonstrate that continental extension was variable in time, space, and depth.

Analysis of geophysical data demonstrates that the continental crust did not completely break apart until the Early Albian. Thus, prior to approximately 112 ma, the continents were still locked at parts of the Santos / Namibe and Equatorial Atlantic margins, and climate cyclicity played a more critical role in controlling local lake-levels than global sea-level. Once full ocean circulation was established in the Albian, open marine conditions existed along the entire conjugate margins.

## 3. Paleogeography

We used GETECH's South Atlantic Geodynamics and Petroleum Geology study to understand regional paleogeographic controls on deposition. From latest Barremian to Aptian, prior to ultimate break-up, a mega-regional depositional fairway existed between the Romanche fracture zone to the north and the Walvis Ridge to the south. Rift tectonics set the stage for both source and reservoir distribution along the conjugate margins. The early rift stage was dominated by volcanics and continental siliciclastics overlain by lacustrine carbonates and shales. Local basins were separated by dominant rift-related topography and volcanic centers, creating a "fill and spill" drainage pattern along the axial system. In late Aptian, changes in plate motions, depth-dependent stretching, and sub-aerial volcanism associated with an emergent spreading center, led, in some cases, to very wide "hyper-extended" margins with extensive, partially restricted, hyper-saline, sag basins, formed near base level.

## 4. Climate Modeling

Paleogeographic models and digital elevation models provide input to global paleoclimate and mega-regional drainage models, in order to determine both regional and local controls on source and reservoir distribution. We used the plate configuration and paleotopography from the PaleoMap Project (Scotese)Fast Ocean Atmosphere Model (FOAM), a coupled ocean-atmosphere model designed to simulate long-term climate variability. We used FOAM (PaleoTerra) to model precession-scale climate end members, using plate configuration and paleo-topgraphy from the PaleoMap project. For the purpose of regional basin analysis, our study focused on evaluating surface temperature, precipitation, river runoff, runoff to ocean, and Koppen climate classes. Runoff was calculated from the FOAM simulation (precipitation minus evaporation, soil moisture and infiltration) in conjunction with drainage basins calculated directly from paleotopography.

Figure 1 shows an example of compiled climate data for one paleoclimate end member, "Hot Southern Hemisphere Summer". The Aptian axial drainage basin occupied a large area in the tropics while the transverse drainage basins had smaller areas located in temperate, semi-arid, and arid climate. As a result, the volume of the axial river drainage is significantly larger than the volume of the transverse (local) drainage.

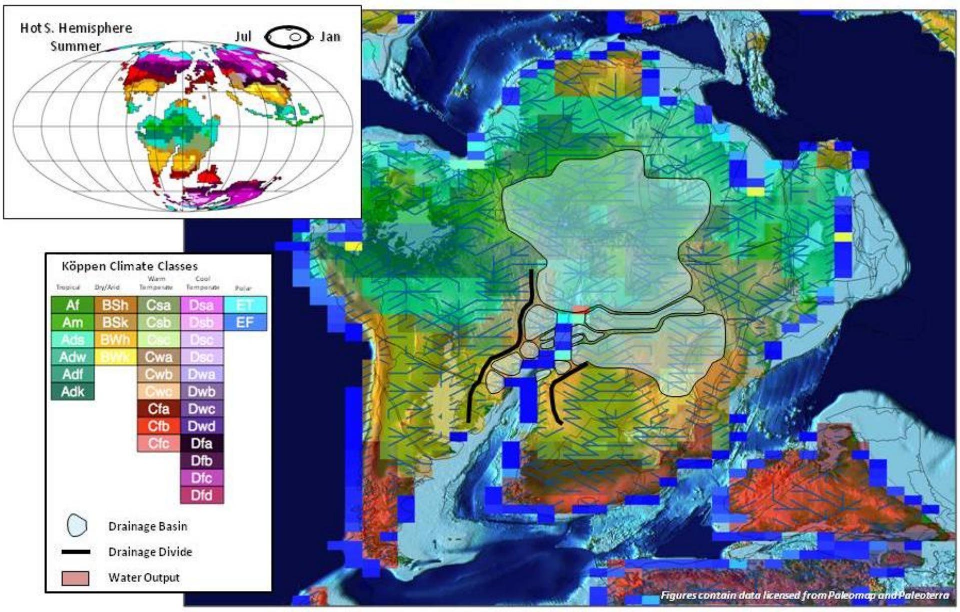


FIG.1 – Compiled Koppen climate, drainage, and run-off, Hot S. Hemisphere Summer

## 5. Depositional Models

Precipitation was much greater in the tropics at the northern end of the rift system. Consequently, water and sediment input was dominated by a major axial system extending from north to south. Arid to semi-arid conditions in the south supported development of carbonate platforms underpinned by syn-rift basement highs, as shown in Figure 2.

There were significant seasonal and orbital cycle variations in climate and run-off. Total run-off varied by twelve percent from the maximum climate extreme ("Hot Equinox") to the minimum ("Hot Northern Hemisphere Summer"). The variability between "Hot Equinox" and "Hot Southern Hemisphere Summer" was 10%. Most of the run-off variability comes from the axial system alone. However, there is a significant sixty percent difference in transverse run-off between climate extremes.

The southern basins had limited input from local transverse rivers, and therefore had net evaporation during periods of the Aptian. Evaporite volume increased to the south, while siliclastic input decreased from north to south. The carbonate platforms in the south were frequently sub-aerially exposed due to significant seasonal and orbital cycle variations in climate and run-off.

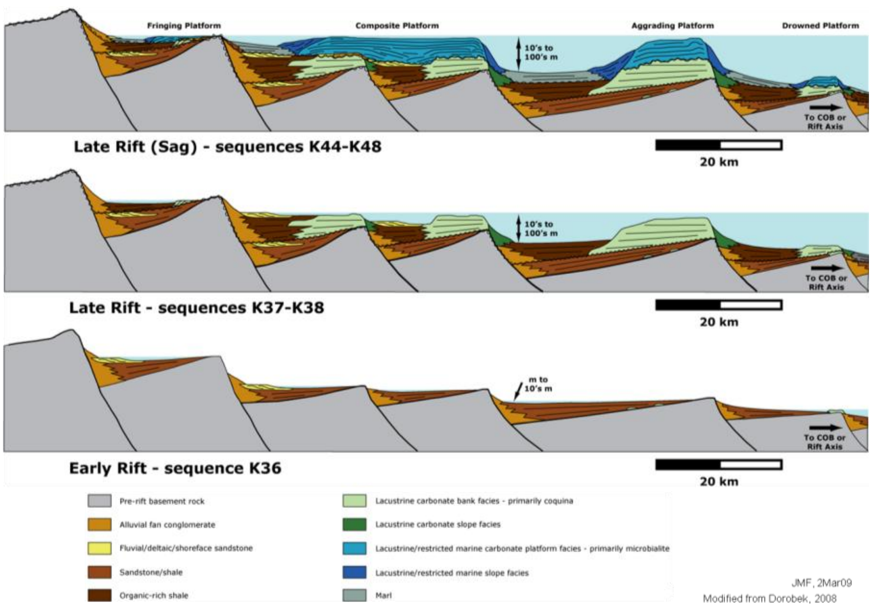


FIG.2 – Pre-salt Depositional Model

**7. Application to Campos and Santos Basins and Conclusion**

Offshore Brazil, in both the Campos and Santos basins, pre-salt depositional systems were dominated by carbonate platform trends underpinned by basement highs; however, differences in depositional environments resulted from differences in the underlying rift tectonics of each basin. The Campos carbonate platform was formed on a basement high connected to the rifted craton. As a result, the Campos Basin Pre-Salt has a complex mixing zone of siliciclastic and carbonate sediment. The carbonate platform in the Santos basin formed over an outer basement high resulting from extreme crustal asymmetry in the Santos rift system. The Santos platform was therefore isolated from significant siliclastic input.

Integrated basin analysis has proven to be an important technique for play prediction. Our workflow integrates mega-regional to pore-scale observations with quantitative modeling to better understand the evolution of the South Atlantic pre-salt petroleum systems.

*Acknowledgements*
*The authors thank The PaleoMap Project, GETECH, and PaleoTerra for their contributions to our models, and for permission to use figures from their licensed studies.*

# Deep Crustal Structures of the Central Atlantic Ocean conjugate margins: Combined Approach of Seismic, Gravity and Magnetic Investigations

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*ABSTRACT*

*A joint-interpretation of the seismic and potential field data available both on the Northeast American and Northwest African conjugate margins allows us to better understand the evolution of the Central Atlantic Ocean. The slope of the Northeast American margin is characterized by a magnetic anomaly, the East Coast Magnetic Anomaly (ECMA) which has a conjugate on the Northwest African margin (the West African Coast Magnetic Anomaly, WACMA). The ECMA is thought to mark the continent-ocean transition, and is considered to represent the magnetic response of thick volcanic sequences, typically expressed on seismic as Seaward Dipping Reflectors (SDRs) and underlying mafic intrusions emplaced during the onset of breakup. However, potential SDRs are not clearly identified all along the Northwest African margin and consequently the origin of these coastal magnetic anomalies remains locally enigmatic.*

*KEYWORDS: Central Atlantic margins, ECMA/WACMA, magnetic and gravity modeling, wide-angle and refraction seismic*

## Introduction

In this study, we integrate seismic data with gravity and magnetic modeling at a regional scale in order to test different basement structural alternatives and better constrain the architecture of the conjugate Central Atlantic margins. The meaning of the magnetic anomalies and the possible identification of a true conjugate volcanic system on both side of the Central Atlantic Ocean is crucial to better assess the geodynamic processes and mechanisms involved during the onset of continental breakup.

The opening of the Central Atlantic basin (FIG.1) is assumed to have started during the Late Jurassic. However, the exact position of North America respect to Northwest Africa and timing of breakup remained controversial. Sahabi *et al.* (2004) greatly improved the fit by juxtaposition of the both conjugate ECMA and WACMA  and by further correlation of the salt provinces observed offshore Morocco and Nova Scotia (FIG.1).They assumed an age of Late Sinemurian (195 Ma; Gradstein *et al.*, 2004) for the first oceanic crust. The present study attempts to better understand the early development of the conjugate margins of the Central Atlantic Ocean since that time, with special focus on the Baltimore Canyon-Dakhla segment.

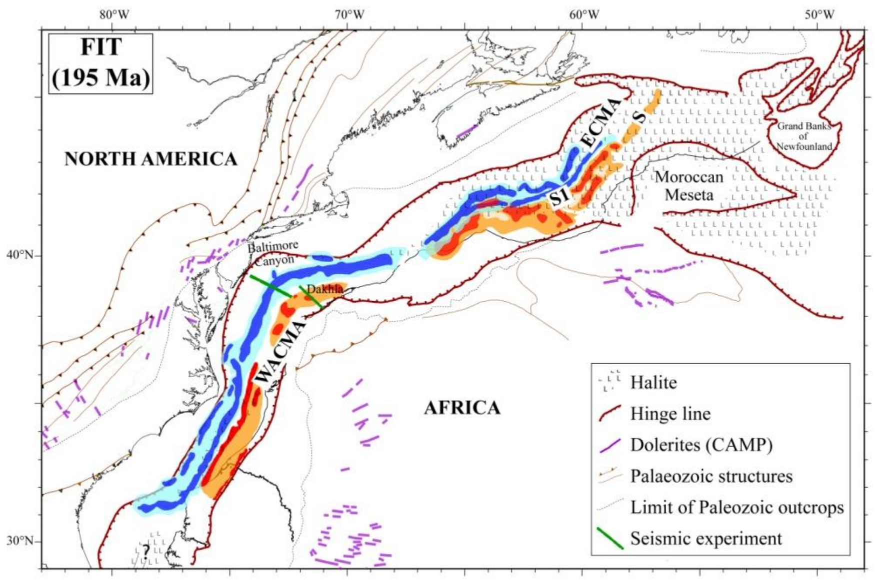


FIG.1 - Closure of the Central Atlantic Ocean according to Sahabi *et al.* (2004), at the Late Sinemurian (195 Ma; Gradstein *et al.*, 2004). The conjugate ECMA (blue) and WACMA (red) anomalies are displayed, as well as the wide-angle and refraction seismic experiments (green) that are discussed in the text.

## Data

Whereas the Northeast American margin has been largely investigated by marine geophysical measurements, the conjugate Northwest African margin is still poorly constrained. Recent data provides new information about the deep crustal structure of the margin offshore Dakhla (FIG.1). During the Dakhla experiment, a joint collaboration project between Ifremer and Total, a total of 1500 km of multichannel reflection (MCS) and wide-angle seismic (OBS) data were acquired. The profiles consisted in two long profiles perpendicular to the margin extended onshore with land-based stations, and two shorter profiles parallel to the margin (see Klingelhoefer et *al.*, 2009; Labails *et al.*, 2009).

## Tectonic settings

Breakup in the Central Atlantic seems to have occurred in a single phase, near the Triassic-Early Jurassic boundary and strictly followed earlier collisional sutures, the Alleghanian-Hercynian orogen, that had developed during the final amalgamation of the Pangaea supercontinent in Carboniferous-Permian times. Initial breakup of Pangaea was also associated with widespread volcanism observed on both side of the Atlantic Ocean and also known as the Central Atlantic Magmatic Province (CAMP; Olsen, 1999).

## Observations & discussion of the data

The ECMA, discovered by Keller *et al.* (1954), is typically several hundred gammas in amplitude, about 70 to 120 km wide. Although varying in amplitude and shape, the ECMA is clearly defined as a large magnetic high that is located near the continental shelf edge along the Northeast American margin. The ECMA is thought to mark the boundary between continent and ocean (COB). However, the observed similarity in strike between the Appalachian structures and the magnetic lineation has often let to its interpretation as an

Alleghanian suture during the Late Paleozoic (McBride and Nelson, 1988; Matte, 2002). On the Northwest African margin, the conjugate WACMA (including anomalies S as defined by Sahabi *et al.*, 2004) has weaker amplitude (about twice less than the one of the ECMA) but its trend and location along the margin is strikingly similar to the one of ECMA. The ECMA is often associated with SDRs, often interpreted as subaerial lava flows (e.g. Talwani *et al.*, 1995) and underlying mafic igneous body with a high velocities (7.2 to 7.5 Km/s) (Holbrook *et al.*, 1994) that may represent significant magmatic activity during the onset of breakup.

The wide-angle reflection and refraction data collected during the LASE experiment (LASE Study Group, 1986) provides a detailed image of the architecture of the margin across the Baltimore Canyon margin, off the U.S. East Coast (FIG.2). There, the Moho depth is decreasing from about 40 km landward of the hinge line at the continental part to less than 20 km beneath the oceanic domain. A sedimentary basin up to 13 km is observed beneath the foot of the continental slope, which includes a Jurassic prograding carbonate sequence associated to a high-velocity zone (> 5.0 km/s). It is overlying the SDRs wedge, a thinned continental crust (less than 5 km) and a deep high velocity layer with Vp of about 7.2 km/s. On the conjugate margin, seismic results from the Dakhla experiment reveals that the crustal thinning from about 28 km at the continental part to 7 km in the oceanic domain occurs over a 100 km wide zone. The continental slope domain is characterized by a 10 km deep sedimentary basin, including a sequence of high seismic velocity carbonates similar to those offshore the East Coast of North America. However, the presence of a thick carbonate platform, observed on MCS profiles does not allow a proper seismic imaging of deep crustal structures on the conjugate African system. Consequently, potential SDRs are not clearly identified all along the margin and the origin of these coastal magnetic anomalies remains enigmatic.

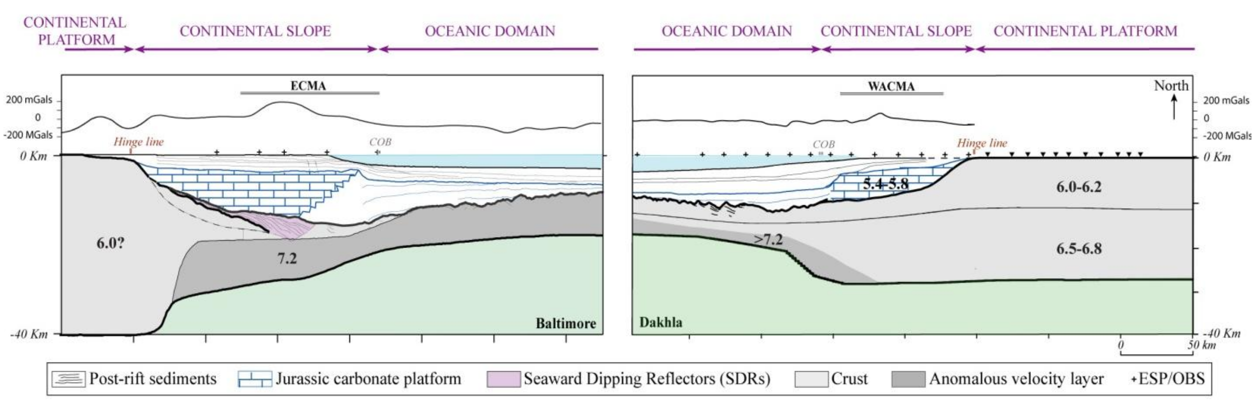


FIG.2 - Conjugate cross-sections Baltimore (Northeast America) vs. Dakhla (Northwest Africa). Seismic velocities are from Lase Study Group (1986) for the Baltimore profile and from Klingelhoefer *et al.* (2009) for the Dakhla profile. Structural analysis detailed of the conjugate margins in Labails *et al.* (2009). Note the presence of SDRs only on the Northeast American margin.

## Preliminary results & conclusion

By mean of potential field modeling and magnetic depth estimation automatic methods, we tested different hypotheses about the deep nature of the Northwest African margin and possible origin of the WACMA. Preliminary results on modeling imply a presence of shallow and upper crustal sources at about 10 km deep at foot of the continental slope; the remanence required to fit the continental slope anomaly WACMA (0.5-1 A/m) suggests the presence of crustal intrusion and lava flows just underneath the Jurassic carbonate platform. In addition, the WACMA coincides with a long wavelength gravity high observed on the free-air gravity data that involves the contribution of a high density lower crust underneath the probable magnetic unit. Modelling also suggests the presence of a small sedimentary basin closer to the coastline.

*Acknowledgements*

*This work follows upon previous work that was done in the framework of the Dakhla project. Therefore, we especially thank F. Klingelhoefer, D. Aslanian, J.-L. Olivet, L. Géli and others collaborators from Ifremer as well as P. Unternehr and P. De Clarens from Total for permission to use data and discussions.*

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# Variations in crustal structure across the Nova Scotia continental margin and its conjugate

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*ABSTRACT*

*The East Coast Magnetic Anomaly and associated seaward dipping reflectors, both suggesting volcanism, are observed on the south-western Nova Scotia margin but quickly reduce in magnitude to the northeast. A comparison of seismic observations across three previous refraction profiles (from NE to SW: SMART-1,2,3) also shows a parallel decrease in syn-rift volcanism as the margin becomes non-volcanic near the central line (SMART-2). A velocity model from a new profile northeast of SMART-1 suggests continuation of non-volcanic features, such as serpentinized mantle and thin oceanic crust, to the north-eastern end of the margin. Being conjugated to SISMAR-4 on the Moroccan margin, this new profile facilitates a better constrained kinematic reconstruction of the rifting and breakup of the complete Nova Scotia-Morocco conjugate margins.*

*KEYWORDS: Nova Scotia, Morocco, Atlantic, Conjugates.*

## 1. Introduction

The Nova Scotia rifted continental margin lies in a transitional segment between the volcanic US East Coast margin to the south and the non-volcanic Newfoundland margin to the north. The East Coast Magnetic Anomaly (ECMA) and the associated seaward dipping reflectors (SDR), both well-known volcanic margin phenomena, are observed off Georges Bank on the south-western part of the margin, but they quickly reduce in magnitude to the northeast (FIG.1). A comparison of seismic observations across different parts of the margin also shows a parallel decrease in syn-rift volcanism as defined by three previous cross-margin refraction profiles (SMART-1,2,3). The margin changes from volcanic to non-volcanic between the southern line (SMART-3; Dehler *et al.*, 2004) and the central line (SMART-2; Wu *et al.*, 2006).

In addition to the lack of evidence for syn-rift volcanism, there is another feature that uniquely defines the non-volcanic part of the margin. Existing data between the central and the northern line (SMART-1; Funck *et al.*, 2004) show a wide continent-ocean-transition (COT) zone characterized by a pervasive layer with velocities of 7.3–7.9 km/s, intermediate between crust and mantle, that we interpret as partially serpentinized mantle (FIG.1, 2b & c). The nature of the crust overlying the partially serpentinized layer is, however, difficult to define as it was under-sampled due to sparse receiver spacing. Furthermore, there is a lack of a conjugate pair profile with the SISMAR-4 profile on the Moroccan margin. Therefore, new data acquisition was necessary to reduce the uncertainties in crustal interpretations and conjugate margin reconstructions.

In November 2009, a new refraction profile was acquired by the Offshore Energy and Technical Research (OETR) Association of Nova Scotia along a coincident deep reflection profile (ION/GXT NovaSPAN 2000) to the northeast of SMART-1 (FIG.1). The profile was obtained using 100 ocean-bottom seismometers and with particularly dense spacing (2.5 km) within the COT that gives greatly improved resolution in this region. It also extends 125 km seaward of the reflection profile to better constrain the oceanic crust. Please refer to Makris *et al.* (in section Nova Scotia, this conference) for details on data acquisition and velocity modelling. In this paper, we present our interpretation of this new velocity model and integration with other observed refraction and coincident multi-channel reflection profiles in the study area. This comparison clearly demonstrates a northeastward continuation of the non-volcanic structures. A comparison of conjugate margin structures confirms a marked asymmetry with a much narrower COT off Morocco.

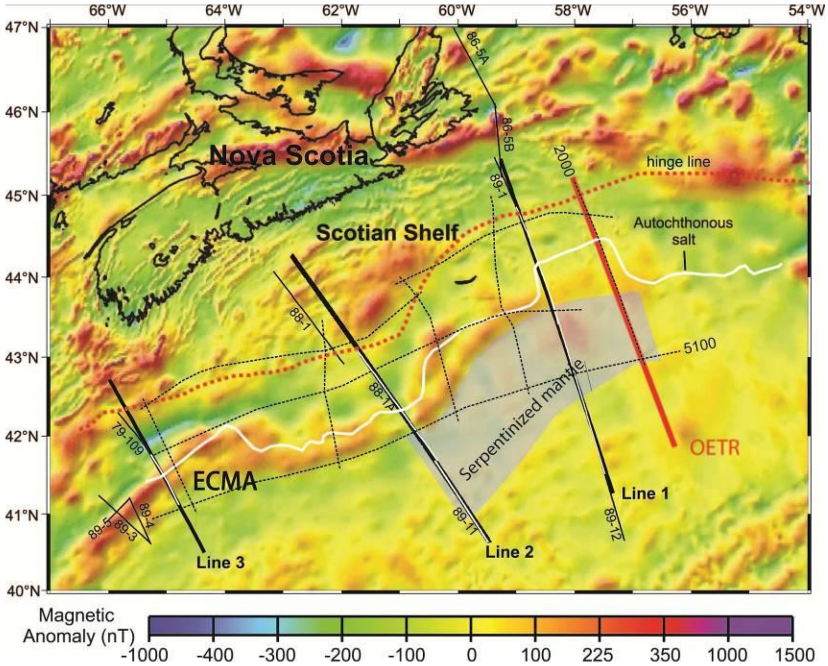


FIG.1 – Magnetic anomaly map of Nova Scotia margin. Red line – new refraction profile (OETR). Thick black lines – SMART profiles. Thin black lines – Lithoprobe profiles. Dashed black lines – ION/GXT NovaSPAN profiles.

## 2. Structural variations

FIG. 2a shows the velocity model of the OETR profile. This simple model shows structures very similar to those determined for SMART-1 (FIG.2a & b). This comparison indicates similar non-volcanic characteristics of the three major crustal zones, namely continental, transitional and oceanic. Firstly, the continental crust in the NW of profile OETR thins over a relatively wide zone (> 180 km). Even wider rifts are observed on the SMART-1 and SMART-2 profiles. Secondly, the oceanic crust composed of layers 2 and 3, is found to be thinner than average. In the SE of profile OETR, oceanic crust is 4–5 km thick, which is similar to SMART-1, while for SMART-2, it increases only slightly to ~ 6 km. Thirdly, there is a wide transitional zone (COT) on all profiles that cannot be explained by either a continental or oceanic crustal model. The COT is modeled on profiles OETR and SMART-1 as two layers above normal mantle. The lower layer, interpreted as partially serpentinized mantle, has velocities of 7.2–7.6 km/s and a thickness of ~ 6 km. A similar layer is observed on profile SMART-2 but with higher velocities (7.6–7.8 km/s) and smaller thicknesses, suggesting a lower degree of serpentinization.

The upper layer of the COT is the most variable crustal feature along the margin and its crustal origin is least constrained due to its small thickness and large depth. According to profile OETR, this layer has a velocity of ~ 5.3 km/s and an overall seaward decrease in thickness (from 4 to 2 km). It is best interpreted as oceanic layer 2 as it is continuous with this layer on the seaward end. On SMART-1, a thin layer, with similar velocities, is interpreted as exhumed mantle for the seaward half of the COT. Since we do not see evidence for exhumed mantle on profile OETR and SMART-2, we reinterpret this layer to be ultra-thin oceanic crust. As oceanic layers 2 and 3 are interpreted for the seaward part of the COT on SMART-2, we observe a southward trend of more fully developed oceanic crust above serpentinized mantle.

On the landward part of the COT, the upper layer is interpreted as continental crust on SMART-1 and -2. On SMART-2, it is observed as rotated fault blocks with fanning syn-rift sediment layers in the reflection data. Therefore, on profile OETR, continental crust may possibly extend beyond the seemingly abrupt thinning at ~ 170 km.

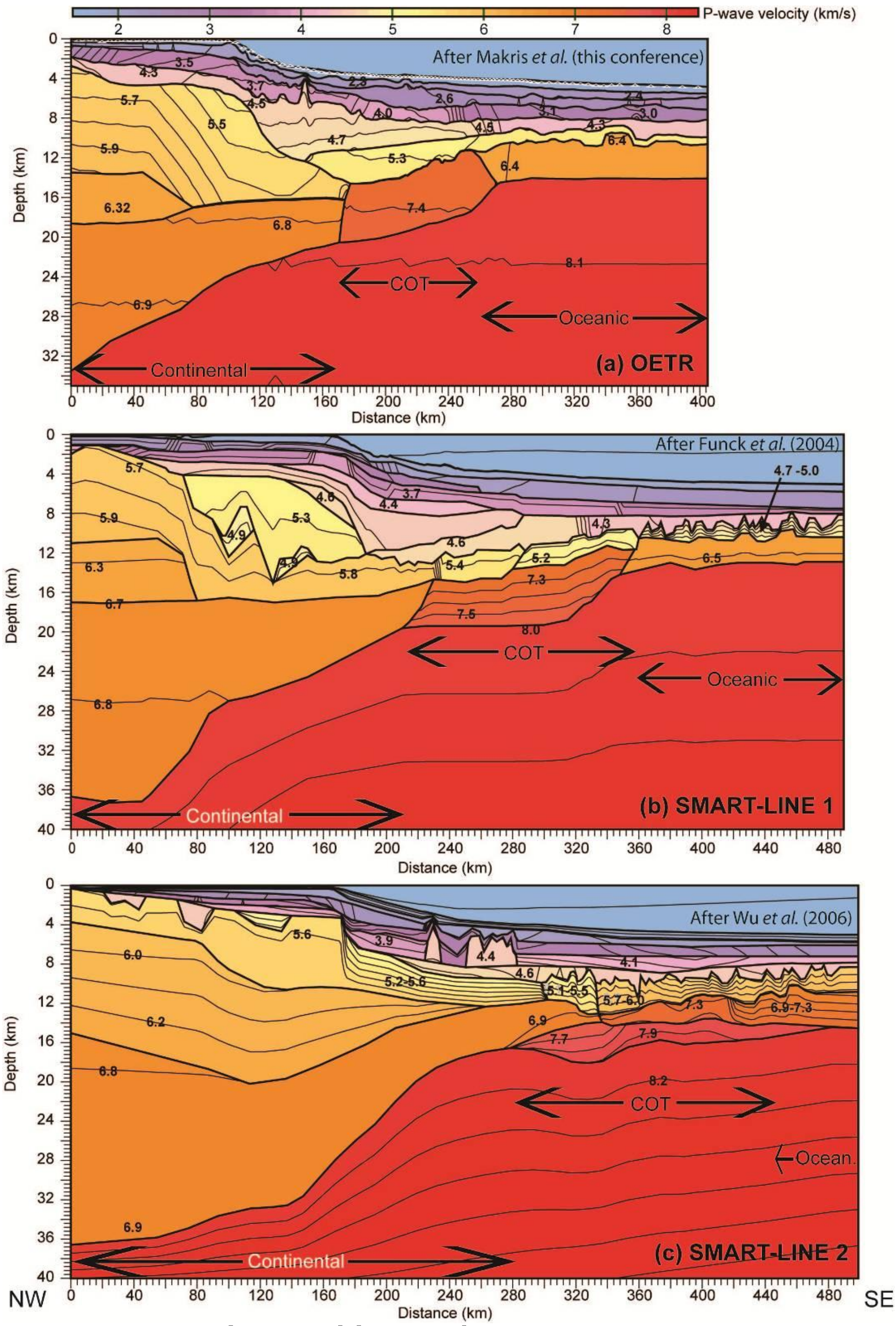


FIG.2 – P-wave velocity models across the NE Nova Scotia margin.

A mapping of the COT zone (FIG.1) shows close correlation with the hinge line of the rift basin, implying a common regional scale forcing behind its formation. Within this zone, a strong crustal reflection (W) is observed on reflection profile NovaSPAN 5100 (FIG.3) at about the depth of the top of the interpreted serpentinized mantle, suggesting an abrupt velocity contrast across the boundary. Therefore, a mapping of the 3-D geometry of this reflection would help to discriminate between the different crustal models of the transitional upper crust.

A kinematic reconstruction of the rifting and breakup of the complete Nova Scotia-Morocco conjugate margins will be presented using these new results. After plate reconstruction, a dramatic asymmetry in all three crustal zones (i.e. width of continental thinning, nature of the COT and oceanic crustal thickness) is clearly observed on the Moroccan margin along profile SISMAR-4, which is nearly conjugate to NovaSPAN 2000 (Contrucci *et al.*, 2004). Either a ridge jump or post-spreading volcanism may be required to explain such asymmetry.

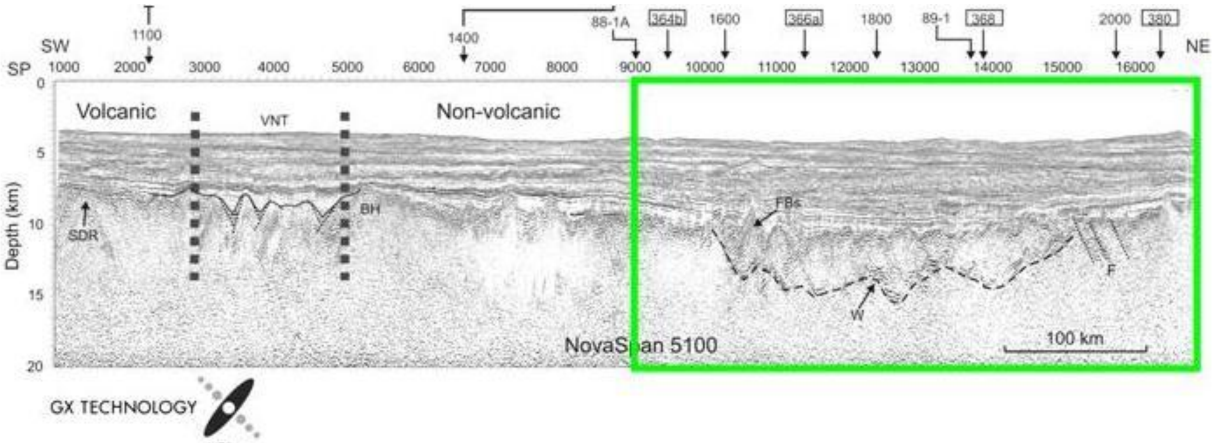


FIG.3 - Prestack depth migrated section of NovaSpan 5100 (see Fig. 1 for location). Green box encloses the NE half of the profile where partially serpentinized mantle is interpreted. W - a strong crustal reflection possibly related to the top of the serpentinized mantle layer. FB - fault block. F - fault.

## 4. Future work

We will refine existing models targeting detailed velocity structures of the upper transitional crustal layer. For line OETR, the close spacing of OBS receivers should allow a refined model with unprecedented level of detail for the structures already identified. We will also map in 3-D the strong reflection within the OCT using newly reprocessed MCS data.

*Acknowledgements*
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# Deep to surface processes of the French Guiana transform margin, eastern Demerara plateau

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*ABSTRACT*

*Transform margins represent an important part of the equatorial Atlantic margins. They usually present a very steep ocean-continent boundary inherited from the vertical transform fault along which opening occurred. A marginal Ridge is also bounding the continental domain. This is expressed on bathymetry by steep continental slopes (on average greater than 20°). Therefore erosional processes and especially slope instabilities prevail in those settings. The geometry of syn- and post-rift sedimentary sequences fundamentally differs from that of classic "divergent" passive margins, and this has consequences for surface processes and fluid migration patterns.*

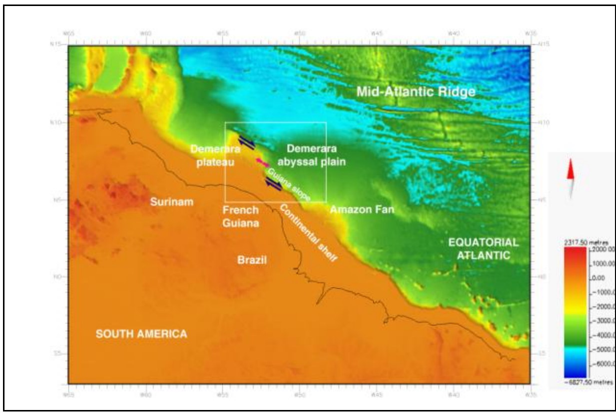
*The Demerara plateau located offshore French Guiana is a salient of the South American continental margin bounded by divergent and transform segments. It has been surveyed in 2003 (GUYAPLAC cruise, part of the French EXTRAPLAC program) using multibeam bathymetry and imagery (EM12), 6 channel seismic data and 3-5 kHz echosounding. The analysis of this dataset has revealed several original patterns from depth to the surface - First, no clear marginal ridge seems to characterize this transform margin, especially when approaching the divergent sections, - Second, the distal part of the continental margin seems to have been tilted seaward during the post-transform stage (Eocene?) - Third, very large slumped masses affect the surface of this tilted area (uppermost 500 meters of sediments over an area of nearly 150 km²) strongly eroding the Demerara plateau,- Finally, several giant pock-mark fields occur on the seafloor in the same area. There, the association of mass-movement and fluid-escape structures suggests that fluid overpressure can be a key factor in the recent evolution of this system.*

*We present here a detailed analysis of this original transform margin that may be considered as an end-member of transform margin structural diversity.*

*KEYWORDS: Transform margin,marginal ridge, slope instabilities, Fluids, Demerara*

## 1. Introduction and geological setting

Although shear margins represent ~30 % of rifted margins around the world, yet few studies have been dedicated to the characterization deep to surface couplings along these margins that display specific structurally-controlled seafloor morphology (and especially a very steep ocean-continent transition). The aim of this study is to investigate levels of coupling between deep and surface processes (slope instabilities, fluid venting) along the transform portions of the French Guiana margin and, in the future, to try to propose an integrated model of its evolution. Another aim of this study is to better characterize the Guiana margin that seems to be an original end member of transform margin's diversity. The study area is located in the western Equatorial Atlantic Ocean, on the French Guiana margin, which is characterized by a broad continental shelf and a steep continental slope that is interrupted at mid-depths along the northern part of the study area by the 1000-2000 m deep Demerara plateau (FIG.1). The Guiana margin is fringed by the Demerara abyssal plain off the northern part of the study area and the distal part of the Amazon Fan to the south. The study area has been structured first by the opening of the Central Atlantic during Early Jurassic times, then by the opening of the Equatorial Atlantic at the end of Early Cretaceous, along a main transform zone (Klitgord & Schouten, 86; Gouyet, 1988, Unternehr et al., 1988, Greenroyd et al., 2008). The studied margin therefore comprises transform and divergent segments (FIG.1). On the Demerara plateau, the post-rift sedimentation consists of successive wedges prograding from the continental shelf, with a maximum total thickness of 6 km at the foot of the upper continental slope. In the abyssal plain, sedimentary thicknesses drastically increase south-eastwards, i.e. towards the Amazon turbidite system.



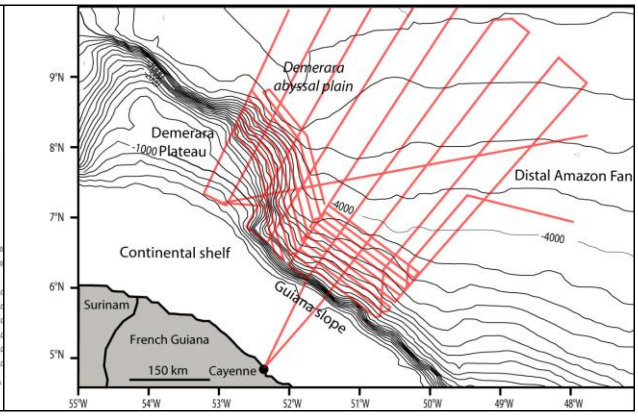




FIG.1 - Location of the study area (white box) situated in the western Equatorial Atlantic Ocean (Bathymetric map modified http://www.ngdc.noaa.gov, 2006). The blue and pink arrows indicate respectively the shear and divergent segments of the studied margin (Gouyet, 1988, Greenroyd et al., 2008)

FIG.2 - Dataset of swath bathymetry, backscatter imagery, 3.5 kHz echograms and 6-channel seismic reflection profiles acquired during the GUYAPLAC cruise (2003, red lines).

## 2. Data set

The French Guiana margin and the adjacent Demerara abyssal plain were surveyed during the GUYAPLAC cruise onboard the R/V l'Atalante (2003, FIG.2), as a part of the EXTRAPLAC French Program (Ifremer-IFP–SHOM-IPEV). The dataset comprises: (1) EM12-Simrad multibeam bathymetry and backscatter imagery, (2) 3.5 kHz echograms with an average penetration of 50 m below seafloor, (3) 6-channel seismic profiles. All data were acquired at a speed of 8 knots. Bathymetric data have been processed using CARAIBES software developed by IFREMER, resulting in a digital terrain model with a 250 m resolution grid. Additional processing has been performed on data from the Demerara plateau at a 125 m resolution grid. The combination of the bathymetric and 3.5 kHz analyses allowed identification and characterization of the main sedimentary processes in the study area. The analysis of seismic profiles allowed to better characterize the structure and history of deformation of this margin.

## 3. Results

### 3.1. Structural analysis – chronology and typology of deformations

The structure and evolution of the French Guiana transform margin are presented here relative to the post-transform unconformity, regionally dated Late Albian by drill-holes (FIG.3). The study area has been divided into 4 parts according to morphological characteristics: the Upper, Intermediate and Lower Plateaus, and the Deep Abyssal Plain. The unconformity and underlying highly deformed layers are observed on the Lower and Intermediate Plateaus. The relative chronology of deformation attests that former tilted blocks with fan-shaped filling were inversed by folds and reversed faults. The spacing of available seismic lines does not allow identifying directly strike-slip displacements or transpression. To the north-east, elongated seismic basement highs could be magmatic intrusions and limit the edge of the Lower Plateau from the abyssal plain. As in other transform margins, but particularly here because of its segmentation, the unconformity is difficult to date precisely because diachronic. Indeed, it marks the transition syn- to post-rift in the divergent segment and the end of strike-slip deformation along the transform segments. The unconformity here clearly seals compressive structures with a progressive erosion of the folds axes. It is later shifted by normal faults affecting mostly the divergent southeastern border. Post-unconformity sediments are stacked by aggradation on the Plateau. After their deposition, they were tilted oceanwards as the whole margin (FIG.3) and affected by massive slides whose scars are located between the Upper and the Intermediate Plateaus **(**FIG.3). The entire demerara plateau seems affected by massive slides since Oligocene (Erbacher et al., 2004; Mosher et al., 2007) The timing of this tilting, based on lateral interpolation of drill data seems to be post-Eocene. In any case, this ocean-ward tilting occurs late in the margin evolution and is followed by massive sliding processes. Finally when considering the lateral evolution of this margin, we observe that unlike further North west (off Surinam, Erbacher et al., 2004, Mosher et al., 2007) or unlike most transform margins, no clear marginal ridge can be observed along the transform boundaries (FIG.3**)**. Instead, subsidence seems to have occurred.

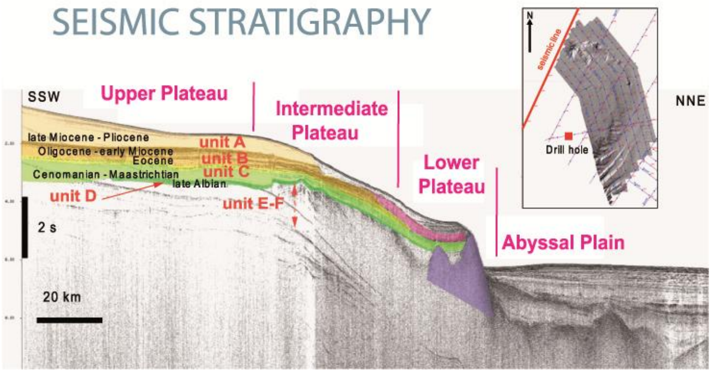



FIGURE - 3.: Seismic profile (Guypalac 1) showing the structure of the Upper, intermediate and lower plateau.

### 3.2. Surface processes and seafloor fluid venting

The Demerara plateau dips seaward and presents a segmented morphology with at least four "en échelon" NNW-SSE trending (i.e. parallel to the initial shear direction) slope breaks giving a “stair” aspect to the intermediate and lower plateau (FIG.4). These NNW-SSE structural steps seem to correspond to oceanwards collapses of wide blocks. On 3.5 kHz profiles (~100 km long, Loncke et al., 2009; Gaullier et al., 2009), slumps initiate upslope along the uppermost NNW-SSE slope break (intermediate plateau). Downslope, these slumps evolve to folded sediments that can correspond to compressive toe of slumps or creeping features. The sediments then thin distally into a rough to transparent mass sometimes showing seismic wipe-outs. At a deeper scale, seismic data show that this part of the margin has undergone repeated slope failure creating deep massive collapses (numerous overlapping transparent masses rooted at about 0.5 second two-way travel time below seafloor, Loncke et al., 2009). The plateau also displays a very rough surface with folds perpendicular to the slope direction probably related to creeping processes as testified by 3.5 kHz data (FIG.4, insert). The continental slope is eroded by numerous regressive scars (Gaullier et al., 2009). The slope gradient of the continental slope is diminishing going SouthEast when approaching divergent segments. Finally, very numerous circular, elongated and/or aligned depressions have been observed on intermediate and lower Demerara plateau. We attribute these features, which are correlated to high reflectivity patches, to pockmarks. Some of them reach 2 km in diameter and 100 m in depth. These pock-mark fields have been observed above a polygonal faulting interval, which, in places, is remobilized by slumping processes (affecting the last 500 m of the sedimentary cover).The South-eastward elongation of these features may be due to a re-shaping by the DWDC (Deep Western Boundary Current, Dengler et al., 2004). Seismic wipe-outs are also identified on the 3.5 kHz echograms all over the plateau and underline the importance of the fluid and gas discharge in this area (Loncke et al., 2009).

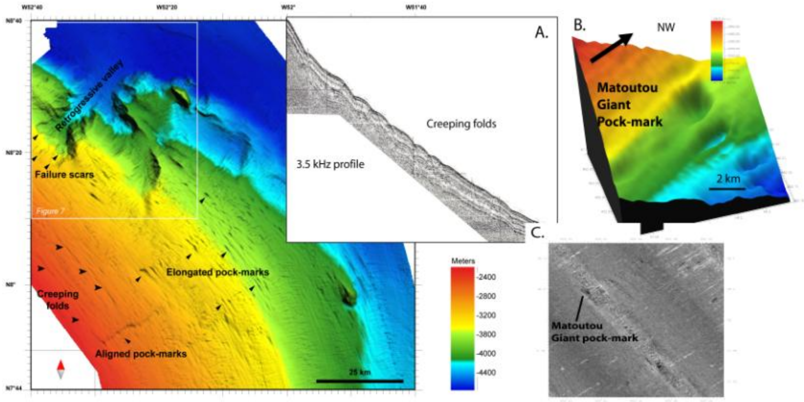



FIG.4 - Main frame: swath bathymetry along the Demerara lower plateau showing creeping sediments and elongated pock-marks. Insert A/ 3.5 kHz echograms with creeping folds, B/ Detail on a Giant pock-mark, C. backscatter imagery on the Matoutou giant pockmark.

## 4. Conclusions

The French Guiana transform margin marking the north-???eastern boarder of the Demerara Plateau is an original transform margin: Unlike most of the transform margins that appear uplifted along the continent-ocean boundary, no actual marginal ridge could be defined. Furthermore, this margin has been lately tilted towards ocean (post-paleogene). After this and till recent times, slope instability seems to prevail on the Demerara plateau. The analysis of seismic and surface data (bathymetry, imagery and chirp data) revealed indeed that most of the Demerara plateau is affected by huge slump deposits. This dataset evidenced also a giant pock-mark field (150 km² in area), that evidences active seepage processes on the seafloor. Fluids are released by a sedimentary unit deformed by polygonal faulting and destabilized slumps. This unit overlies itself the black shales and the deeper Albian unconformity and older sediments, probably allowing fluid migration from depth. The association of slumping and fluid-escape structures suggests that fluid overpressure can be a key factor in the dynamics of this system. The seaward tilting of the margin and the cropping out of the stratigraphic horizons along the continental slope seem to strongly control fluid migration pathways to the surface. This multi-scale analysis of the eastern Demerara plateau shows that structure, slope instabilities and fluid escapes are strongly coupled along this transform margin.

*Acknowledgements*
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# Gross Depositional Environment offshore Nova Scotia: methodologies and preliminary results

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*ABSTRACT*

*In April 2009 a comprehensive review of the prospectivity of the offshore Nova Scotia Basin was commissioned by OETR (Offshore Energy Technical Research Association of Nova Scotia). This was fundamentally based on a complete re-interpretation of existing well and seismic data. In particular, a thorough review was conducted of biostratigraphy from many key wells in order to develop a consistent sequence stratigraphic framework for the basin.*

*This new sequence stratigraphic framework was tied to an extensive 2D and 3D seismic database in an effort to extrapolate facies information away from the wells. The objective was to create a suite of GDE (Gross Depositional Environment) maps which describe facies distribution for key intervals in the evolution of the basin. Sequence stratigraphy integrated with seismic stratigraphic analysis is the main tool in developing these maps.*

*Integrated analysis of well based sequence stratigraphy with seismic data identified 10 sequences of exploration significance. The intent was to develop GDE maps for each of these sequences. These maps can then be used to predict the geographic distribution of reservoirs, seals and source rock.*

*This paper describes the overall approach used in this study and presents some of the early results.*

## 1. Introduction

The Play Fairway Analysis (PFA) programme initiated by OETR (Offshore Energy Technical Research Association of Nova Scotia) is fundamentally based on the creation of Gross Depositional Environment (GDE) maps for key intervals that depict and predict reservoir, seal and source rock distribution. These maps are created through thorough integration of paleo-environment data from wells with seismic facies analysis.

The methodology is essentially based on a rigorous sequence stratigraphic approach. The major innovation in this PFA study was the creation of a systematic sequence stratigraphic framework for offshore Nova Scotia. This analysis was based on 20 key wells of which 6 had new biostratigraphic analyses. Data from the remaining 14 wells were re-interpreted in an internally consistent framework.

The information from these key wells was extrapolated using seismic stratigraphy. Accurate well to seismic ties were established through careful calibration of sonic and density data using established well/seismic correlations methods. In order to ensure the highest possible resolution for calibration to the wells, key seismic lines were reprocessed to improve bandwidth and imaging. These well data were extrapolated using a large seismic database (~70,000 km of 2D and ~30,000 sq km of 3D).

Development of an integrated sequence stratigraphic framework was achieved through thorough iteration with seismic stratigraphic analysis. Biostratigraphic and seismic data have several uncertainties due to various sources of “noise” (e.g. reworking in biostratigraphy and migration noise in seismic). Iteration between the two was therefore essential to develop a regionally consistent framework.

The PFA workflow imposes a rigorous and disciplined integration process. This is designed to ensure that the various input elements of the study are internally consistent. The integration process is continual throughout the programme and is tested fully during the creation of the GDE maps. These maps necessarily have to honour all the data and interpretation that feeds into the process (from the most basic tectonic history, through biostratigraphy, depositional processes as evidenced by sedimentological studies, seismic stratigraphy and, in this instance, salt kinematics).

The PFA project included some 15 horizons that were mapped seismically for structural and stratigraphic control. Of these, 10 surfaces have significance for understanding the most prospective Cretaceous and Jurassic plays. The GDE maps for the most important intervals are interrogated for prediction of distribution of reservoirs, sources and seals.

This paper presents the overall methodology and illustrates the workflow with an example of source rock distribution.

## 2. The Scotian Basin

The Scotian Basin (FIG.1) is a passive continental margin that developed after rifting and separation of the North American and African continents beginning in the Middle Triassic. The rift phase was characterized by continental fluvial/lacustrine/playa red bed and evaporite deposition while the drift phase was characterized by carbonate deposition in the Jurassic followed by major deltaic progradation in the Early Cretaceous.

FIG.2 shows the major events through geological history as previously identified by various workers (Wade et. al. 1995). Figure 2 shows both the pre-existing stratigraphy as defined by Wade et. al and some of the modifications introduced by the work of MacRae et. al. 2010. The latter is based on an internally consistent interpretation of both new biostratigraphic results (from 6 wells) and pre-existing biostratigraphic studies. These data were re-interpreted as needed and iterated with seismic data. This revised stratigraphy identifies multiple deltaic episodes during the Early Cretaceous as well as the latest Jurassic. These observations create some new play possibilities.

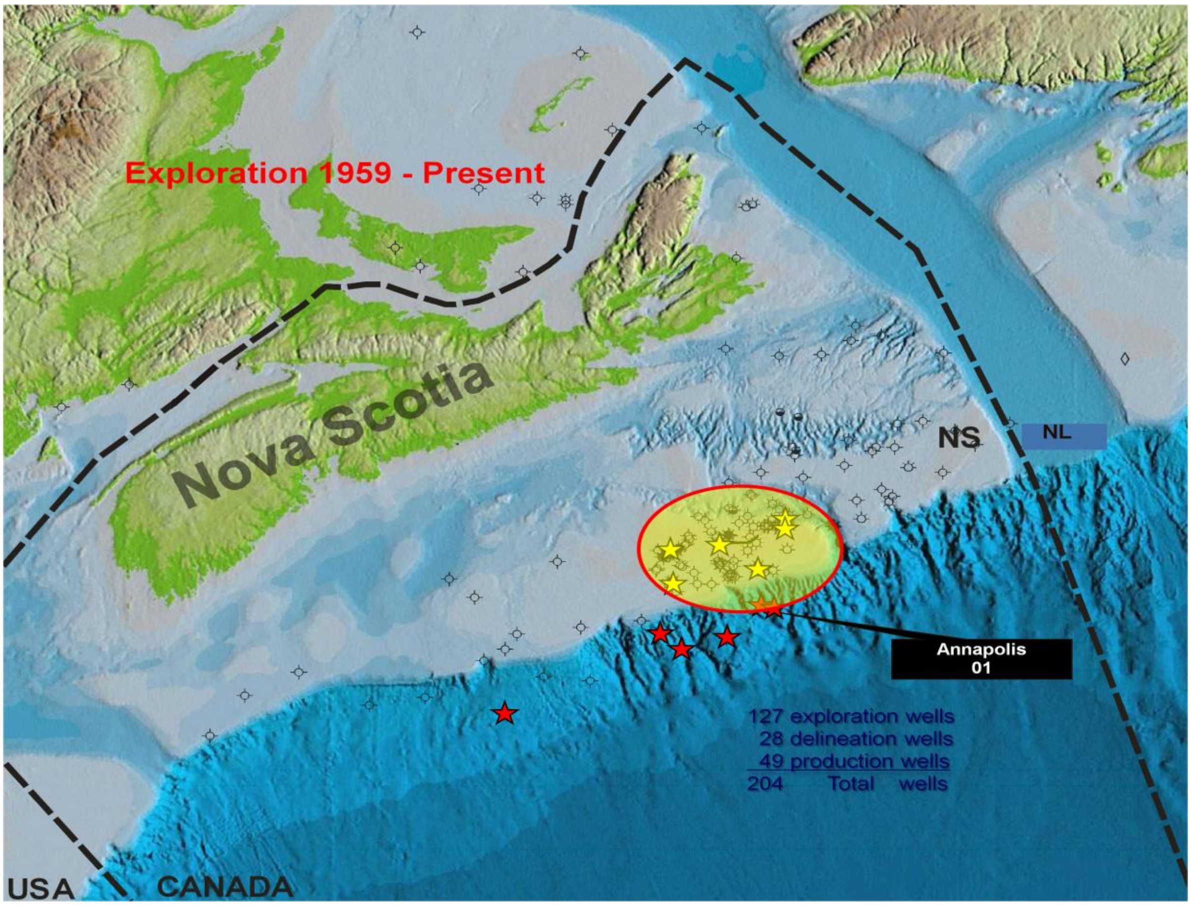


FIG.1 – Overview of Scotian shelf with showing location of main wells.

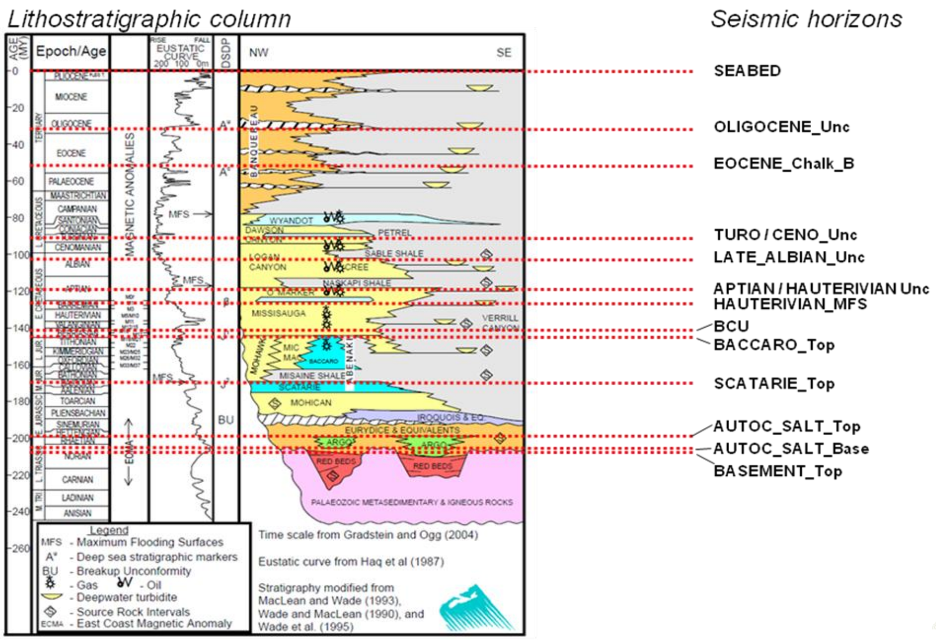


FIG.2 – key sequence stratigraphic surfaces selected for fairway mapping.

A thorough review of the significant surfaces leads to the identification of 15 surfaces that were mapped seismically. The list is shown in Figure 3. Figure 4 shows an example sequence stratigraphic well correlation and Figure 5 a two way time map for the Berriasian/Valanginian surface (near BCU).

Maps such as that shown in FIG.5 are integrated with well correlations and interpreted paleo-environment data from the biostratigraphy study to create regional GDE maps. This paper will present examples of GDE maps for key horizons and intervals with a preliminary interpretation.

| | Seismic Horizon | Age (Ma) | Surface Name | Age | Surface type | Fm / Mb equivalent | Regionally mappable |
|---|---|---|---|---|---|---|---|
| 1 | SEABED | 0 | SB | | | | Yes |
| | MIOCENE_Unc | 25 | T25 | | SB | | No |
| 2 | OLIGOCENE_Unc | 30 | T30 | Rupelian / Chattian | SB | | Yes |
| | EOCENE_Unc | 40 | T40 | Bartonian / Priabonian | SB | | No |
| 3 | EOCENE_Chalk_B | 50 | T50 | ?Early Ypresian | MFS | Eocene Chalk | Yes |
| | CRETACEOUS_Chalk_T | 85 | K85 | Coniacian to Santonian | Lithological Boundary | Wyandot Fm | No |
| | PETREL_Top | 94 | K94 | Cenomanian / Turonian | SB / TS | Petrel Mb | Yes |
| 4 | TURO_CENO_Unc | 94 | K94 | Turonian / Cenomanian | | Base Petrel Mb | Yes |
| | MARMORA_Top | 97 | K97 | Cenomanian / Albian | TS | Marmora Mb | No |
| 5 | LATE_ALBIAN_Unc | 99 | K99 | Late Albian | SB | Cree Mb | Yes? |
| | NASKAPI_Top | 120 | K120 | Aptian | SB | Naskapi Fm | Yes? |
| 6 | MISSISAUGA_Top | 123 | K123 | Aptian / Hauterivian | SB /TS | Upper Missisauga Fm | Yes? |
| 7 | HAUTERIVIAN_MFS | 131 | K131 | Late Hauterivian | MFS | O Marker | Yes? |
| | MISSISAUGA_Middle | 132 | K132 | Intra Hauterivian | SB / TS | Middle Missisauga Fm | Yes? |
| 8 | BCU | 137 | K137 | Valanginian / Berriasian | SB | Verrill Canyon Fm | Yes? |
| 9 | BACCARO_Top | 147 | J147 | Tithonian | TS | Baccaro Mb | Yes |
| | MISAINE_Top | 161 | J161 | Callovian | SB | Misaine Mb | Yes |
| 10 | SCATARIE_Top | 165 | J165 | Late Bathonian | TS | Scatarie Mb | Yes |
| | MOHICAN_Top | 170 | | ?Bathonian to Bajocian | SB / TS | Mohican Fm | |
| | IROQUOIS_Top | | | Early Jurassic | | | |
| | VOLCANICS_Top | | J200 | Early Jurassic | | | |
| 11 | ALLOC_SALT_Top | | SB | | | | Yes |
| 12 | ALLOC_SALT_Base | | | | | | Yes? |
| 13 | AUTOC_SALT_Top | 200 | J200 | ?Triassic | | | No |
| 14 | AUTOC_SALT_Base | 210 | Tr210 | Pre Mesozoic | | | No |
| 15 | BASEMENT_Top | 216 | | Pre Mesozoic | | | Yes? |

FIG.3 - Key seismic surfaces mapped for the PFA.

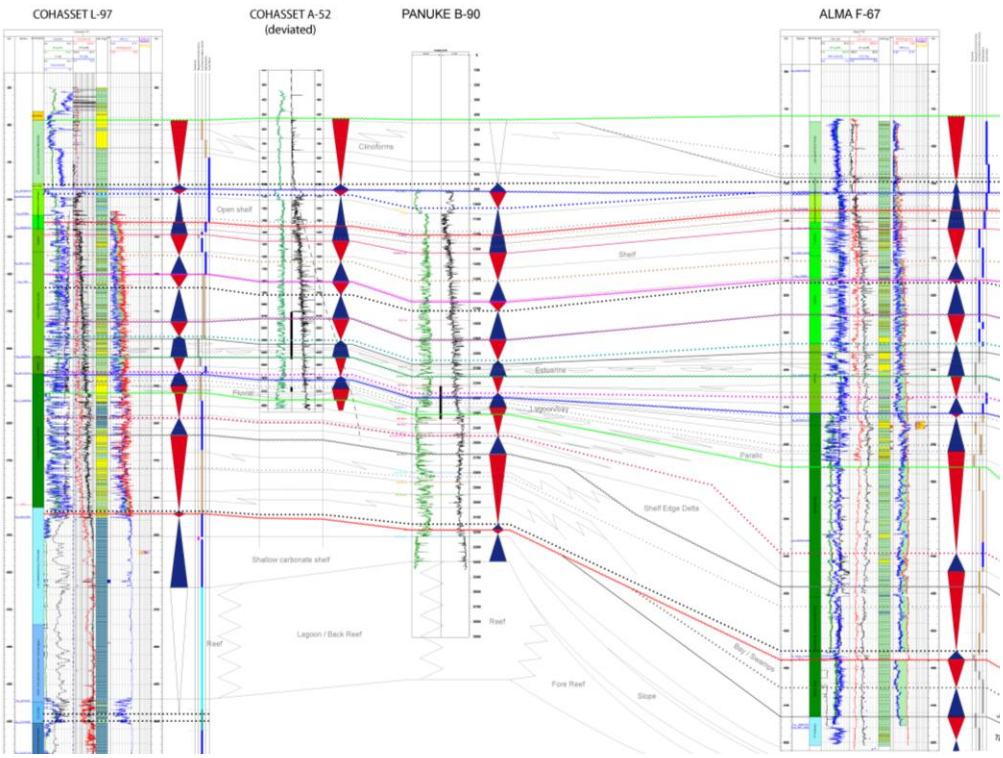


FIG.4 - Early Cretaceous stratigraphy.

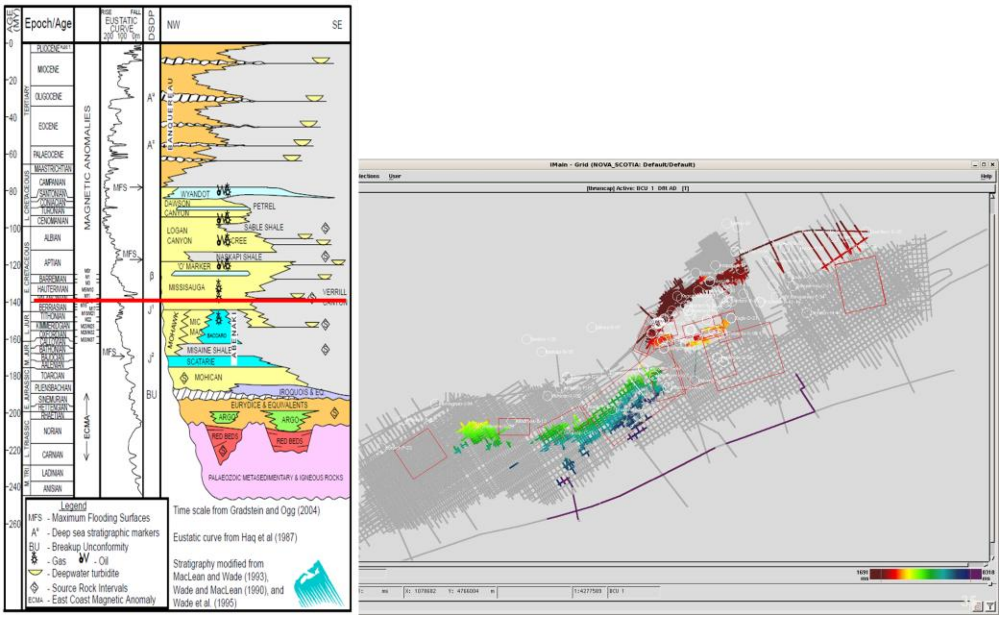


FIG.5 - Berriasian/Valanginian Unconformity (BCU) – preliminary two way time map.

*Acknowledgements*
*The authors thank OETR for providing funding for this work and permission to publish this material.*

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MacRae, A., Ascoli, P., Cooper, K., Fensome, R., Shaw. D., Weston, J. and Williams, G.; 2010 - A revised biostratigraphic and well-log sequence stratigraphic framework of the offshore Nova Scotia Margin, Canada. Lisbon Conjugate Margins Conference

# A revised biostratigraphic and well-log sequence stratigraphic framework for the Scotian Margin, offshore eastern Canada

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*ABSTRACT*

*As part of a Play Fairway Analysis (PFA) of the Scotian Margin, offshore eastern Canada, we have conducted quantitative multi-disciplinary biostratigraphic studies of the Upper Triassic-Cenozoic sections in 6 wells: Bonnet P-23, Chebucto K-90, Cohasset L-97, Glenelg J-48, Glooscap C-63 and South Griffin J-13. These wells were chosen to provide good spatial coverage and stratigraphic penetration, plus correlation with the seismic grid. Using the results from these new wells as calibration, we have also evaluated pre-existing biostratigraphic data and interpreted the well-log sequence-stratigraphy of 14 additional wells using a consistent multi-disciplinary event scheme. Our study provides accurate ties and clarifies the origin of seismic horizons mapped across the area within the PFA project. Key to the dating of some horizons has been integration of the palynology and micropalaeontology (most commonly used for biostratigraphy on the Scotian Margin) with new nannofossil and available calpionellid data. By integrating the biostratigraphic, lithofacies, well log and seismic data, we have enhanced resolution over previous efforts and thus have a better understanding of unconformities and major flooding events in the region. Our component of the PFA should enable better targeting of hydrocarbon exploration efforts on the underexplored Scotian Margin, especially in deeper water..*

*KEYWORDS: Nova Scotia, Biostratigraphy, Scotian Basin, Palynology, Nannofossils, Microfossils.*

## 1. Introduction

The Scotian Basin, offshore Nova Scotia (Wade and MacLean, 1990; FIG. 1) is a producing hydrocarbon region, but it remains relatively unexplored, with about 200 wells to date. Of these, the majority have some type of biostratigraphic data, usually in the form of palynology and foraminiferal studies by the original operators of the wells. Subsequent studies by industry, academia, and government have enhanced the biostratigraphic control in the region (e.g., Ascoli, 1990; Barss et al., 1979; Doeven, 1983; Fensome et al., 2008; Williams, 1975; Williams et al., 1990), however, many outstanding problems remain. Discrepancies between methods often yield significant differences in correlation, making regional stratigraphic studies challenging. An example is shown in FIG. 2, which shows stage-level differences in the age interpretation of stratigraphic units and over 1km of difference in correlations between two wells in the Early Cretaceous part of the section. This has profound implications for petroleum systems modelling and other efforts in the area.

To stimulate exploration of the region, a Play Fairway Analysis of the Scotian Margin was initiated in 2009. Biostratigraphy is a significant component of the study, in recognition of the need for better age and paleoenvironmental control. We have made new analyses of foraminifera, palynology, and nannofossils from 6 wells, and reexamined data from previous studies of 14 additional wells. Wells have been selected to represent a complete section of Scotian Basin stratigraphy from Triassic to Cenozoic and to enable construction of transects from the shelf to frontier areas on the continental slope (FIG. 1).

One key result of the study has been the reconciliation of previous biostratigraphic datasets in cases where different fossil groups have yielded different age interpretations for the same succession. Such integration has revealed that correlation problems often resulted from extensive reworking in Early Cretaceous palaeo-delta slope deposits. The reworking may be related to the mass-transport sedimentary structures reported from core data in a number of wells (Piper, Pe-Piper & Ingram, 2004; Piper, Noftall & Pe-Piper, 2010) and to palaeo-shelf-margin incision recognized from seismic (Cummings et al., 2006; Deptuck et al., 2008). Beyond the reconciliation of the various biostratigraphic datasets, integration of the biostratigraphic data with wireline and lithofacies data, as well as collaboration with seismic interpreters, has enabled the calibration and better understanding of regional seismic surfaces within a sequence stratigraphic context (FIG. 3).

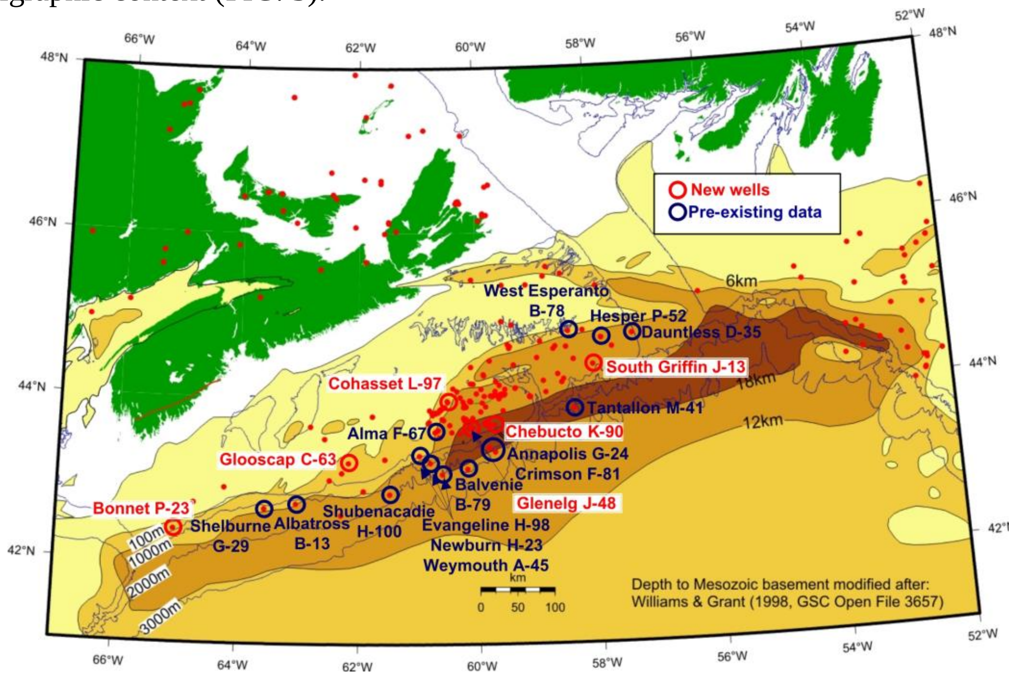


FIG.1 – Location of the Scotian Basin and 20 studied wells.

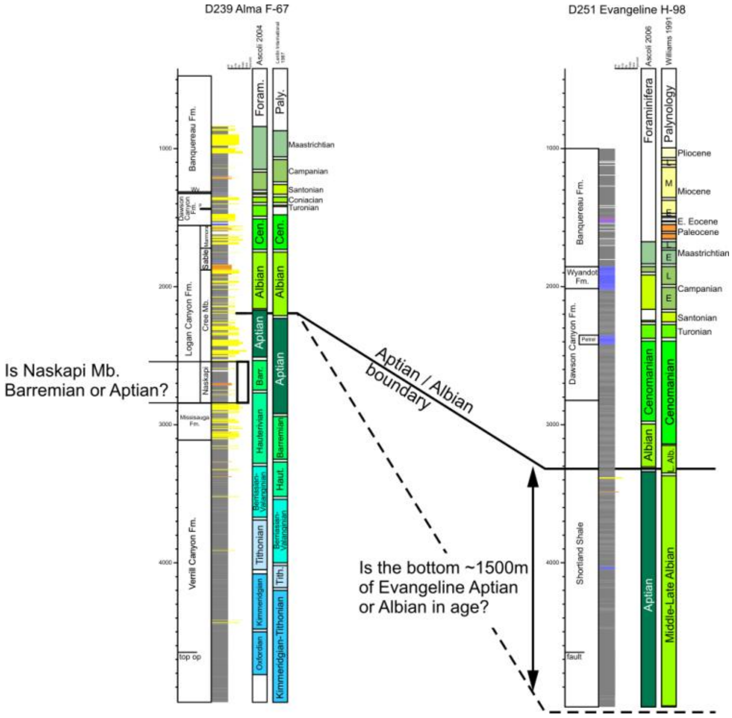


FIG.2 – Example of historical biostratigraphic data from two wells, Alma F-67 and Evangeline H-98, showing over 1500m discrepancy between previous age determinations for the Aptian/Albian boundary. Work in this study suggests the Evangeline well bottoms in the Albian, and Aptian foraminifera and other calcareous microfossils were reworked. Also evident is ~350m difference in the position of the Barremian/Aptian boundary, implying the Naskapi Member in Alma F-67 is either Barremian or lower Aptian in age (other studies and this study indicate the correct age for the Naskapi Member is Aptian).

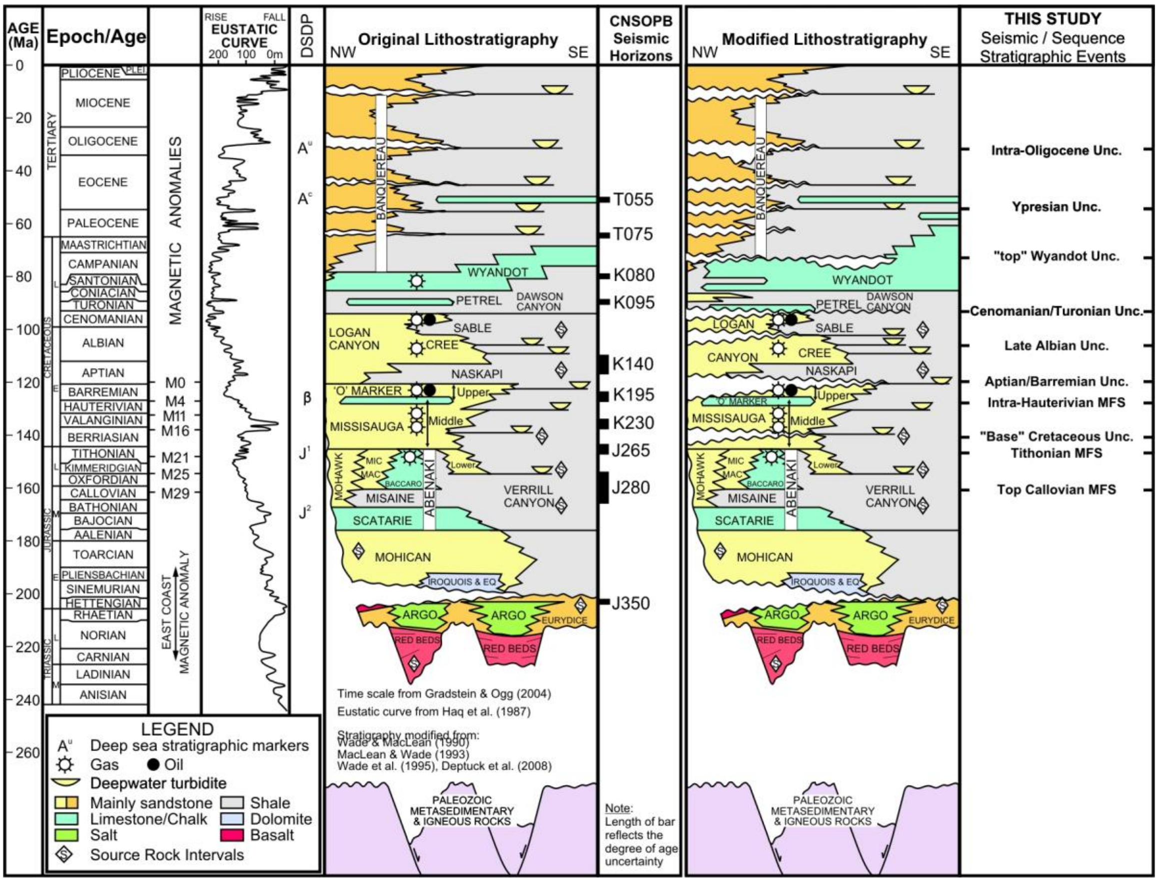


FIG.3 – Event stratigraphy in this study compared to previous sequence stratigraphic frameworks (MacLean and Wade, 1990; MacLean and Wade, 1993; Wade et al. 1995; Kidston et al. 2007; Hogg et al. 2001; Deptuck et al. 2008). Ten events have been regionally recognized, representing major unconformities and maximum flooding surfaces that have a distinctive biostratigraphic signature. Current work is focussed on extending the event stratigraphy into the Early Jurassic and Triassic using additional wells.

*Acknowledgements*

*The authors thank the Offshore Technical Research Association, the Geological Survey of Canada (Atlantic) and Natural Resources Canada, the Canada-Nova Scotia Petroleum Board, and the Nova Scotia Department of Energy for support of this project.,*

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# A crust and basin study of the Nova Scotia margin and its ocean transition based on densely spaced ocean bottom seismic observations

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*ABSTRACT*

*A crustal and basin seismic study of the Nova Scotia shelf/slope and its transition to the oceanic crust of West Atlantic was performed by observing a 400 km long NW-SE oriented seismic profile covered by 100 Ocean Bottom Seismographs (OBS). Four different geological domains have been identified: A continental crust of 33 to 27 Km thickness covers the first 70 Km of the north western part of the line and is covered by 4,5 Km thick sediments. The next 100 Km consist of a stretched continental crust of 27 to 19 km, including 9 km of sediments. At the following 90 km the crust consists of igneous intrusions with Vp-velocity 7.2 to 7.3 Km/s, terminating the continental domain. Strong serpentinization occurs at the top of this intrusion. The last 140 km of the profile are floored by thin oceanic crust of 4 km thickness, which is covered by 4 to 5 km thick sediments. A salt basin extends over the last 60 Km of the stretched continental crust. The conjugate margin of Nova Scotia, which is the Moroccan margin north of Agadir, differs from that of the Canadian side since the stretched continental crust of the Moroccan margin is followed by seafloor spreaded oceanic crust without any igneous intrusions and serpentinized units.*

*KEYWORDS: Nova Scotia, Atlantic conjugate margins, crustal structure.*

## 1. Introduction

On behalf of OETR, GeoPro GmbH, Hamburg, performed in November 2009 a Wide Aperture Reflection/Refraction (WARRP) Seismic Survey off the Scotian shelf/slope offshore Nova Scotia, Canada (Fig. 1). The project goal was to clarify the crustal structure at the ocean continent transition zone (OCT), compare it with older data published by Funck et al (2004) and to reconstruct the Atlantic Rift, prior to oceanization and in connection with its conjugate margin off Morocco. One hundred 4C Ocean Bottom Seismographs (OBS) were deployed along a 400 Km profile of NW-SE orientation, perpendicular to the continental margin, in water depths ranging from 32 m at the shelf to 4803 m in the abyssal plain. Seismic energy was generated by a tuned air gun array ranging between 64 to 40 lit, and was placed at 10 m depth. The array was tuned at low frequencies, in order to observe large offsets. In the following we will present the results obtained from this wide angle seismic experiment.

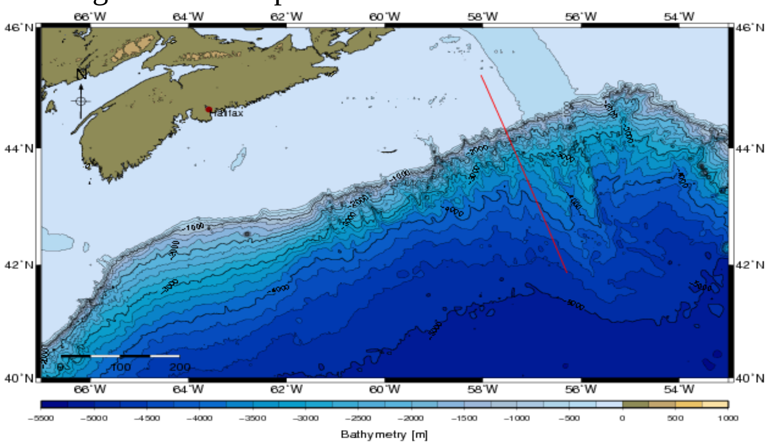


FIG.1 – Location of the OBS seismic line in Nova Scotia, North Atlantic.

## 2. Evaluation of the OBS data and results

The recorded seismic data were evaluated in Common Station Gathers (GStG) and were presented having applied a linear move out using 6 Km/s as reduction velocity. An example of a CStG of OBS position 41 is presented in figure 2. The only correction applied is that of the time drift of the OBS clock. Positions are located from first breaks of the water wave arrivals. Maximum errors at deep water may be up to 500 m off the seismic line.

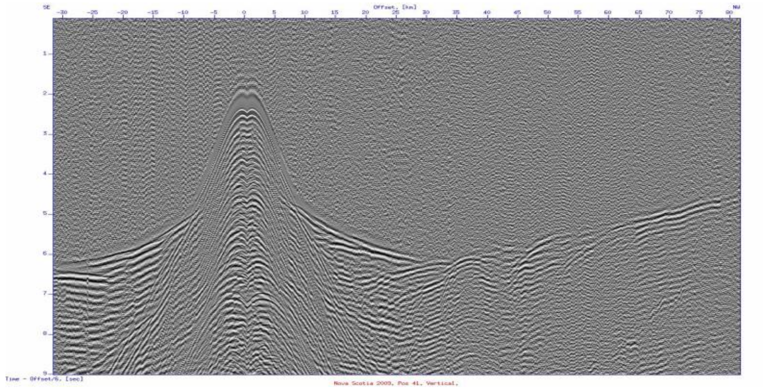


FIG.2 – Common Station Gather of OBS 41.

Evaluation of the OBS data was a combination of tomography (Ditmar & Makris, 1996), forwards kinematic and dynamic ray tracing (Cerveny et al., 1977), and refraction migration (Pilipenko & Makris, 1997). We started with the first break tomography that revealed a velocity model based on velocity gradiance. This model was a starting point for the layered tomography that exploited later arrivals of wide angle reflections, and was further refined by two point ray tracing (see fig. 3).

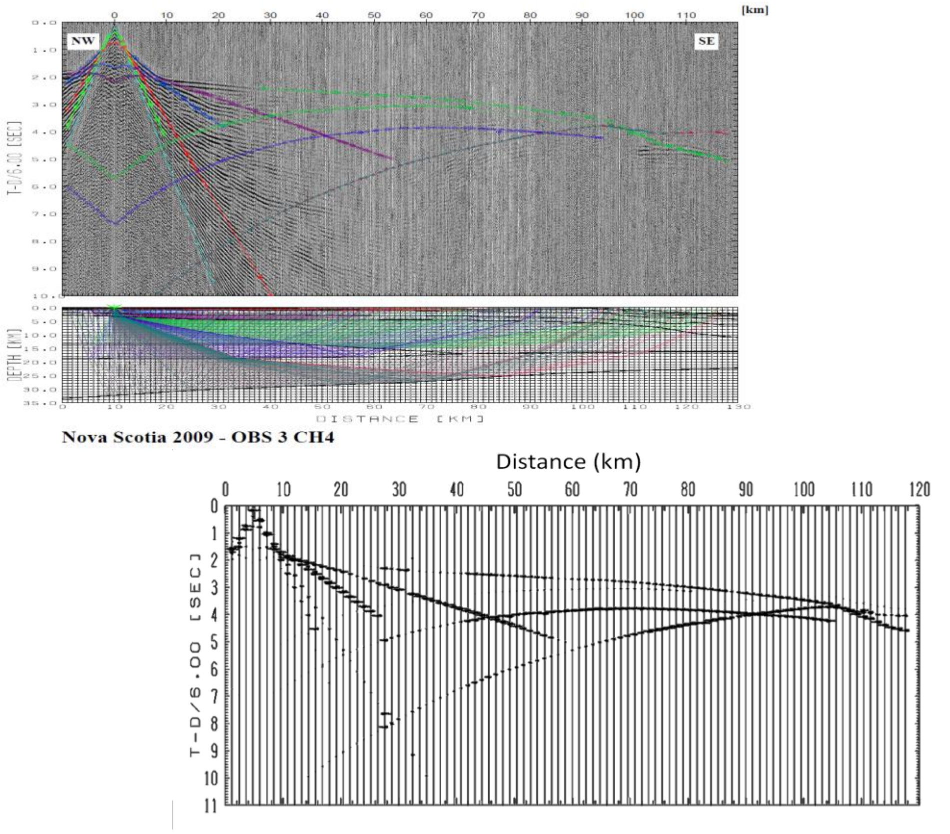


FIG.3 – Ray traced model (up) and synthetic amplitude (down) for OBS 3, Nova Scotia profile.

The velocity model that was finally obtained is presented in Figure 4. The model can be divided into three different domains. From E to W we have a continental domain from 0 to 163 km which is followed by a transition oceanic domain from km 163 to 283 and a true oceanic domain from 283 to 400 km. Accuracy of the model is approximately within ± 5%.

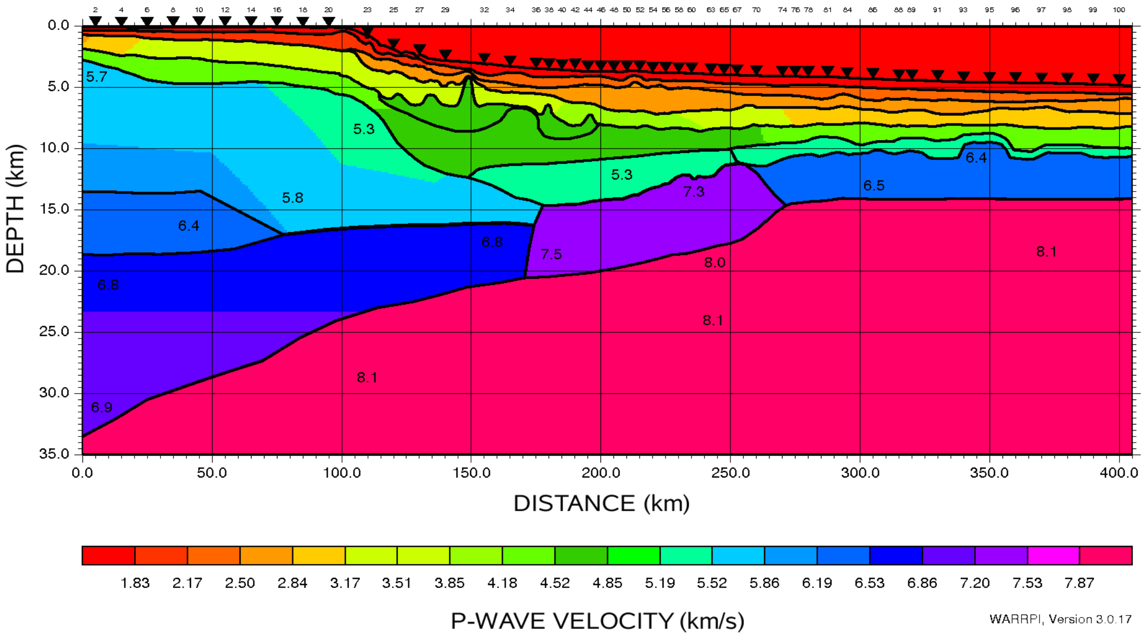


FIG.4 –Vp Velocity Model of Nova Scotia profile.

The continental crust at the Nova Scotia coast is 33 to 35 km thick. It is divided into three layers: an upper crust, a middle crust and a lower crust, and is covered with 3 to 5 km thick sediments. The continental crust thins rapidly eastwards and from OBS 17 (crustal thickness of 25 km) the crust consists of only two layers. The sediments increase in thickness and at km 100 (OBS 21) are 6.5 km thick. The following bathymetric escarpment displaces the seafloor from 100 m to more than 3 km depth within a horizontal distance of 25 km. The sediments increase very rapidly and at the end of the steep escarpment (OBS 31) are 9.5 km thick. At OBS 36 the stretched continental crust is abruptly terminated. An upper mantle intrusion extends from OBS 36 up to OBS 69, from km 170 to km 255. This part of the section contains a highly serpentinized layer directly above the upper mantle intrusion of Vp-velocities between 7.1 and 7.3 km/s. Vp-velocities in the serpentinized layer vary irregularly between 5.1 and 5.4 km/s. From OBS 70 to the end of the line, up to km 400, the crust is oceanic and its thickness is 4 to 4.5 km. Sediments thin progressively from the escarpment depression (9.5 km thickens) to only 4 to 5 km at the end of the line. We could also map the salt basin across the domain of the Diapiric Province extending from OBS 25 to OBS position 94, over a distance of 60 km. The refraction migration (fig. 5) defines the top of the oceanic crust and that of the strongly serpentinized upper part of the intruded igneous body between the continental edge and the true seafloor spreaded oceanic domain.

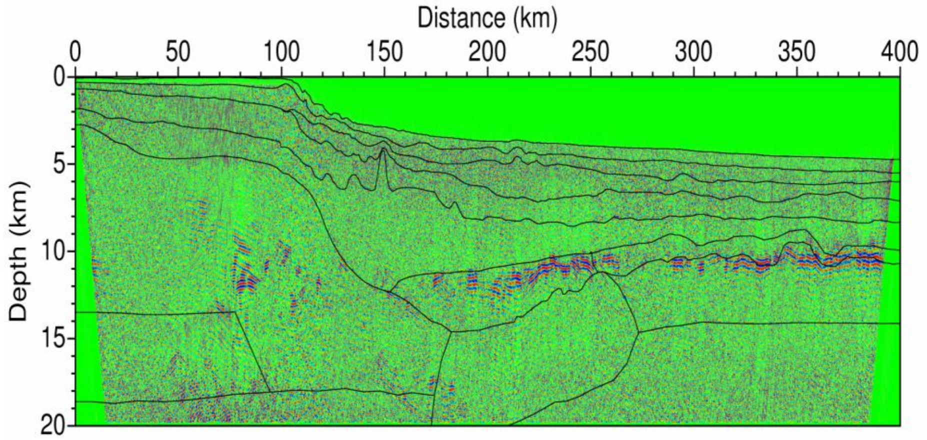


FIG.5 – Refraction Migration of Nova Scotia profile with velocity interfaces.

## 3. Conclusions

The evaluation of the 100 OBS positions along the 400 Km seismic line across the Nova Scotia margin of Canada revealed the existence of four different geological domains. The first, starting at the north western end of the profile, extends for 70 km and consists of a continental crust of 33 to 27 km thickness. An upper, middle and lower crust, very similar in structure and velocities to those observed further south across the Canadian continental margin, were resolved. Sediments in this part of the profile have a maximum thickness of 4,5 km. The second domain, of 100 Km width, consists of a stretched continental crust thinning from 27 to 19 km, including more than 9 km thick sediments. Several salt bodies were identified within the sedimentary sequence and cover most parts of the stretched continental crust. This part of the basin belongs to the salt province that strikes parallel to the Canadian continental shelf. Here the continental crust is terminated. For the following 90 km the crust consists of an igneous intrusion with Vp-velocity ranging between 7.2 and 7.3 Km/s. This intrusive body is covered by a layer with Vp velocities ranging between 5,1 and 5.4 Km/s, which are highly irregular. This indicates that this part of the igneous body is strongly serpentinized. The next 140 km of the profile are floored by thin oceanic crust of about 4 km thickness, which is covered by 4 to 5 km thick sediments.

The conjugate margin of Nova Scotia is that of Morocco extending north of Agadir. The Moroccan margin differs from that of the Canadian side since the stretched continental crust of the first is followed by seafloor spreaded oceanic crust without any igneous intrusions or serpentinized units.

*Acknowledgements*
*The authors acknowledge the permission of OETR Canada – Government of Nova Scotia for presenting the OBS data collected during the November 2009 seismic survey.*

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# Hydrocarbon Prospectivity of a New Deepwater Petroleum Province, Offshore Senegal

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(4) Hunt Oil Company, Dallas, TX

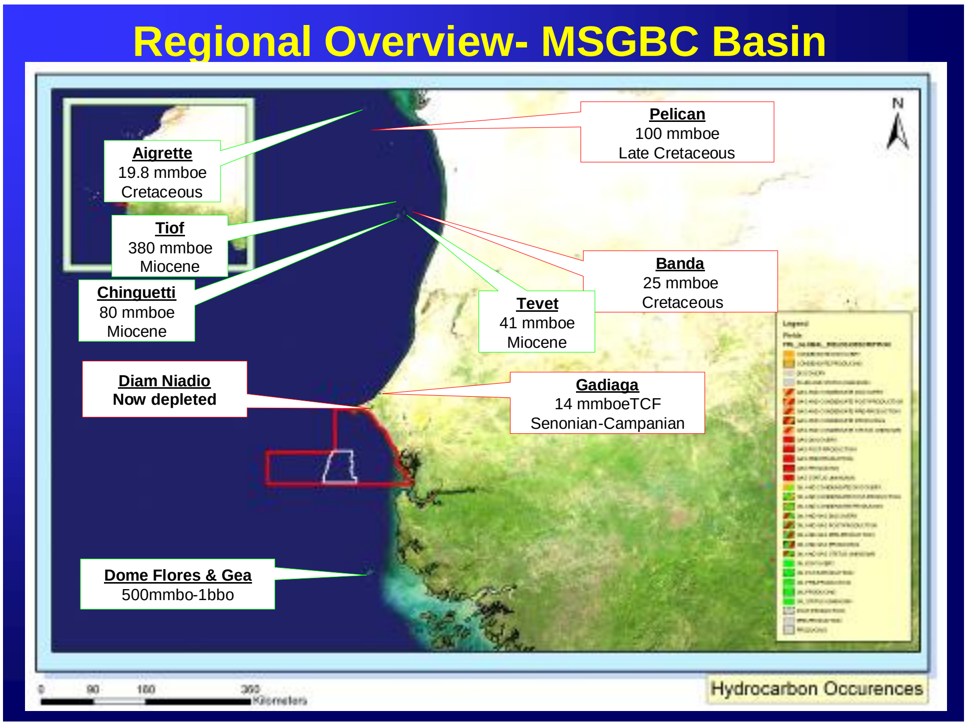
*ABSTRACT*

*Recent 3D seismic offshore, deepwater Senegal reveals two new hydrocarbon plays. 1. The erosion of the Albian-Aptian carbonate shelf by the Senonian unconformity with concurrent reservoir enhancing karstification of the platform and rotation due to salt withdrawal forming a broad closure. 2. A series of Santonian silica-clastic and carbonate stacked upper slope fans formed from the erosional debris. A Turonian source rock kitchen has been generating oil since the Maastrichtian and feeds the two plays.*

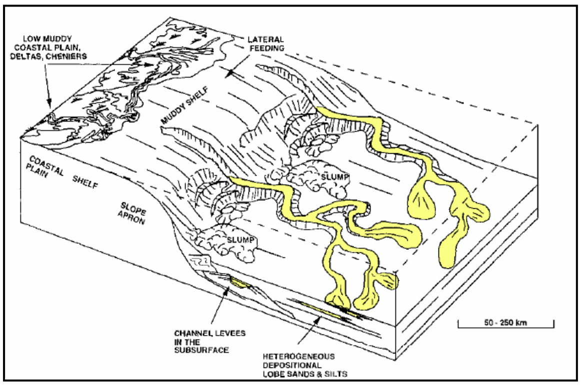
*KEYWORDS: Senegal; Hydrocarbons; Cretaceous plays; Karst unconformity; Slope fans.*

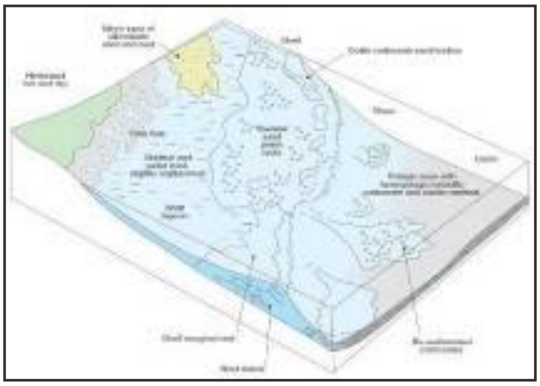
## 1. Introduction

The Senegalese portion of the greater MSGBC Basin, located offshore and south of the Dakar peninsula and north of Gambia, is under-explored.



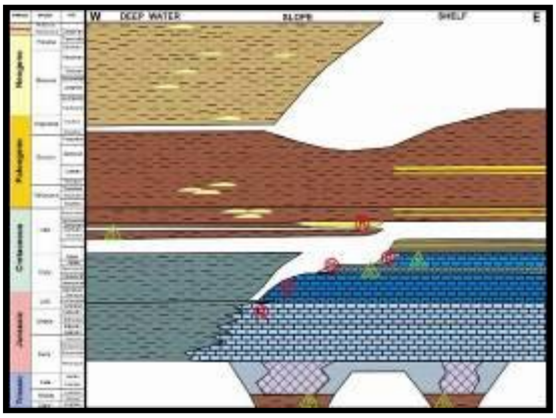

This study identifies the elements of a petroleum system and points to the exploration potential of the untested, deepwater portion of the Senegalese basin margin. 3D seismic data (2050 km2) acquired in 2007 reveal the existence of a long-lived carbonate platform and associated incised canyons with genetically related down-slope debris aprons/turbidites.

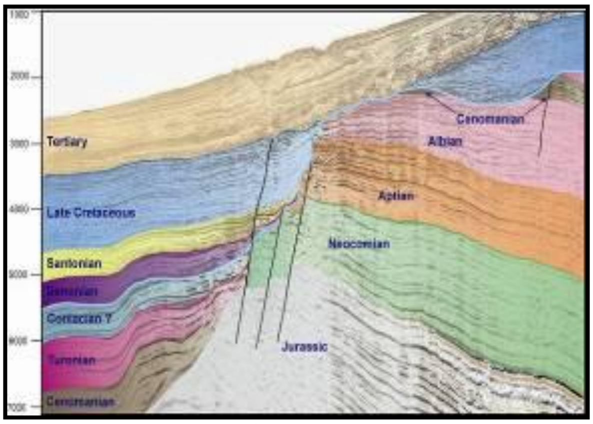


## 2. Geological Framework

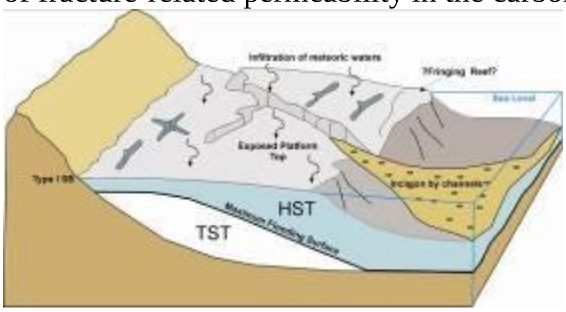
Seismic interpretation and multidisciplinary geologic studies indicate that the offshore region can be subdivided into two main para-sequences: the Pre-Senonian unconformity section and the syn-post Senonian unconformity section.

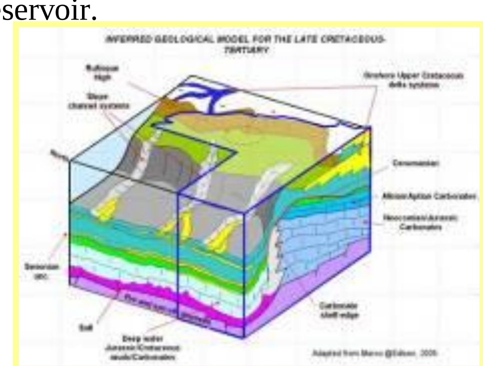



Chronostratigraphy Geoseismic

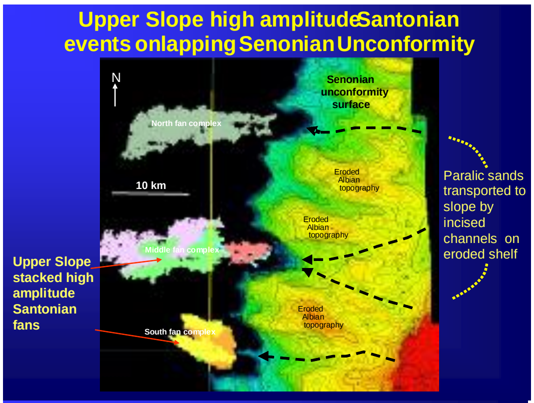
The pre-Senonian age section includes the long-lived carbonate platform of Jurassic to Cenomanian age. Uplift and subaerial exposure of the platform during Late Cretaceous time led to karstification and erosion that we believe are key to development of fracture-related permeability in the carbonate reservoir.

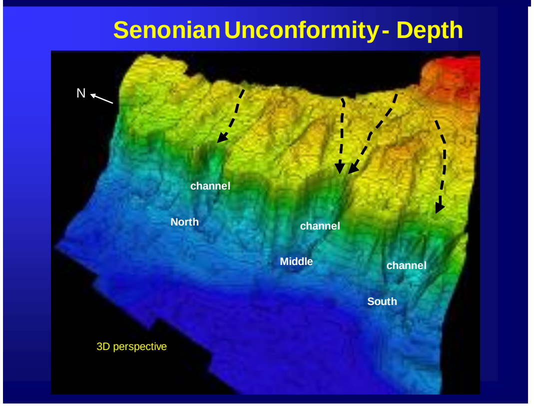


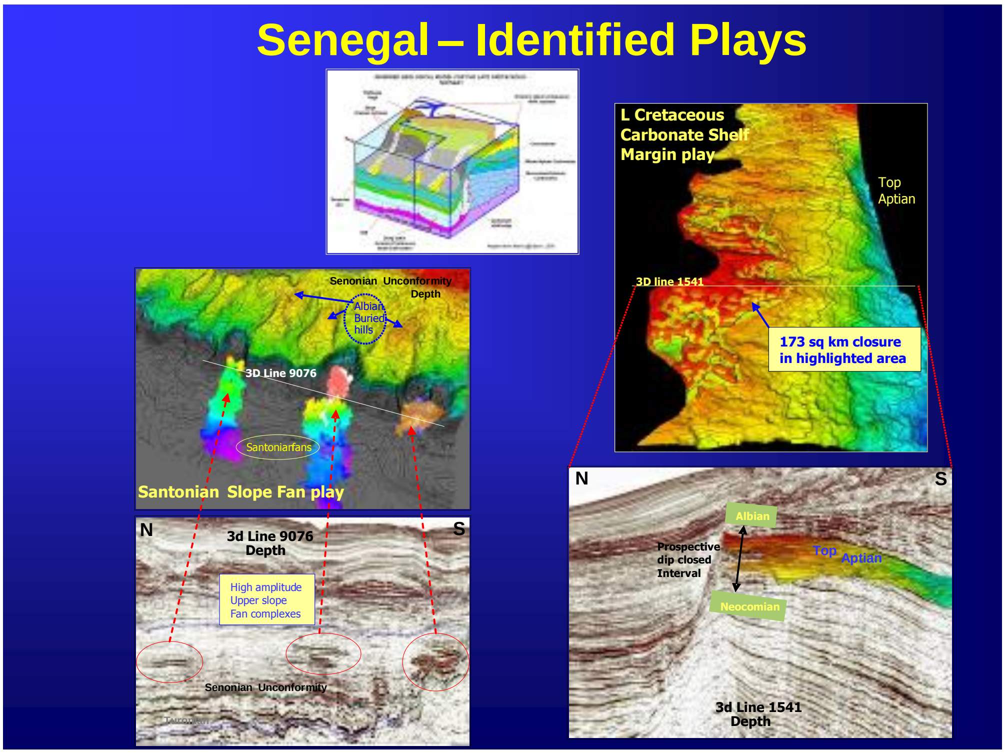

Uplift was likely associated with differential rotation induced by withdrawal of Triassic age salt in the southern MSGBC. Erosion is marked by the Senonian age unconformity that is easily recognizable on seismic and yields seismic evidence of karstified topography. In contrast, the syn-post Senonian age section consists mainly of

stacked Santonian age fans with multiple stacked amplitudes on seismic, and an overlying
Tertiary age succession.

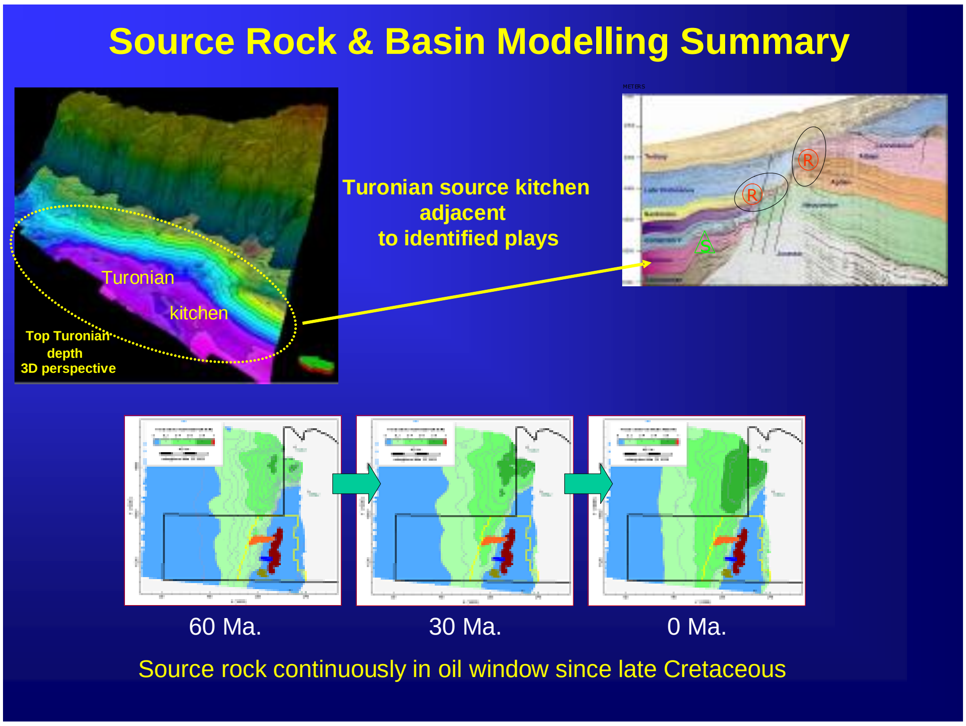



3. Hydrocarbon prospectivity

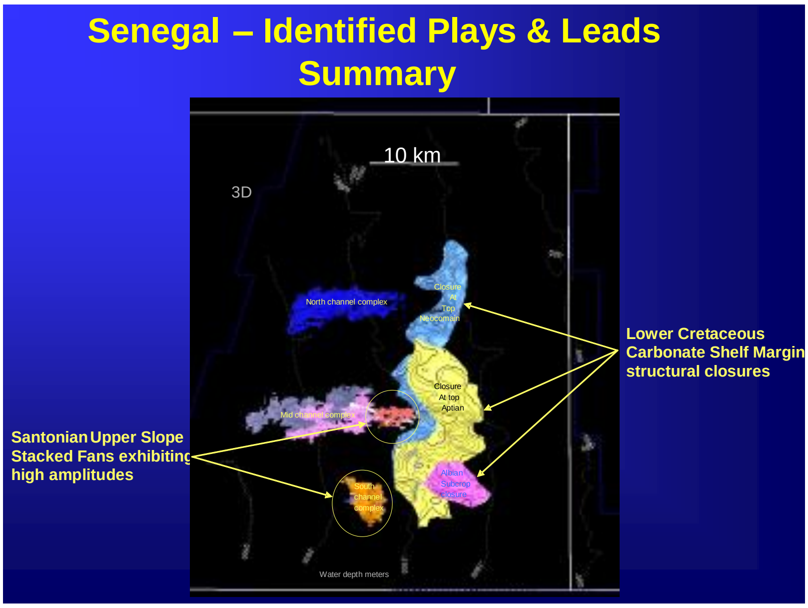


Detailed rocks physics and attribute analysis indicate that the turbidites are a mixed lithology of reworked carbonate material and paralic siliciclastic sediments. The paralic sands were transported from the shelf into the basin through incised valleys that also are clearly observable on seismic. 3D basin modeling was used to determine the timing of generation and spatial extent of the petroleum kitchen for the well-documented Turonian age source shale that was deposited along the west African margin.




Generation began during Maastrichtian time and continues through present-day, and the down-slope debris aprons and turbidites, as well as the karstified carbonate platform, are located either within or adjacent to the present-day kitchen.

## 4. Conclusions




Drawing on analogues from recent discoveries in Late Cretaceous age turbidites offshore Ghana, we believe that the Senegalese offshore basin is an exciting new deepwater province along the northwest African margin.

# Mesozoic magmatism at the West Iberian Margins: timing and geochemistry

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*ABSTRACT*

*The West Iberian Margins (Lusitanian and Algarve basins), preserve evidence of three Mesozoic magmatic cycles related with different phases of the Atlantic evolution and the kinematics of the Iberian plate.*

*The geochemical evolution from tholeiitic (202-198 Ma; 1st cycle), through transitional (147-141 Ma; 2nd cycle), to alkaline (94-72 Ma; 3rd cycle) expresses the increasing role of the sub-lithospheric mantle source(s), whereas some of the first and second (?) cycles magmas show traces of contribution from the sub-continental lithosphere affected by supra-subduction processes during the Hercynian orogeny.*

*KEYWORDS: Mesozoic, Magmatism, Portugal, Atlantic*

## 1. Magmatic chronology

The fragmentation of Pangaea started in the Mesozoic with the formation of intra-continental rifts, which later evolved to open the Atlantic Ocean.

Resulting from the continental fragmentation and relative motion of Eurasian, African and North American lithospheric plates, Mesozoic margins adjacent to the old Palaeozoic basement were formed at the Iberian microplate. Those margins were the locus for three Mesozoic magmatic cycles with distinct geochemical characteristics and separated by time lags of ~50 My (e.g. Martins, 1991).

The 1st cycle (202-198 Ma; Rapaille et al., 2003; Verati et al., 2007), is linked to the initial stages of the Central Atlantic opening. In Iberia (Martins, 1991; Martins et al., 2008), this episode was mainly extrusive, (subaerial lava flows, pyroclastic deposits and peperites), and post-dates the deposition of the first syn-rift terrigenous sediments of the Algarve Basin. Smaller occurrences also crop out in the Lusitanian and Alentejo basins at Sesimbra and Santiago do Cacém, respectively. The 530-km-long Messejana-Plasencia dike (Martins, 1991; Cebriá et al., 2003), with the same general orientation of the great CAMP dykes of Morocco also belongs to this cycle always characterized by tholeiitic magmatism. This magmatism is part of the Central Atlantic Magmatic Province (CAMP) (Marzoli et al., 1999) which includes coeval voluminous occurrences in the conjugate North American margin, and also in the conjugate margins of South America and NE Africa.

The 2nd cycle occurred in the Jurassic-Cretaceous transition (147-141 Ma; Grange et al., 2008; Alves et al., 2010a) and is restricted to the central part of the Lusitanian Basin (Soure-Óbidos region). Here, hypabissal rocks of transitional affinities (moderately alkaline to sub-alkaline) occur, mainly along two submeridian alignments, spatially associated with salt diapirs (Martins, 1991; Alves et al., 2010b). This cycle is coeval of the migration of the rift axis from the Lusitanian basin to West of the

Berlengas islets and is associated with an extensional phase also affecting the Grand Banks.

The 3rd cycle was the most voluminous in Iberia. It occurred during late Cretaceous (94 to 72 Ma; Miranda et al, 2009), was of alkaline nature and comprised two pulses. The first (94–88 Ma) occurred during the opening of the Bay of Biscay and consequent rotation of Iberia, is located between 38º26' and 39º00' N and includes the Paço d'Ilhas and Foz da Fonte sills. The second pulse (75–72 Ma) has a wider geographical distribution (N 37º to N39º), includes the intrusive massifs of Sintra (Matos Alves, 1964), Sines (Canilho, 1971) and Monchique (Rock, 1978) as well as the littoral Algarve lamprophyre-basanite suite (Martins, 1999) and the Lisbon Volcanic Complex (Palacios, 1985; Miranda et al., 2009). This last pulse is contemporaneous with the initial stages of the Alpine orogeny in Iberia that led to the tectonic inversion of the Mesozoic basins.

## 2. Petrology and geochemistry

The Mesozoic magmatic rocks of the Portuguese margins have MgO, Cr and Ni contents lower than the values attributed to primary magmas (Martins, 1991; Alves et al., 2010b) suggesting that the magmatic liquids resided in magmatic chambers where they evolved by fractional crystallization processes before their installation. Some of the rocks also show signals of crustal contamination, by Palaeozoic carbonates in the 1st cycle of Algarve (Martins et al., 2008), by Hettangian evaporites and dolomites in the 2nd cycle of Lusitanian Basin (Alves et al., 2010b) and by a siliceous contaminant in the more evolved rocks from the 3rd cycle (Palácios, 1985; Miranda, 2009a).

The evolution of the magmatic geochemical nature from tholeiitic (1st cycle), through transitional (2nd cycle) to alkaline (3rd cycle) is expressed by TAS diagram (Fig. 1), and geochemical characteristics of uncontaminated rocks, summarized in Table 1 (values from Leal, 1990; Martins & Olivença, 1998; Martins 1999; Youbi et al., 2003; Martins et al., 2008; Miranda 2009a,b; Alves, 2010).

On the 3rd cycle, the two pulses, initially defined on a geochronological basis, are also distinguishable based on the geochemistry. Occurrences from the second pulse show multielemental plots with negative K, Zr and Hf anomalies suggesting equilibration with phases rich in these elements, possibly as a result of interaction between the ascending magmas and the mantle lithosphere, while such anomalies are absent in unfractionated rocks from the first pulse. It is suggested that such differences are due to changes in the lithospheric stress field. During the first pulse the rotation of the Iberian plate may have favoured the opening of fractures and quick magmatic ascent, while in the second one the onset of collision between Iberia, Africa and Europe restrained the opening of feeders and promoted equilibration of magmas with the mantle lithosphere (Miranda et al., 2009).

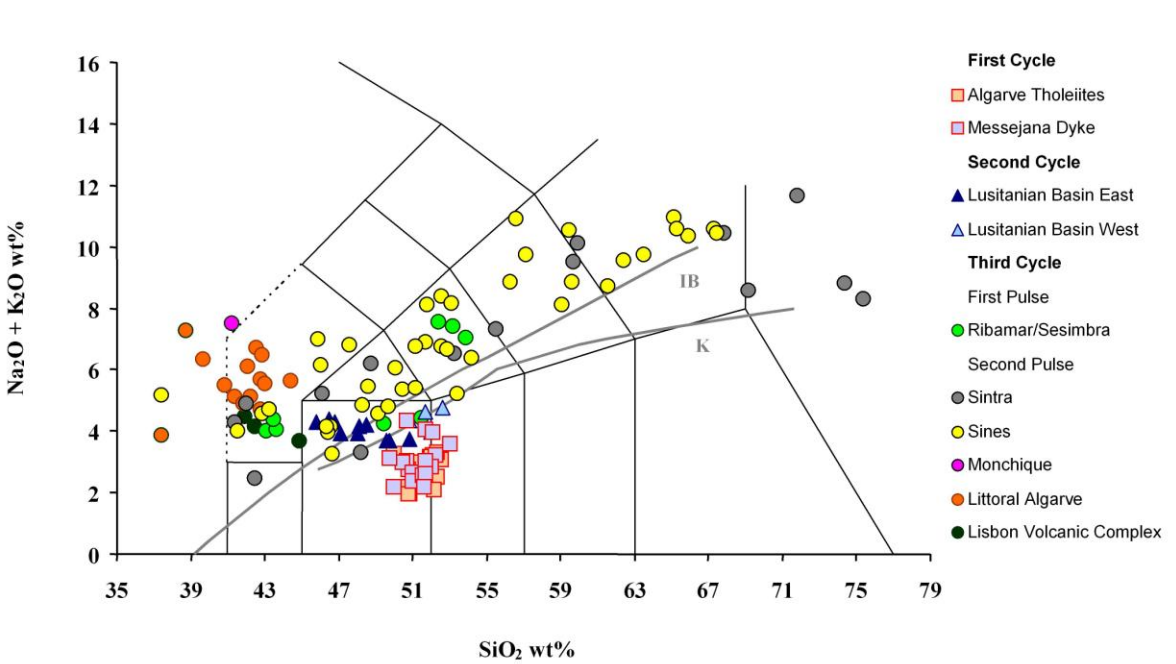


FIG.1 – Total Alcalis Silica diagram for representative samples from the 1st, 2nd and 3rd cycles of Iberian West Margin Mesozoic magmatism. The boundary lines between subalkaline and alkaline fields are from Kuno (1966) and Irvine & Baragar (1971). Selected data from references in the text.

| Geochemical Marker | 1st cycle | | 2nd cycle | 3rd cycle | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | 1st pulse | 2nd pulse | | | |
| | Algarve tholeiites | Messejana Dyke | Lusitanian Basin | Ribamar/ Sesimbra | Sines | Monchi-que | Littoral Algarve | Lisbon Volcanic Complex |
| Ni (ppm) | 45 - 102 | 45-140 | 134-214 | 41 - 57 | 62-160 | 21 | 79-210 | 59-176 |
| Zr/Nb | 7.7-12.6 | 6.9-10.7 | 4.6- 8.7 | 3.4-3.5 | 2.9-12.1 | 2.7 | 2.7-4.0 | 3.3-4.2 |
| $(La/Yb)_n$ | 2.77-3.43 | 2.52-2.94 | 5.92-11.22 | 19.9-20.9 | 3.09-21.7 | 29.1 | 19.9-39.1 | 14.8-21.4 |
| $(^{87}Sr/^{86}Sr)_0$ | 0.705390-0.706240 | 0.705219-0.706051 | 0.704041-0.704863 | 0.702870-0.703850 | | | | |
| $(^{143}Nd/^{144}Nd)_0$ | | 0.512268-0.512462 | 0.512531-0.512664 | 0.512894-0.517580 | | | | |

Table 1 – Summarized geochemical characteristics for less evolved rocks (MgO>8 wt%) of the three magmatic cycles. Selected data, and ages used to calculate initial isotopic ratios, from references in the text.

Magma generation in the West Iberian Margins records the mantle response to the opening of the Atlantic from the onset of continental rifting (1st cycle), through the continental break-up (2nd cycle), to the late Cretaceous evolution of Iberia (3rd cycle). The geochemical magmatic evolution from tholeiitic (202-198 Ma), trough transitional (147-141 Ma), to alkaline (94-72 Ma) expresses the increasing role of the sub-lithospheric mantle source(s) which dominate the last cycle whereas the geochemical properties of some of the first and second (?) cycles magmas show traces of contribution from the sub-continental lithosphere affected by supra-subduction processes during the Hercynian orogeny.

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# Salt Tectonics in the Western Gulf of Cadiz (SW Iberia)

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*ABSTRACT*

*Recent developments in hydrocarbon exploration offshore Portugal, in particular in the Algarve basin, have increased the interest in salt tectonics studies in this area. Development of a comprehensive study of the petroleum systems of this basin is inevitably connected to the analysis of the salt system and related tectonics. This study presents the results from the interpretation of an extensive and recent regional 2D seismic survey. Seismic examples of typical halokinetic structures as reviewed and discussed in this work include a wide spectrum of features, from extensional rollers, salt pillows, salt diapirs, to compressional structures including squeezed diapirs and allochthonous salt bodies. Two different salt units were identified in the offshore Algarve basin: a lower one of Late Triassic/Early Jurassic (Hettangian) age and an allochthonous unit originated from the Hettangian salt. The Hettangian unit is mainly characterized by an autochthonous salt layer reaching a maximum thickness of 1500 metres, salt diapirs, salt walls and pillows, and occurs throughout the basin. The allochthonous unit is confined to the eastern part of the basin. The allochthonous salt nappe and canopies originated from extrusion of the autochthonous salt along salt-walls and diapirs later recovered by the Cretaceous and Cenozoic sediments. As the focus of worldwide exploration along passive margins is gradually shifting to deepwater regions, the offshore Algarve Basin has the potential to become a deepwater petroleum province in the near future.*

*KEYWORDS: Portugal, Gulf of Cadiz, Salt tectonics.*

## 1. Introduction

Recent developments in hydrocarbon exploration offshore Portugal, in particular in the Algarve basin (Figure 1), has increased the interest in salt tectonics studies in this area. Development of a comprehensive study of the petroleum systems of this basin is inevitably connected to the analysis of the salt system and related tectonics. The Triassic-Hettangian salt identified in the onshore Algarve basin has been studied in the field, at outcrops and in an underground mine (Terrinha et al., 1990, Terrinha, 1998). However, the knowledge of the correlative extensive offshore unit has, so far, been limited by the scarcity of coverage and poor resolution of available seismic data. Salt tectonics plays an important role in sub-basin development and thin-skinned mechanisms of rifting and tectonic inversion in both the onshore and offshore basins along the west and southwest Iberian continental margins (Terrinha, 1998, Kullberg, 2000, Alves et al., 2006) and therefore, salt kinematics and geometry play an important role in the evaluation of hydrocarbon generation and accumulation in the Algarve basin, offshore Portugal. The present study shows the results of the regional interpretation of a high-resolution, high quality 2D seismic dataset acquired in the offshore Algarve basin by TGS in 2000–2001. The objective of this study is to contribute to the knowledge of salt tectonics in the offshore Algarve basin through: a) identification and description of the salt units present in the basin within the whole western Gulf of Cadiz; b) presentation of schematic and detailed maps of the distribution of the different salt units; c) geometric characterization of the salt-related structures and fault families; d) definition of major salt tectonic domains.

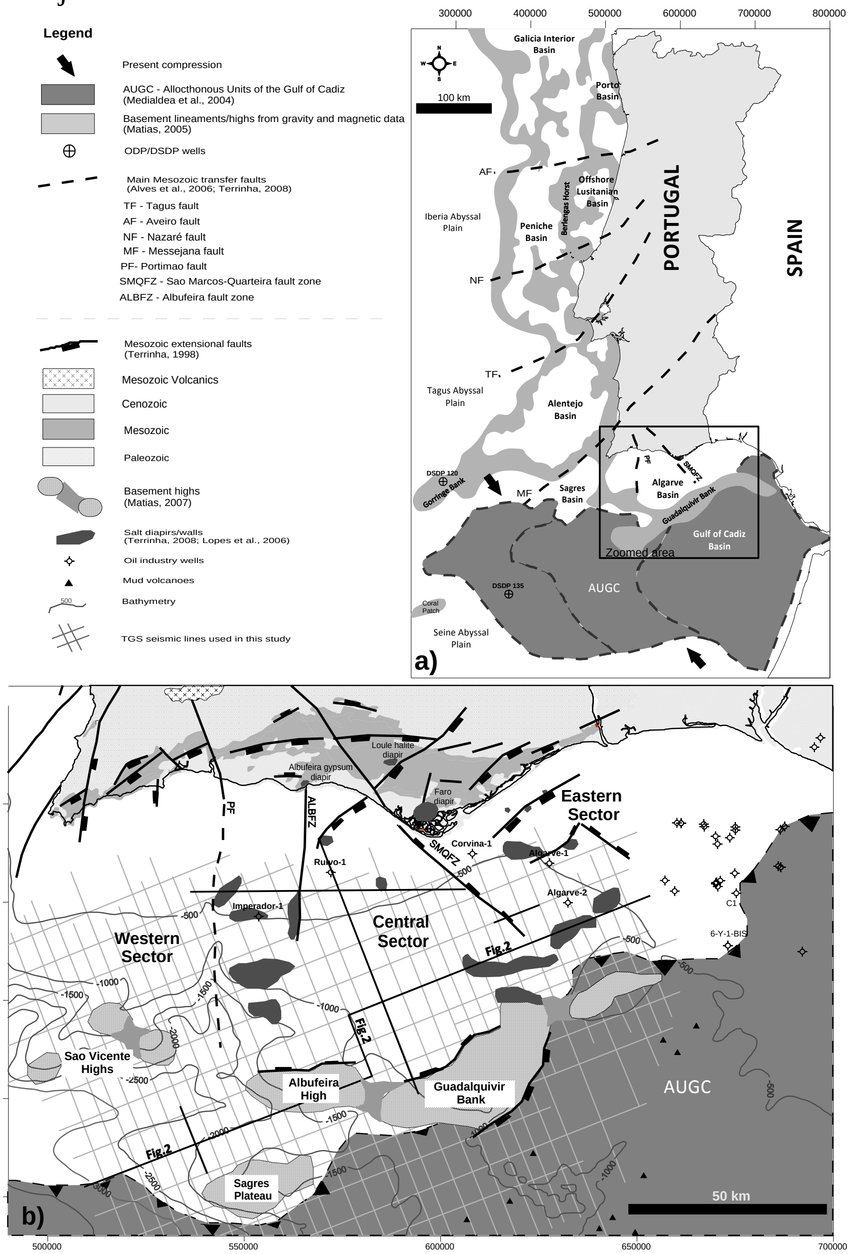


FIG.1 – Location of the study area. A) Map of the Iberian continental margin showing the NW Gulf of Cadiz (Algarve and Sagres Basin), major tectonic features and adjacent offshore basins. B) Map of the NW Gulf of Cadiz illustrating the interpreted seismic grid and main structural elements.

## 2. Results and Discussion

Seismic examples of typical halokinetic structures as reviewed and discussed in this work include a wide spectrum of features that include extensional rollers, salt pillows, salt diapirs, and compressional structures including squeezed diapirs and allochthonous salt bodies. Two different salt units were identified in the offshore Algarve basin: a lower autochthonous unit of Late Triassic/Early Jurassic (Hettangian) age, and an allochthonous unit that originated from the Hettangian salt and was emplaced as nappes and tongues during the Upper Jurassic- Lower Cretaceous into the Upper Jurassic and

Lower Cretaceous unconformity. The Hettangian unit is mainly characterized by an autochthonous salt layer reaching a maximum thickness of 1500 metres, salt diapirs, salt walls and pillows, and occurs throughout the basin. The allochthonous unit is confined to the eastern part of the basin.

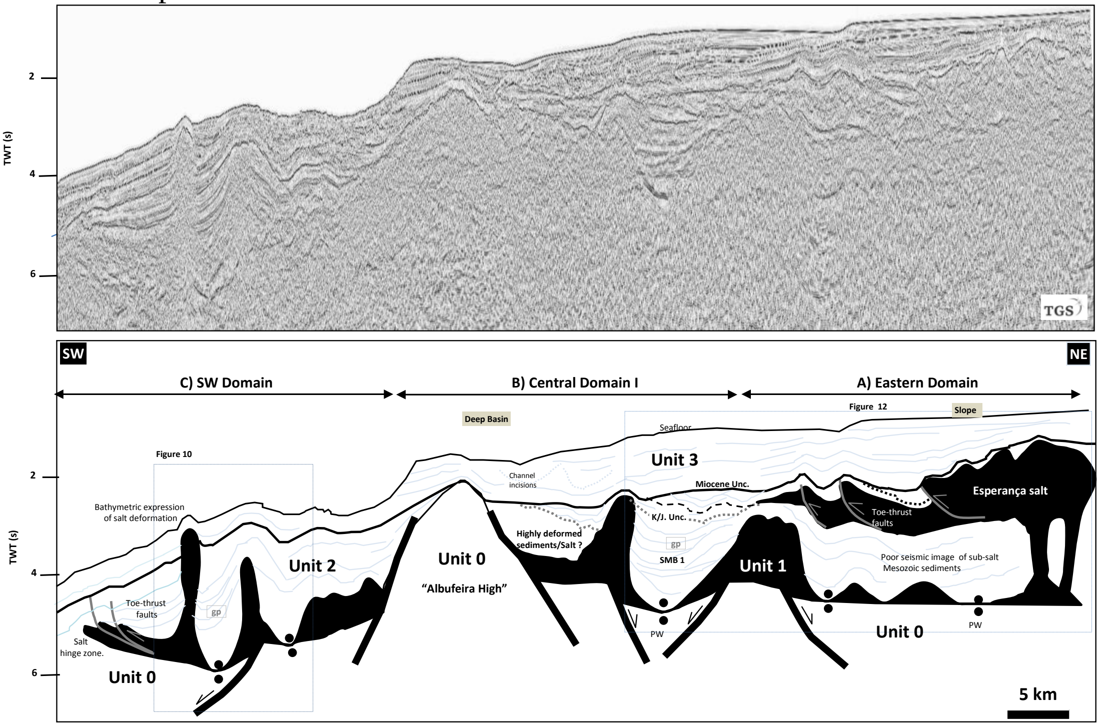


FIG. 2 – Composite regional seismic line from the Eastern to the Western sectors with main salt tectonic domains. gp – growth patterns; SMB – Salt Mini-basin; PW - Primary welds; Unit 0 - Paleozoic-Triassic Basement; Unit 1 – Late Triassic-Hettangian Salt; Unit 2 – Jurassic through Paleogene; Unit 3 – Miocene to Recent. For location of this seismic line see figure 1. (Data courtesy of TGS)

The allochthonous salt sheet and canopies originated from extrusion of the autochthonous salt as salt-walls and diapirs that later were covered by Lower Cretaceous strata. The alternative interpretation of an autochthonous origin for the Late Jurassic salt is not supported by the seismic and geological interpretation (Matias et al., 2005; Mohriak, 2005). Most salt movement was initiated by extension, which was probably triggered during Lower to Middle Jurassic clastic progradation episodes. Although the time of initiation of salt movement cannot be precisely determined, its final movement occurred during Pliocene-Quaternary time, and locally it is observed to affect the present-day bathymetry. Growth on Mesozoic structures during the Cretaceous and Jurassic times has been widely recognized in the basin, suggesting that salt movement and displacement was contemporaneous with deposition along salt structures. Salt diapirs seem to have been formed by the combined effect of the basement structure that controls the main trends of the salt-walls, Mesozoic sediment loading, and Cenozoic compression (Figures 2). As a consequence of halokinesis, several salt-related traps and plays were created, together with widespread salt chimneys that acted as heat conduits that might have enhanced the maturation potential of the Jurassic and Cretaceous source rocks. In addition, migration of hydrocarbons generated in, and expelled from Jurassic and Cretaceous source rocks, occurred along salt diapir flanks, using the faults as pathways into Tertiary turbiditic reservoirs. The overall analysis indicates that salt tectonics in the offshore Algarve basin may have played an active and important role in hydrocarbon generation, migration, and accumulation. Therefore, it should be considered as a major factor when carrying out risk analysis in future exploration projects. The progressive compressional deformation of vast amounts of salt during the Upper Cretaceous/Lower Tertiary period created a world-class frontier salt basin from an exploration standpoint. As the focus of worldwide exploration along passive margins is gradually shifting to deepwater regions, the offshore Algarve Basin has the potential to become a deepwater petroleum province in the near future.

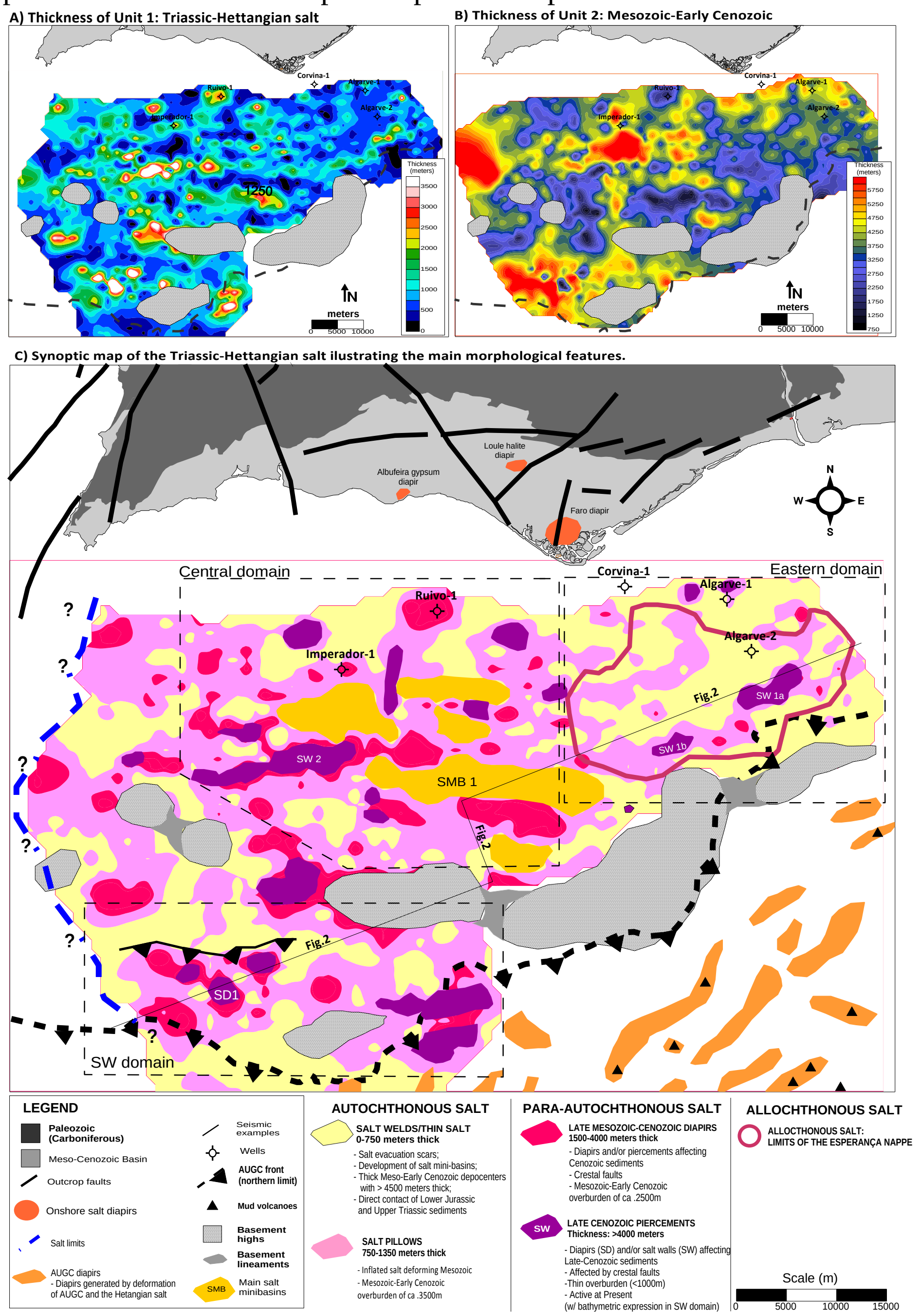


FIG.3 – Synoptic map with main salt geomorphological features, structural features and elements, and the location of the seismic profiles discussed in this work.

*Acknowledgements*

*We are especially grateful to TGS for allowing publication of parts of their multi-client seismic dataset. Within industry, Seismic Microtechnology Inc., donated the software which was used at UERJ and Universidade de Lisboa.*

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# Provenance of reservoir sandstones in the Flemish Pass and Orphan Basins (Canada): U-Pb dating of detrital zircons using the laser ablation method

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*ABSTRACT*

*U-Pb age dating has been undertaken on detrital zircon populations from Tithonian, Berriasian and Aptian age sandstones from three Flemish Pass basin wells and one Orphan basin well. The U-Pb age data for Tithonian and Berriasian sandstones are indicative of distinct North American and Iberian provenance signatures, and provide a test of plate reconstruction models.*

## Introduction

The Flemish Pass Basin is located in the northeastern Grand Banks of Atlantic Canada, approximately 250 km northeast of the Jeanne d'Arc Basin, and 100 km southeast of the Orphan Basin (FIG.1). Utilising the laser ablation U-Pb method, $^{207}Pb/^{206}Pb$ ages have been determined for detrital zircons from Jurassic and Cretaceous reservoir sandstones from three wells in the northern Flemish Pass Basin, and one in the western Orphan Basin (Mizzen L-11, Mizzen O-16, Baccalieu I-78, and Blue H-28; Figure 1). U-Pb dating of detrital zircon has been undertaken to shed light on sandstone provenance in northern Grand Banks, as well as a test of palinspastic reconstructions of the North Atlantic.

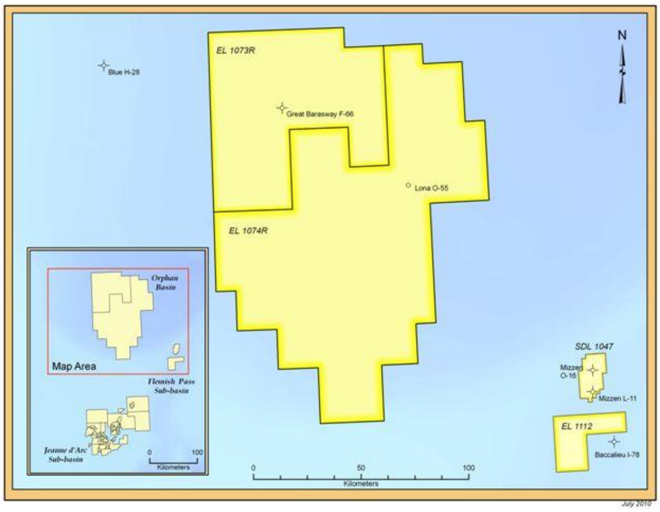


FIG.1 - Location map of the exploratory wells in Flemish Pass and Orphan basins.

The Flemish Pass Basin is filled with Kimmeridgian through Albian rift sediments (Foster & Robinson, 1993), and comprises an elongate oblique slip extensional basin on the margin of the Flemish Cap. The main phases of rift-related sedimentation in Flemish Pass Basin occurred in Tithonian and Berriasian times. In essence, the basin forms a displacement transfer system connecting late Jurassic to early Cretaceous rifting in the Jeanne d'Arc Basin to the south with extension in the Orphan Basin to the northeast (Aarseth *et al.*, 2004; FIG.2).

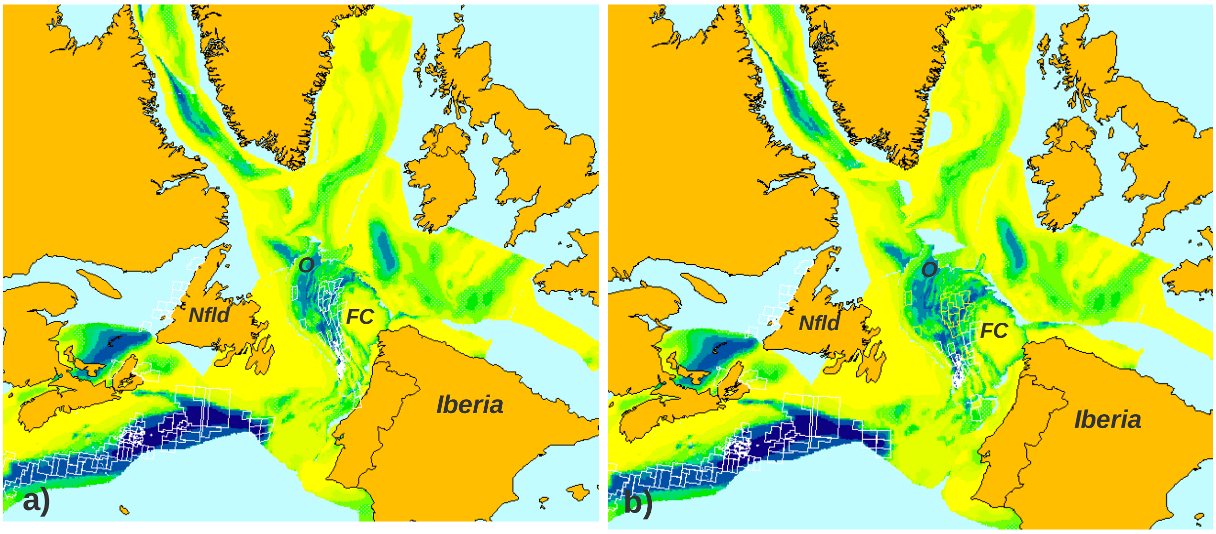


FIG.2 - Deformed plate margin palinspastic reconstructions of the North Atlantic for Kimmeridigian (a) and Berriasian (b) times with restored crustal □-factors; O, Orphan Basin; FC, Flemish Cap (from Aarseth et al., 2004).

**Detrital Zircon Dating**

Results of the laser ablation U-Pb dating of detrital zircons from Flemish Pass and Orphan basins are very consistent from well to well. There are three primary detrital zircon $^{207}Pb/^{206}Pb$ age populations in Lower Cretaceous (Berriasian) and Upper Jurassic (Tithonian) sandstones, which are approximately: 1) 340-460 Ma; 2) 530-680 Ma; and 3) broadly Grenvillian ages in the range of 0.9-1.2 Ga. A secondary age population in late Jurassic sandstones ranges from 295-325 Ma (FIG.3 and 4).

Detrital population (1) has multicyclic zircon grains with 340-460 Ma $^{207}Pb/^{206}Pb$ ages that are interpreted to be derived from the Central Meguma belt of the Appalachian orogen, with a probable derivation from the south and southwest. Detrital zircons of population (2) are also multicyclic, and have 530-680 Ma $^{207}Pb/^{206}Pb$ ages that are indicative of sandstone provenance from the Avalon Belt of eastern Newfoundland, or alternatively from pre-Variscan granites of Flemish Cap and Iberia, which were connected in Jurassic times (FIG.2). The Grenvillian $^{207}Pb/^{206}Pb$ ages of population (3) can arguably have been derived from North American and/or Iberian sources, and are not diagnostic in terms of provenance.

The secondary population of detrital zircons with 300-325 Ma $^{207}Pb/^{206}Pb$ ages occurs in Jurassic sandstones from 3 wells. Intrusive rocks of this age range are not known as a provenance source within North America. These are equivalent in age to Variscan granites of the Iberian Peninsula (Montero et al., 2004), and are therefore interpreted to be indicative of Iberian sediment provenance.

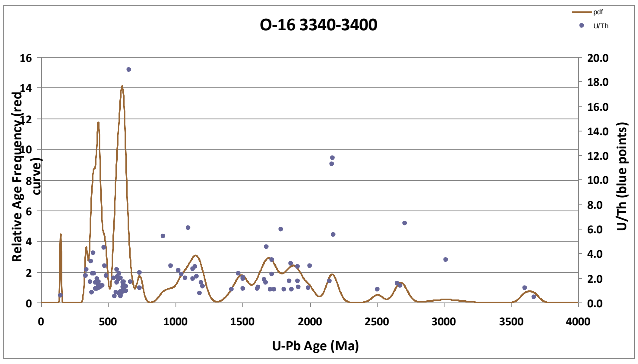


FIG.3 - Relative age frequency distribution for detrital zircons from Tithonian sandstone in Mizzen O-16.

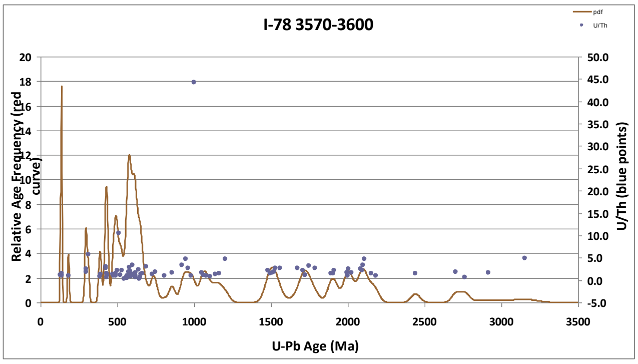


FIG.4 - Relative age frequency distribution for detrital zircons from Tithonian sandstone in Baccalieu I-78**.**

Reconstructions of the North Atlantic indicate that the continental basement of Flemish Cap and Iberia formed a continuous landmass prior to late Jurassic to early Cretaceous rifting (FIG.2). The Flemish Cap forms a steep borderland to the northern Flemish Pass Basin, and was exposed for much of the Jurassic, forming a proximal source for sediment derivation. It is underlain by ca. 697 Ma granodiorites (King et al., 1985), which likely contributed detritus to the Flemish Pass Basin in late Jurassic times.

Berriasian and Tithonian sandstones from the Flemish Pass Basin also contain elongate, prismatic zircon grains with concordant $^{207}Pb/^{206}Pb$ ages that cluster at 141 Ma. Their morphology indicates that they are of volcanic origin, and they are therefore interpreted to be rift related. However, the prismatic zircons have ages that are younger than the Tithonian sandstones from which they were sampled. Therefore, they are interpreted to be derived from cavings in the wells from early Cretaceous tuffs that have elevated U and Th (FIG.5). The tuffaceous material is of very low shear strength and probably continuously sluffed material into the wellbore during ongoing drilling. The upper radiogenic interval in Figure 5 immediately underlies the Base Valanginian (140.2 Ma) Unconformity in the O-16 well. The age of volcanism is consistent with the ca. 146 Ma volcanics of the Bonavista C-99 well (Enachescu, 1992), located on the western margin of Orphan Basin.

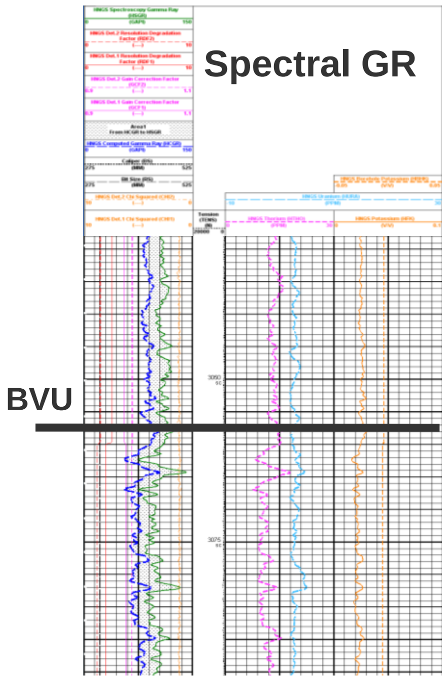


FIG.5 - Spectral Gamma Ray log from Mizzen O-16 illustrating the potential tuff at 3,063 – 3,065 m MD; BVU= Base Valagnian Unconformity; pink curve= Th; light blue curve= U.

## Conclusions

The new detrital zircon data from Flemish Pass and Orphan basins demonstrate an Iberian connection for sediment provenance, and therefore provide an independent validation of the Kimmeridgian and Berriasian palinspastic reconstructions. However, the U-Pb data do not provide insight into the nature of Flemish Pass-Orphan extension. Future work will focus on dating of Jura-Cretaceous sands from Orphan basin to test the Flemish Cap escape model (Aarseth et al., 2004; Enachescu et al., 2005), as well as high resolution U-Pb dating of both the detrital and volcanic zircon populations from Jura-Cretaceous sandstones in Flemish Pass and Orphan basins.

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# Petroleum systems modeling offshore Nova Scotia, an integrated approach

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The goal of the Play Fairway Analysis (PFA) program initiated by OETR (Offshore Energy Technical Research Association of Nova Scotia) is to estimate the volume and distribution of the Yet-To-Find (YTF) hydrocarbons offshore Nova Scotia. The intention is to predict the scale of the remaining exploration opportunity and to describe the risks associated with each play fairway.

The approach described in this paper is to construct 1D, 2D & 3D petroleum systems models based on input from Gross Depositional Environment (GDE) maps produced by the play fairway interpretation. The GDEs provide inputs for distributions of source rocks, seals and reservoirs as well as calibration for their stratigraphic history. Figure 1 displays a section constructed from the NovaSPAN seismic line ION-GXT 1400 integrating sequence stratigraphy interpretation and facies derived from well data located on or projected to the section. This section, generated from the geological model, is one of the many key 2D models constructed for understanding the petroleum systems of the Nova Scotia margin.

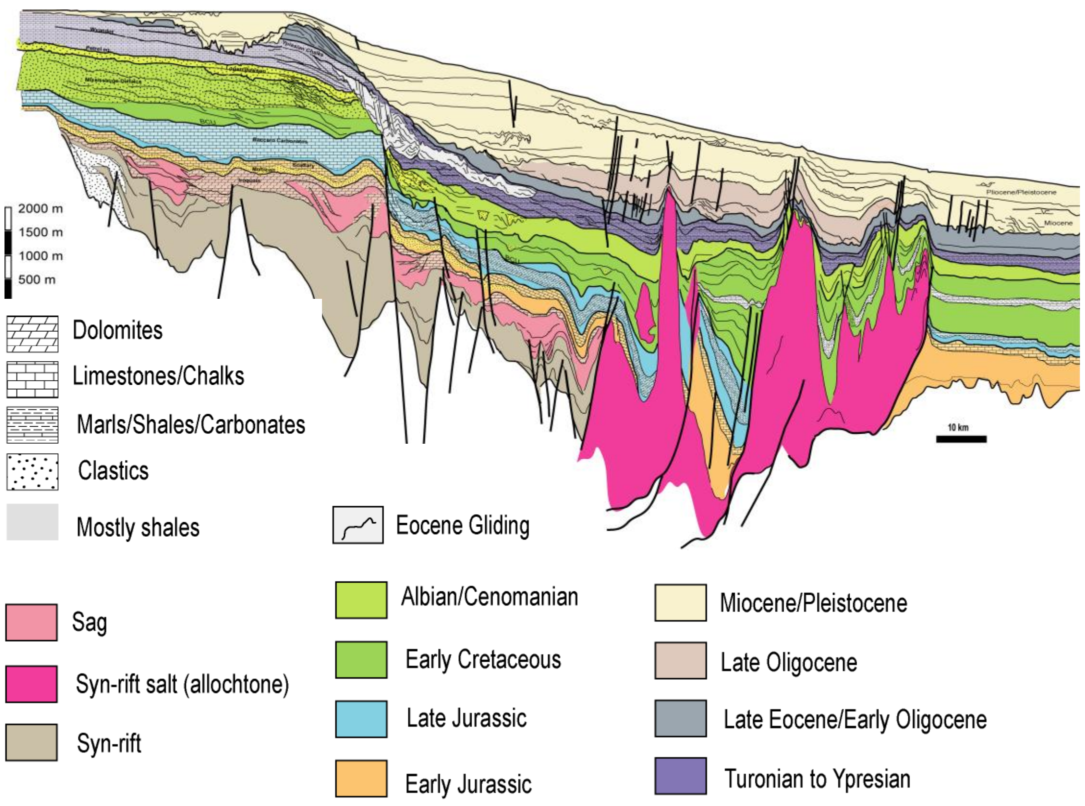


FIG.1 - Interpreted section (Seismic line NovaSPAN ION- GXT 1400) integrating sequence stratigraphy interpretation and facies derived from well data located on or projected to the section (In progress).

The source rock distribution information from the GDE maps is integrated with an extensive investigation of the geochemistry of known source rocks and fluids offshore Nova Scotia. A key component of the PFA was a major geochemistry project that reviewed a large number of wells (~40) that were sampled for potential source rocks as well as hydrocarbon liquids. A full range of geochemistry analyses were conducted including RockEval, vitrinite reflectance and GCMS (to assess the molecular signature of source rocks and hydrocarbons). TOC/Rock Eval data, though often contaminated by the use of oil-based drilling mud, suggest multiple possible source rocks: 1) terrestrial Type III in the Cretaceous delta of the Sable Subbasin (Missisauga formation), 2) marine oxic to sub-oxic, (not so well preserved) in Late Jurassic shale overlain by the delta (Verril Canyon formation). A third source rock never observed thus far by TOC/Rock Eval analyses, possibly a lacustrine or marine (Type I or II) deposited in a hypersaline environment, is inferred by the biomarker signature of one condensate sample recovered from a test in the Venture B-13 well at 4572-79m. Figure 2 displays the mass-chromatogram (ion 191) of the Venture B-13 condensate. The high relative abundance of Gammacerane in that condensate is believed to reflect deposition of its source rock under hypersaline conditions. This is a hint that such a source rock, which would only be compatible with syn-rift Late Triassic lacustrine or slightly younger earliest Jurassic shallow marine carbonate environments, should exist in rift grabens until the early days of the carbonate sedimentation. Comparing the biomarker signatures of the Venture B-13 condensate and extracts from the Pliensbachian source rock of Portugal published by Luiz Carlos Veiga de Oliveira et al. (2006), convincingly suggests that a source rock deposited in an environment similar to the Pliensbachian of Portugal, and possibly contemporaneous, is present on the Nova Scotia margin.

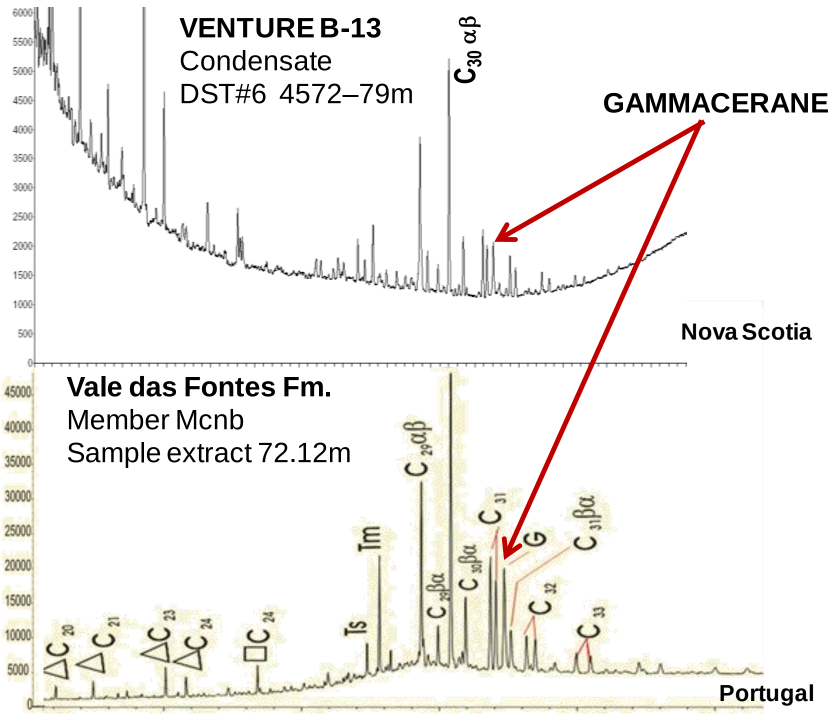


FIG.2 - Comparison between the biomarker signatures of the Venture B-13 condensate and an extract from the Pliensbachian source rock of Portugal published by Luiz Carlos Veiga de Oliveira et al. (2006) suggests that a source rock deposited in an environment similar to the Pliensbachian of Portugal, and possibly contemporaneous, is present on the Nova Scotia margin.

The petroleum systems approach then integrates geochemistry and play fairway mapping to produce 1D, 2D and 3D models that describe the generation, migration and trapping of hydrocarbons through geologic time. This gives a natural way to estimate the likely scale of the YTF for each play identified by the PFA. Figure 3 displays the maturity history of a 1D model for the deepwater Balvenie B-79 well, one of the many used for calibration of the thermal history at various locations on the Scotian shelf and slope, and to be used for constraining the 3D models. It provides also a first assessment of the important timings occurring along the development of the petroleum systems of the Nova Scotia margin.

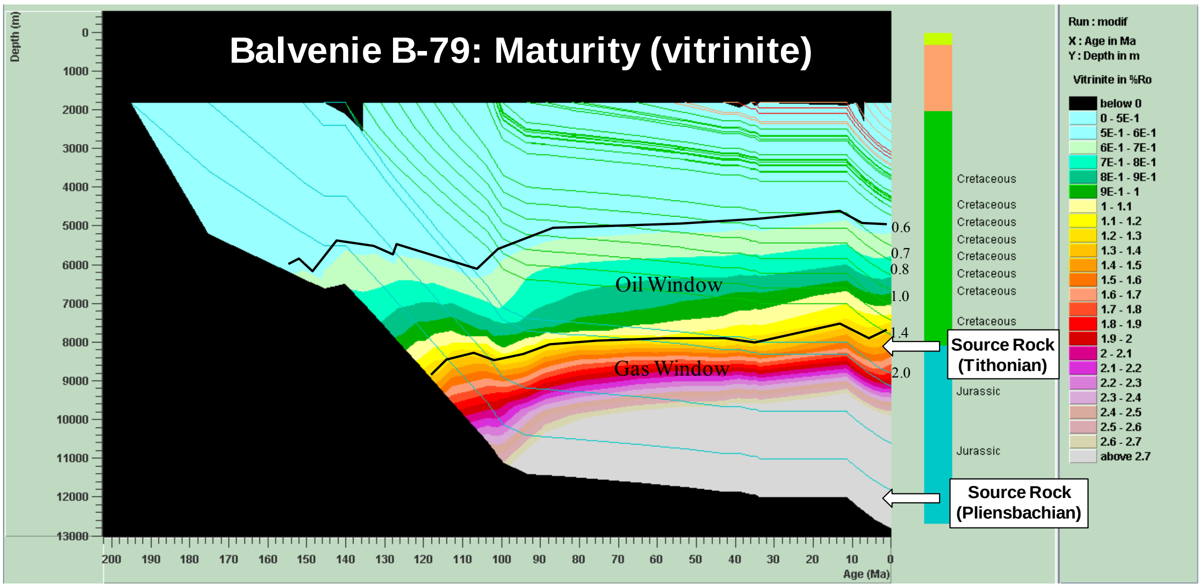


FIG.3 - Maturity history of a 1D model for the Balvenie B-79 well. It is one of the 40 wells used for calibration of the thermal history at various locations on the Scotian shelf and slope, and to be used for constraining the 3D models. It also provides a first assessment of the important timings occurring along the development of the petroleum systems of the Nova Scotia margin.

Calibration of the 3D model(s) with exploration history data and integration of analogues and interpretation uncertainties, leads to the production of Common Risk Segment (CRS) maps for each play fairway. These maps summarize the play risks associated with each play and are a convolution of risk maps for each individual play element (seal, source/charge and reservoir).

The paper presents the overall approach illustrated using preliminary results of the modeling work.

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# Continental slope sediment distribution and characterization and implications to hydrocarbon prospectivity: case studies from the Scotian margin

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*ABSTRACT*

*Numerous unsuccessful deep water exploration wells indicate a global need to recognize and understand continental shelf-to-slope and slope sedimentary systems. This study addresses this issue through study of analogues on the Scotian margin using 3D seismic volumes and an extensive network of 2D seismic data. Results indicate the need for regional comprehension of the margin that includes ties to global paleoceanographic events in order to establish the stratigraphic framework and predict lithologic facies.*

*KEYWORDS: continental margin, sedimentation, deposits, petroleum potential.*

## 1. Introduction

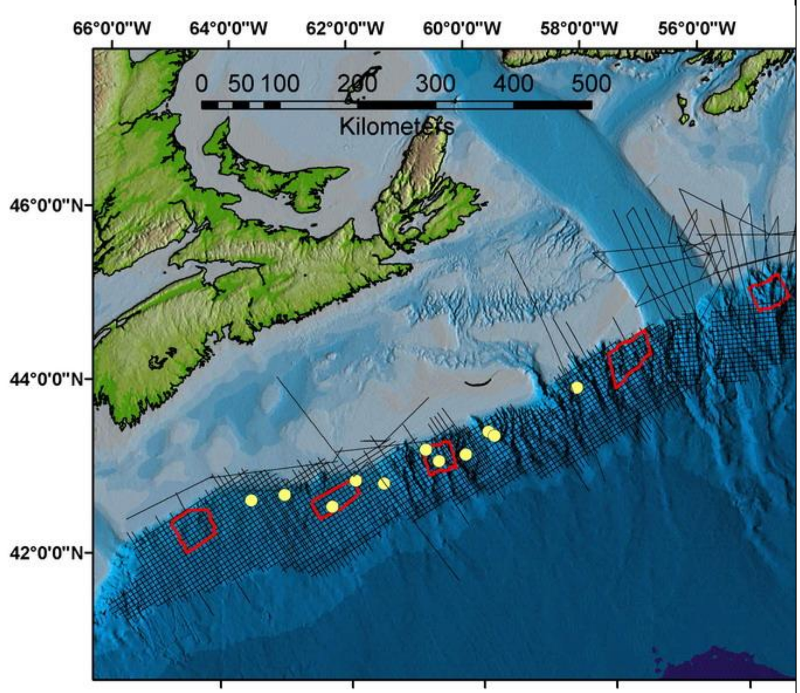


FIG.1 - The modern seafloor of the Scotian margin shows numerous canyons. Red polygons are 3D seismic volumes used in this study. Black lines are 2D seismic track lines. Yellow dots are exploration wells on the slope.

The Scotian margin endured a number of unsuccessful hydrocarbon exploration attempts in large part because of insufficient understanding of continental shelf-to-slope and slope geologic processes. These poor results highlight a global need to recognize and understand continental shelf-to-slope and slope sedimentary processes and depositional systems. This study addresses this issue through study of analogues on the Scotian margin, which have had a complex geologic history with canyon incision, salt tectonism and glacial influences.

## 2. Methods

Five 3D seismic volumes distributed across the Scotian margin and an extensive grid of 2D seismic data were interpreted for this study (Figure 1). Data were interpreted on seismic workstations, including application of modern practices of seismic stratigraphy, sequence stratigraphy, seismic geomorphology and attribute analysis.

## Results and Discussion

For the Scotian margin, application of conventional seismic sequence stratigraphic methods has proven difficult to apply because of the dominance of erosive processes. Such processes include numerous episodes of canyon cut and fill coupled with slope bypass, mass transport reworking and re-deposition, and along-slope sediment erosion and transport by deepwater contour currents (contourites). These processes dominate over sediment input and sea level controls and greatly impact the preserved stratigraphic record with significant spatial and temporal variation.

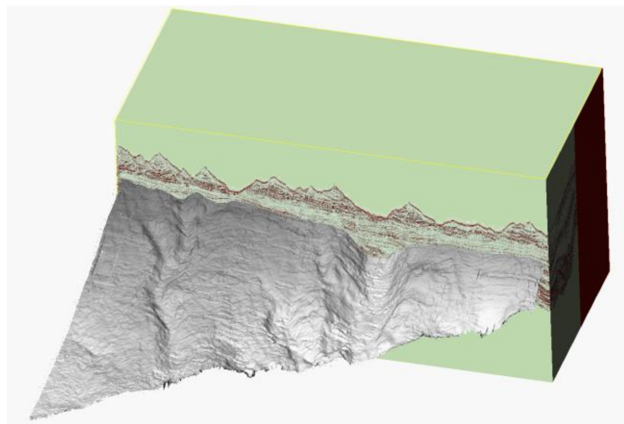

Figure 2. A 3D surface render of a preseumed Oligocene canyon system on the Scotian Slope (from Brake, 2009)

The modern seafloor of the eastern Scotian Slope is heavily incised by canyons and valleys, providing recognizable conduits for off-shelf sediment transport, slope by-pass and deposition on the continental rise and abyssal plain (Fig. 1). Canyon incision appears to have been episodic throughout the Cenozoic, involving multiple phases of cut-and-fill with new systems often re-occupying old (Fig. 2). This episodic canyon incision indicates a limited residence period of sediments on the shelf and slope, having implications for potential reservoir distribution.

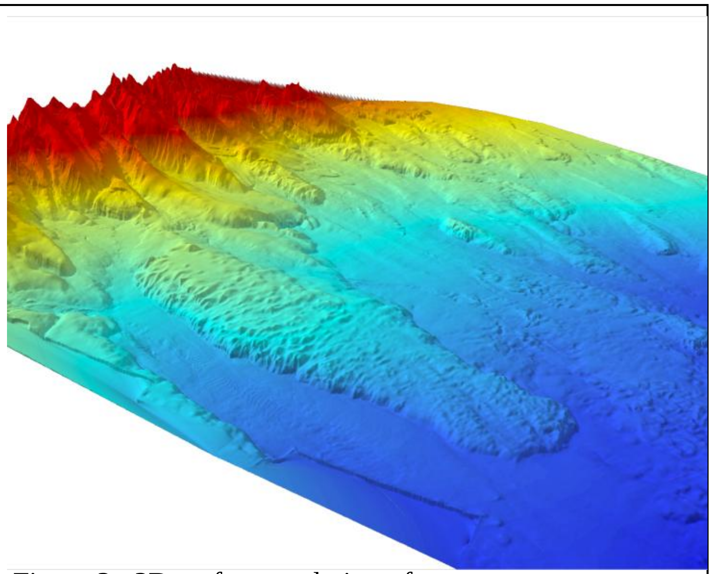

Figure 3. 3D surface rendering of a mass transport deposit on the Scotian Slope.

Mass transport processes are a fundamental aspect of continental slope construction (Fig. 3), yet their significance in sediment delivery in terms of processes and quantities, to deep water remains poorly understood. As a result, their impact on oil and gas exploration has yet to be fully understood.

The magnitude of sediment redistribution by contour-currents was only recently recognized along the Scotian margin (Fig. 4). This process leads to difficulty in predicting sediment distribution patterns and ultimate prospectivity for hydrocarbons.

Little is known of the ultra-deep water region of the base-of-slope. It appears to be a region dominated by mass transport and turbidite deposits (e.g. Fig. 5). It may well represent a sediment catchment zone, but it is important to understand sediment deposition patterns in time and space in order to understand its prospectivity for hydrocarbons.

Despite these complexities and differences in sedimentary processes, there are consistencies in depositional patterns across and amongst continental margins. Atlantic-wide paleoceanographic events permit establishment of a broad stratigraphic framework. For example, a major Eocene canyon cutting period and a mid-Miocene bottom current intensification period provide stratigraphic markers throughout the western Atlantic, despite having varying depositional signatures across defferent margins. These results indicate the need for regional and in fact global comprehension of the margins that include ties to global paleoceanographic events.

**3. Conclusions**

- Along the Scotian margin, canyons and mass-transport processes provided mechanisms for slope bypass and delivery to the rise and abyssal plane.
- Mass transport processes resulted in removal of stratigraphic section and transport of significant amounts of sediment downslope.
- Significant deep water margin erosion occurred at certain periods, apparently related to development of strong along-slope bottom currents. These currents were responsible for removal and redistribution of vast amounts of material.

The processes indicated above indicate that reservoir-grade sediments can be reworked, relocated and transported to great water depths and offer significant challenges to reservoir detection along the Scotian margin. A thorough understanding of the interplay and complexity of these processes is necessary to develop and apply exploration models.

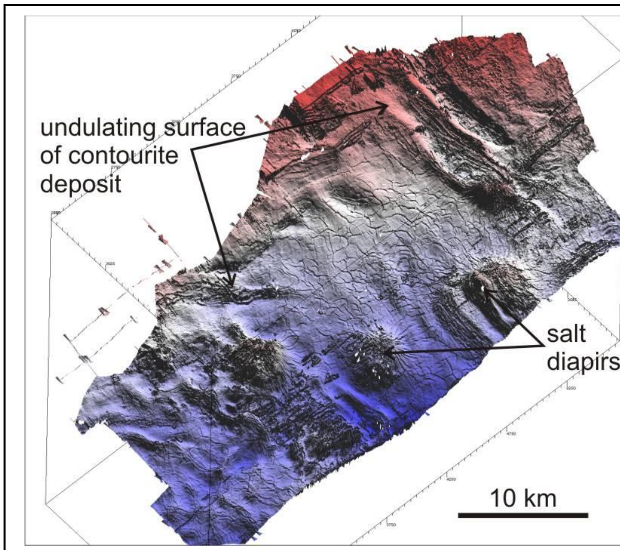


Figure 4. A 3D surface rendering of a seismic horizon with bedforms resulting from along-slope bottom currents.

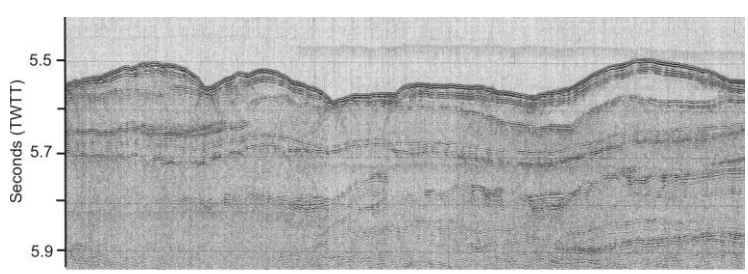


FIG.5 - Seismic profile of stacked MTDs on the Scotian continental rise

## *Acknowledgements*

*We would like thank TGS-Nopec, EnCana, Conoco-Phillips and Repsol USA for their generous contributions of datasets, without which student research projects would not be possible. Financial and/or in-kind support of OETR (Offshore Energy Technology Research association), NRCAN, NSERC, Respsol, the Nova Scotia Department of Energy and Pengrowth was provided to the principal investigators and scholarships to students*.

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# Seismic Stratigraphy of the Suriname margin, South America

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*ABSTRACT*

*The Suriname continental margin, South America, is the youngest rifted margin along the Atlantic.The Demerara Rise is a deep water extension of this margin where the stratigraphy is well known. The margin is an ideal location to study early post-rift stratigraphy and sedimentation patterns. Seismic data demonstrate evidence of Jurassic to Cretaceous trans-tensional extension with synrift clastic sedimentation. By mid-Cretaceous, a ~90 m-thick unit of black shale deposited between Cenomanian and Santonian times. Neogene sediments are thin on the rise and thicken inboard. Miocene erosion removed much of the Oligocene succession and normal faulting and mass-wasting continued throughout the Rise's history. Significant margin progradation occurred in the Cenozoic in response to sea level change, as the shelf edge migrated some 20 km seaward.*

*KEYWORDS: Seismic stratigraphy, sea level, sedimentation, continental margin.*

## 1. Introduction

The Suriname continental margin, South America (Fig. 1), is in a critical position to record final Atlantic rifting and opening of the Atlantic Gateway. As such, it represents the youngest portion of the Atlantic, providing an ideal location to study early Atlantic post-rift stratigraphy and sedimentation patterns. The area is a recent exploration frontier with 2D and 3D MCS reflection data and exploration well data available. The outer portion of the margin (Demerara Rise) was recently drilled during Ocean Drilling Program Leg 207. These scientific boreholes and the exploration well data provide age control and groundtruth for seismic interpretation.

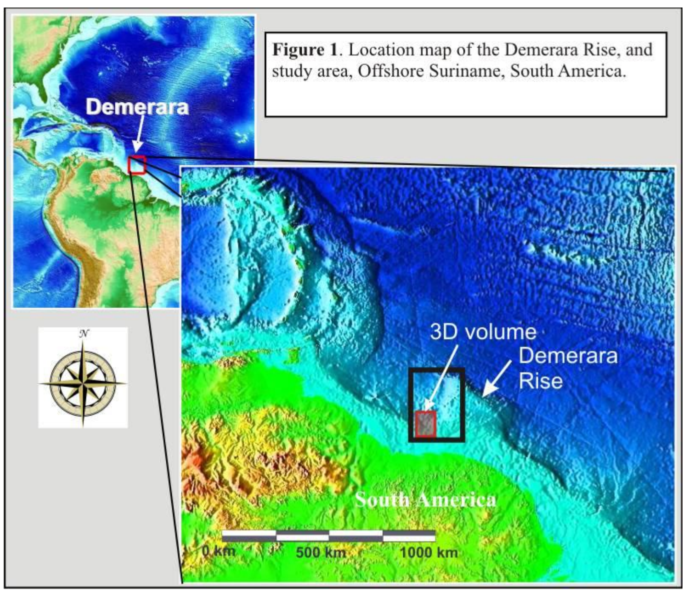


**Figure 1**. Location map of the Demerara Rise, and study area, Offshore Suriname, South America.

## 2. Methods

Regional 2D and a 3D seismic volume span the shelf to slope transition zone in Block 30, offshore Suriname (Fig. 1). With these data, pre-Albian to Recent strata were placed into a stratigraphic framework consisting of seven key reflection horizons and eight units. This seismic stratigraphy was correlated to the North Coronie-1 industry well and Ocean Drilling Program Leg 207 Sites 1257-1261. Additionally, reflection stacking geometries were interpreted into the context of lowstand, transgressive, and highstand systems tracts. These system tracts and associated maximum flooding surfaces and reflection characteristics (facies) were used to interpret modes of deposition.

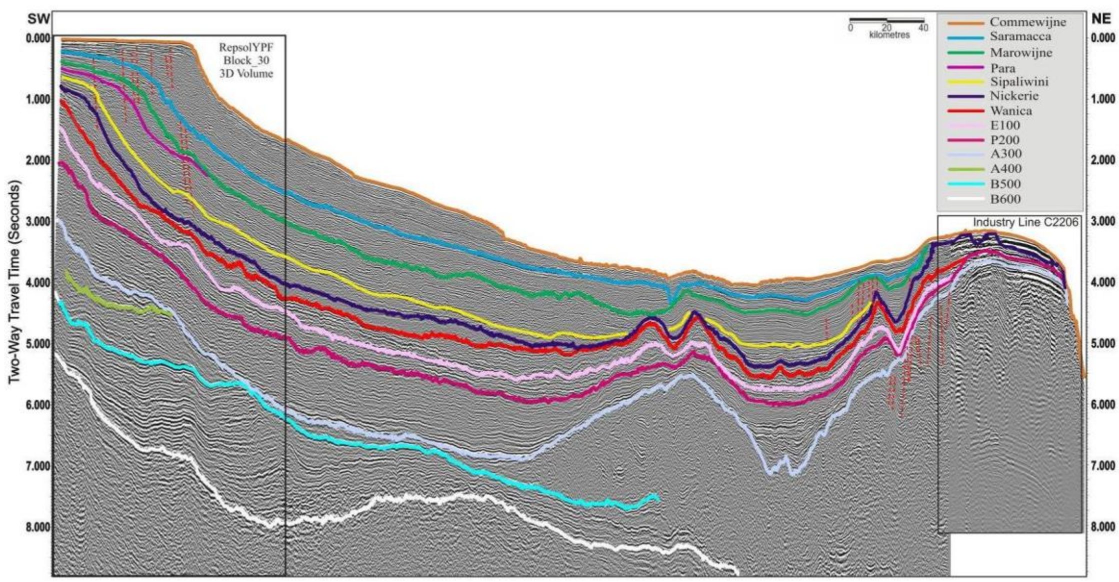


FIG.2 - Seismic profile across the Suriname margin to the outer Demerara Rise

## 3. Results and Discussion

A stratigraphic succession of eight seismic units was defined, based on regional correlation of key seismic horizons (Figs. 2 and 3). The lowest unit consists of complex patterns of faulting and folding observed in the pre-Albian succession; interpreted to represent sedimentation during subsidence following late stage trans-tensional rifting between the Demerara Rise and its conjugate; the Guinea Plateau of West Africa. Final separation between South America and Africa in the Albian created a regional unconformity (C reflector) across the breadth of Demerara Rise (DR) and onto the Suriname margin proper. Sparse samples from below the C unconformity on the Demerara Rise suggest synrift sediments consist of mixed lithologies of an apparent marine setting, including claystone, siltstone and sandstone. The sedimentary sequence above the C horizon, from Cenomanian to Recent, forms a 400 to 1000 ms-thick (400-1200 m) cap across the outer DR that is largely flat-lying and uninterrupted by faults. This package thickens substantially inboard and is over three seconds two-way traveltime (> 4 km) thick beneath the outer Suriname Shelf.

The base of the post-rift succession, between the “C” and “B” horizons consists of 90-125 m-thick sequence of black shale across the DR. This unit reflects a mid to Late Cretaceous period of ocean anoxia. Sedimentologic interpretations suggest the margin subsided rapidly in combination with global sea level rise during this time. By Late Turonian/earliest Campanian, pelagic conditions prevailed and anoxic conditions declined, resulting in deposition of pelagic chalks. This lithologic change is correlatable across much of the rise.

Campanian to Paleogene sediments are open marine calcareous chalks with a few recognizable hiatuses and mass-flow deposits. Reflector “B”, within this interval, correlates throughout the northern tip of the Demerara Rise with the K/T boundary. An increase in clay content marks the Paleocene-Eocene Thermal Maximum, with sediments returning to calcareous ooze and chalk above.

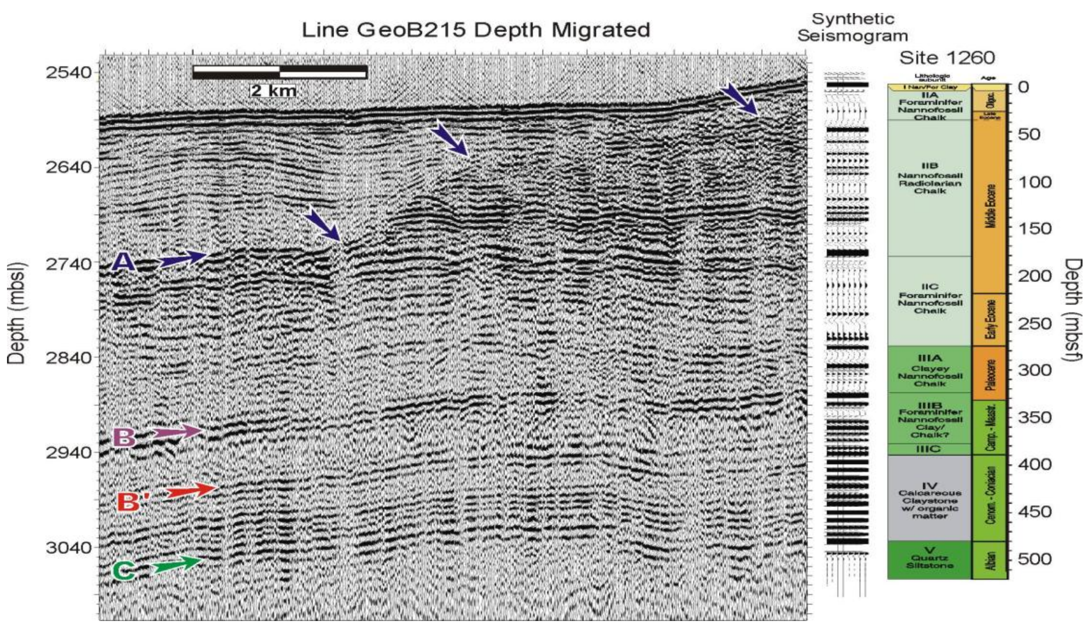


FIG.3 - Seismic and lithostratigraphy ties at ODP Site 1260. A synthetic seismogram confirms correlation of the seismic data to drilling results.

A prominent erosional surface developed on the Demerara Rise in the late Oligocene to early Miocene and is correlated as reflector “A” on seismic profiles. This surface is traced across the entire northwestern portion of the plateau and onto the Shelf (Fig. 2). The channels presumably carried sediment east-to-west over the flank of the plateau with the result that most of the Neogene sedimentary sequence (calcareous ooze) is thin or absent from the distal portions of the plateau. In the Middle Oligocene, Early-Middle Miocene, and Early-Late Miocene, significant erosion produced outer shelf and slope channels with minor gully incision. These are interpreted as sea level lowstands. Channel flow generally bypassed the upper to middle slope region, resulting in turbidite deposits accumulating in lowstand wedges. During the Late Oligocene, Middle Miocene and the middle Late Miocene, backfilled channel and gully incisions are associated with high sedimentation interpreted to result from periods of rising sea level and transgressive phases culminated in the formation of a maximum flooding surface. During the Latest Oligocene-Earliest Miocene, Middle to Late Miocene, and Latest Miocene, outer shelf deltas aggraded and sediments drape the outer shelf and upper slope with linked condensed sections in the lower slope regions. These patterns are believed to represent periods of high sea-level.

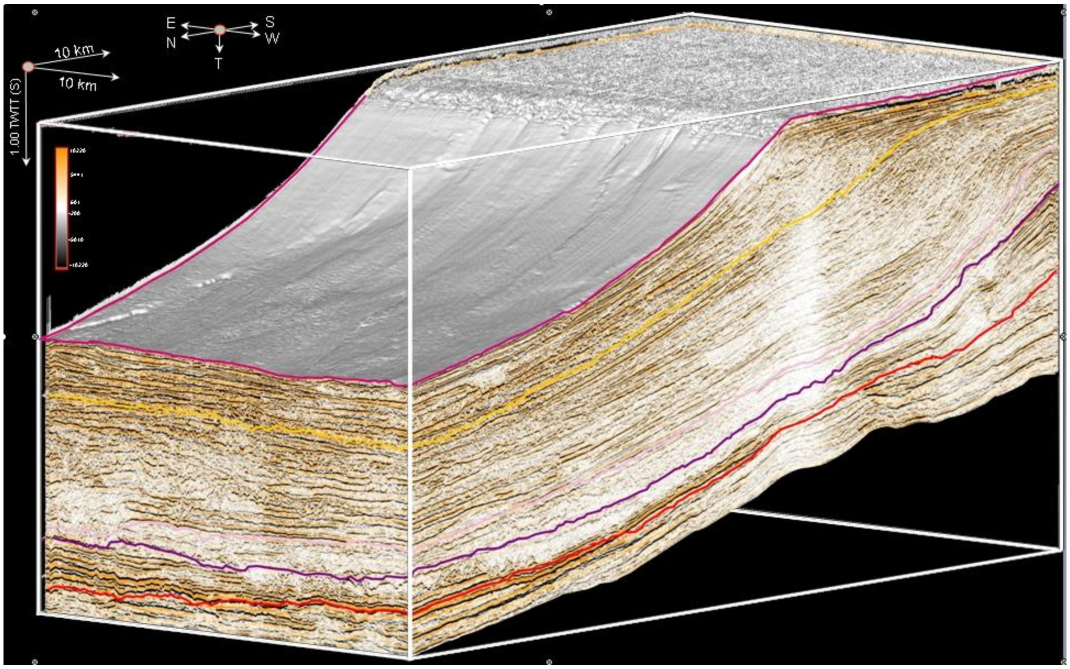


FIG.4 - 3D perspective view of the seafloor and subsurface reflection patterns, outer shelf and uppermost slope, offshore Suriname.

The sedimentary section above the "A" horizon is nearly absent on the outer DR but thickens inboard. It forms a sequence of progradational clinoforms under the Suriname shelf and slope, with several correlated horizons marking sequence stratigraphic boundaries. The shelf break advanced seaward by nearly 20 km to its present day location between mid-Miocene and Recent. Little evidence of tectonic effects is recognized along this margin since initial breakup and subsidence; thus, the Cenozoic stratigraphic architecture was developed principally by high sedimentation rates interacting with global sea level positions.

**Conclusion**

The Suriname margin represents the location of the last phase of Atlantic rifting. As such, it hosts the youngest post-rift succession along the western Atlantic margin. Sediments are well preserved and less affected by subsequent tectonic, paleoceanographic and compaction events. It is an important end-member, therefore, to which comparisons of other margins can be made. It shows a relatively complete Neogene succession underlain by Cretaceous black shales. Sequence stratigraphic analysis of the Cenozoic succession demonstrates strong linkages to relative sea level and sediment supply. Global paleoceanographic events such as mid-Miocene erosion are apparent within its succession.

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# Geodynamic keys of the Santos Basin

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*ABSTRACT*
*Understanding the genesis of the very peculiar 600 km wide Santos Basin - São Paulo Plateau system and its narrow conjugate Namibe margin is an old geodynamical and structural problem. Several hypotheses have been proposed which imply the same amount of horizontal movement. We propose to investigate the consequences of the movement based on plate kinematic reconstruction. The new kinematic history of this system that we present here, based on interpretation of seismic profiles and dedicated kinematic constraints, has strong geodynamical consequences: 1) there is no need for a ridge jump 2) the Namibe margin evolved as a transform passive margin; 3) the opening direction of the Santos Basin - São Paulo Plateau system is oblique to general opening motions of the South American and African plates and 4) this opening is younger that those of the other basins of the central segment of the South Atlantic.*
*KEYWORDS: Kinematic reconstruction, Continental Passive Margin, Santos Basin, Namibe Margin, Brazil, South Atlantic.*

## 1. Introduction

The Santos Basin-São Paulo Plateau System (SSPS) represents a kinematic buffer between the Central Segment and the Austral Segment of the South Atlantic Ocean (Moulin *et al.*, 2010): while the southern segment opened between the anomalies M13 and M4 (Rabinowitz and LaBrecque, 1979), respectively 139.5 Ma and 130 Ma (Gradstein *et al.*, 2004), the oceanic spreading in the Central Segment started more than 18Ma later, at the end of evaporite deposition (Upper Aptian – Lower Albian: 112 Ma) (Rabinowitz and LaBrecque, 1979). The basin is situated immediately north of the Florianópolis Fracture zone (FFZ). This fracture zone separates a domain of magma-rich margin to the south from a domain of evaporitic, magma-poor margin to the north. The SSPS seems to coincide with the location of "second-order intra-plate boundaries" as defined by Olivet *et al.* (1984) in relationship with the Paraná-Etendeka Continental Flood Basalts, the Florianópolis Platform and the Walvis-Rio Grande Ridge (Curie *et al.*, 1984; Unternehr *et al.*, 1988; Nürnberg and Müller, 1991) to the south, and with the Cabo Frio High and the Jean Charcot Seamounts to the north.

Although many geophysical investigations were carried out during the 1970's, the origin, history and evolution remained largely unknown. Different interpretations are given for this segment of margin, based on different geological and geophysical datasets.

1) The existence of extremely stretched continental crust underlying the São Paulo Plateau was proposed by numerous authors, based on seismic studies, gravity modeling and backstripping analysis.

2) Others authors suggested that the core of the São Paulo Plateau might be a micro-continent, partly covered by break-up extrusives. Nevertheless, the tightest

paleogeographic reconstruction proposed by Moulin *et al.* (2010) does not allow enough room for this hypothesis, and therefore invalidates it.

3) Seismic refraction data (Leyden *et al.*, 1971; Leyden *et al.*, 1976; Kowsmann *et al.*, 1977) showing velocities ranging between 5.07 to 5.56 km/s and 6.07 to 6.78 km/s in the São Paulo Basin, as well as residual gravity anomalies (Meisling *et al.*, 2001) and the presence of weak linear magnetic anomalies G, M3 and M0 on the Plateau (slightly north-east of the gravity anomaly) suggest either the presence of a thickened oceanic crust in the São Paulo Plateau or the presence of a failed spreading ridge located in a thinned continental crust domain or the presence of an oceanic propagator in the southern part of the basin. The narrow strip of salt layer in the narrow conjugate margin (between the Benguela and northen Namibe basins) and the results of ODP sites on the African margins (Sibuet *et al.*, 1984) support this idea of an eastward mid-ocean ridge jump at late Aptian-Early Albian times (Ponte and Asmus, 1976; Kumar *et al.*, 1977; Kumar and Gambôa, 1979).

4) At last, using a compilation of seismic profiles and precise kinematic constraints (Moulin *et al.*, 2010), Aslanian *et al.*, (2009) recently proposed a non-conservative model for the genesis of the passive margins of the Central Segment that implies a phase of lower crust and/or upper mantle exhumation, which can represent a significant part of the basins substratum. The Santos Basin could therefore include some exhumed material together with a failed oceanic crust.

Except for the second one, the above hypotheses have similar implications in term of horizontal movement. The goal of this work is to test the ridge jump hypothesis in the global and precise reconstructions given by Moulin *et al*., (2010).

## 2. The Geodynamic keys of the Santos Basin

On the base of the gravity map (Sandwell & Smith, 1997) and the salt distribution (Fig. A), the Santos – São Paulo Plateau system can be divided in two sub-basins: a) a 350km-broad sub-basin, limited on its northern boundary by the Cruzeiro do Sul lineament which connects the Cabo Frio High, the Jean Charcot Seamounts, and on its southern boundary by the São Paulo Ridge close to the Florianópolis fracture zone (Souza, 1991). This basin presents a more than 2 km thick late Aptian salt layer (Freitas, 2006; Mohriak & Szatmari, 2008); b) a narrower 270km-wide sub-basin without any salt layer in the deep domain, limited to the south by the Florianópolis Fracture Zone. Those two sub-basins are separated by the Capricórnio Lineament (Fig. 1), which include the positive gravity anomaly off the coast, southeast of São Paulo City and which is parallel to the Cruzeiro do Sul lineament (Bueno *et al.*, 2004). It is worth to note that those lineaments are oblique to the main flowlines of the South Atlantic Ocean.

We used also one line-drawing, which characterizes, together with gravity and magnetic maps, the segmentation of the two sub-basins. In the western sub-basin, the gravity map presents a strong positive anomaly, whose NW portion corresponds, to the Avedis Ridge (Demercian, 1996; Meisling *et al.*, 2001) (Fig. 1). This NE-SW trending oval structure was interpreted as volcanic rocks on continental crust near the southern end of a fossil oceanic ridge underlying the São Paulo Plateau. Southwest of the Capricornio Lineament, a major tectonic feature (Abimael Ridge) is marked by a positive gravity anomaly and negative magnetic anomaly that may correspond to a V-shaped oceanic propagator that advanced from the Pelotas basin but could not penetrate further in the Santos Basin (Mohriak, 2001; Gomes et al., 2008). Early interpretations based on gravity data assumed that most of the anomaly was located on continental crust (Macedo, 1989) but the continent-ocean boundary was identified across the structure (Karner, 2000).

The line-drawing confirms this interpretation, by showing the seismic Moho depth, which decreases between 180 and 260 km from 11 s (twtt) to 9 s (twtt) and suggests a failed oceanic axis. We therefore divide this sub-basin into 5 segments (from A to E) (FIG.1). Segment C represents the failed oceanic ridge. On both sides, segment B and D can either be a highly stretched continental crust or exhumed material. In that hypothesis, segments A and E are supposed to be thinned upper continental crust. Gladczenko et al. (1997) and Mohriak (2004) suggest however that most of the rocks between the outermost limit of the salt and the Florianópolis Fracture Zone correspond to basaltic layers, whereas Gomes et al. (2008) and Zalán et al. (2009) advocate exhumed mantle.

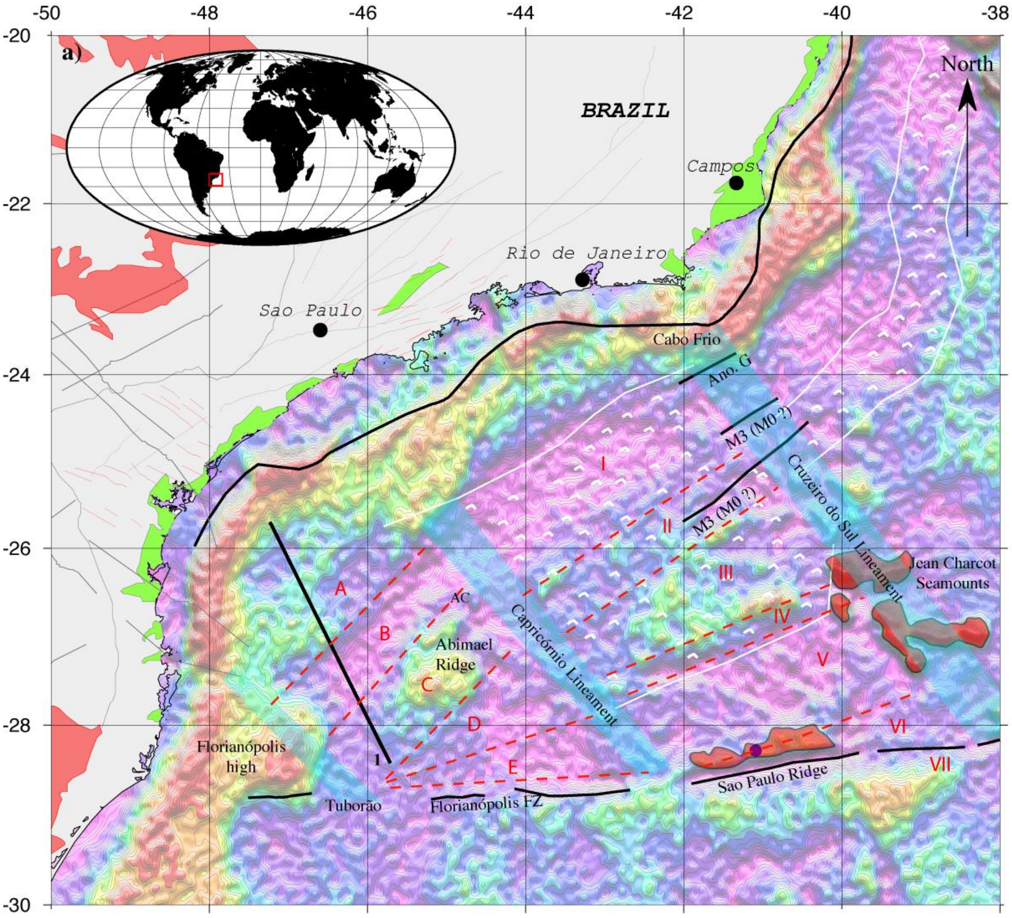


FIG.1 – Satellite-derived free air gravity anomaly map (Sandwell and Smith, 1997) of the study area

Seismic facies and gravity data allow us to divide the northern western sub-basin in 7 segments (from I to VII). Segment III is characterised by strong gravity and magnetic anomalies, a deeper salt base layer and a canopy-shaped salt domain, and is comparable with the segment C of the eastern sub-basin. On the unpublished ION-GXT multi-channel depth-migrated seismic lines (Zalan et al, 2009), the segment III coincides also with a 5km thick layer of strong crustal reflectors. On both sides, the domains II and IV present some connected diapirs, an irregular salt base layer and the visualisation of the deep structures is rather poor. Segments I and V present some deep reflections. These two segments correspond to the central negative gravity anomaly.

The salt layer presents some isolated diapirs up to 200km. From there basinward, a 2km thick massive salt layer occurs. Except for a small tongue in the western end, the salt layer disappears on segment V. On Segment V, no deep reflectors can be described on this seismic line, however, the deep seismic reflection profiles acquired by ION-GXT (Zalan et al, 2009), in this area, images an asymmetrical crustal shape, with deepest reflector at about 23 km. The top of the crust has a more convex swollen-shape. The segment VI is a small triangle-shaped area at the southeastern end of the SSPS, in continuation of the São Paulo Ridge (fig 1a). The observations induced from the high quality reflection profiles acquired by ION-GXT (Zalan et al, 2009) in this segment indicate that the top of the crust is sharp and angular. This segment is separated from the segment VII, which represents true oceanic crust, by the Florianópolis Fracture Zone.

## Perspectives

In order to test the presence of the two hypothetical abandoned oceanic ridges and their formation, together with the hypothesis of an eastward ridge jump (Kumar and Gamboa, 1979; Meisling *et al.*, 2001; Mohriak, 2001), we reconstruct the evolution of the whole SSPS, by considering segment V and E as two microblocks of (extended) continental crust called respectively here after microblocks São Paulo-E (where the São Paulo Ridge is located) and São Paulo-W. We will present here the new results of this study and the consequences for the formation of the conjugate 600 km wide Santos Basin - São Paulo plateau system and its narrow conjugate Namibe Margin.

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# Combined rigid/deformable plate tectonic reconstructions for the Central Atlantic margins

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*ABSTRACT*

*Oceanic crust and highly extended continental crust have very similar physical properties and for this reason, the exact location of the continent-ocean boundary (COB) along passive continental margins can be difficult to define. The effect of igneous intrusions and magmatic underplating on calculations of crustal thickness further complicates this issue. A number of geological and geophysical datasets such as magnetic isochron data have been employed to define new plate boundaries and infer the location of the COB.*

*The Iberian and Newfoundland conjugate margins are zones where anomalously large amounts of crustal extension have occurred, and are difficult to reconstruct in a global context using plate tectonic models based on rigid plates.*

*A self-consistent global, plate tectonic model is presented here that incorporates stretching factors, deformable plates and scales deformation for the Cenozoic and Mesozoic for the entire Atlantic margin. Restoration to pre-rift geometries has been achieved by removal of plate 'overlap' of the deformed regions in the reconstructions, and is consistent with estimated stretching factors derived from deep seismic crustal studies across the conjugate margins.*

*KEYWORDS: Plate Tectonic Modelling, Rifting, Deformation, Passive Margins*

## 1. Introduction

Plate tectonic reconstructions are essential for placing geological information in a correct spatial context, understanding depositional environments and defining basin dimensions and evolution, and serve as a basis for palaeogeographic mapping. Well-known problems with traditional 'rigid' plate reconstructions are overlap and under-fit of plates when restored in their pre-drift assemblages. These problems are attributed to factors such as: internal deformation during rifting and continental break-up, uncertainties in the precise locations and geometries of plate boundaries, and interpolation errors of finite rotation poles during initial formation of ocean crust. They result in the overestimation of basin sizes when applying 'relaxed fits', or data overlap when applying 'tight fits' in the reconstructions. A clear example of this problem is found in the restoration of the Iberian and Newfoundland conjugate margins, which are zones where anomalously large amounts of crustal extension have been documented (Fig. 1). To confront these issues, a new high-resolution global plate kinematic model known as Plate Wizard™ has been developed. This model incorporates deformable plates, which record the amount of deformation in the global restorations.

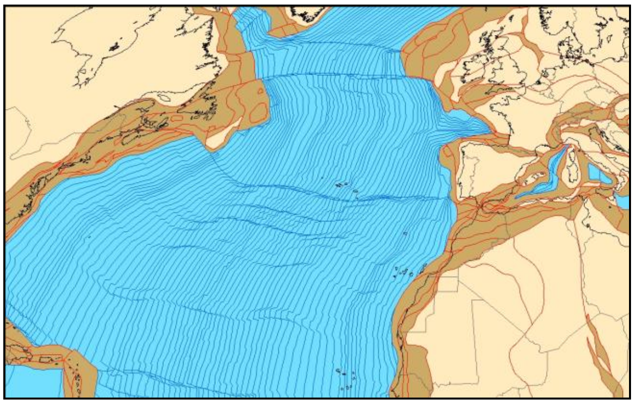

FIG.1 - Plate tectonic model for the Central Atlantic at present day. The dark brown areas represent deformable margins and the paler brown areas are rigid microplates and interior cratonic areas. The oceanic plates are depicted in blue. Present day coastline is overlain for reference.

## 2. Method

### 2.1 Plate boundary definitions and modelling of 'rigid plates'

New plate boundary definitions have been achieved based on a range of available geological and geophysical information such as; Bouguer gravity anomalies, 3-D modelling of crystalline crustal thickness, detailed geological mapping, river drainage analysis and public domain datasets. Large tectonic plates were broken down into 'rigid cores' and 'deformable margins' which accommodate most of the continental deformation. Satellite-derived Bouguer gravity anomaly and crystalline crustal thickness gridded datasets provided by Fugro Gravity and Magnetic Services (FGMS), Houston, USA were used to define the extent of the deformable region across the passive margins.

Differences in the crustal signature (fabric) across continental, oceanic and transitional crust have been observed in terms of: crystalline crustal thickness, Moho depths, rock densities and gravity anomalies, and were used to map the position of the COB within the continent-ocean transition zone. A high gradient in gravity anomalies, in Moho depths and crustal thickness suggests a cut-off in the inner boundary of deformation related to extension, at crustal thicknesses of ~19-21 km. Margins affected by the presence of large accumulations of mafic igneous rocks display an increase in crustal thickness values and impede a precise definition of the COB.

Relative plate motions between major tectonic plates across large ocean basins were determined by matching fracture zones and magnetic anomalies of similar age. These were then integrated into a global plate circuit that utilises Euler pole addition to calculate relative plate motions of less well-constrained plates. Plate modelling for the Labrador Sea, based on sea-floor spreading anomalies (Srivastava and Roest, 1999), was used as a frame to model the drift of Iberia from Newfoundland, but modifications were required in order to obtain an improved fit for the initial rifting geometries of Pangaea that commenced in the Triassic.

### 2.2 Modelling of extended margins

A definition of deformable plates within a global plate model has the advantage of allowing the visualisation of predicted amounts of extension and compression for particular plate tectonic environments. In the model, the deformation area is constrained by the overlap and/or underfit of the deformable plates. The method involves the restoration of both margins and the measurement of overlap or underfit. This is then used to calculate the beta factors involved in extensional deformation (stretching), or compression (de-stretching).

The trajectory of movement for the deformation is constrained by relative plate motions during the appropriate episodes of rifting (or convergence/compression). The timing of these tectonic events was constrained using Fugro Robertson Limited's regional palaeogeographic studies and the available literature.

These techniques are appropriate for modelling extension and compression over large areas at a global scale. However, when the deformation is modelled in this way, the following assumptions are necessarily inherent: that the deformation occurs at a constant displacement rate over the specified time period, and that there are equal amounts of extension occurring on both margins. The nature of the software can allow more detailed modelling for smaller areas where the deformation can be modelled in stages and different beta factors can be used on either side of the margin to model asymmetric deformation.

## 3. Results

Seventeen regions along the Atlantic margins and from the Indo-Asiatic margins have been modelled in the course of the project. These show different rates and amounts of extension relating to the different episodes of that precede continental break-up. The regions of most extension are located within Newfoundland, Galicia-Iberia, Porcupine High - Hatton Bank, Greenland - North America (FIG.1). These regions coincide with larger zones of deformable plates, and contrast with the margins of the South Atlantic and Central Atlantic.

Extension at the Newfoundland and Porcupine conjugate margins was modelled between 105 Ma and 83 Ma, and is consistent with work by Shannon *et al.* (1993, 1995) who interpret mid-Aptian to Albian strata as the product of a rifting event. This view is supported by Johnston *et al.* (2001) who suggest that the Atlantic spreading centre propagated northwards during the Aptian from a triple junction west of Galicia Bank. Early geophysical studies by Cutt and Laving (1977) suggest that sea-floor spreading in the area to the south of the Charlie-Gibbs Fracture Zone began during the Campanian (71-84 Ma). Johnston *et al.* (2001), based on the work of Chalmers *et al.* (1993), suggest that spreading was arrested south of the Charlie-Gibbs Fracture Zone at 61 Ma but it is likely that, during the Cretaceous, extension propagated northwards ahead of the spreading ridge. This work is also consistent with the modelling done here for this region.

Modelling of the conjugate segment of northwestern Iberia and Flemish Cap was achieved in three phases of extension, mainly due to changes in relative motions between the North American, Iberian and Eurasian Plates. The oldest rifting events between the Flemish Cap and Iberia have been modelled in three phases of extension: 181 Ma to 157 Ma, 157 Ma to 131 Ma, and 131 Ma to 116 Ma (FIG.2). Sea-floor spreading in this region also forms a triple junction between the Eurasian Plate, the Iberian Peninsula and North America, presently located in the Bay of Biscay. Srivastava and Verhoef (1992) suggest that the onset of rifting at this triple junction took place between 230 and 180 Ma, which is consistent with the interpretation in the model used here. Srivastava and Verhoef (1992) and Boillot *et al.* (1988) also interpret the separation of Galicia Bank from Flemish Cap to have taken place during the Aptian (125-112 Ma).

Extension between the Lusitanian Basin and Northwestern Iberia has also been modelled in two phases: 131 Ma to 116 Ma (FIG.2), and 116 Ma to 81 Ma. Sibuet *et al.* (2004) estimate that between 156 and 118 Ma there was N-S extension with rifting reactivating faults in southern France and northern Spain. The opening of the Bay of Biscay occurred between 118 and 80 Ma with an absence of magnetic anomalies younger than 80 Ma indicating the end of sea-floor spreading

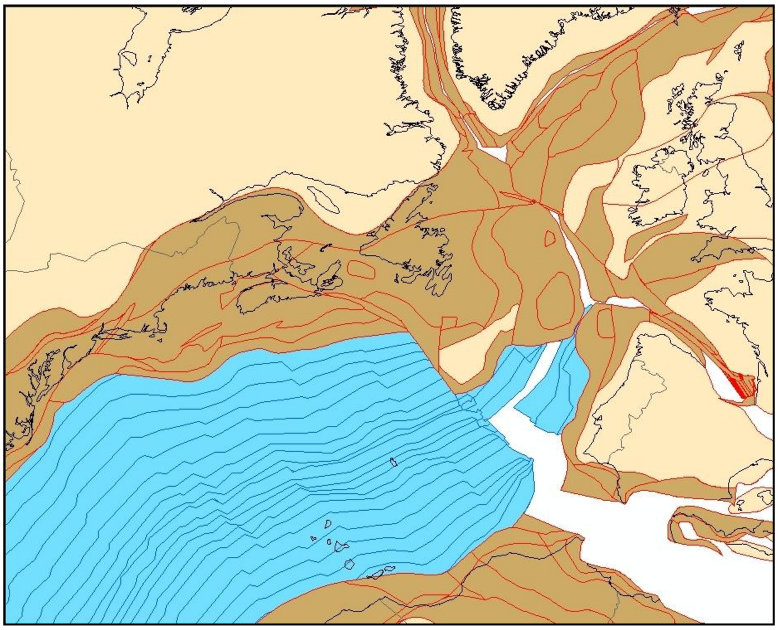

FIG.2 - Plate tectonic reconstruction at 125 Ma for the conjugate margins of Newfoundland, Greenland, Europe and Iberia. The reconstruction demonstrates the deformable plate model by removing the extension that has occurred along these margins.

## 4. Conclusions

The application of deformable plates in the global reconstructions allows measurable amounts of extension and contraction to be accounted for in each particular tectonic setting. These can be refined to a regional scale and locally adjusted and compared with alternative methods, such as regional cross section restorations or subsidence curves. Beta values of 1-2 were calculated for extension between Iberia and Newfoundland for distinct episodes of tectonic extension. These values are comparable with work by; Srivastava and Verhoef (1992), Chadwick *et al.* (1989) and Keen *et al.* (1987) amongst others.

To date, a self-consistent global, plate tectonic model has been achieved that incorporates stretching factors and scales deformation for the Cenozoic and Mesozoic of the entire Atlantic margin. Restoration to the pre-rift geometries of the margin in these areas can be refined further by detailed modelling of tectonic evolution and the extent of crustal deformation. Furthermore, by resolving deformation geometries to pre-drift positions, the imprints of earlier rifting, strike-slip, and collisional histories are more clearly defined.

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# Thermal modelling of the central Scotian Slope, offshore Eastern Canada: Seafloor heat flow data, hydrocarbon maturation potential and the effects of salt on heat flow

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*ABSTRACT*

*The Scotian Slope is an under-explored deepwater sedimentary basin, located offshore eastern Canada. As few wells sample the Scotian Slope, the thermal structure and maturation of the inferred Verrill Canyon Formation source rocks remains unknown. Seafloor heat flow measurements were acquired in an attempt to better constrain the thermal structure of the central Scotian Slope. Local thermal anomalies associated with high thermal conductivity salt bodies are evident in the heat flow data. Seafloor heat flow data are coupled with simple crustal rift models, well data and 2D seismic data in constraining dynamic 3D thermal models of the study area to predict the maturation of varying source rock intervals. Early results suggest the Verrill Canyon shales occur within the late oil/wet gas producing zones.*

*KEYWORDS: Heat flow, Thermal modelling, Scotian Slope, Salt.*

## 1. Introduction

The passive continental Scotian margin located offshore Nova Scotia formed as the result of Late Triassic rifting of the North American and African plates. The associated Scotian Basin underlies both the shallow water Scotian Shelf (<200 m) and the adjacent deeper water Scotian Slope (200-4000 m) (FIG. 1). This basin comprises a series of deep sedimentary subbasins that resulted from syn-rift and three post-rift phases of subsidence (Jansa and Wade, 1975). The Scotian Basin has been the site of active hydrocarbon exploration since the 1960's. To date hydrocarbon exploration has been focused on the Scotian Shelf, which has been sampled by over 150 boreholes. Despite continued exploration, production has so far been confined to the Sable Subbasin on the outer shelf in the region surrounding Sable Island (FIG. 1). The successful drilling on the Scotian Shelf has yet to be replicated in the deepwater as none of the 12 slope wells yielded commercially significant hydrocarbon shows. In the absence of wells, few temperature or vitrinite reflectance data are available for analysis of the thermal evolution and maturation history of Scotian Slope sediments (Mukhopadhyay et al., 2006). A Kimmeridgian shale has been inferred as likely source rock for the Scotian basin, following results from other eastern Canadian sedimentary basins (Enachescu et al. 2010). The goal of this study is to couple new seismic interpretations and heat flow measurements with simple rift models to better constrain the thermal structure and maturation history of the deep water Scotian Slope.

## 2. Thermal Modelling

Thermal and petroleum systems models are useful in predicting the hydrocarbon potential of a basin if sufficient data are available to constrain the models. Of particular importance in predicting the maturation potential of a basin is the use of vitrinite reflectance data (%Ro) in constraining the basin's thermal history. However, where vitrinite reflectance data are lacking, such as deep water frontier basins with limited drilling, other techniques must be applied. Thermal constraints are derived from surface heat flow measurements taken using a shallow marine probe along three deep MCS profiles across the central margin (FIG. 1).

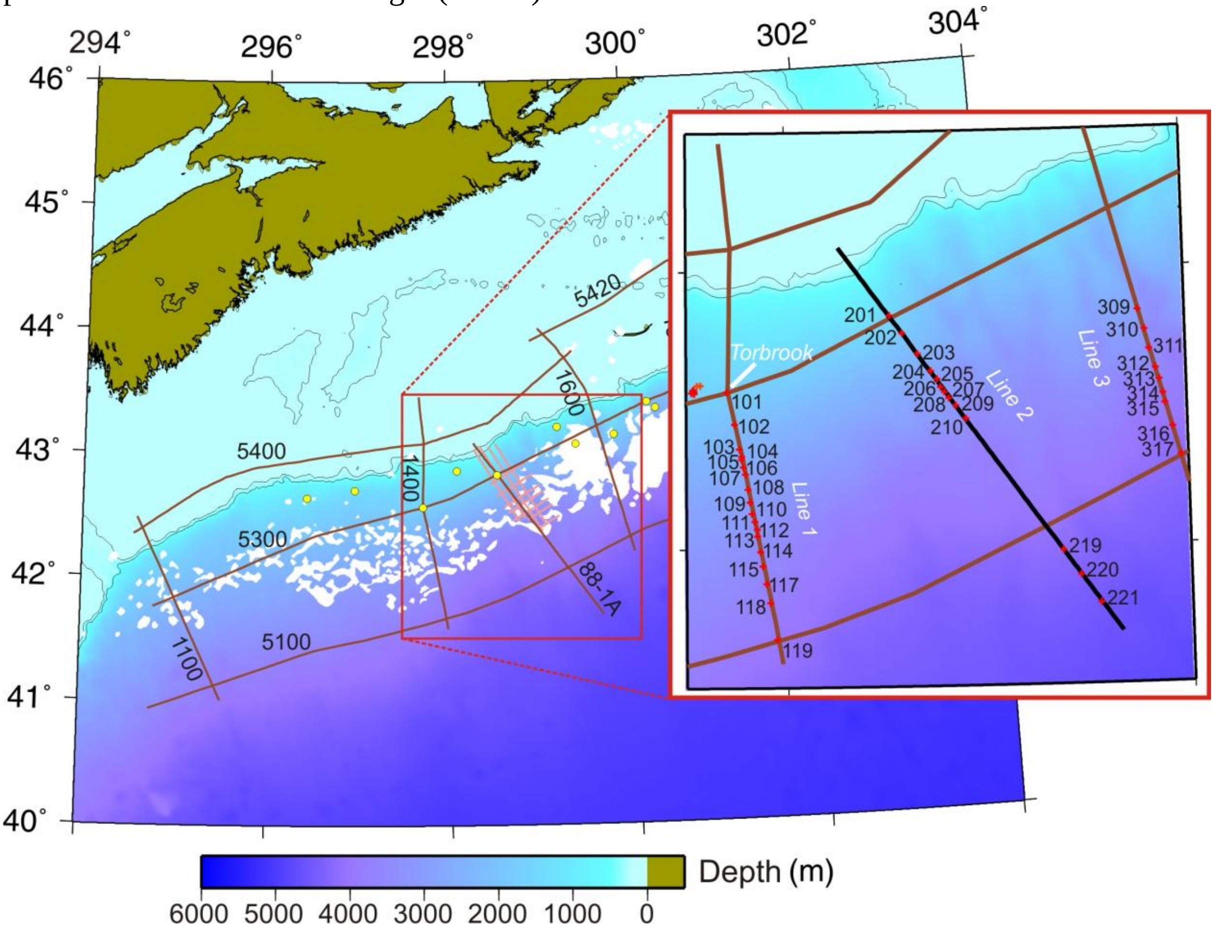


FIG.1 - Location map of the central Scotian Slope study area showing NovaSPAN seismic profiles in brown, TGS-Nopec NS-100 seismic lines in pink, and Lithoprobe line 88-1a in black. Yellow circles represent Scotian Slope boreholes, white represents shallow salt after Shimeld (2004) and 200 m and 400 m seafloor depth contour intervals are shown as fine black lines. Zoom section shows locations of seafloor heat flow stations as red crosses at the Torbrook gas hydrates mound (Torbrook) and along the traces of seismic reflection profiles 1400 (Line 1), 88-1a (Line 2) and 1600 (Line 3).

Thermal models, constrained by available well data from the Scotian Slope, seafloor heat flow data, available 2D seismic data (FIG.1), and simple crustal rift models are used to constrain structure and stratigraphy. The pure shear uniform stretching model of McKenzie (1978) was employed to predict the basal heat flux history of the study area. Crustal stretching factors across the central Scotian Slope were defined after velocity modelling of seismic refraction profile SMART Line 2 (Wu et al. 2006). To constrain other parameters in the model that are important for predicting the history of basal temperatures (e.g. lithospheric thickness and asthenospheric temperature), predicted crustal heat fluxes are compared with the recently acquired observed seafloor heat flow data, after correction for the effects of salt and sedimentation. An initial lithospheric thickness of 100 km and athenospheric temperature of 1350 °C yielded the best fit to the corrected seafloor heat flow data;

however, it should be noted that these models do not account for radiogenic heat production within the sediments or crust.

Two dynamic 3D models (Model 1 and 2) were run using PetroMod® 11 basin modelling software. This bottom-up modelling package is used to model the thermal evolution and structure of the central Scotian Slope since Late Triassic rifting. The two models run both contain the same geologic structure and boundary conditions with the exception of the basal heat flux history curves. Model 1 was constrained using the basal heat flux derived from the uniform stretching model with a 100 km thick lithosphere, while Model 2 was constrained using a 125 km thick lithospheric heat flux. Both models include radiogenic heating within the sediment column. The second model was run in an attempt to lower the predicted present day seafloor heat flow, as Model 1 with the presence of radiogenic heating, when compared to our measured data, over predicted seafloor heat flow in the seaward limits of the study area. The predicted seafloor heat flow values are plotted against our measured seafloor heat flow data in Figure 2. In regions unaffected by salt there is good

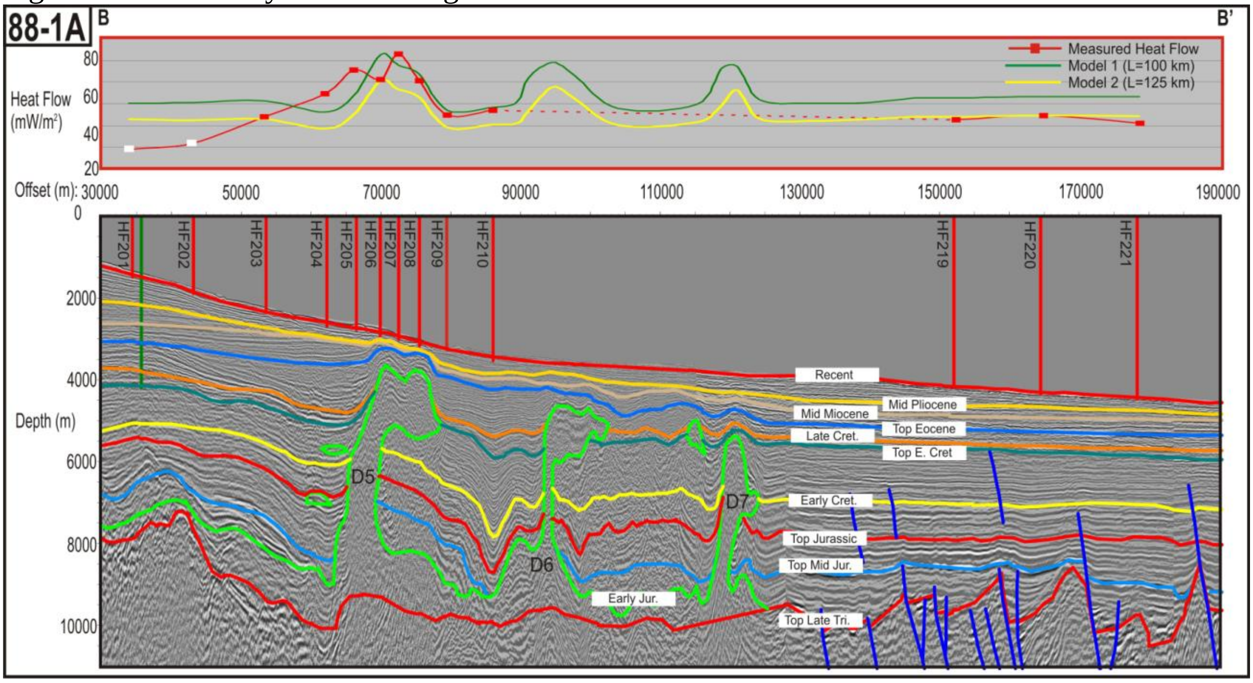


FIG.2 - Seismic interpretation of Lithoprobe Line 88-1a. Basement is outlined in red, and salt in green. Vertical red lines represent locations of seafloor heat flow stations, vertical green line represents the location of the Shubenacadie H-100 well and inclined blue lines are faults. Three salt diapirs are labeled D5-7. Plotted above the seismic interpretation are both measured (red) and modelled (green and yellow) seafloor heat flow curves. White squares represent heat flow measurements which recorded anomalously low geothermal gradients

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agreement between modelled and measured seafloor heat flow data (the most landward two seafloor heat flow measurements record anomalously low geothermal gradients and may be ignored). The seaward measured heat flow data fits the Model 2 predictions best, while the landward data better matches Model 1 predictions. The increase in measured heat flow in the landward direction may be the result of increased radiogenic heat production in the thickening continental crust not accounted for in our 3D models. While there is relatively good agreement between measured and modelled seafloor heat flow in regions unaffected by salt, modelled values above salt bodies do not always fit our measured data. Local increases above salt, as expected, are predicted by the models;

however, large variability in measured heat flow above single diapirs suggest additional process to conductive heat transfer may be affecting the seafloor heat flow which are not accounted for in the dynamic 3D models.

In addition to predicting the seafloor heat flow of the central Scotian Slope the models also predict the maturation of inferred source rock intervals. According to Model 1 the Kimeridgian Verrill Canyon source rocks occur within the wet gas window, while model 2 places these same source rocks in the late oil producing zone. This shows that variations in the basal heat flux history can have significant effects on the maturation of hydrocarbons. While the method derived above combining seafloor heat flow data, seismic data and simple crustal models is useful as a first approximation to the hydrocarbon maturation potential of a deepwater frontier basin, to truly constrain the maturation of Scotian Slope source rocks deep drilling is required.

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# Long-term post-orogenic evolution of N Atlantic conjugate margins constrained by on- and offshore data

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*ABSTRACT*

*We apply a range of different geoscience disciplines to the investigation of the evolution of North Atlantic conjugate margins. Numerical models develop promising asymmetries.*

*KEYWORDS: Geophysics, geomorphology, thermochronology, numerical modelling, orogeny.*

## 1. Introduction

Late Palaeozoic into early Mesozoic collapse and rifting processes began to dismember the Caledonide orogen after its formation. This also produced the deep late Palaeozoic and Mesozoic sedimentary basins on the continental shelves of north-western Europe and east Greenland (FIG.1) (Dunlap and Fossen, 1998). After a phase of intense tectonism involving early Paleocene magmatism in widely separated areas throughout the N Atlantic realm, rifting finally led to ocean formation and extensive flood basalt production in late Paleocene-early Eocene (Skogseid et al., 2000).

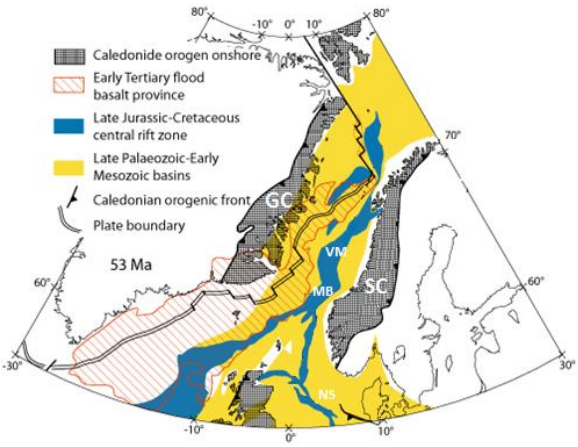


FIG.1 – Location of the study area in the North Atlantic. SC Scandinavian Caledonides; GC Greenland Caledonides; VM Vøring Margin; MB Møre Basin; NS North Sea. Redrawn mainly after Skogseid et al. (2000).

The possibility of plume-assisted N Atlantic break up as well as enigmatic, hypothesised, mainly Neogene, tectonic uplift has made the N Atlantic conjugate margin a focus of our multidisciplinary investigations. Numerical modelling of geological processes is an integrated element. Here we summarise previous and recent results (Nielsen et al., 2009) and new developments, which strongly suggest that inferences of Neogene tectonic uplift of the margins of the N Atlantic realm must be tempered with the influence of flexural isostasy as a function of differential erosional unloading (e.g. Medvedev et al., 2008) and relief reduction caused by glacial buzzsaw and peri-glacial processes (Egholm et al., 2009).

## 2. Geophysics

The deeper structure of southern Norway recently has been targeted using receiver function seismology (Svenningsen et al., 2007; Nielsen et al. 2009), refraction seismology (Stratford et al., 2009), P-wave tomography (Medhus et al., 2009), and surface waves (Weidel and Maupin, 2008). Receiver functions and refraction data yield consistent Moho depths, which correlate well with average topography and Bouguer gravity. Crustal thicknesses range from ~40 km in areas of high mean topography to ~30 km in coastal areas. Both methods detect that the deepest Moho (by ~2 km) is 50 to 70 km laterally offset from the highest topographic peaks. This is readily explained by differential exhumation in the presence of lithospheric strength and some lateral density variations in the crust and upper mantle. Different seismological experiments and Bouguer gravity hence confirm the standard Airy model of isostatic support of topography mainly by a thick and buoyant crust. It is important to realise that this relationship does not extend significantly beyond the Caledonide deformation front to the east (Ebbing, 2007; Nielsen et al., 2009, 2010). Subcrustal velocity anomalies in southern Scandinavia from teleseismic arrivals (Medhus et al., 2009) could point to a step in lithospheric thickness across the Oslo Graben. The uppermost-mantle S-velocity anomaly found under a large part of southern Scandinavia (Weidle et al., 2007; Medhus et al., 2010) is enigmatic. First, eventual buoyancy effects are not required to support the topography, and, second, physically based mechanisms that could produce the anomaly cannot produce the hypothesized Neogene tectonic uplift of 1-2 km. At present, we target the high topography of the central fjord area of E Greenland by receiver function and surface wave seismology in an experiment of duration 2 years.

## 2. Geomorphology

Peneplanation followed by episodic, epeirogenic uplift (Reusch, 1901; e.g. Lidmar-Bergström et al., 2000) is difficult to reconcile with the limited palette of tectonic uplift generating geodynamic mechanisms and observations, including the presence of topography supported by a buoyant crust. Had the topography been peneplained, the buoyancy of the crust would also largely have vanished along with the Bouguer gravity low. However, glacial buzzsaw and peri-glacial processes provide another possible explanation for the existence of low-relief high-elevation landscapes: Whenever a landscape crosses the snowline, it falls prey to buzzsaw erosion at and above the snowline, which over millions of years together with peri-glacial processes concentrates surface area in a window just below the snowline (Egholm et al., 2010). The hypsometry of the topography above the snowline is a function of the tectonic uplift rate. Southern Norway, the Torngats (Labrador) and the Urals, which potentially are cases for extinct mountain ranges undergoing only isostatic uplift caused by erosional unloading, globally have the least above snowline topography (Pedersen et al., 2010).

## 3. Thermochronology and maturity modelling

At present, an extensive apatite fission track (AFT) data set exists for Scandinavia as well as E and W Greenland. Sampling in June 2010 by our group (EM and RS) on Baffin Island presently will yield data from the Canadian margin. Our new AFT data from NE Greenland reveal that the relationship between age and distance from the coast for sea level samples is apparently dissimilar to the relationship seen in W Scandinavia, where the age decreases with distance from the coast. This relationship is readily explained by differential exhumation with the coastal areas passing through the partial annealing zone (PAZ) as a consequence of late Palaeozoic and early Mesozoic rifting (Dunlap and Fossen, 1998; Nielsen et al., 2009). Inland, topography has been undergoing exhumation at least since Caledonian time. Recently the fjords were carved significantly below sea level, contributing to the flexural isostatic exhumation. Maturity modelling in the eastern North Sea (Japsen et al., 2007) has been used as an argument for deep late Neogene exhumation related to the assumed tectonic uplift of W Scandinavia and S Sweden. However, this data set is in fact in better agreement with the default subsidence history defined by the drilled stratigraphy (FIG.2). From the analysis of all the wells of the study of Japsen et al. (2007) and a number of central North Sea wells we conclude that the thermal maturity structure of the eastern North Sea is consistent with late Cretaceous inversion movements (Nielsen et al., 2007) and inconsistent with the assumed Neogene uplift and erosion.

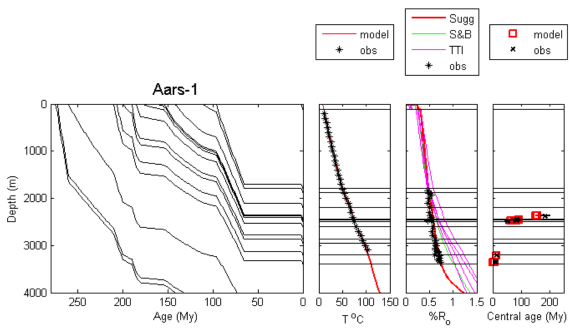


FIG.2 – Example of maturity modelling in the eastern North Sea. Unusually high-quality present-day temperatures, vitrinite reflectances, fission track ages and lengths (the latter not shown) leave no room for Neogene tectonic uplift and erosion during the long-lasting post Cretaceous hiatus visible in the subsidence diagram of the well Aars-1. A variety of vitrinite reflectance models are not consistent with the self-consistent FT-temperature system.

## 4. Geodynamic modelling

Models of N Atlantic convergence and extension apply a self-consistent representation of the lithosphere and sub-lithospheric mantle to a depth of 660 km (methodology according to Gerya and Yuen (2003) with further developments by K.D. Petersen). The thermo-mechanical coupling between the lithosphere and asthenosphere is allowed to evolve dynamically as a function of tectonic processes, for given rheology of the constituent materials (sediments, upper and lower crust, mantle) (FIG.3).

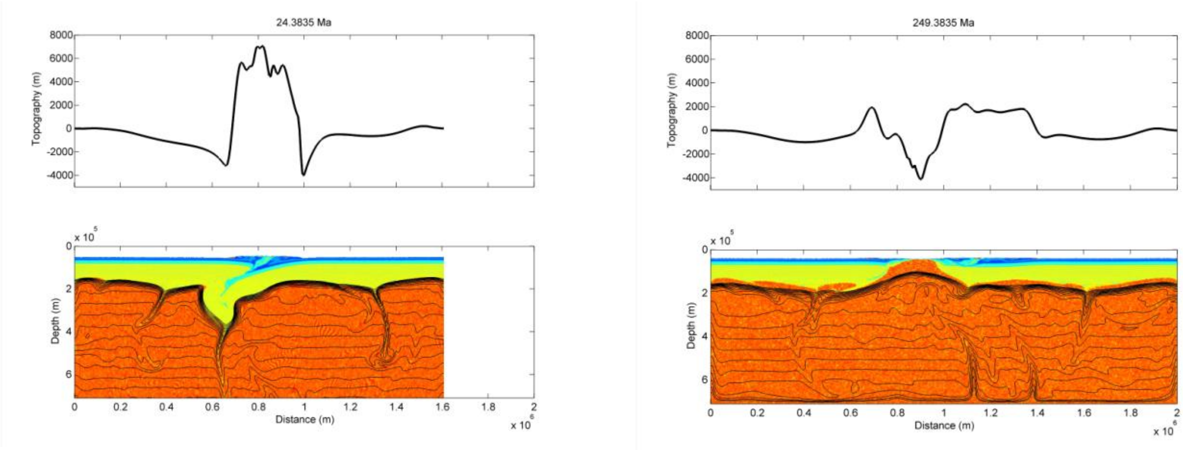


FIG.3 – Left: topography (upper panel) and the lithosphere-upper mantle configuration (lower panel) at the end of a continent-continent collision lasting for c. 24 Myr. Dark blue: upper crust; light blue: lower crust; yellow: mantle initially below 1200 ºC; orange: mantle initially above 1200 ºC. Right: Structure at c. 250 Myr, c. 50 Myr after rifting cessation. Black lines: Isotherms. Thermal gradient in convecting mantle: c. 0.6 K/km. Notice the steeper thermal gradient in the thermal boundary layer at base of the lithosphere, where heat transport changes from advection to conduction.

In FIG.3 convergence grades into slow extension at c. 24 Myr, which ceases at c. 200 Myr. During extension, the orogen becomes separated in two unequal size parts by an asymmetric sedimentary basin, which at c. 250 Myr (Fig.3, right) is in the process of slow thermal recovery. The basin has a steeper lithosphere-asthenosphere boundary at the eastern flank (yellow in FIG. 3, right) at the time of rifting cessation. We expect such asymmetries to have the potential to explain differences between N Atlantic margins.

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# Comparative analysis of the Porcupine Median Volcanic Ridge with modern day Pacific Ocean seamounts – further evidence of an amagmatic Mesozoic basin history for the South Porcupine Basin, offshore Ireland.

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*ABSTRACT*

*The Mesozoic Porcupine Median Volcanic Ridge (PMVR) is located in the frontier deepwater South Porcupine Basin (SPB) some 200 km off the southwest coast of Ireland. The PMVR is important because it provides a potential insight into whether Mesozoic rifting of the South Porcupine Basin was magmatic or amagmatic. The PMVR also forms the edifice for the Lower Cretaceous Dunquin carbonate platform exploration prospect, which is considered one of the largest un-drilled exploration targets offshore NW Europe. The composition of the PMVR remains unknown and previous workers have suggested that it is composed of volcanic, sedimentary or metamorphic (serpentinitic) rock. Here, we measure the gross geometry and morphology of the PMVR using recently acquired two-dimensional long offset seismic reflection data and compare/contrast the PMVR with modern day potential seamount analogues in the Pacific Ocean. This quantitative analysis of large-scale morphology contrasts with the subjective analysis of smaller scale features common to most seismic interpretation studies of the PMVR. The results show that the PMVR differs significantly from modern volcanic seamounts in its morphology. Since it seems unlikely that Mesozoic seamounts would display significantly different morphology statistics than modern seamounts, this analysis supports our views that the PMVR is a fault block composed of sedimentary rock, and that the SPB experienced an amagmatic rifting history. If this view is correct, the positive implications for the hydrocarbon prospectivity of the basin are significant. In addition, there may be similar implications for other hyper-extensional basin systems along the conjugate amagmatic margins of the Central and North Atlantic.*

*KEYWORDS: Ireland, South Porcupine, Volcanism, Amagmatic margins, Hyper-extension.*

## 1. Introduction

The South Porcupine Basin (SPB) is one of a number of linked Mesozoic deepwater rift systems located on the Irish Atlantic Margin (Croker & Shannon 1987, FIG. 1). The main phase of basin extension is thought to have occurred during the Late Jurassic-Early Cretaceous period (Baxter *et al.* 1999) with an associated total strain (beta factor) of c. 6.0 (Conroy & Brock 1989). The SPB contains a number of significant internal ridge elements that are of unknown composition, as well data in this frontier basin are very limited. The most significant of these ridges is the Porcupine Median Volcanic Ridge (PMVR) and a number of basin development hypothesis have been proposed to explain the genesis mechanisms of this ridge. If the composition of the PMVR were known, it would provide a key insight into the history and basin development of the SPB and profoundly impact the petroleum potential of this vast unexplored NW European Atlantic Margin frontier basin. In this paper we will compare and contrast the PMVR with modern seamount analogues from the Pacific Ocean, and also with data on mud volcanoes. These comparisons suggest it is unlikely that the PMVR is composed of magmatic or metamorphic material.

## 2. The Porcupine Median Volcanic Ridge (PMVR)

The PMVR was originally interpreted as an extrusive syn-rifting volcanic construction (Tate & Dobson, 1988), then as a sedimentary rotated fault block (Arveschoug *et al.* 1999) and finally as an extrusive construction of serpentinite mud (Reston *et al.* 2001, 2004). The PMVR is on-trend with the Porcupine Arch (PA) to the north which is widely accepted to be an area of relatively elevated mantle (Johnson *et al.* 2001; Readman *et al.* 2005). Recent published material has suggested that the PA is dominated by overlying detachment style deformational structures similar to those seen elsewhere along the eastern Atlantic Margin such as on the West Galicia Margin (Reston *et al.* 1995). This interpretation was subsequently extended southwards to the PMVR suggesting that the latter may be of metamorphic (serpentinitic) origin, a result of exhumation of the mantle due to extreme crustal extension. Recently completed modeling of deep seismic refraction data over the PA, however, do not support further crustal thinning and mantle exhumation south of the PA in the SPB and therefore lend less credence to the metamorphic model (Hauser & O'Reilly 2010).

## 3. Modern Day Pacific Ocean Analogue Comparisons

A Woods Hole Oceanographic Institute survey of 85 modern day seamounts situated in the Pacific Ocean has been used as a comparator dimensional dataset for the PMVR mapping (Smith 1988). This survey reveals systematic relationships between the various dimensions of modern day oceanic seamounts. Most of the morphological variation is encapsulated by two variables: flatness and summit height. The 85-point sample mean of the height-to-basal-radius ratio is 0.21 ± 0.08, implying that a seamount's summit height is typically 1/5$^{th}$ its basal radius (FIG. 2). Mapping of the PMVR suggests a height which is c. 2/5$^{th}$ the basal radius. Therefore, the PMVR falls significantly outside the trend that would be expected based on modern day seamount analogues.

Modern day serpentintic mounds can also be described in terms of their height-to-basal-radius ratio. Qualitatively, the PMVR is taller and narrower than a typical serpentinitic mound. However a statistically representative dataset was not available for detailed quantitative analysis and comparison.

## 4. Conclusions

Comparison of the PMVR with modern day volcanic and metamorphic analogues in the Pacific Ocean strongly suggests that the PMVR is not an extrusive volcanic construction, and also suggests that it is not a serpentinite mound. If these conclusions are to be rejected, then very different kinds of processes must be invoked for the ancient versus the modern. These conclusions support the idea that the PMVR is a rotated fault block composed of sedimentary rock. If this is indeed the case, it would have a positive and important impact on the petroleum systems and future hydrocarbon potential of the South Porcupine Basin.

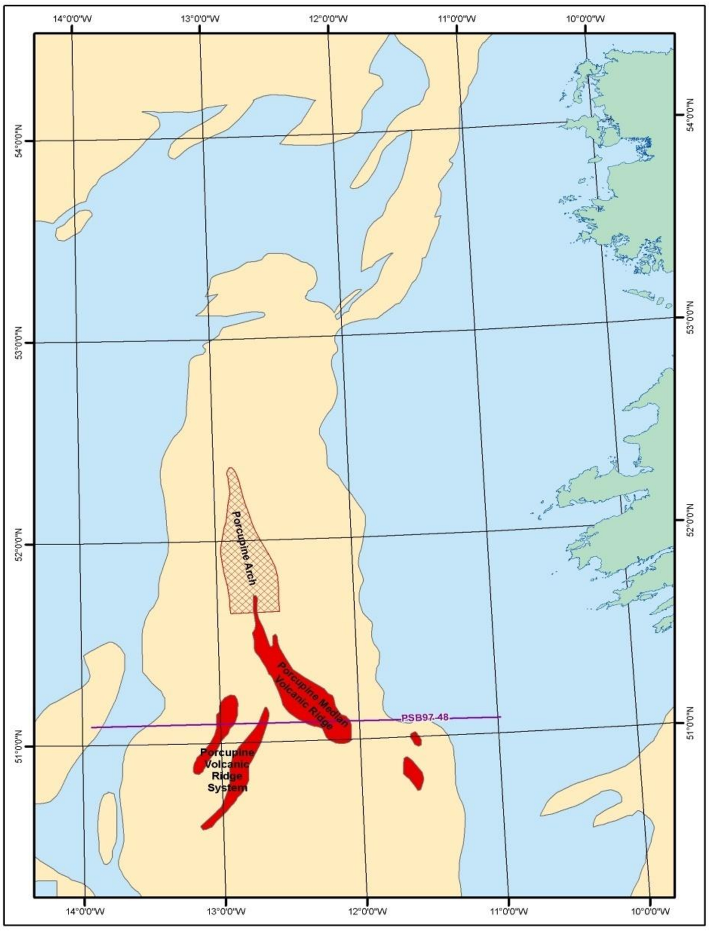


FIG.1 – Location of the Porcupine Basin showing major internal ridge elements

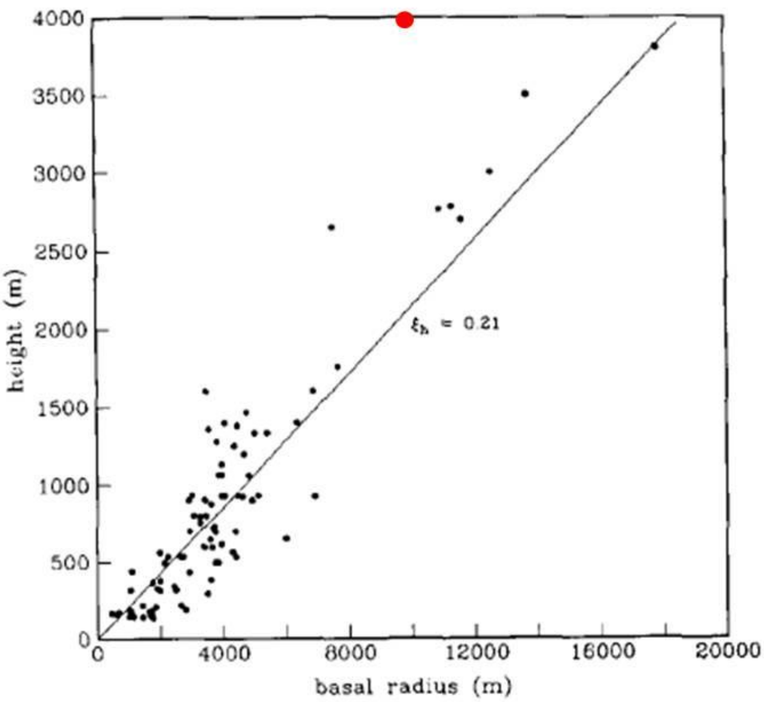


FIG.2 – Dimensional comparison of the PMVR (red) with Pacific Ocean Seamount database

*Acknowledgements*

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# Nova Scotia Play Fairway Analysis Upper Jurassic–Lower Cretaceous Depositional Systems

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*ABSTRACT*
*This presentation focuses on a key sequence of interest on the Scotian margin from a hydrocarbon standpoint: the Upper Jurassic and Lower Cretaceous clastics sedimentary rocks. It presents new data on interactions between uplift events inferred from the geological record onshore Nova Scotia and Newfoundland and the resultant depositional systems in the Scotian Basin. Mineralogy studies provide evidence for sediment provenance. Depositional environments are inferred from studies of conventional cores, informed by seismic correlation. Reservoir quality depends in part on regional variation in diagenesis, influenced by both detrital supply and depositional setting. Predictions are made about the type of deposition and reservoirs in areas poorly tested by wells on the southwest and southeastern part of the margin.*
*KEYWORDS: Nova Scotia, Scotian Basin, detrital petrology, reservoir quality, tectonics..*

## 1. Introduction

The delivery of sand to the Scotian Basin, offshore eastern Canada, increased 3-4 fold in the latest Jurassic and Early Cretaceous. Delta progradation resulted in a sediment pile several km thick and created reservoirs for gas and minor oil on the shelf. Understanding the tectonic regime that led to the dispersion of sand, the provenance of the sand, and the manner in which it was deposited are all important for exploration models for new reservoirs and for understanding controls on diagenesis and reservoir quality.

## 2. The record of faulting on land

The fluvial Chaswood Formation in Nova Scotia and New Brunswick is coeval with the thick Lower Cretaceous deltas offshore. All the well-studied occurrences (FIG.1) show evidence for major syn-sedimentary faulting on NE-trending faults and detrital petrology suggests shedding of sediment from local horsts. These regional NE-trending faults extend westward to New England and may be related to opening of the Labrador Sea.

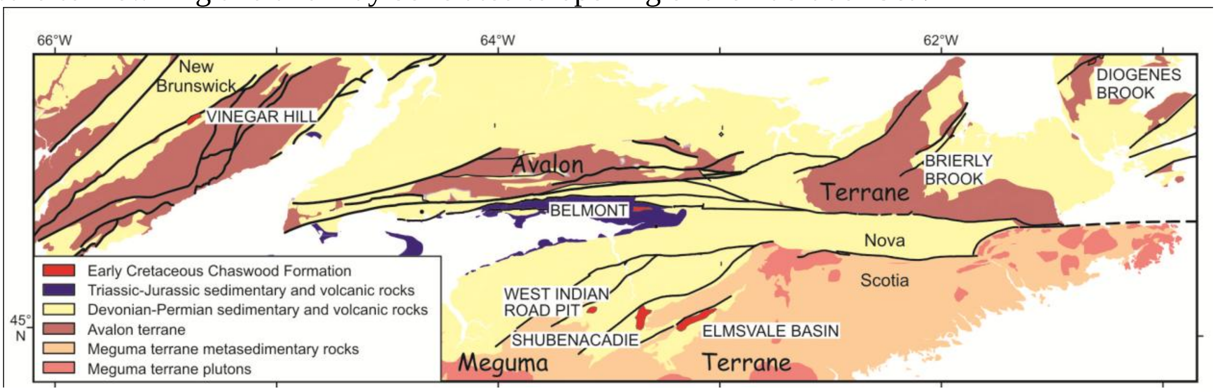



FIG. 1 – Distribution of the Lower Cretaceous Chaswood Formation (red) showing relationship to NE-trending faults.

**3.**

Cretaceous sandstones of the Scotian Basin. This study included the geochronology of the detrital minerals zircon, monazite and muscovite; varietal heavy mineral analysis that focussed on tourmaline, garnet and chrome spinel; petrographic identification of lithic clasts; and bulk geochemistry and Nd isotopes from both sandstones and shales.

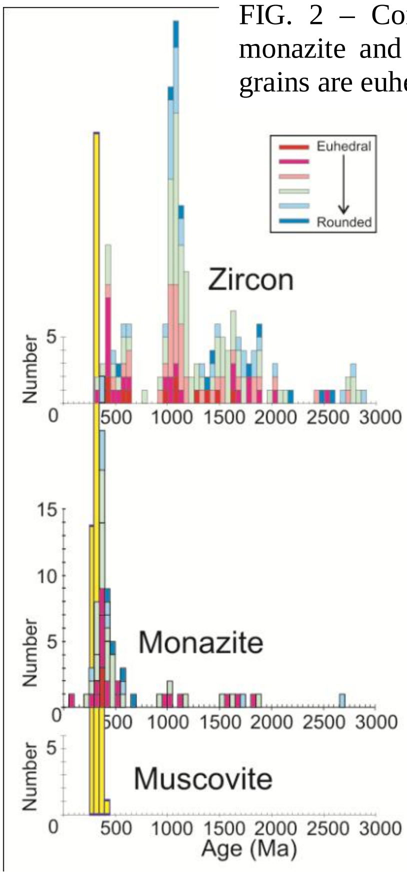



FIG. 2 – Comparison of single-grain geochronology of muscovite, monazite and zircon from the Sable Sub-basin. Also shows whether grains are euhedral or rounded.

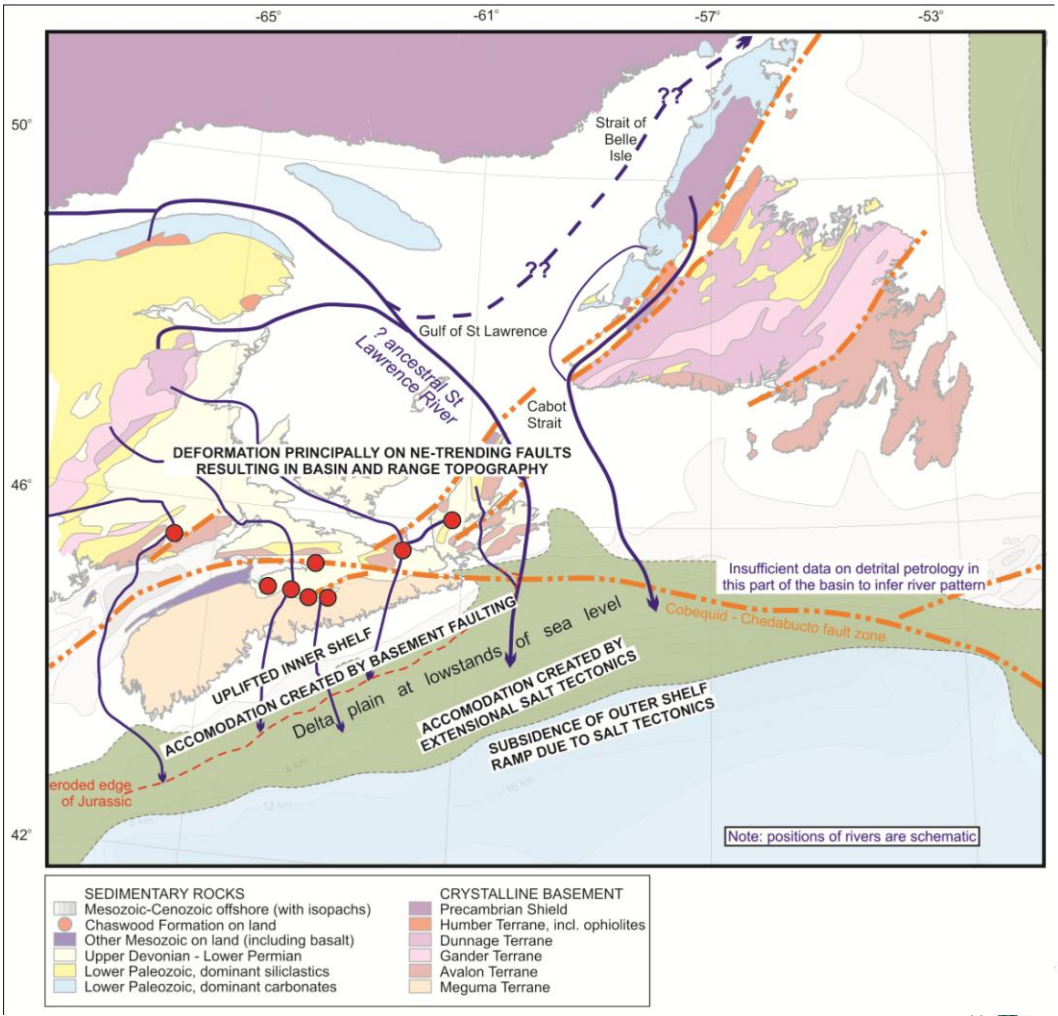
These data show that the minor sandstones in wells on the La Have Platform were sourced principally from the Meguma Terrane of southwestern Nova Scotia. The Sable Sub-basin, in contrast, has much greater sand supply and apparently much more varied sources. Detrital muscovite (FIG.2) is sourced from Meguma Terrane metapelites on the inner shelf that were metamorphosed in the Alleghanian orogeny (Reynolds et al., 2009). Detrital monazite, which is more resistant to transport, but is principally first cycle, is derived principally from Ordovician-Devonian Appalachian crystalline basement with a minor input from Precambrian Shield sources (FIG.2). Euhedral to subhedral detrital zircon shows a similar distribution of sources, but with a greater contribution from late Neoproterozoic (Avalon Terrane) and Mesoproterozoic (Grenville province) rocks. However, rounded and broken zircons predominate and include a wide range of ages of apparently reworked zircons (FIG.2). Some of these reworked zircons are of Devonian age, suggesting reworking through Carboniferous sedimentary rocks.

Other data suggest that a large proportion of the sediment supplied to the Sable Sub-basin is polycyclic. Bulk rock geochemistry shows strong covariance of Cr and Zr, principally in the minerals chrome spinel and zircon that do not co-occur in crystalline rocks but are ultra-resistant heavy minerals that are concentrated in polycyclic sandstones. The uniformity of chrome spinel varieties in different stratigraphic levels, compared with great variability in Appalachian source areas, suggests homogenization through polycyclic reworking.

The sand supplied to the Abenaki Sub-basin on the eastern Scotian Shelf shows many similar features to the Sable Sub-basin, but also significant differences that suggest the involvement of a different river system. Sandstone distribution also implies a separate depocentre. Detrital geochronology shows a much greater proportion of Precambrian monazite and zircon. The mineral tourmaline is much less common and present in different varieties compared with the Sable Sub-basin. The bulk geochemistry in the Abenaki Sub-basin is also different, and suggests a greater supply from felsic igneous rock sources. The proportion of polycyclic ultra-resistant heavy minerals is lower.

Petrographic studies from several wells show rather different supply of lithic clasts and some heavy minerals in the Barremian-Albian compared with the Tithonian-Hauterivian. These differences are smaller than the observed geographic differences between the LaHave Platform, Sable Sub-basin and Abenaki Sub-basin. They imply renewed uplift of the hinterland in the Barremian-Aptian with greater amounts of polycyclic sediment in the Sable Sub-basin and perhaps more metasedimentary detritus in the Abenaki Sub-basin.

The detrital petrology data for the offshore wells and the Chaswood Formation have been synthesised into a regional dispersion model (FIG. 3).




## 4. Depositional environments

Conventional core was systematically logged from the Scotian Basin at the same time as sampling for petrographic studies. Our interpretations resemble those of Cummings and Arnott (2005) except that we recognise a much greater role for delta-front turbidites (Gould et al., 2010). For example, thick reservoir sandstones in the Venture and Thebaud fields are graded beds of prodeltaic turbidites (FIG.4). Some facies interpreted as shoreface or tidal by previous authors are re-interpreted as more distal delta-front turbidites. Lateral variation in facies has been determined from logging conventional core in the same stratigraphic interval in closely spaced wells.

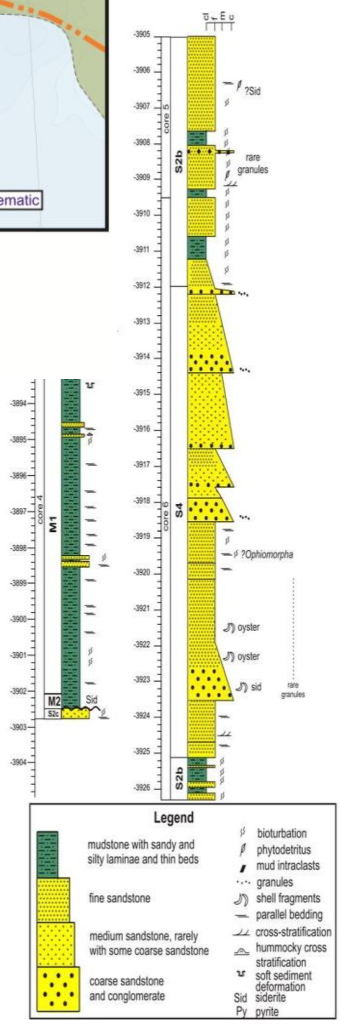
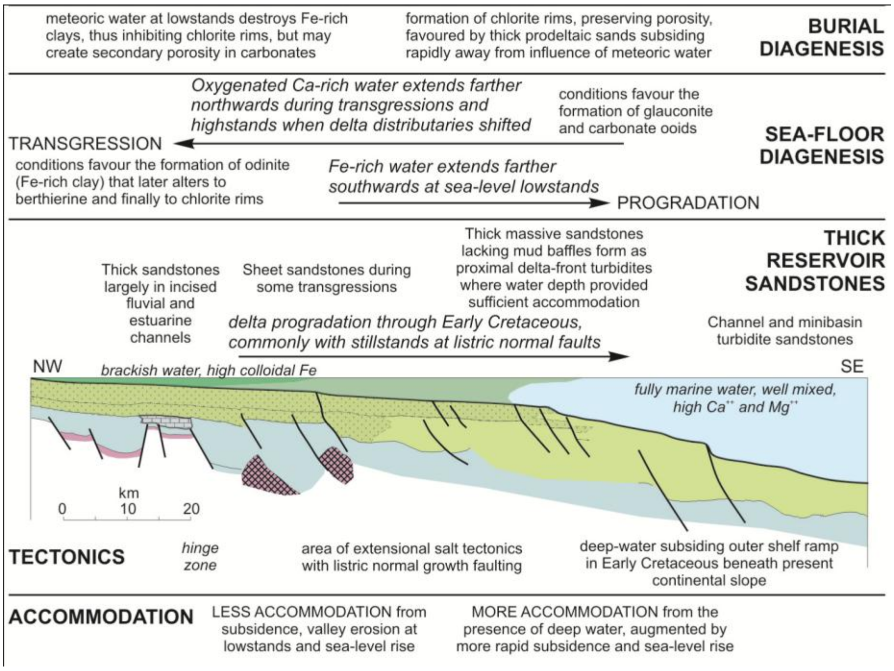



FIG. 4 – Delta-front turbidite sandstones in Thebaud C-74 well

## 5. Diagenesis and reservoir quality

The preservation of porosity in the Scotian Basin is generally the result of either the inhibition of silica cementation by chlorite rims on framework grains, or the patchy development of late carbonate cements. Work is currently underway to relate style of diagenesis to (1) variations in detrital sediment supply (FIG.3); (2) the conditions of early diagenesis and particularly the formation of Fe-silicate precursors of chlorite rims and the role of seafloor diagenetic cements including Fe-calcite and siderite (FIG.5); and (3) the influence of lowstands of sea-level in providing meteoric water that corrodes early Fe-silicates and carbonates.




## 6. Discussion

The complex relationship between tectonics and accommodation results in two types of delta progradation: (1) into deep outer-shelf water as "shelf-edge deltas" commonly at growth faults, where there is accommodation for thick stacks of delta front turbidites and rapid growth faulting minimizes the impact of meteoric water diagenesis. (2) into shallower water at highstands or in incised valleys, where Fe-silicates are more likely to form, but will generally be destroyed by meteoric water. The former setting has thicker sands and a higher probability of the preservation of porosity by chlorite rims.

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# Multiphased syn-rift segmentation on the SW Iberian margin

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*ABSTRACT*

*The Alentejo Basin in palaeogeographic proximity to neighbouring provinces such as the West Tethys, North Africa and the conjugate South Newfoundland margin is a key area to clarify some of the unclear aspects of the syn-rift evolution and the geometry of non-volcanic rift margins.*

*The analysis of 2D seismic surveys, boreholes and dredge data allow recognizing three discrete Syn-Rift phases and their correlated structural sectors across the SW Iberian margin, evidencing nearly continued subsidence from the Late Triassic to the Late Jurassic. Significant extension occurred during the Middle Jurassic, synchronous to extension between the North Africa-Nova Scotia conjugate. Late Jurassic subsidence at the distal margin, ultimately lead to seafloor spreading west of the Tagus Abyssal Plain is coeval to extension in Newfoundland.*

*During continental extension of the SW Iberian margin major subsiding sectors migrated westwards towards the locus of continental breakup, which is interpreted to have occurred by the latest Jurassic-earliest Cretaceous.*

*KEYWORDS: multiphased extension, rift migration, SW Iberia, North Atlantic.*

## 1. Introduction

From the Late Triassic to the Early Cretaceous, the western margin of Iberia and its conjugate from Newfoundland (Canada) evolved from continental fragmentation to oceanic breakup and posterior passive margin divergence (e.g. Tucholke and Sibuet, 2007). Within this setting, the Southwest margin of Iberia (namely the Alentejo Basin) is a crucial area to clarify unclear aspects on the evolution of non-volcanic rifted margins, such as the age of breakup and the position of the Ocean-Continent Transition in the southernmost segment of the North Atlantic, the geometry of the proximal margins during continental extension prior to breakup and the relation to neighbouring basins from the West Tethys and North Africa.

Using 2D high resolution seismic data tied to exploration boreholes, dredges and outcrop information from Southwest Iberia, the present work addresses the syn-rift seismic stratigraphy, structural segmentation and evolution of the margin from initial continental rifting to breakup.

## 2. Structuration of the SW Iberian margin during continental extension

Structural segmentation across the West Iberia and Newfoundland rifted margins has been described mainly using the models defined on the Galicia and the Alps (Manatschal and Bernoulli, 1998, 1999) and has been long studied as an example of an asymmetric rift (sensu Lister et al., 1986).

The analysis of the seismic profiles imaging the transition from thick continental crust to the thinned domain where ultimately oceanic crust was created, the Southwest margin of Iberia reveals three distinct structural sectors showing superimposed growth strata (Fig. 1). To the hinterland, the inner proximal margin overlays a thick continental crust evidencing limited subsiding tilt blocks, similar to the observed on outcrops of

Santiago do Cacém, Bordeira and to the North, in the Lusitanian Basin. Here, syn-rift deposition is scarce as evidenced by Late Triassic to Early Cretaceous sediment thickness up to 1,2 km.

The outer proximal margin (broadly coincident with the continental slope), reveals increased subsidence over a thinned continental crust resulting in the deposition of Late Triassic-earliest Jurassic, Middle Jurassic and Late Jurassic-earliest Cretaceous growth strata. Master faults in this sector broadly aligned SSW-NNE, dip either to the East or to the West. Such faults bound thick syn-rift depocenters, up to 2,4 ms TWT (approximately 4,8 km). The distal margin shows distinct superimposed growth strata revealing that most of subsidence prior to breakup occurred during the Middle Jurassic and the Late Jurassic. Similarly to the "S" reflector described in the Galician margin (Pérez-Gussinyé et al., 2001; Wilson et al., 2001), the crustal profile in this sector shows a deep crustal reflector likely reflecting the upper-lower crust detachment.

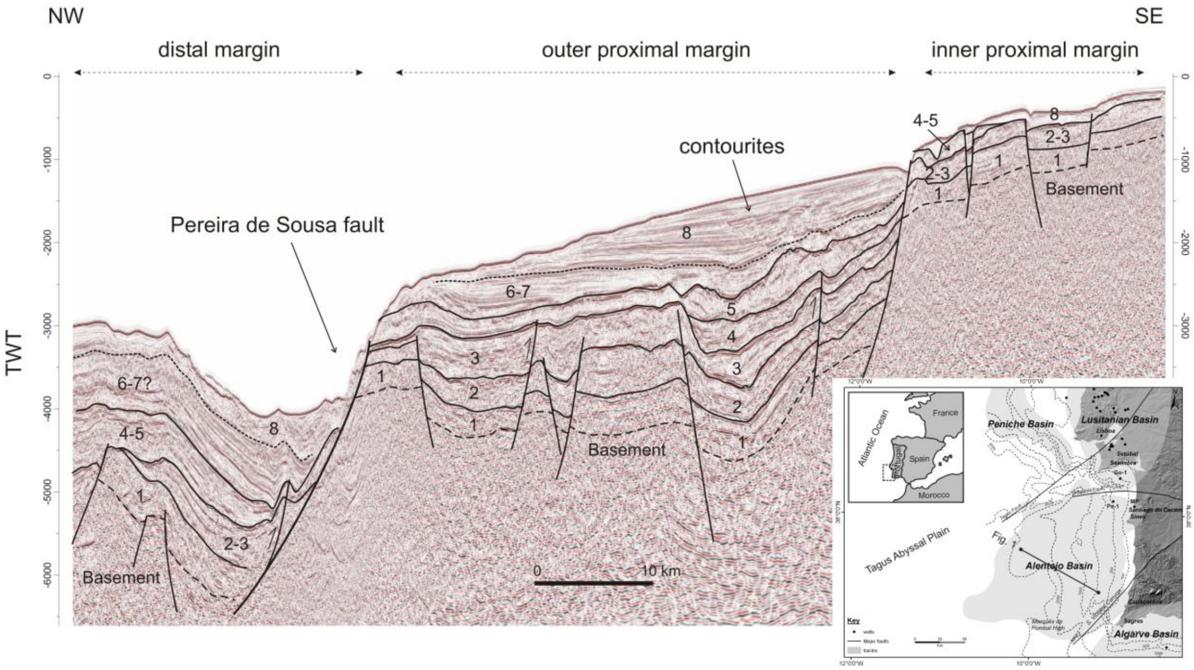


FIG.1 – Structural segmentation in the SW Iberian margin, revealing significant Middle to Late Jurassic subsidence. 1 – Carnian(?)-Hettangian, 2 – Sinemurian-Callovian, 3 – Oxfordian-Berriasian(?), 4 – Berriasian-middle Aptian, 5 – middle Aptian-Maastrichtian(?), 6 – Paleocene-middle Eocene(?), 7 – middle Eocene-mid Miocene, 8 – mid Miocene to recent.

Each of these structural sectors show distinct unconformity bounded seismic megasequences (sensu Hubbard et al., 1985) that can be correlated to major lithostratigraphic units, unconformities and hiatuses defined from outcrops and exploration wells, which include: 1) Carnian?-Hettangian, 2) Sinemurian-Callovian and 3) Oxfordian-Berriasian?. Seismic reflections in the study area (megasequences 4) reveal that deposition from the earliest Cretaceous onwards downlaps the syn-rift. Accordingly, the late Jurassic to earliest Cretaceous breakup unconformity is interpreted to depict the onset of oceanic crust generation west of the Tagus Abyssal Plain. Magnetic anomalies identified in the distal margin (M20-17) (Mauffret et al., 1989; Srivastava et al., 2000) are interpreted to be synchronous to this unconformity.

## 3. Multiphased extension and rift locus migration

The analysis of the syn-rift geometry and the correlative depositional megasequences across the margin shows that three major extensional events occurred during segmentation of the Iberia-Newfoundland conjugate, i.e. Syn-Rift I, II and III.

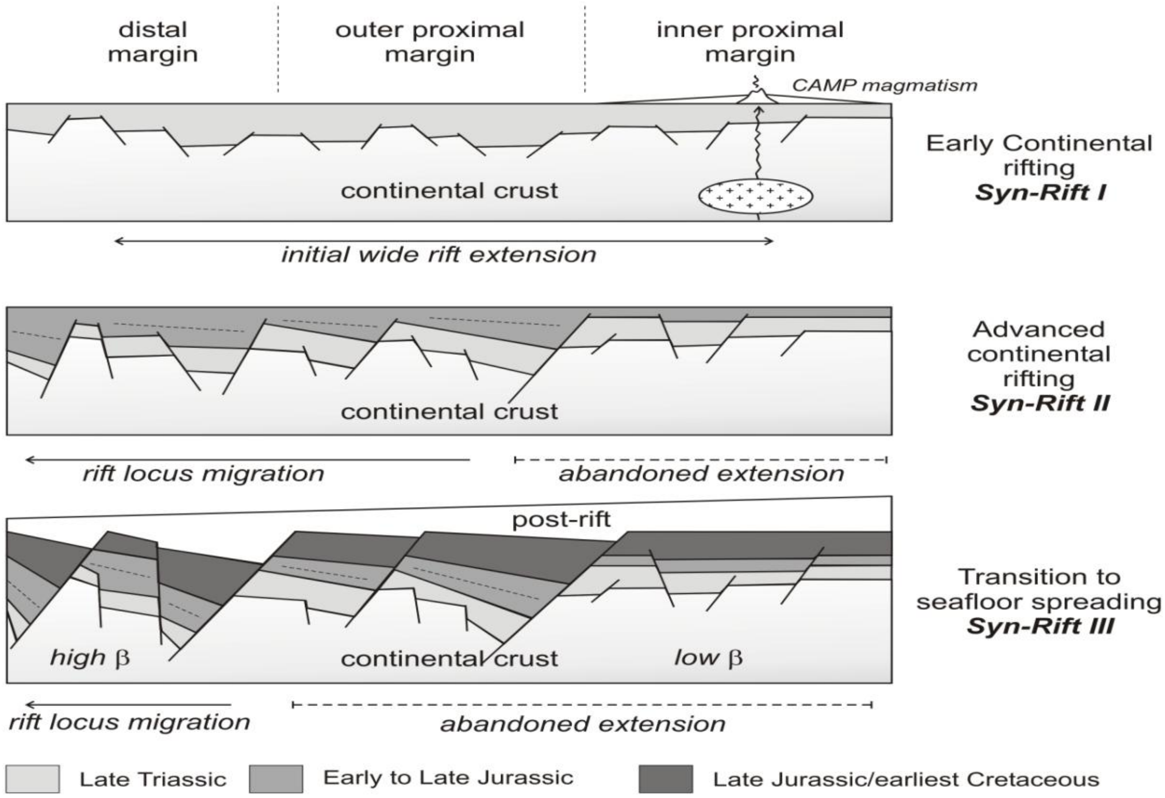


FIG.2 – Schematic evolution of the proximal to distal margin structuration and the relative rift locus migration across SW Iberia.

Syn-Rift I (Carnian-Hettangian) expressed widely in the North Atlantic is characterized by early continental rifting on a wide rift mode. Magmatism from the Central Atlantic Magmatic Province (CAMP) (e.g. Martins et al., 2008) marks the onset of a new period of extension (Syn-Rift II) from the Sinemurian to the Callovian, similar to rift subsidence from South Newfoundland, Whale Basin (Balkwill and Legall, 1989; Hubbard, 1988). Increased subsidence during this phase, suggests synchronicity with the extension towards breakup occurring at North Africa-Nova Scotia conjugate (e.g. Hiscott et al., 1990). The final extensional pulse expressed at SW Iberia (Syn-Rift III, Oxfordian-Berriasian?) is synchronous to extension reported from the Lusitanian and Jeanne d'Arc Basins. At the SW Iberia-S Newfoundland conjugate, the margin evolved passively from the earliest Cretaceous onwards, whereas at northern basins, onset of seafloor spreading occurred in the Aptian and Albian.

## 4. Conclusions

The Southwest margin of Iberia records three nearly continuous major Syn-Rift phases of extension expressed differently across the margin: I) Late Triassic-earliest Jurassic, II) Early Jurassic-Middle Jurassic and III) Late Jurassic-earliest Cretaceous. During this period, the margin was segmented into discrete structural sectors recording differential subsidence, interpreted to represent relative rift locus migration towards the position of continental breakup. Onset of seafloor spreading is interpreted to have occurred by the latest Jurassic-earliest Cretaceous.

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# The continent to ocean transition across the SW Iberian margin: The effect of syn-rift geometry on post-Mesozoic compression

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*ABSTRACT*

*The southwest Iberian margin, records the complex geological processes leading to continental extension, breakup and posterior post-rift compression.*

*The interpretation of 2D seismic-reflection profiles from the margin, tied to exploration boreholes and outcrop data reveals that the inherited syn-rift geometry and rheology of both deep continental crust and overlaying sediments, plays a major role in the positioning and typology of the distinct structural styles resulting from the post-rift Late Cretaceous to present day basin inversion. The analysis of the syn- to post rift structural geometry allows estimating the position of the Ocean-Continent Transition.*

*Compression is interpreted to have initiated as early as the latest Cretaceous, but is most significant through a period of time spanning the middle Eocene and the Late Oligocene-Miocene to recent times. Moreover, data reveals that shortening along and across the margin is neither synchronous nor similar.*

*KEYWORDS: post-rift compression, ocean-continent transition, southwest Iberia, north Atlantic.*

## 1. Introduction

Southwest Iberia (Fig. 1) is a type example of a non-volcanic rift margin, which experienced continental extension from the Late Triassic (or older?) to the latest Jurassic-earliest Cretaceous (Mauffret et al., 1989a, b). During extension, continental crust was thinned into distinct structural domains (Afilhado et al., 2008; Alves et al., 2009) recording multiphased syn-rift events which lead to rift locus migration prior to breakup. From the earliest Cretaceous onwards, southwest Iberia evolved as a passive margin until the Late Cretaceous when collision with Eurasia in the Late Cretaceous resulted in early shortening of the margin (Malod and Mauffret, 1990; Srivastava et al., 1990). Compression continued to the present day, but was mainly focused in the Eocene, Oligocene and mid Miocene (e.g. Alves et al., 2003; Mougenot et al., 1979).

The comprehensive interpretation of extensive 2D seismic surveys, integrated with results from boreholes, dredges and outcrops allow an innovative description of the timing of compressive events and features expressed across the margin, their relation to the inherited syn-rift geometry and the position of the deep crustal domains at the transition from the continental crust to the oceanic domain.

## 2. Compressive events at SW Iberia

The interpretation of major compressive events was accomplished by applying seismic stratigraphic concepts (sensu Cartwright, 1989) to the areas denoting significant deformation or by identifying chief erosional surfaces interpreted to depict the main compressive events. The analysis of the major compressive events reveals that the onset of post-rift compression was initiated as early as the Late Cretaceous, likely associated to the hinterland uplift by intrusion of large igneous bodies and post-rift thermal differential subsidence across the margin and the collision of northern Iberia with Eurasia. Late Cretaceous effects of compression are mainly observed on the inner proximal margin and are characterized by limited reverse faulting and depositional hiatuses hindering the preservation/sedimentation of most of the upper Cretaceous.

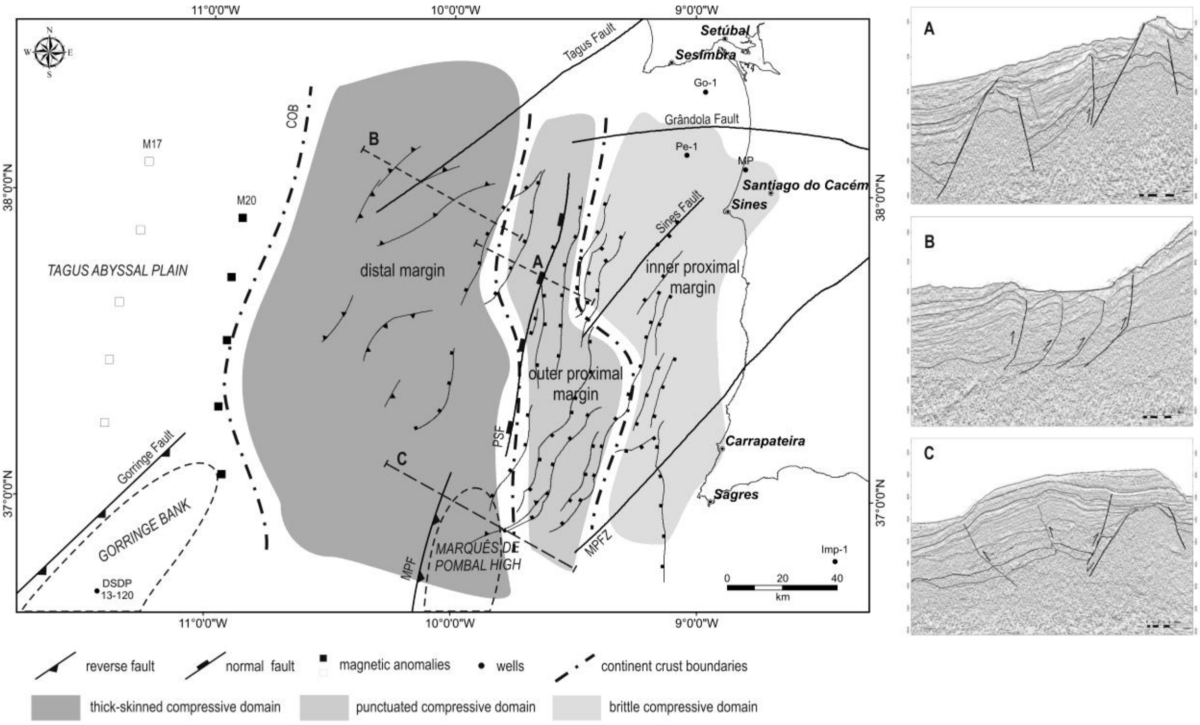


FIG.1 – Location and expression of major structural compressive styles across SW Iberia, in relation to crustal domains. Magnetic anomalies from Mauffret et al. (1989b) and COB from Rovere et al. (2004).

During the Cenozoic two major unconformities can be recognized across the margin, either expressed as downlaping towards incipient anticlines, deposition of axial fans at the base of folded limbs and incision surfaces (Fig. 1). In the absence of well control in most of the study area, the earliest compressive event is interpreted to record the mid Eocene compressive phase, which is expressed in the proximal margin by intense erosion resulting from uplift of the margin and by incipient folding in the distal margin.

The Oligocene to mid Miocene compressive events are expressed in proximal margin of southwest Iberia by localized folding and reverse faulting, which are likely rooted at deep detachment viscous evaporitic sequences from the Late Triassic-earliest Jurassic. Additionally this phase is characterized at the proximal margin by deep incision of palaeocanyons interpreted to result from noteworthy uplift. At the distal margin, shortening is expressed by broad anticlines, reverse faults and “piggy-back” thrusting associated to transpression (Fig. 1). Both folding and faulting in this sector are broadly aligned WSW-ENE, suggesting that chief compressional efforts currently recorded in the margin are likely dominated by the Miocene direction of compression.

Another aspect of the compressive related uplift across the southwest Iberian margin is the heterogeneous distribution of major Eocene to present day depocenters. As a result, thick Cenozoic successions occur mainly at the distal margin.

Compression continues to the present day as expressed by seafloor deformation, blind faulting and folding and by recurrent seismicity.

This work reveals that compression in southwest Iberia is neither synchronous nor similar across the margin.

Moreover, compressive events are interpreted to have occurred over long disperse periods, as jumping shortening boundaries alternately accommodate compression.

### 3. Significance of compressive domains across SW Iberia

Across the Southwest margin of Iberia the distinct sectors of compression broadly coincide with the inherited syn-rift geometry. The thick continental crust of the inner proximal margin dominantly reveals a brittle behaviour during compression, whereas at the outer proximal margin, compression is mainly expressed by diffuse shortening of the syn- to post-rift deposits. Shortening of the distal margin is mainly dominated by transpressive thick-skinned deformation rooted at deep lower crust detachments. The compressional sectors identified across the margin additionally reveal that the effects of compression are related to the rheology of syn- to post rift successions but primarily by the thickness and rheology of the crust.

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# The formation and evolution of crustal blocks at rifted margins: new insights from the interpretation of the Jan Mayen microcontinent.

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*ABSTRACT*

*The conjunction of high-quality seismic surveys, deep sea drilling, and progress in numerical modelling changed the way of thinking about how continents rift and oceans form. Although rifted margins now appear to be more complex their study worldwide shows that there are in fact a limited number of structures observed in seismic images that characterize their architecture. The margin's "building stones" include crustal blocks of various sizes, often referred to as microcontinents, continental ribbons, H-blocks, extensional allochthons and outer highs. Using the example of the North Atlantic, we illustrate the geometries and structures of these different blocks and suggest that they are the result of specific rift processes that correspond to a sequential evolution from stretching, to thinning and exhumation of the continental lithosphere. We also present a new interpretation of the Jan Mayen area, a typical microcontinent surrounded by oceanic crust.*

*KEYWORDS: lithospheric extension, rifted margin, microcontinent, crustal blocks.*

## Introduction

It is well known that extensional processes can lead to different crustal configurations, depending on lithospheric composition, thermal structure and extension rate. In the context of rifted margins, several types of crustal blocks have been observed and described, including microcontinents (Vink et al. 1984; Müller et al. 2001), continental ribbons (Lister et al. 1986), H-blocks (Lavier and Manatschal 2006), extensional allochthons (Froitzheim and Manatschal 1996) and outer highs (Planke et al. 2000). We believe that each of these blocks, by their similarities and differences, refer to distinct rifting and/or magmatic processes. Mapping and studying such structures may help to get insights on these processes, modes of deformation and their evolution during rifting and the onset of continental breakup.

In this contribution, we propose, using the example of the North Atlantic, that these blocks are the result of specific rift processes that correspond to the sequential evolution from stretching, to thinning and exhumation of the continental lithosphere. Then, based on a new geophysical dataset, we present an updated seismic interpretation of the Jan Mayen microcontinent (JMMC).

## Crustal Blocks at Rifted Margins

FIG.1 reports the various crustal blocks that characterize rifted margins in the North Atlantic.

FIG.2 proposes a conceptual rifting evolution including the definition of these specific blocks.

**Microcontinents** are commonly defined as large isolated pieces of continental crust surrounded by oceanic crust. A typical example is Jan Mayen in the Norwegian-Greenland Sea (Gaina et al., 2009). In contrast, **continental ribbons** refer to slightly extended continental blocks observed in proximal margin settings(e.g. Flemish Cap, Galicia, Porcupine, Rockall and Hatton Banks (Fig. 1). They are separated from the main continental area by sedimentary basins often showing a "V-shaped" regional geometry and are usually bounded by major crustal structures relayed by detachment faults and high-angle normal faults in the adjacent basins or distal margins. The **H-block** (Hanging wall block) is a concept that was first defined in a dynamic model by Lavier and Manatschal (2006). The H-block is, in its initial stage, the equivalent of a keystone that forms between conjugate normal faults. It represents a piece of relatively undeformed upper crust, which preserves its pre-rift stratigraphic cover. Depending on various parameters such as structural heritage, extension rate, lithospheric thermal configuration, the H-block can be of various shapes, sizes and thicknesses depending on the preservation of its lower crustal material during extension, and on the progress of the rifting. The origin of **extensional allochthons** as a concept goes back to the description of blocks overlying exhumed crust or mantle in highly extended areas such as the Metamorphic Core Complexes in the Basin and Range of the United States (Lister and Davis, 1989) or the Tethys margins in the Alps (Margna/Sesia block, Froitzheim and Manatschal, 1996; Parsettens block, Manatschal and Nievergelt, 1997). These blocks are, like "klippen" in compressional tectonics, i.e. unrooted pieces that are directly linked to detachment systems. The most spectacular examples are the extensional allochthons exposed in the Err and Platta nappes in the Alps (e.g. Manatschal and Nievergelt, 1997). In the Iberia-Newfoundland rifted margins, an extensional allochthon was seismically imaged and drilled at ODP Site 1069 in the Iberia Abyssal Plain. **Outer highs** correspond to topographic highs within the distal margins and limit the ill-defined crust of the transitional domain from unambiguous layered oceanic crust (North Atlantic). It actually marks the transition into first unequivocal oceanic crust. Although the processes that are related to the formation of the outer high are yet little understood, it seems as if they are linked to breakup and related to a major magmatic event which resulted in an underplating of previously exhumed and serpentinized subcontinental mantle.

**The Jan Mayen Microcontinent**

We update the interpretation of the basement and sedimentary structure of the JMMC, based on a new and vintage geophysical dataset, and taking into account new rifting evolution concepts.

This interpretation suggests multiple phases of deformation in space and time of the JMMC. Following the results of Kodaira et al. (1998)and Gudlaugsson et al. (1989), the Main Ridge and Southern Ridge Complex are supposed to correspond to the thickest crustal bodies. These ridges are flanked by thinning (and exhumation) structures which formed the adjacent basins. Tilted crustal blocks bordered by high angle faults are also reported; these are either related to the stretching phase, or to the subsequent thinning phase. The sag-type basins are supposed to be floored by thinned continental crust and, at some points, by exhumed mantle, potentially covered by crustal allochthons. Our model proposes also that the extensional deformation that affected the JMMC increased significantly southward. We suggest that the southern part of the JMMC could correspond to a zone of high degree of extension (thinning-exhumation mode) where continental crust has been highly thinned and eventually ruptured at some points, what permitted the formation of windows of exhumed mantle (exhumation mode). The JMMC was also likely associated with magmatism, which amount and composition is unknown. We believe these windows could correspond to the 'propagators' interpreted by Gaina et al. (2009). However, if these mantle windows are associated with true oceanic spreading activity or with extreme rift lithospheric extension is a difficult question. The different interpretation have been tested by the gravimetric and magnetic modelling. .

**See Peron-Pinvidic & Manatschal (Petroleum Geoscience 16, 2010) for further details on the study; and Peron-Pinvidic, Gernigon & Gaina (in prep. for GJI).**

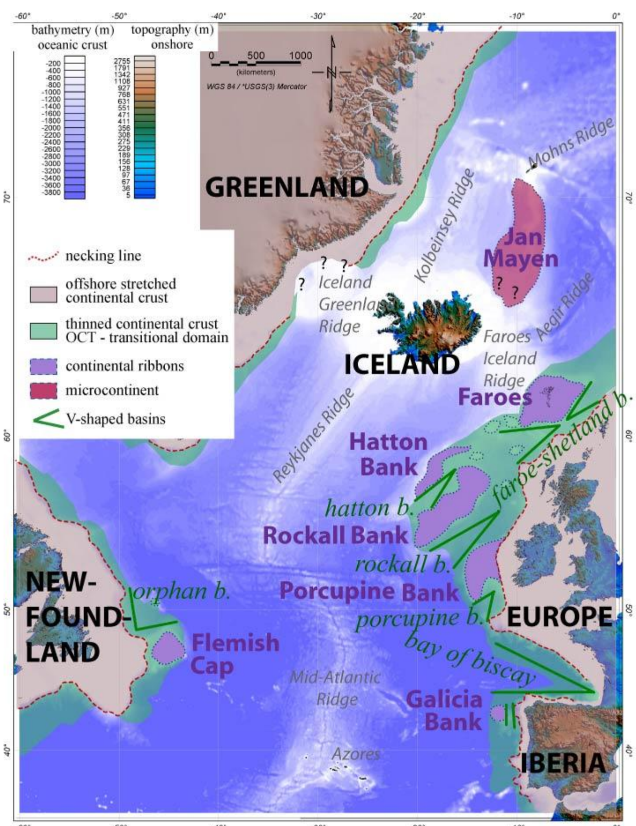


FIG.1 - Bathymetric map of the North Atlantic ocean with outlines of different categories of crustal blocks (continental ribbon and microcontinent) and of crustal settings from unthinned (onshore continent), stretched (offshore proximal margins; brown areas) to highly thinned continental crust (distal margins, ocean-continent transitions, V-shaped basins; green areas).

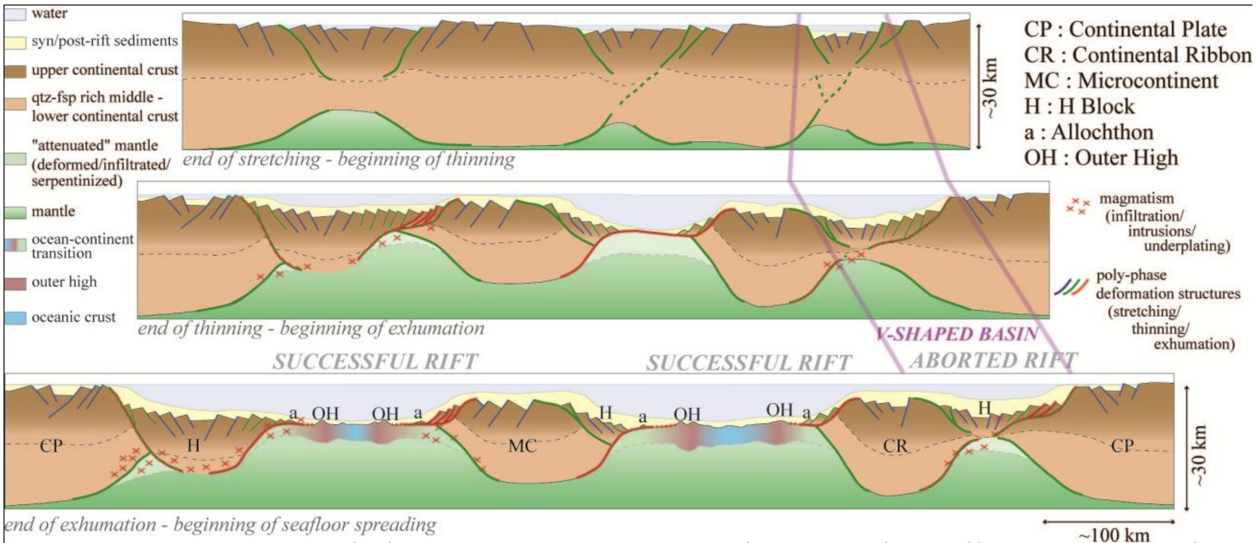


FIG. 2 - Schematic model of rifting evolution illustrating the formation of the different categories of crustal blocks. The genesis, evolution, final shape and position in the margin of each block are related to the distinct modes of deformation affecting the margin during rifting. See Peron-Pinvidic& Manatschal (2010) for details.

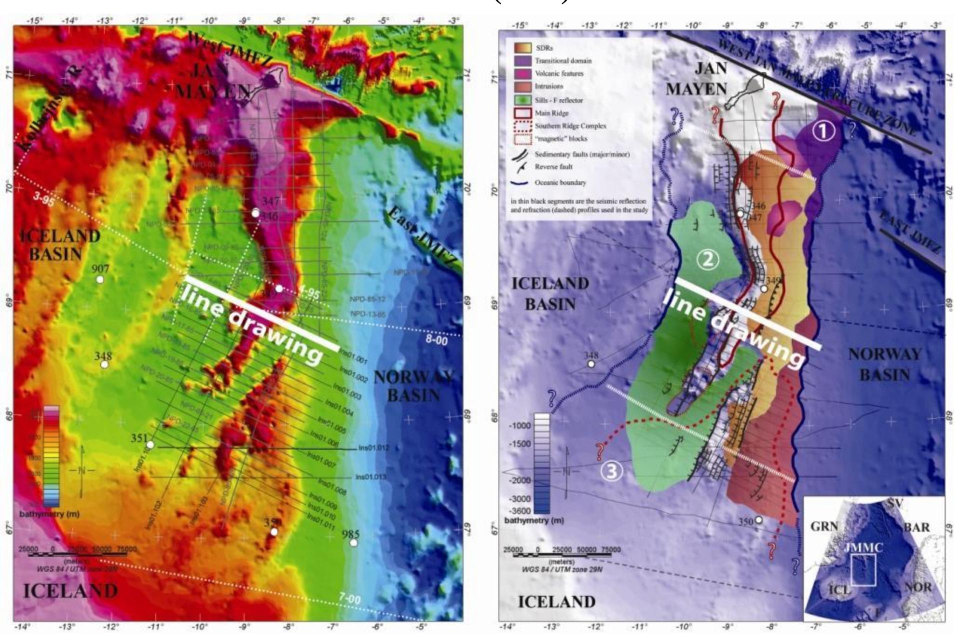


FIG.3 - Left: Bathymetric map over the JMMC with location of the MCS profiles used in the study.
Right: Structural map proposed for the JMMC.
See Peron-Pinvidic et al. (in prep. for GJI) for further details.

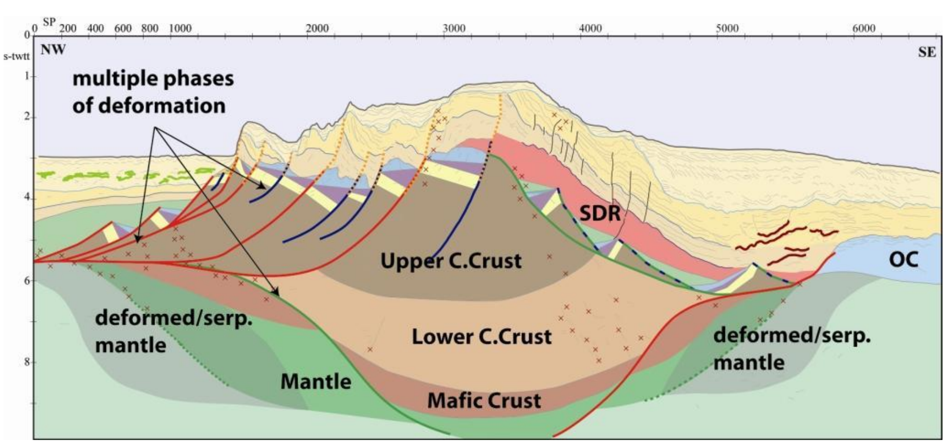


FIG.4 - Schematic interpretation of the JMMC architecture.
See Peron-Pinvidic et al. (in prep. for GJI) for further details.

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# Characterization of sills associated with the U reflection on the Newfoundland margin: Evidence for widespread early post-rift magmatism on a magma-poor rifted margin

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*ABSTRACT*

*In the Newfoundland margin, drilling during ODP Leg 210 penetrated two post-rift sills in the deep sediments overlying OCT basement. The shallower of the two sills coincides with the high-amplitude U reflection observed throughout the deep basin, and strong reflectivity in the sub-U sequence suggests that a number of other sills are present there. In this contribution, we use MCS reflection data and synthetic seismograms to investigate the nature, magnitude, and extent of this post-rift magmatism. Interpreted sills occur only over transitional basement; they cover an area of ~80,000 km$^2$, with a crude estimate of ~5,800 km$^3$ for their total volume. This is significant for a margin usually described as 'non-volcanic'. We also discuss competing hypotheses about the source of the magmatism, which is still uncertain.*

*KEYWORDS: rifting, sills, magmatism, breakup, post-rift.*

## INTRODUCTION

The Newfoundland and Iberia conjugates are considered to be archetypes of 'magma-poor' rifted margins, with wide zones of exhumed serpentinized mantle. However, the deep Newfoundland margin was affected by widespread post-rift magmatism. Drilling during ODP Leg 210 encountered evidence for early post-rift magmatic activity. Two sills dated at ~105.3 Ma and ~97.8 Ma were encountered in deep sediments that closely overlie transitional basement at Site 1276 (Hart & Blusztajn 2006). Shillington et al. (2007) demonstrated that the sills correlate with high-amplitude reflections in multichannel seismic reflection (MCS) data, with the shallower of the two sills emplaced at the level of a regional seismic marker termed the U reflection. The U reflection is very strong throughout the deep Newfoundland Basin, and it often overlies deeper high-amplitude reflections (Tucholke et al. 1989); these features suggest that there was large-scale sill injection both at and below U in the post-rift sediments.

In this contribution, we investigate the post-rift sill magmatism in the Newfoundland Basin using MCS data. We interpret the distribution and configuration of sills based on seismic reflection characteristics, and we use synthetic seismograms to estimate the thickness of the intrusions. These analyses are used to constrain the volume, extent, and timing of post-rift magmatism. Finally we examine hypotheses for the possible source of the magmatism.

## SILLS ASSOCIATED WITH THE U REFLECTION

### Method

If the high-amplitude U reflection correlates to diabase sills at ODP Site 1276 (Fig.1), it is not necessarily true that all strong reflections in the sedimentary sequence correspond to intrusions. To map sills over the Newfoundland Basin, we considered a reflection to be a possible sill if it is a high-amplitude event and if it also satisfies additional criteria related to structural and stratigraphic features, characteristic of intrusions (Y-like junctions, finger-like structures, disruptions, mimic of the underlying basement topography, perturbation of the overlying sedimentary section) (see Planke et al. 2005).

**Distribution of sill-related features**

Features that are interpreted as sills cover an area of ~80,000 km$^2$. They are restricted to the area of the transitional domain, over the deepest basement in the Newfoundland Basin. Overall, the distribution of various sill-related features suggests that there was a center of magmatic activity located in the region of the SCREECH 3 profile and extending north to the area of SCREECH 2 (see Fig.2). This central region is characterized by strong, relatively continuous sill reflections, local highs that were possible loci of magma injection, and common fluid venting features in the overlying sediments. It also contains the thickest high-reflectivity sequence in the sub-U interval, suggesting that it is closest to the source. To the north and south of this zone the sub-U sill sequence is thinner, and the sills at U have lower reflectivity and/or tend to be less continuous.

## DISCUSSION

### Area & Volume

The large area affected by sills (~80,000 km$^2$), the evidence for at least two intrusions at Site 1276, and the common occurrence of strong sub-U reflections all suggest that a series of sills was intruded during multiple magmatic events.

Calculating a total volume of magmatic intrusions is subject to numerous uncertainties. However, we believe that a realistic approximation can be obtained if we assume that about 26% of the interval with high-amplitude reflections is igneous, with an average velocity of 3.16 km/s (for details see Peron-Pinvidic et al. 2010). The total igneous rock thickness then ranges from ~7 m to ~180 m, with a mean of ~73 m; and the total volume of igneous rock would be ~5,800 km$^3$. This estimate is ~half of the minimum estimated for the Møre-Vøring deep margins (Planke et al. 2005). It however represents a significant amount for a margin that was essentially non-volcanic during its rifting phase.

### Source

- *Mantle plume?*

Duncan (1984) proposed that the Newfoundland Seamounts and the Southeast Newfoundland Ridge were formed by magmatism associated with the migration of the Azores, Madeira and Canary plumes across the region between about 110 and 80 Ma (Fig.2), and Karner & Shillington (2005) proposed that these plumes could be responsible for the post-rift sill intrusions in the Newfoundland Basin. However, one difficulty with invoking the Madeira plume is that the older 105 Ma sill was emplaced >10 Myr before (and >300 km ahead) of the calculated arrival of the plume at the western edge of the Newfoundland Basin. It should also be noted that wide-angle seismic data from the Newfoundland Basin (Funck et al. 2003; Lau et al. 2006; Van Avendonk et al. 2006) show no evidence for significant mafic underplating, which might be expected to be associated with the passage of a mantle plume. It is however possible that magma, rather than forming an underplate, was retained in the mantle, as is observed in slow-spreading oceanic crust;

incomplete melt extraction from the mantle also could have occurred.

- *Off-axis magmatism during early seafloor spreading?*

Magmatism could also have been stimulated by thermal/compositional perturbations associated with the end of rifting and the gradual organization of magmatism at the new mid-ocean ridge axis. Complicated three-dimensional variations in lithospheric thickness, that are expected to arise from rifting, may influence and guide the migration of magmas from various magmatic sources (Ebinger and Sleep 1998; Cannat et al. 2009; Shillington et al. 2009). In addition, numerical models suggest that convection cells and thermal anomalies induced by rifting can persist for tens of millions of years after continental separation (Boutillier & Keen 1999). In fact, geochemistry and dating of rocks recovered at Site 1277 on the Newfoundland margin and at transition-zone drillsites on the conjugate Iberia margin imply the continuation of a complicated off-axis magmatic/hydrothermal system long after the cessation of rifting (Jagoutz et al. 2007). If small-scale convection instabilities were present in the widening rift, low-degree decompression melting could have been associated with these cells at the lithosphere-asthenosphere boundary. Peron-Pinvidic and Manatschal (2010) and Van Avendonk et al. (2009) hypothesized that mantle rocks on the outer parts of the Newfoundland and Iberia margins were exhumed from beneath Newfoundland, which could have favored the genesis of such instabilities under that margin. We expect that the total volume of magmatic material resulting from waning, rift-induced thermal anomalies and/or off-axis MOR magmatism would be more modest than what would be expected from a plume, which would be consistent with the observations. According to this scenario, magmatism associated with the Madeira plume would have been restricted almost entirely to formation of the Newfoundland Seamounts.

**See Peron-Pinvidic et al. (GJI 182, 2010) for further details on the study.**

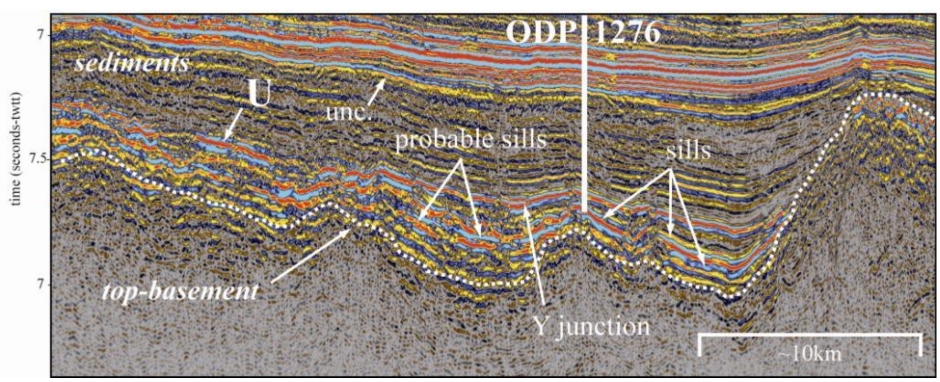


FIG.1 - Enlargement of the SCREECH 2 profile across Site 1276. Location on FIG.2.

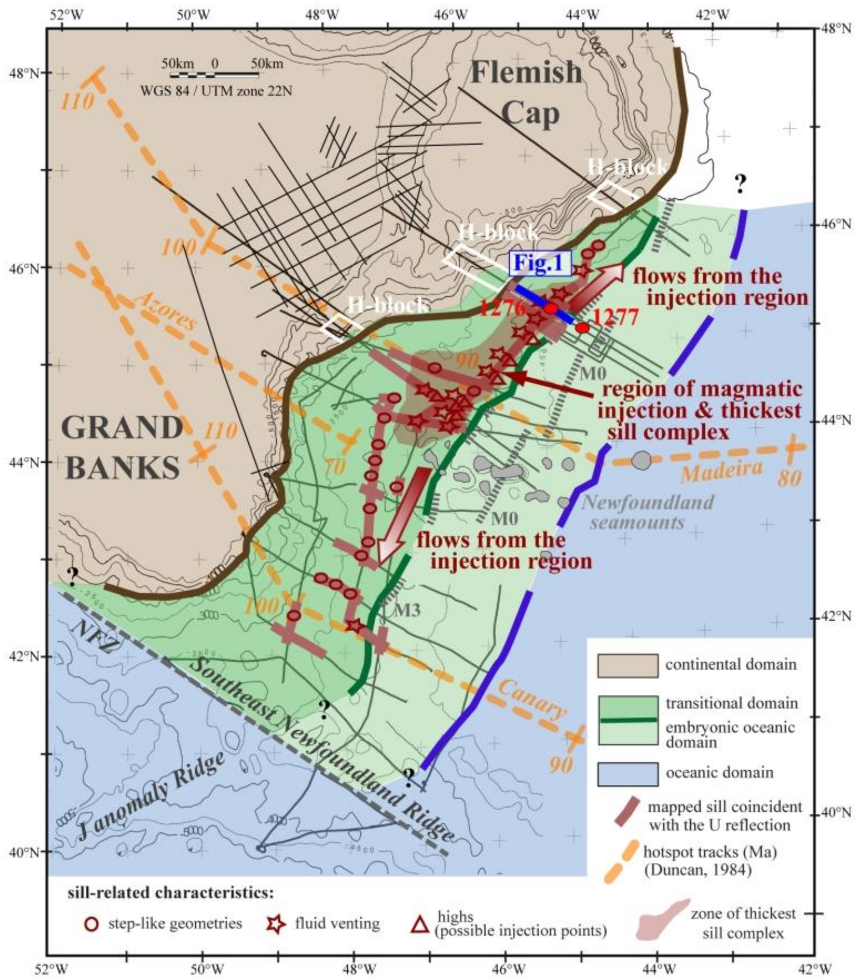


FIG.2 - Map summary of basement types and distribution of post-rift igneous sills. Tracks of the Canary, Azores, and Madeira plumes (Duncan 1984) are shown. Red bars along ship track lines show the distribution of mapped sills coincident with the U reflection. The light red shading within the transitional domain shows where the sill complex is thickest; this area is considered to be the main locus of magma injection into post-rift sediments. As suggested by the arrows, magma may have been distributed away from this area within both the lithosphere and the sediments. Red symbols, identified in the legend at lower left, denote the general distribution of characteristic sill features in the basin.

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# Orphan Knoll as a Window that Stands Slightly Ajar To view the Subsurface Geology of the Western Irish Continental Shelf and Porcupine Bank

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*ABSTRACT*
*Orphan Knoll was identified as a continental fragment in 1970 and has received little attention in the past 40 years. Dredged samples from 1971 have revealed that the Knoll comprises Palaeozoic marine sediments below the known Jurassic non-marine section. These data have been brought to the surface of the Knoll by diapirs that are very apparent as a series of over 200 prominent 'mounds' along the northeast margin of the Knoll. The Palaeozoic marine rocks of Orphan Knoll offer an easy and inexpensive way of sampling the deep marine sediments of the western Irish continental shelf and those below Porcupine Bank.*
*KEYWORDS: Northwest Atlantic, Orphan Knoll, Western Irish Continental Shelf, Porcupine Bank, Palaeozoic marine sediments, Old Red Sandstone.*

## 1. Introduction

Orphan Knoll as a pronounced kidney-bean-shaped topographic feature on the ocean floor 550km NE of Newfoundland was unidentified and virtually unknown prior to its recognition in the Fall of 1969 as a possible continental remnant. This recognition came from bathymetry alone. It was nominated as a drilling site for the Deep Sea Drilling Project in late 1969 and was accepted on the basis of tracks of JEAN CHARCOT V and CNAV SACKVILLE showing no prominent magnetic anomaly that would indicate a volcanic sea mount. It was named in the expectation that it was a continental remnant left behind as Europe separated from Labrador and Newfoundland of the North American continent. Orphan Knoll is about 75km in breadth and 190km in length oriented NNW-SSE between 49 deg 50'N and 51 deg 30'N. It rises to 1800m from the 2800m depths of Orphan Basin to the west and from the 3400m depths to the south. Its NE margin drops precipitously to the Abyssal Plain at 4000m.

The Knoll has stood as an isolated topographic high for in the order of 60my and has been blanketed by a thin 250m thick sequence of a compressed Jurassic-Cretaceous (Bajocian sandstone to Albian limestone to Maastrictian chalk ) to Tertiary section. Orphan Knoll has never been buried by the North American continental- and continental shelf-derived turbidity currents that have deposited up to 15,000m of sediments in Orphan Basin to the west. Instead these flows have swept around Orphan Knoll to the north and out the gap eastward between the Knoll and Flemish Cap to the south.

## 2. Deep Sea Drilling Project, Site 111

The final effort on the 1970 DSDP Leg 12, Site 111 hole on Orphan Knoll managed to cut a metre-long core as the diamond bit wore out 250m below the ocean floor on top of the Knoll. It was a black, anthracite-rich, Bajocian (Jurassic), non-marine sandstone. This confirmed the continental nature of the Knoll. The underlying Jurassic was interpreted in 1970 as the 'basement' to the small linear NW-SE-trending, thin Cretaceous basin seen on top of the Knoll. The drilling results on Orphan Knoll suggest a much closer relationship to Europe than to N. America. There is no source of anthracite coal known in Atlantic Canada but there are anthracite deposits known in Great Britain not far to the east in the reconstructed pre-drift continent. The Maastrictian chalk can be traced westward from the thick chalk sections in France to England and thinning to the 10m found to the west on Orphan Knoll on the western margin of the reconstructed pre-drift continent.

## 3. The ‘Mounds’ of Orphan Knoll – A Paucity of Data

What were recognised for the first time in 1970, but not understood, and what have received very little attention until mid-2010, were the ‘bathymetric ‘peaks’, or better called the ‘mounds’, on the top of Orphan Knoll. The narrow Cretaceous basin on top of the Knoll is flanked by two fields of diapir-like features. These are often buried, or have failed to reach the surface, on the SW margin of the Knoll; they generally protrude above the smooth upper surface of the Knoll along its NE margin. The 'NE mound field' comprises more than 250 mounds whereas the 'SW mound field' is barely a tenth the size as it is presently known. The NE mounds rise 115 to 320m above the sea floor. Some of the partially-buried mounds exceed 600m in height and the basal widths are in the order of less than 3km. Other than a 1971 dredging attempt from the LYNCH and two other dredge hauls from HUDSON in 1978 the mounds have received no further focused survey attention after two passes by the GLORIA bottom-mapping swath tool of the British in 1979 and 1981 by STARELLA and FARNELLA respectively. It was not until July 2010 that the mounds received specific attention when HUDSON was equipped with a ROPOS tethered ROV with a 3500m capability designed to examine the ahermatypic corals on both the 1600m volcanic seamount that stands just east of the southern extension of Orphan Knoll and on several of the exposed mounds of the NE field.

Orphan Knoll has not ever been the subject of a systematic geophysical survey; swath bathymetry is only available over a small area of its deeper SE margin. There is no deep seismic multichannel seismic coverage to speak of. One pre-1970 Seiscan Delta proprietary industry line ran up on to the top of the Knoll and in 2000 two GSI 2D spec lines ran partway up the SW flank profiling three buried and two protruding mounds of the SW field. Orphan Knoll is crying out for a systematic marine seismic, magnetic, gravity and swath bathymetry survey that will be fully available for scientific study.

Orphan knoll is also in need of a serious geologic sampling program. To date only the material in the 1971 LYNCH biologic dredge has been fully examined. The two 1978 dredge hauls of HUDSON recovered 16.3 and 19.1%, by weight, limestone, skeletal limestone and dolomite and other than a careful indexing and description by the authors in

1989 has not ever been examined in detail. The success of the HUDSON 029 cruise in July 2010 is not yet known vis-a-vis its bedrock recovery. The two GSI deep seismic lines lead to the suggestion in 2005 that the mounds were actively growing organic mounds, or bioherms.

**4. 1971 Dredge Results**

The 1971 biologic dredge recovery of fragments of limestones and skeletal limestones has yielded some most tantalizing results that have received little petroleum industry, or scientific, attention. The dredge was dragged over a 1km track immediately adjacent to the base of one of the mounds in the NE field. These pebble-sized samples yielded:

a) a unique Ordovician assemblage of silicic ostracods which is endemic at the species level contains two new species and a new genus, plus eleven other new forms left in the open nomenclature. The ostracods have North American and North European affinities. There are no known locations in the NW Atlantic for this material unless one invokes presently-unknown outcrops under the glacial ice of Greenland, Baffin, Devon or Ellesmere Islands.

b) Ordovician basalia sponge spicules which are not known from any source in the NW Atlantic and which bear a close resemblance to Australian forms; these forms are almost unknown in the literature. The 1971 material also contains Devonian heteractinid skeletal material which is almost impossible to move to Orphan Knoll from any known locations by ice-, or iceberg-transport.

c) Devonian conodonts which again cannot come from any presently-known sources of marine Devonian rocks in N. Canada, or Greenland, in the past 5,000 to 10,000y.

d) Early Silurian graptolites which only could have come from Cornwallis Is. in the central Arctic Islands; this was not possible in the past 5,000 to 10,000y.

Thus one is left with ice- and iceberg-transport from a presently-unknown outcrop to the north, or the Palaeozoic material recovered was derived from the nearby outcropping mound(s). If a) to d) above all came from the same sample then ice- transport can be invoked. But they did not come from the same sample. Thus the small, but finite, probabilities for each of cases a) through d) having come from a presently-unknown outcrop somewhere to the north under glacial ice and dropped in the same spot on the top of Orphan Knoll must be multiplied and this yields an near-vanishing probability worse than that of winning at any national lottery. We do not believe that the mounds of Orphan Knoll are living, or former, bioherms, but rather are the result of diapiric activity.

**5. Palaeogeographic Implications – Future Work**

It is much more probable that the 1971 Palaeozoic material came from scree on the nearby mounds and was swept off the mounds by periodic slumps of the steady rain of pelagic material. We are left with the interpretation that the diapiric mounds have carried a selection of the Palaeozoic rocks that underlie the Jurassic of Orphan Knoll up to the present seabed surface. We also conclude that the Ordovician-Devonian marine intracratonic platform sediments had a wider geographic extent than has been previously recognised. And this leads to our conclusion that a marine re-entrant must have penetrated the Old Red Sandstone.

Thus the deep Palaeozoic section of the European side of the conjugate margin which is buried west of Ireland beneath the Irish continental shelf and Porcupine Bank can perhaps be accessed and examined rather inexpensively at Orphan Knoll along its steep NE facing margin where there are many probable bedrock outcrop areas by using both geophysical survey techniques and off-the-shelf tethered ROVs, or submersible equipment.

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# Opening of the Atlantic and development of the Iberian intraplate rift basins during the late Jurassic-early Cretaceous

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*ABSTRACT*

*A comparative approach of the late Jurassic-early Cretaceous Iberian intraplate rift basins is presented. To do it a restoration of the basins at chron M0 (125 Ma) was performed. When the Bay of Biscay began its oceanization and spread through the continental crust of Iberia, two lines of trenches appeared: the Pyrenean Rift and the Cantabrian-Iberian-Catalan Rift, both separated by the Ebro High. The Iberian intraplate rift basins were a part of the network of rifted basins of the northwestern Peri-Tethyan platform, that evolved during the break-up of Pangea, and gave rise to the opening of the Alpine Tethys and North Atlantic.*

*KEYWORDS: Iberia, Tethys, Atlantic, Rifting, Basins.*

## 1. Introduction

During late Permian to Triassic times, Iberia was affected by a first rifting phase during late Permian to Triassic times which controlled the development of the basins within it: the NE-SW striking Catalonia-Valencia-Prebetic basins, the E-W trending Pyrenean-Cantabrian basins and the NW-SE oriented basins in the Iberian Chain area. This rifting cycle was followed by a period of relative tectonic quiescence and thermal subsidence, spanning from the late Hettangian to the Oxfordian times. A second rifting cycle commenced at the end of the Oxfordian and lasted till the early late Albian times. During this second rifting phase the Iberian intraplate rift basins developed in two lines of troughs: the Pyrenean Rift and the Cantabrian-Iberian-Catalan Rift (Fig.1). Late Cretaceous to Paleocene times corresponds to a period of relative tectonic quiescence and regional thermal subsidence of the Iberian intraplate rift basins. During Paleogene times the Iberian-Catalan basins were inverted to form the NE-SE striking Iberian Chain and the NE-SW-trending Catalan Coastal Chain, while the Pyrenean basins were inverted from the late Santonian times. Late Oligocene-early Miocene rifting, related to the subsidence of the Western Mediterranean, overprinted the Catalan Coastal Chain and the south-eastern parts of the Iberian Chain (Salas *et al*., 2001).

This paper deals with a comparative approach of the Iberian intraplate rift basins development during the late Jurassic-early Cretaceous times. In this paper we review the tectonic and sedimentary evolution of these basins.

## 2. The Iberian intraplate rift basins at chron M0r (125 Ma)

The location of the Iberian intraplate rift basins has been restored at chron M0 (125 Ma) (Fig. 1) on the basis of the plate reconstruction of the North Atlantic and Bay of Biscay made from Sibuet *et al.* (2004). The Bay of Biscay had begun its oceanization and spread through the continental crust of Iberia by two lines of trenches: Pyrenean Rift and the Cantabrian-Iberian-Catalan Rift, both separated by the Ebro High. These trough alignments are composed of individual basins bounded by faults that are spatially relayed: the Pyrenean Rift is formed by the following basins: 1) Parentis, 2) Arzacq, and 3) Organyà, whereas the Cantabrian-Iberian-Catalan basins are: 4) Basque-Cantabrian, 5) Cameros, 6) South Iberian, 7) Maestrat, 8) Columbrets, and 9) Garraf.

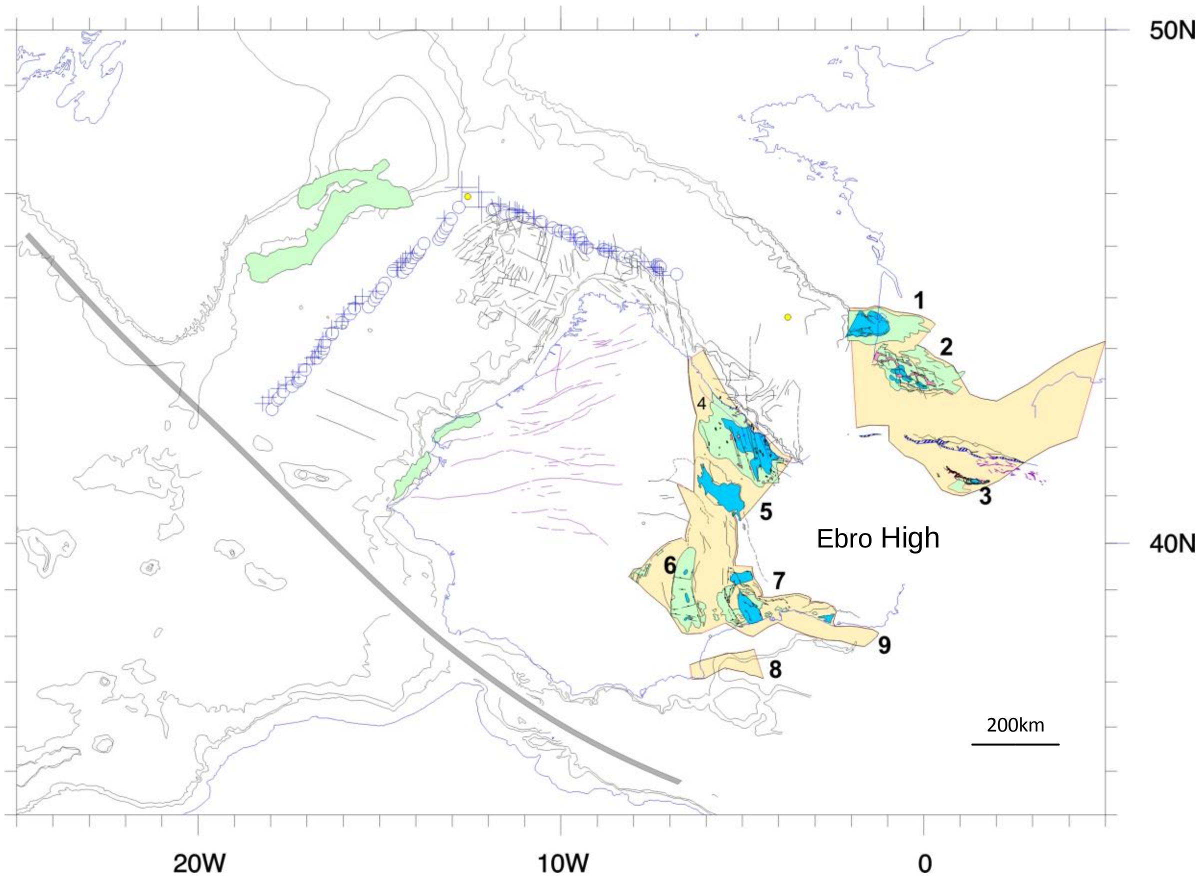


FIG.1 – Location of the Iberian intraplate rift basins at chron M0 (125 Ma). Plate reconstruction of the North Atlantic and Bay of Biscay from Sibuet *et al.* (2004). See text for further explanation.

## 3. Timing of rifting

Rifting commenced at different times across the area: latest Oxfordian in the Maestrat basin, early Kimmeridgian in the Organyà basin (Vergés and García-Senz, 2001), early Tithonian in the Cameros basin, late Tithonian in the Basque-Cantabrian basin, and Berriasian in the South Iberian basin (and possibly the Columbrets sub-basin). The syn-rift sedimentary fill of these depocentres is up to 8 km thick and bounded by two significant unconformities. The stratigraphic gap associated with the basal unconformity spans early Tithonian to Barremian times in the Cameros basin (Mas *et al.* 1993) and late Tithonian to late Valanginian in the Basque-Cantabrian basin, whereas in the Maestrat basin it is much smaller and affects only the upper part of the latest Oxfordian *Planula* biozone (Aurell 1991). The upper boundary of the syn-rift succession is formed by an intra-Albian regional unconformity which preceded the onset of the late Cretaceous post-rift thermal subsidence stage during which a large carbonate platform developed in northeastern Iberia.

## 4. Syn-rift structures and strain state during rifting

Faults bounding the basins, or developed within them, are normal faults, mostly trending E-W and NW-SE. They are decakilometric to kilometric in length scale. As a result of their activity, variations of the order of many hundred to some thousand of meters in the syn-rift sediment thickness are observed. Hectometrics to metric-scale length normal faults are also commonly found in the syn-rift rocks. These faults often display slikensides indicating a highly dominant normal dip-slip. From the previous, a polydirectional extensional regime is deduced.

## 5. Subsidence patterns

In order to further assess the Mesozoic evolution of the Iberian intraplate rift basins some previously published quantitative subsidence curves (Salas and Casas 1993; Ramos *et al*., 1996; Van Wees *et al*., 1998; Stampfli, 2000; Salas *et al.*, 2001) were reviewed and new ones calculated. All the subsidence curves show four phases of tectonic subsidence, each characterised by an initial interval of rapid subsidence followed by an interval of decelerating subsidence. This model of tectonic subsidence is usually diagnostic of rifting processes, which comprise an initial period of fault-controlled rapid syn-rift subsidence, followed by a post-rift interval of asymptotically decreasing subsidence, controlled by thermal relaxation of the lithosphere. Taking into account the four phases observed of tectonic subsidence and the structural and regional setting of the control points, the following rift-postrift phases can be distinguished: 1) late Permian-Triassic Rifting Cycle 1, 2) early and middle Jurassic Post-rift Stage 1, 3) late Jurassic-early Cretaceous Rifting Cycle 2, and 4) late Cretaceous Post-rift Stage 2.

The second cycle of accelerated subsidence corresponds to the latest Oxfordian-middle Albian time interval and thus to the Rifting Cycle 2. This rifting cycle was complex and apparently comprises three phases of subsidence, two of accelerated subsidence that were interrupted by a short phase of decelerated subsidence during the Neocomian (Salas et al. 2001). The latest Aptian-early Albian final part of this rifting phase was again characterised by decelerating subsidence rates.

## 6. Summary and discussion

The Iberian intraplate rift basins was a part of the network of rifted basins of the northwestern PeriTethyan platform that evolved during the break-up of Pangea, and gave rise to the opening of the Alpine Tethys and the North Atlantic. These basins developed in the late Permian-Triassic rifting cycle during which the Tethys and Arctic-North Atlantic rift systems propagated westwards and southwards, respectively (Ziegler, 1988). During the early and middle Jurassic, the evolution of the Iberian intraplate rift basins was governed by post-rift thermal subsidence. Late Triassic to Mid-Jurassic alkaline magmatism took place in the Iberian Chain.

Rifting resumed during the late Oxfordian and persisted till the early late Albian times. This rifting cycle can be subdivided into three discrete rifting pulses which controlled the development of the study basins. This second rifting cycle coincides with rifting activity in the North Atlantic domain, culminating in the mid-Aptian separation of Iberia from North America and Europe and the opening of the oceanic North Atlantic and Bay of Biscay basins. During the late Albian to the Maastrichtian times the Iberian Basin subsided in response to post-rift thermal re-equilibration of the lithosphere.

During the mid and late Cretaceous the study area underwent alkali basaltic volcanism, metamorphism, and thermal heating associated with high thermal gradients. Hg-Sb bearing deposits were also formed during this time. The volcanic system occurs as a WNW–ESE belt of alkali basaltic character along the northern Iberia offshore, the Basque-Cantabrian Range and the Pyrenees. It displays strong lateral variations in thickness and facies and is complexly interfingered with deep-sea sediments. These volcanic rocks occurred in an extensional geodynamic context (Albian-Santonian) generated by the drifting of the Iberian plate with respect to the European plate.

The evolution of the Iberian intraplate rift basins was coeval with the development of the North Atlantic margin basins (Tankard and Balkwill, 1989), the Aquitaine Basin (Brunet, 1984; Le Vot et al., 1996), and the Mesozoic part of the Ebro Basin (Desegaulx and Moretti, 1988).

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# Modeling of Cretaceous uplift and erosion events in the Lusitanian Basin (Portugal)

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*ABSTRACT*

*The Lusitanian Basin is located in the Western Iberian Margin, corresponding to a passive margin of the North-Atlantic opening - a NNE-SSW elongated depression, with around 300 km x 150 km, where the sediment column reaches, at its deepest, approximately 5km. The evolution of the basin is intimately related to the successive attempts of North Atlantic rifting, since the Upper Triassic break of Pangea until the Lower Cretaceous break-up and drift.*

*The modeling of Cretaceous uplift and erosion events in the Lusitanian Basin has been approached in order to constrain the break-up related geodynamics of the basin. The method consisted mainly in identifying and characterizing Lower Cretaceous unconformities on geological maps, and to estimate the thicknesses of the missing sequences. Erosion/uplift maps show paleogeographical heterogeneities, related to the mains structural trends of the basin.*

*KEYWORDS: Lusitanian Basin, North Atlantic, Cretaceous break-up, uplift, erosion.*

## 1. Introduction

The Lusitanian Basin (Fig.1) is a Mesozoic basin surrounded by Paleozoic basement and its limits are the Porto-Tomar fault to the E, the granitic and metamorphic Berlengas horst to the W, the Porto Basin to the NW and the Arrábida Fault to the S. The reactivation of pre-existing Variscan fractures, in the basement and propagating into the sedimentary cover, has strongly conditioned its Mesozoic (mostly distensive) and Cenozoic (mostly compressive) evolution (Rey *et al*,2006). Besides the Mesozoic sedimentary infill, with variable subsidence and sedimentation rates, basin-scale uplift and erosion events took also place, with differential rates in different areas of the basin. The main erosive events occurred during the Cretaceous, related with the successive break-up events at the Western Iberian Margin and regional tectonic inversion induced by the Atlantic ocean-floor spreading (Azerêdo *et al*,2003).


FIG.1 – Geographical location of the Lusitanian basin (source: Google Earth 5.0).

## 2. Approach and Methodology

The present study aimed to identify and characterize those Cretaceous events, based on the analysis of 28 published 1:50.000 geological maps of the basin, implying a re-analysis of the lithostratigraphic charts (Reis *et al*,2010) of old and recent maps. On each map, unconformities between Cretaceous units and older Cretaceous or Jurassic units have been identified and multiple points have been marked (Fig. 2a and 2b). Lithostratigraphic charts and interpretative cross-sections were also used in the identification of the units and unconformities. The thicknesses of the missing sequences have been estimated, based on time-interval isopach maps of the basin's infill, previously compiled from well and outcrop data. The geographical coordinates of those 1101 points were plotted in ArcGIS, with different colours/symbols for the age of the unconformity, the age of the underlying unit and the estimated erosion/uplift. This plotting has been overlaid to a map with the main regional faults, aiming to relate it with the main structural trends of the basin. The resulting 2D and 3D interpolations (Fig. 3a and 3b respectively) recreated in a simple way the structure of the basin.

## 3. Results and Conclusions

Three major Cretaceous unconformities have been identified: DC1 of Berriasian age, DC2 of Barremian age, and DC3 of Aptian age. According to the compiled data and resulting maps, the following conclusions may be drawn: i) uplift and erosion thicknesses are in the order of a few hundred meters in the southern sector of the basin, whereas in the northern sectors they attain more than 1500m; ii) unconformity DC3 (Aptian), is by far the most relevant unconformity in the basin; iii) uplifting processes tended to migrate in time and to increase in amplitude northwards (Fig. 5a and 5b); iv) the age and intensity of unconformities is clearly related to the successive episodes of the North Atlantic break-up, migrating northwards along the Western Iberian Margin: DC1 related to the Iberian Segment, scarcely present in the southern sector; DC2 related to the Tejo Segment and present in the central sector; and DC3 related to the Galiza segment and mostly present with the higher values in the northern sector; v) basin dynamic was mostly in a horst/graben system, with some of the blocks tilted (Fig. 4); vi) data distribution is structurally controlled by faults and, in DC3, also by evaporitic intrusive bodies (Fig. 2); vii) halocinetic phenomena began during the Upper Jurassic and lasted untill the Lower Cretaceous.

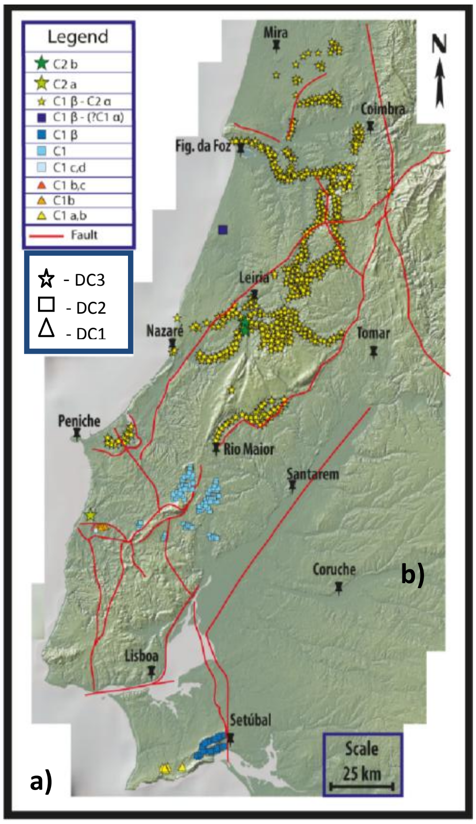



FIG.2 a) - Cretaceous outcrops with K-J discontinuities identified on cartography.
DC1 – Berriasian / Valanginian (140 Ma);
DC2 – Lower/Upper Barremian (127 Ma):
DC3 – Upper Aptian / Lower Albian (110 Ma).

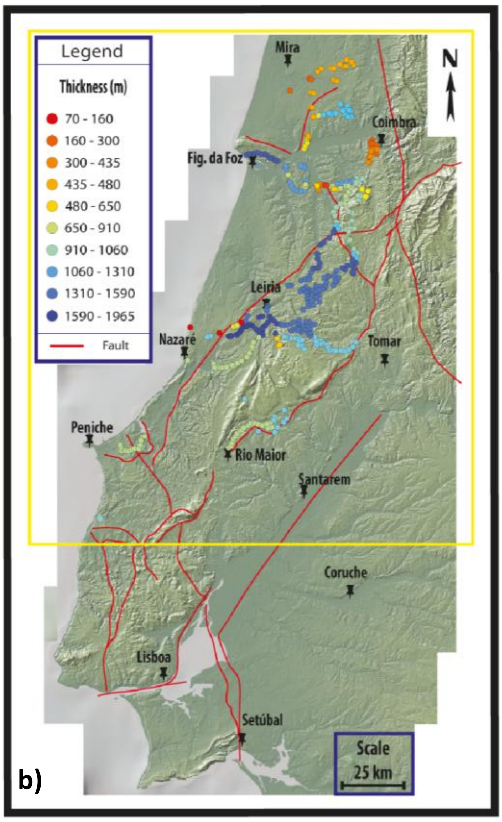



FIG.2 b) – Eroded thicknesses related with DC3 unconformity (Aptian) which was proven to be exclusively limited to the northern sector of the basin (N of the Torres Vedras-Montejunto Fault).

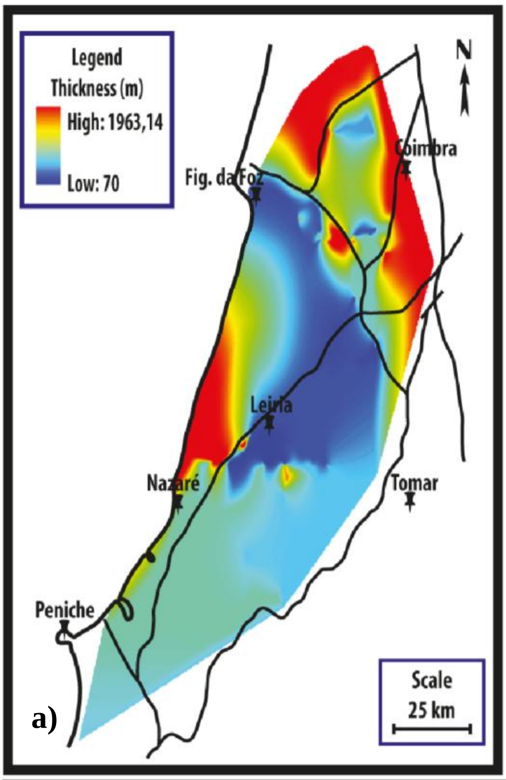
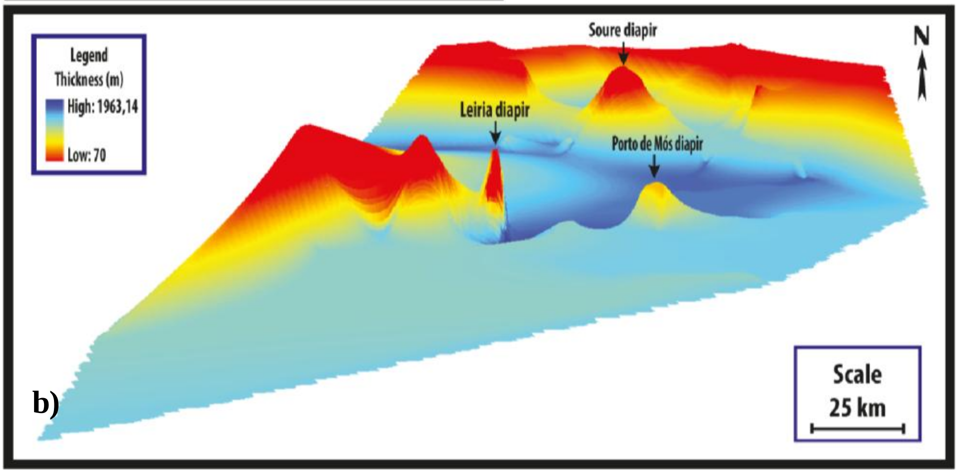



FIG.3 a) - Spatial Interpolation using the "nearest neighbor method" to obtain erosion thicknesses for the DC3 unconformity, revealing heterogeneities related with the tectonics.

FIG.3 b) - 3D view of Figure 3a, highlighting the ascension of diapiric bodies. Halocinetic phenomena began during the Upper Jurassic and lasted untill the Lower Cretaceous, since the significative (> 1000 m) eroded thicknesses observed in the nearby areas require long-lived erosion



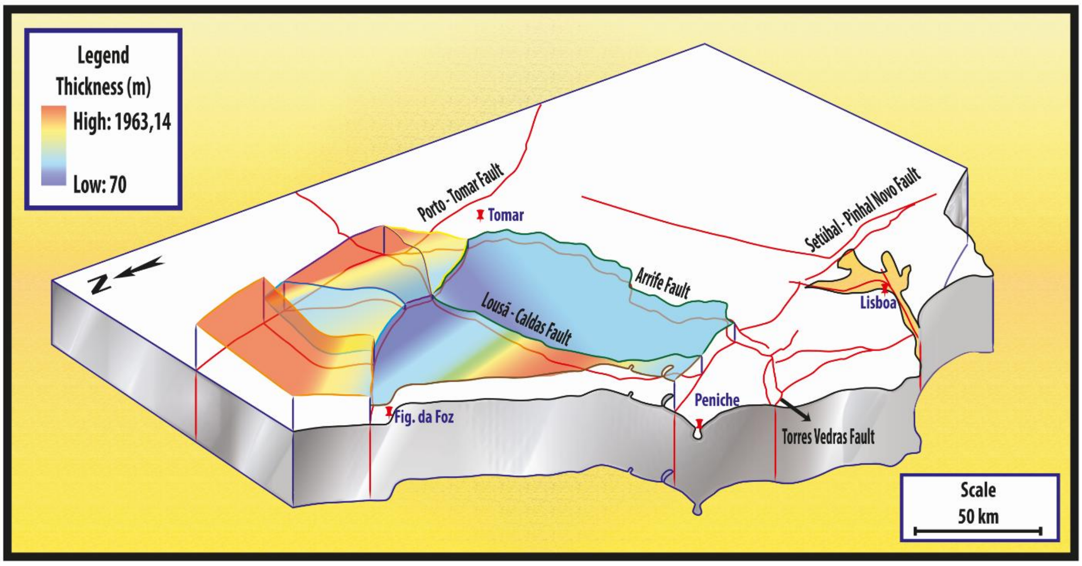
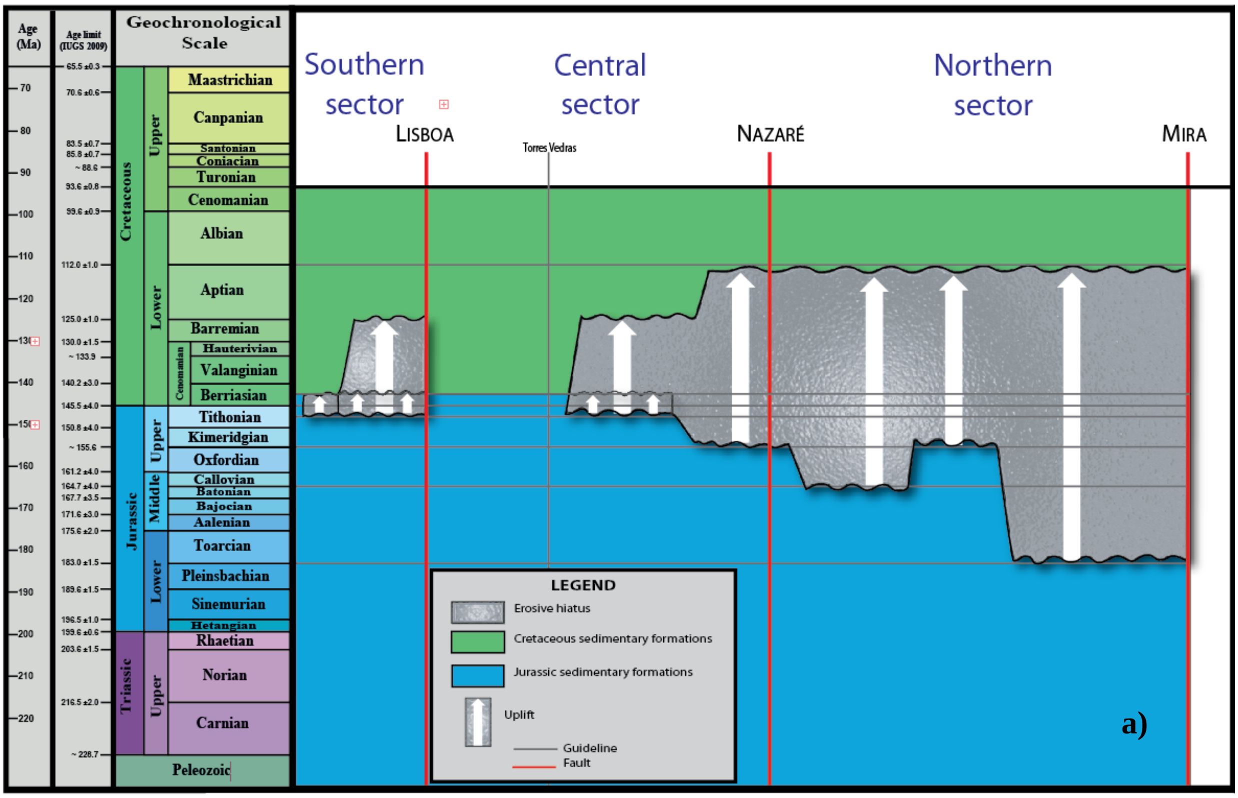



FIG.4 - 3D schematic representation of the tilted blocks reconstructed from the erosion values of DC3 unconformity. This scheme reflects the geodynamics associated to the opening of the North Atlantic during the Lower Cretaceous.



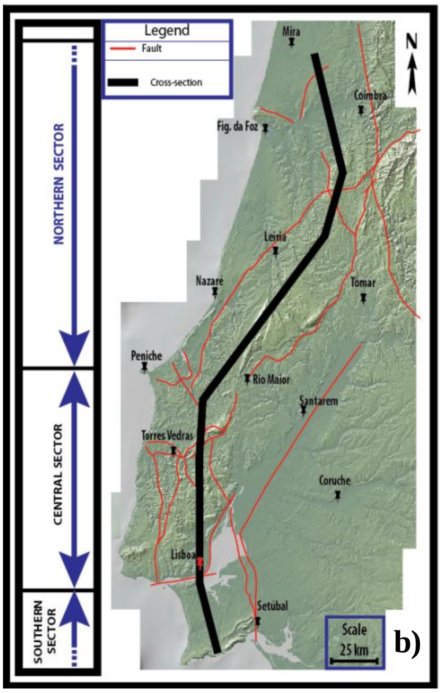




FIG.5 a) – Simplified schematic demonstrating the erosive dynamic of the Lusitanian Basin during the Lower Jurassic/Lower Cretaceous interval. The northern sector was more intensively affected by uplifting processes, whereas the central sector presents higher erosion values than the southern sector. Between Lisboa and Torres Vedras no unconformities were identified. In short, there is a northwards increase in the uplift throughout the basin.

FIG.5 b) - Location of the cross-section showed in Figure 4a.

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# Contribution to the knowledge of petroleum generative potential of Late Sinemurian – Pliensbachian of the Lusitanian Basin - northern sector (Portugal)

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*ABSTRACT*

*The Late Sinemurian – Pliensbachian interval of the Lusitanian Basin is characterized by marly limestone deposits sometimes with organic-rich layers. The study of these levels in outcrops located in the northern part of the Lusitanian Basin using some geochemical parameters such as total organic carbon (TOC) and Rock-Eval pyrolysis, allowed the definition of its petroleum generative potential with high stratigraphic accuracy.*

*There are two stratigraphic intervals particularly rich in organic matter, which are positioned in the Polvoeira Member of Água de Madeiros Formation and in the Marly limestones with organic-rich facies member of the Vale das Fontes Formation. These intervals are characterized by a high frequency of TOC values greater than 1% and/or several high values that can reach about 10%. The Rock-Eval pyrolysis parameter S2 is frequently above 10 mg HC/g rock, with highest value of 43.81 mg HC/g. The values of HI obtained for these intervals, very often larger than 150 mg HC/g TOC, show potential for generation of oil and gas-oil.*

*KEYWORDS: Rock-Eval pyrolysis, petroleum generative potential, Lower Jurassic, Portugal.*

## 1. Introduction

The occurrence of organic-rich marls in the Lower Jurassic of the Lusitanian Basin (Portugal) has always been considered a potential oil generative rock, as confirmed by GPEP´s most inclusive study of organic geochemistry (GPEP, 1996), which utilized a great number of samples of exploration wells and some samples of the outcrops of the Lusitanian and Porto basins. On the other hand, the organic geochemical and petrological study conducted by Dias (2005) in samples collected only in wells of the onshore basin discard this interval after finding only small levels of total organic carbon (TOC) within the interval. However, in the last years, based on a detailed stratigraphic framework (Duarte & Soares, 2002), some works/papers have been published focusing on the organic geochemical analysis of the late Sinemurian – lower Toarcian of the Lusitanian Basin (e.g. Duarte *et al*., 2010; Oliveira *et al*., 2006; Silva *et al*., 2006, 2007).

Through TOC and Rock-Eval pyrolysis analysis, this work presents a geochemical characterization of organic-rich sediments of the Água de Madeiros and

Vales das Fontes formations (late Sinemurian – Pliensbachian; Duarte & Soares, 2002) that crop out in the northern sector of the Lusitanian Basin (FIG. 1).

This work complements the evaluation of the petroleum generative potential by Oliveira *et al*. (2006) in the Peniche sector, with widening of the study to include the Água de Madeiros Formation, and adds a perspective of lateral variability with respect to the Vale das Fontes Formation.

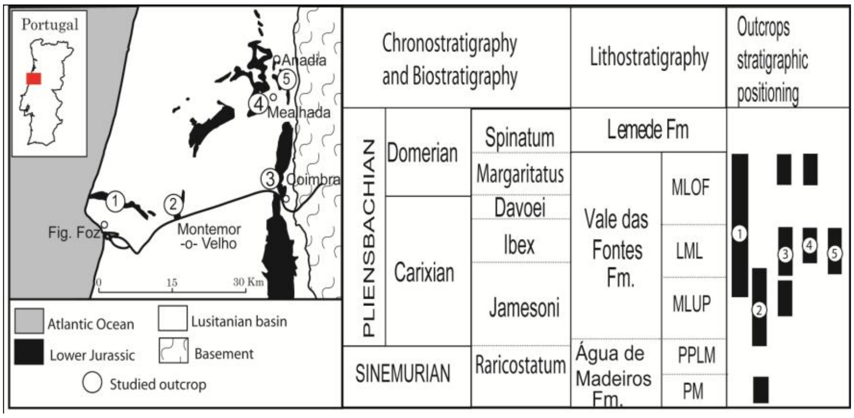


FIG. 1 – Geological map of Lower Jurassic in Lusitanian Basin and stratigraphic chart with positioning of studied Sinemurian – Pliensbachian outcrops: 1) Figueira da Foz; 2) Montemor-o-Velho; 3) Coimbra; 4) Mealhada; 5) Anadia.

## 2. Material and methods

The sampling was performed almost exclusively with dark gray and/or laminated marls, occasionally several samples per layer, where interesting vertical variations of facies occur. A total of 136 samples were collected for organic geochemical analysis of TOC and Rock-Eval pyrolysis.

Every rock sample was first submitted to acidification with HCl to remove carbonate content and determine the insoluble residue (IR), then pyrolysed with Leco-SC444 equipment. The $CO_2$ resulting from the organic matter combustion in oxidant atmosphere was measured and results calculated in initial weight percentage (wt. %).

The samples with TOC content greater than 1% were submitted to Rock-Eval pyrolysis, following the procedures of Espitalié *et al*. (1977). Four parameters were obtained: S1, S2, S3 and Tmax. The S1 and S2 parameters refer to the registered peaks of hydrocarbon release during heating up to 550ºC, expressed in milligrams (mg) of hydrocarbons (HC) per gram (g) of rock. The S3 parameter, expressed in mg $CO_2$/g rock, is the quantity of $CO_2$ generated during the temperature increase of up to 390ºC. The Tmax parameter refers to the temperature that occurs at the maximum rate of S2 hydrocarbon generation. From these, new parameters derived include the Hydrogen Index (IH = S2/TOC x 100; in mg HC/g TOC) and Oxygen Index (OI= S3/TOC x 100; in mg $CO_2$ /g TOC), both used to classify the type of organic matter in terms of hydrocarbon generative potential (see Espitalié *et al*., 1977, 1985a,b, 1986; Peters, 1986).

## 3. Results and discussion

In the group of outcrops studied, 136 samples were collected for TOC analysis, 47 of which analyzed by Rock-Eval pyrolysis. TOC content above 1% are present in each studied member (see Silva *et al*., 2006, 2007; Duarte *et al*. 2010), although the richest section of Marls and limestones with *Uptonia* and *Pentacrinus* (MLUP) with a maximum content of 3.79% are not shown in FIG. 2.

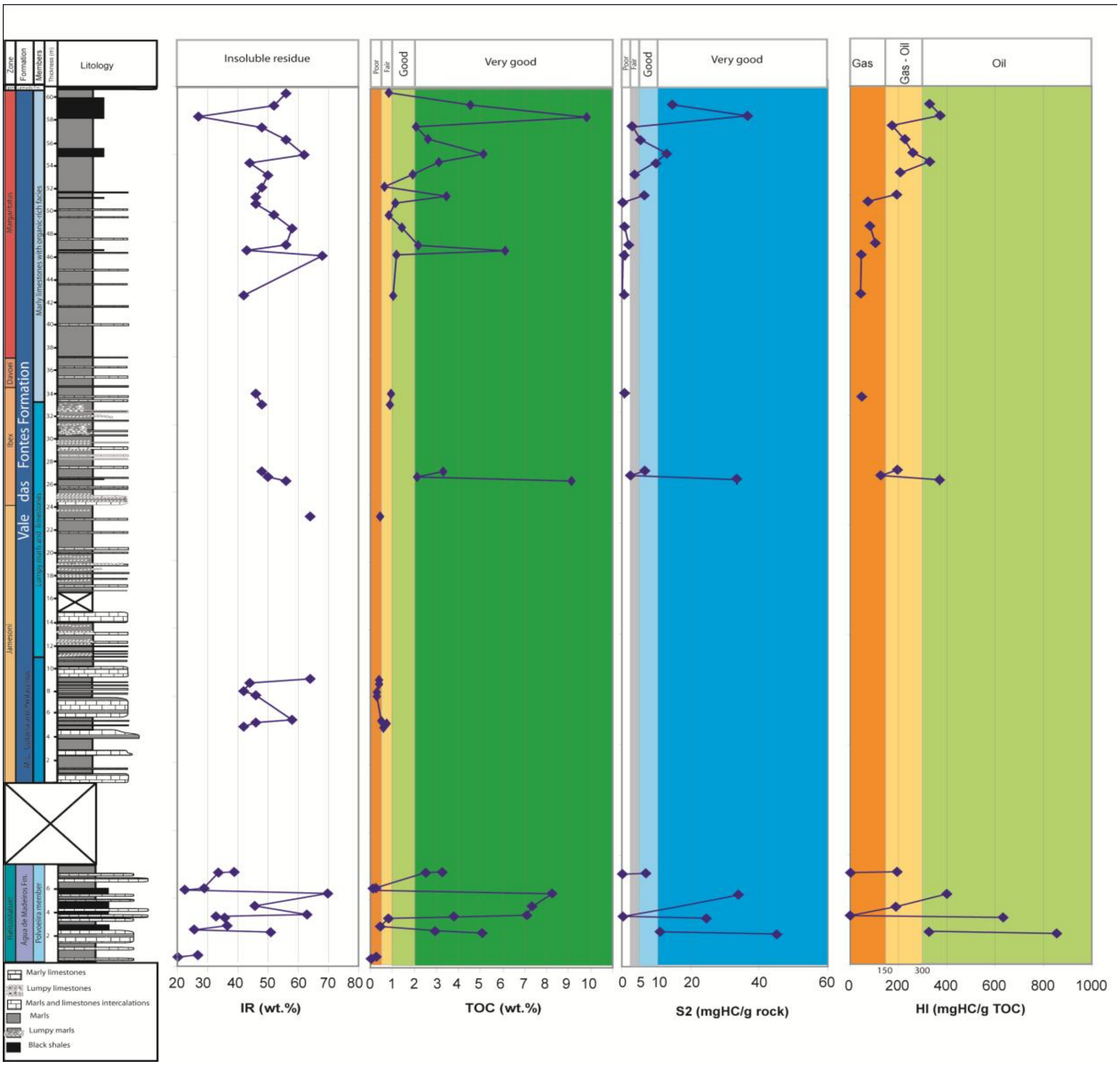


FIG. 2 – Vertical distribution of IR, TOC, S2 and HI content of Vale das Fontes Formation in Figueira da Foz and Água de Madeiros in Montemor-o-Velho.

The Rock-Eval pyrolysis reveals that the studied 8 m of Polvoeira member (PM) contains very high values of the S2 parameter, with 43.81 mg HC/g rock and HI of 843.96 mg HC/g TOC (FIG. 2), demonstrating type I and type II organic matter. On the other hand, there are layers rich in TOC but low S2. The study of this interval in S. Pedro de Moel in a more distal sector of the basin shows a larger and richer thickness of organic-rich levels (Duarte *et al*., 2010).

The lack of Rock-Eval pyrolysis results does not reveal the real potential of MLUP. The most marly and organic-rich part of the member with TOC maximum of 3.79 wt% was sampled in the Montemor-o-Velho (Duarte *et al*., 2010) but was not analysed. The section shown here was obtained in more calcareous portion located stratigraphically above (FIG. 2).

Few but very rich organic layers in the Lumpy marls and limestones member (LML) were found. The highest values of S2 parameter were 32.91 mg HC/g rock in

Figueira da Foz (FIG. 2) and 24.36 in Coimbra, with HI values of 360.86 mg HC/g TOC and 376.74, respectively. These values are indicative of type II organic matter.

In the Marly limestones with organic-rich facies member (MLOF), 26 samples were studied using Rock-Eval pyrolysis, with medium value of the S2 parameter reaching 7.14 mg HC/g rock in Figueira da Foz, 3.83 mg HC/g rock in Coimbra and 4.31 mg HC/g rock in Mealhada, and a maximum HI of 549.72 mg HC/g TOC. The data presented are correlated with those of Oliveira *et al*. (2006) obtained in Peniche, but with lower values in every parameter.

## 4. Conclusions

The data presented reveal that within the late Sinemurian - Pliensbachian of the Lusitanian Basin there exist at least two intervals with high hydrocarbon generation potential which correspond roughly to the Polvoeira and MLOF members. The PM contains organic-rich levels of Type I and Type II, and are therefore the most oil prone (see Espitalié *et al*., 1977; Peters, 1986). In the MLOF, the organic-rich levels of type II and type III are very frequent along the member (up to 28 m) throughout the basin, making it an interval of reference with potential to generate oil and gas. The remaining members of the Vale das Fontes Formation also present layers of high TOC content, which does not exclude the possibility a bigger importance in others parts of the Lusitanian Basin.

*Acknowledgements*
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# Contrasts between the two main Jurassic source rocks in the western margin of the Lusitanian Basin (Portugal)

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*ABSTRACT*

*The objective of this work is to show the main differences regarding the organic content between the two main Jurassic source rocks in the western margin of the Lusitanian Basin: the Marly limestones with organic-rich facies member of the Vale das Fontes Formation (Pliensbachian) and the Cabaços Formation (early?/middle Oxfordian). This study was carried out on more than 100 samples collected for palynofaciological observation and organic geochemistry analysis.*

*The data show that the organic matter of the Marly limestones with organic-rich facies member is composed of a variable mixture of marine and continental components, preserved in a marine depositional environment. In the Cabaços Formation, the organic-rich facies are mainly restricted to its base and have a predominantly continental character, punctuated by minor marine incursions.*

*KEYWORDS: Source rock; Vale das Fontes Formation; Cabaços Formation; Jurassic; Lusitanian Basin*

## 1. Introduction

In the Jurassic sedimentary record of the Lusitanian Basin (LB), several organic-rich intervals are recognized and two of them correspond to the main source rocks relevant for hydrocarbon exploration in this basin. The first interval is represented by the Marly limestones with organic-rich facies member (MLOF mb) of the Vale das Fontes Formation (Pliensbachian), and the second one by the Cabaços Formation (early?/middle Oxfordian). These two units are related to distinct sedimentary environments and, therefore, have a different organic content.

The aim of this work is to characterize the organic content and associated parameters of these intervals in the western margin of the LB, based on palynofacies observation and organic geochemistry analysis of more than 100 samples from on-shore outcrops, contextualizing these occurrences in the LB Mesozoic evolution.

## 2. Geological setting of the two studied intervals

The LB is a small North-South elongated basin located on the western side of the Iberian Massif (FIG.1). The basin is one of several Atlantic margin rift-basins whose origin is linked to the opening of the Atlantic Ocean (e.g. Wilson et al., 1989) and presents several similarities with other neighbouring basins (Azerêdo et al., 2002; Duarte et al., 2010 and references therein). Four rift-phases are usually distinguished in the Mesozoic evolution of the BL, corresponding to the Triassic–earliest Jurassic, Early Jurassic–Middle Jurassic, Late Jurassic (Oxfordian) and Late Jurassic or earliest Early Cretaceous (Rasmussen et al., 1998). The Silves and Dagorda units from the first rift-phase are overlain by the Coimbra, Brenha and Candeeiros units, representing the development of a carbonate ramp depositional system (second rift-phase) (FIG.1). The MLOF mb of the Vale das Fontes Formation is included in the informal Brenha Group and it is age constrained to the top Ibex−Margaritatus zones (Pliensbachian). Usually, it is represented by organic matter rich marl-limestone hemipelagic deposits with abundant benthic and nektonic macrofauna (Duarte & Soares, 2002; Duarte et al., 2010). During this time interval, deposition took place on a north-westerly dipping low-energy carbonate ramp, where the eastern sections record the most proximal marine environments (e.g. Duarte, 2007; Silva et al., 2010a).

The Middle-Upper Jurassic transition corresponds to a major disconformable basinwide hiatus, spanning from the late Callovian to the early Oxfordian in the west; to the east, the disconformity locally develops on upper Bathonian limestones. This disconformity is preceded by a complex forced regression, resulting in sharp variations across the ramp environments (Azerêdo et al., 2002). In the west, the late Callovian mid-outer ramp deposits evolve to proximal facies with minor erosion features while, to the east, the inner ramp upper Bathonian carbonates are capped by a major palaeokarstic surface. The lowermost Oxfordian sediments (Cabaços Formation) from the third rift-phase correspond to freshwater lacustrine, brackish lagoonal and shallow-marine deposits (Azerêdo et al., 2002) (FIG.1). The studied Pedrógão section encompasses upper Callovian marine facies unevenly overlain by the Cabaços Formation fresh to brackish water facies with subaerial exposure, grading upwards into marginal- to restricted- marine facies (Azerêdo et al., 2002; Barrón & Azerêdo, 2003; Azerêdo & Cabral, 2004).

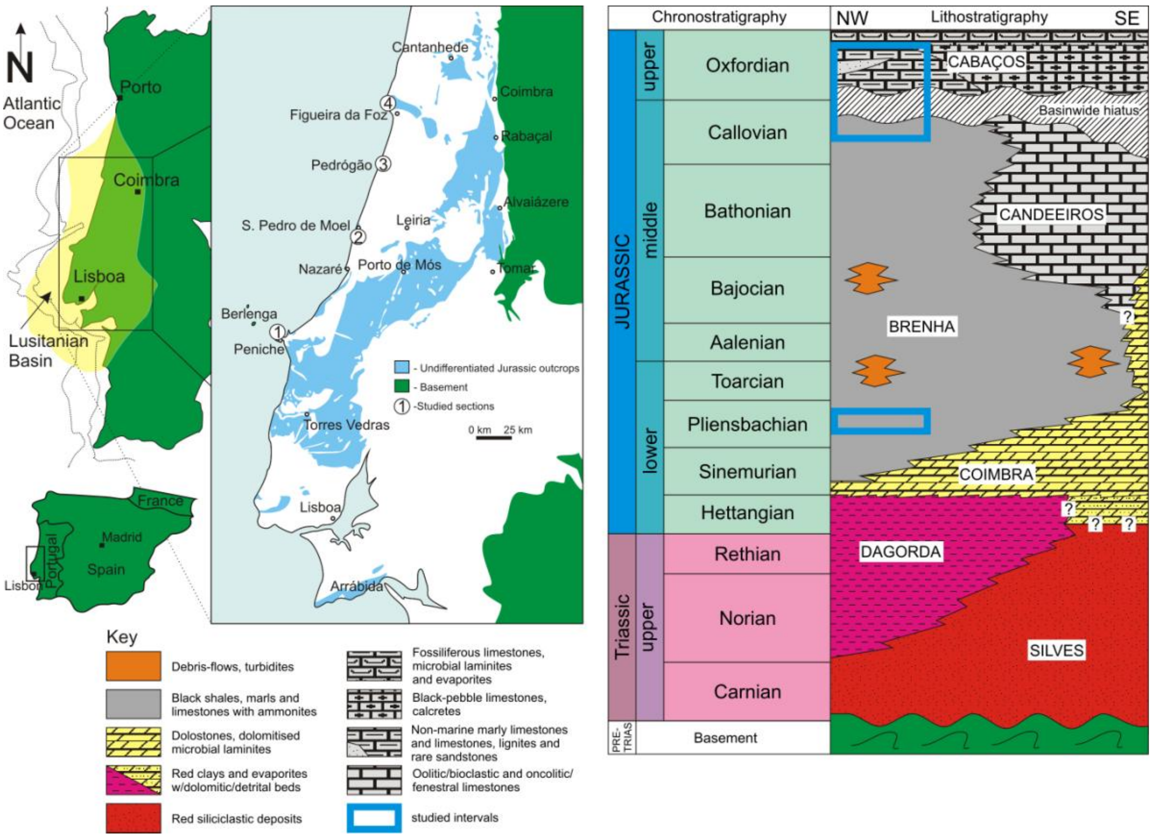


FIG.1 – Simplified geological map and main informal lithostratigraphic units of the LB, from the Triassic to lowermost Upper Jurassic, modified from Azêredo et al. (2002) and references therein. Studied sections: 1-Peniche, 2-S. Pedro de Moel, 3-Pedrógão, 4-Cabo Mondego.

## 3. Materials and methods

This study used more than 100 outcrop samples of marls to marly limestones, collected for analysis of Total Organic Carbon (TOC), palynofacies and biomarkers in the saturated fraction, after extraction with dichloromethane, and liquid chromatography at LAFO (Laboratório de Palinofácies & Fácies Orgânica, Federal University of Rio de Janeiro).

## 4. Organic content and associated parameters of the studied lithostratigraphic units.

The MLOF mb is characterized by the occurrence of several organic-rich facies, which are particularly well developed in the western, distal hemipelagic sectors (Duarte et al., 2010). Commonly, these facies correspond to grey and dark marls, locally showing strong lamination (black-shale type), with a proven high potential for hydrocarbon exploration (Oliveira et al., 2006). Usually, the highest TOC values, around 15–20%, are recorded in the distal areas (western, namely at Peniche and S. Pedro de Moel), decreasing gradually to the inner locations of the basin. However, one black-shale level, located at the Ibex–Davoei transition, systematically has higher TOC values (reaching up to 26.3%), even in the proximal hemipelagic sectors. Palynofaciological observations (FIG.2a,b) and source-related biomarkers from the Peniche and São Pedro de Moel sections (Silva et al., 2010b,c) show that the organic content of this unit consists of a variable mixture of marine and continental components, preserved in a marine depositional environment with variable redox conditions.

The organic-rich facies at Pedrógão are mainly restricted to the base of the Cabaços Formation and consist of grey to black marls, sometimes with a net lamination. The highest TOC values, reaching up to 4.7%, are recorded at two marl/clay intervals, associated with diverse evidence of fresh to brackish water facies with subaerial exposure (see e.g. Azerêdo & Cabral, 2004). This maximum TOC value contrasts with the much higher maximum values at Cabo Mondego (30.6%). The palynofaciological studies undertaken at Pedrógão show that the organic content of the Cabaços Formation is dominated by a continental signature (mainly phytoclasts, pollens and spores), punctuated by minor events of marine influence (e.g. occurrence of rare prasinophyta algae and dinoflagellate cysts). Some of the analyzed levels have an important contribution of freshwater algal palynomorphs, namely *Botryococcus* sp. (see also Barron & Azerêdo, 2003; FIG.2c,d). The source-related biomarkers are consistent with the optical observations.

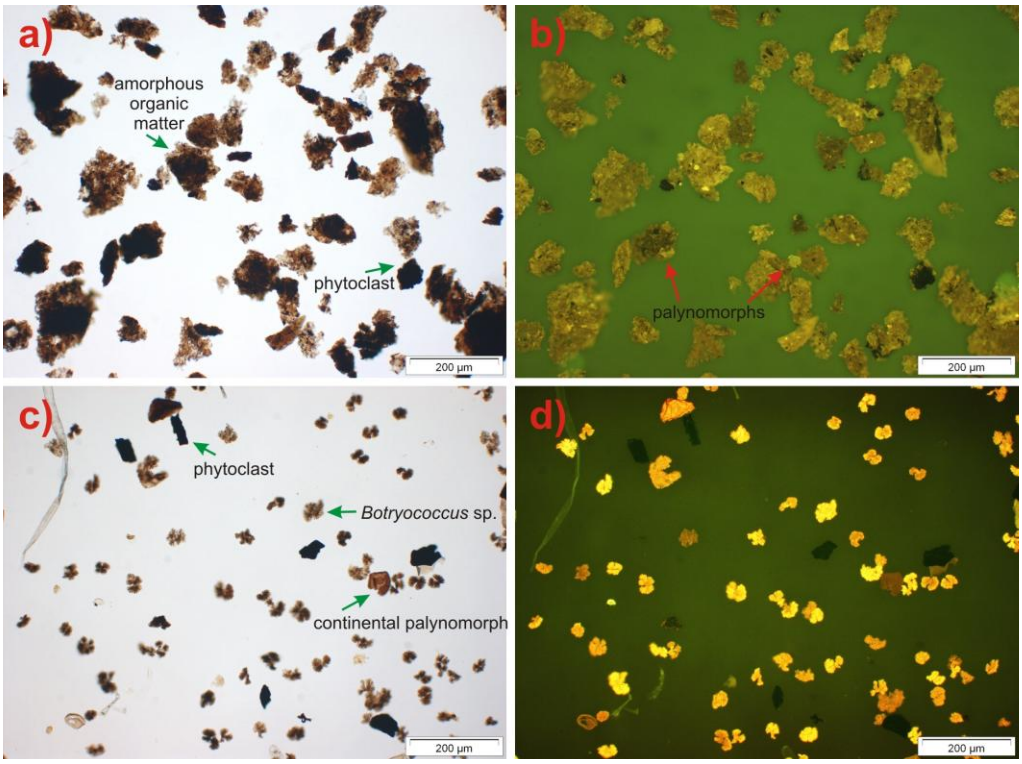


FIG.2 – Particular aspects of the kerogen assemblage of the MLOF mb of the Vale das Fontes Formation at Peniche [a) and b)] and of the Cabaços Formation at Pedrógão [c) and d)]. Photomicrographs a) and c) in transmitted white light, b) and d) in incident blue light fluorescence.

## 3. Concluding remarks

In the LB, the MLOF mb and the Cabaços Formation correspond to the main source rocks relevant for hydrocarbon exploration. Due to the distinct sedimentological setting of the two units, the organic content and related parameters show a strong differentiation between them.

The integration of our data with those previously published will enable refinement of the currently accepted stratigraphic frameworks and/or definition of new palaeoenvironmental models, through finer-tuning of the sedimentological, biological and hydro-atmospheric conditions correlative of sedimentation for the referred time intervals.

*Acknowledgements*
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# The Jurassic Reef Carbonate Reef Trend Offshore Nova Scotia

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*ABSTRACT*

*An Upper Jurassic carbonate bank extends for over 650 kilometers along Nova Scotia's offshore from the Sable Island area, southwest to the U.S. border. With only 21 exploration wells drilled into this bank since 1970, one commercial field was discovered along the reef margin. EnCana's Deep Panuke Offshore Gas Development Project will begin producing up to 892 Bcf of recoverable gas in 2011. With 630 kilometers of under explored bank edge remaining, more discoveries are anticipated. The carbonate bank can be divided into three geologically distinct sections. The Shelburne segment extends 120 km northeast from the U.S. border, has no wells and is poorly imaged on seismic. This transitions into the central Acadia segment that continues for 400 km and is characterized by erosion above the prominent bank edge. There is also faulting and collapse along this bank edge which is penetrated by seven wells. The Panuke segment defines the north eastern portion of the bank and has prominent bank edge morphology that extends 120 km before transitioning into a carbonate ramp geometry north of Sable Island. Here, the influx of Jurassic clastics from the Sable Delta system overwhelmed carbonate production. The Panuke section is penetrated by 14 exploration wells and includes Nova Scotia's only commercial carbonate reservoir to date. This 3500m subsea reservoir is contained along the reef margin and consists of high porosity, fractured, dolomtized and leached limestones along with vuggy, cavernous zones. This gas development occurs in shallow water depths of approximately 50 m.*

*KEYWORDS: Canada, Nova Scotia, Atlantic, Carbonates, Jurassic, oil & gas.*

## 1. Introduction

During Middle-Upper Jurassic time, North America, including the Gulf of Mexico, was rimmed by a carbonate-prone continental shelf. Offshore of Nova Scotia this bank margin extends 650 km beginning at the U.S. border and trending along the present day shelf edge before curving north near the Verrill Canyon (Figure 1). The carbonate shelf profile changes dramatically just north of Sable Island from steeply-dipping shelf in the southwest to a low-angle ramp in the northeast .

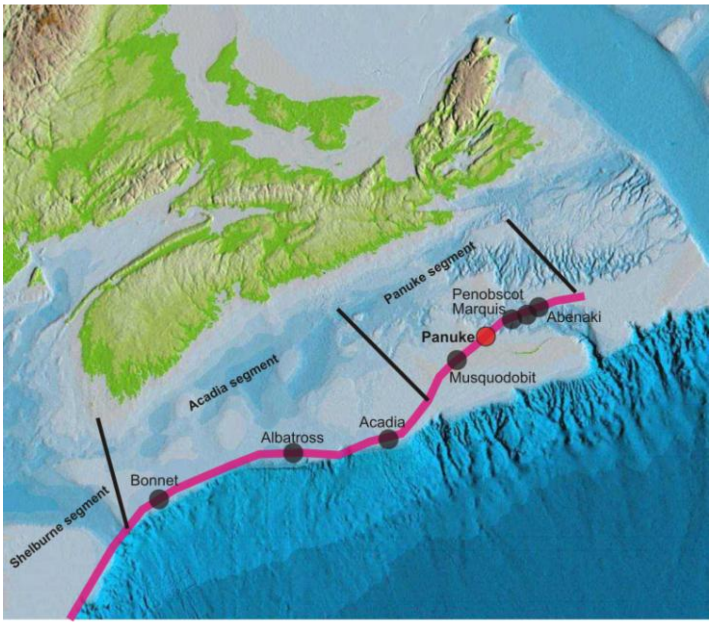


FIG. 1 –Carbonate bank location

## 2. The Upper Jurassic Abenaki Formation

The Abenaki Formation was described by Eliuk (1978) followed by a subsequent update (1981) and further studies ( Ellis, Crevello and Eliuk, 1985; Eliuk and Levesque, 1989; Eliuk, 1989; Wierzbicki, Harland and Eliuk, 2002). Using well and seismic datasets, Wiessenberger et al. (2000), and later Wierzbicki et al. (2002), defined the Abenaki within a sequence stratigraphic framework, particularly for the Bacarro Member within which over 1 TCF of in -place gas was discovered in 1999 at the Deep Panuke field. (PanCanadian Energy, 2002). The age of the Abenaki Formation extends from the Middle Jurassic (mid Bajocian) to the lowermost Early Cretaceous (basal Vallanginian) representing 40 million years of virtually continuous carbonate deposition. The Abenaki is divided into four members representing different stages of the Jurassic platform and margin facies' evolution (Figure 2) and in ascending order, are the Scatarie, Misaine, Baccaro and Artimon.

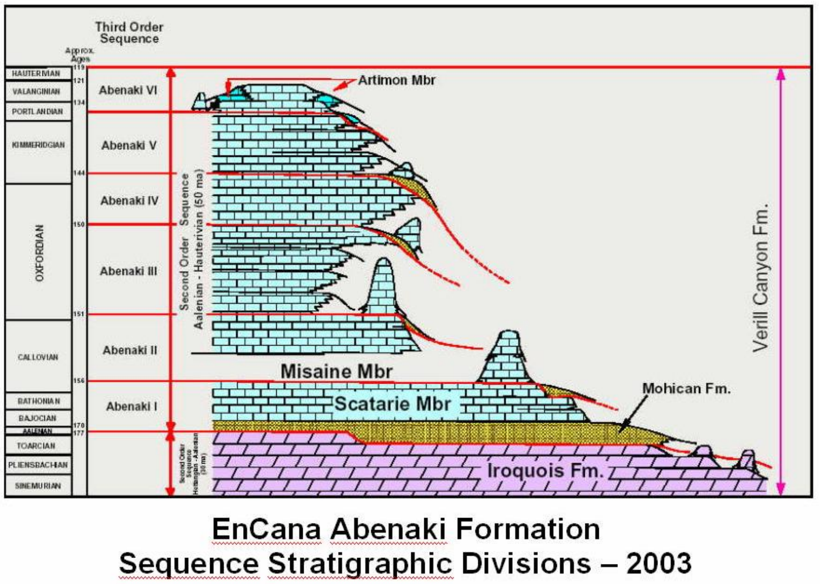


FIG.2 –Abenaki sequence

In the CNSOPB's Kidston et al. (2005) study, the platform area was subdivided into three segments consisting of the Panuke, Acadia and Shelburne segments as shown in figures 1 and 3. The Panuke segment is 120 km long, lies adjacent to the Sable subbasin and includes EnCana's Deep Panuke gas discovery made on the bank edge in 1999. Deep Panuke is a combined structural and stratigraphic trap that is scheduled to begin production in 2011. An Abenaki 5 3-D time surface for the Panuke segment is included in Figure 3. This approximates the top of the reservoir zone. Significant hydrocarbon accumulations to date have been limited to the Abenaki 4, 5 and 6. This segment has 14 of the 21 exploration wells, seven on the bank edge, six in the back-reef and one on the foreslope. The Cohasset/Panuke oil production (44MMB) was from Cretaceous sands draped over the bank edge.

The Acadia segment extends 400 km from the edge of the Sable area to the Northeast Channel adjacent to George's Bank. Unlike the Panuke area, this segment is faulted, eroded and intruded by salt but the presence of reefal facies and circulation losses while drilling indicates probable reservoir development. There are seven wells in this area, three on the bank edge and four in the back-reef with no discoveries, but encountered reservoir and mud-gas shows.

The Shelburne segment is about 120 km long and includes the George's Bank Moratorium area extending to the U.S. border. This area is the least understood because of dated 1970s and 1980s vintage seismic coverage and a lack of wells. Ten wells were drilled in the US basin southwest of the Yarmouth Arch in the early 1980's without success.

## 2. Exploration History

Exploration on the carbonate platform began when Shell drilled Oneida O-25 in 1970 looking for draped reservoir over a basement high. This was followed by two more platform wells (Abenaki J-56, Mohican I-100). Mobil drilled the first bank margin well in 1973 at Cohasset D-42 discovering light gravity oil in the overlying Early Cretaceous Mississauga sandstones. Three more bank edge wells were drilled at Shell Demascota G-32, Chevron Acadia K-62 and Mobil Cohasset L-97 plus a foreslope well at PEX Penobscot L-30 and a platform interior well at PEX Moheida P-15. In 1984-85, Petro-Canada completed the Bonnet P-23 and Albatross B-13 wells without success. Four platform interior wells were drilled during this period: Glooscap C-63 (Husky), Dover A-43 (Petro-Canada), Kegeshook G-67 (Shell) and Como P-21 (Petro-Canada), with no discoveries.

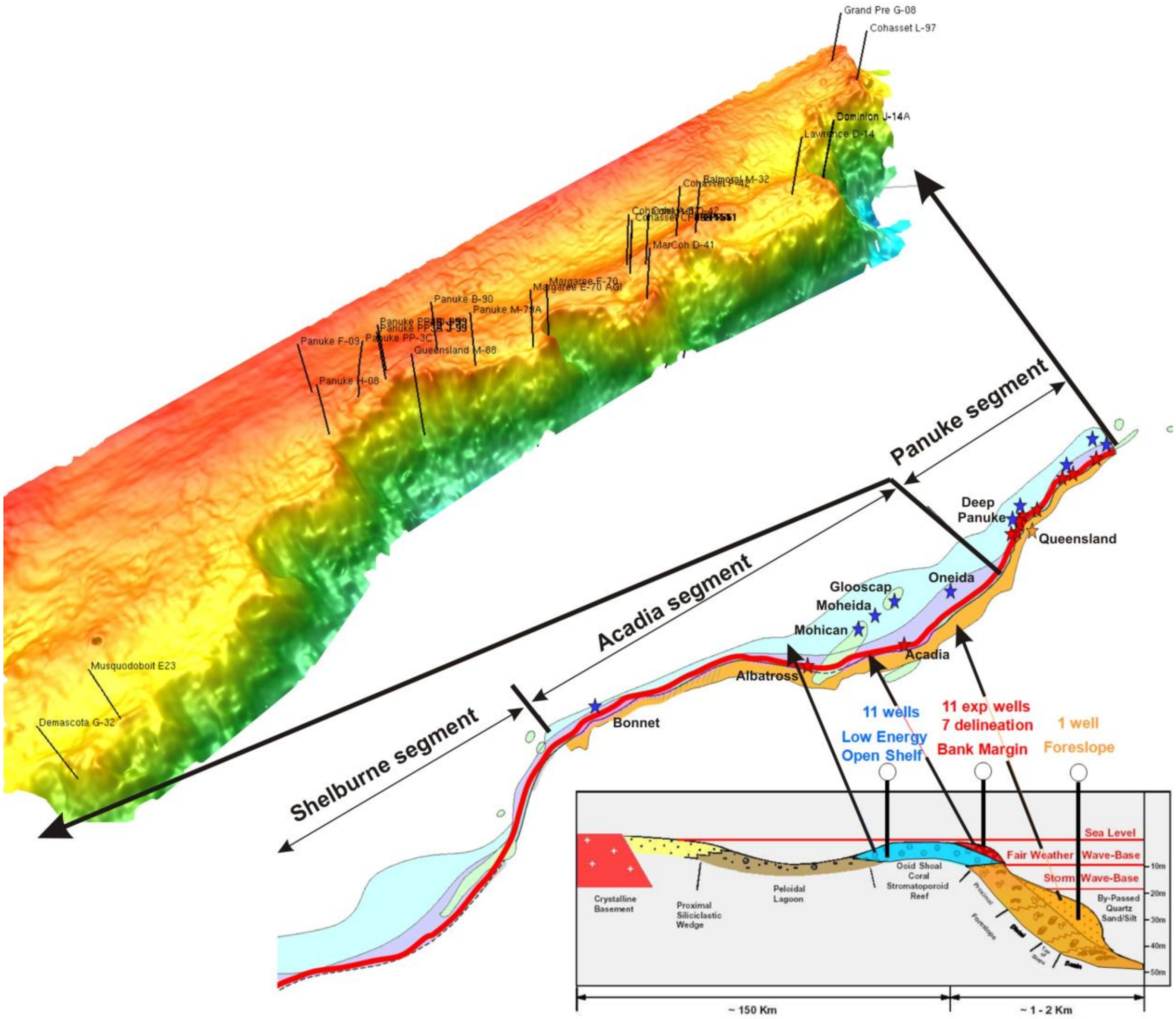


FIG.3 –Bank margin components with Panuke segment inset

In 1986 Shell drilled the Panuke B-90 well which only penetrated about 300 m of the Abenaki limestone. Although the Abenaki reservoirs were tight, light gravity oil was discovered in overlying Cretaceous, similar to that found in Cohasset D-42. These discoveries were eventually developed as part of the Cohasset/Panuke oil project that produced 44.4 million barrels of light gravity crude from 1992 to 1999.

The next exploration well drilled on the bank margin was in 1999 when PanCanadian drilled an Abenaki amplitude anomaly beneath the shallow Panuke oil field from the Panuke J-99 production platform. The Deep Panuke gas discovery well, PP-3C, encountered approximately 75 meters net pay of vuggy limestones and dolomites and tested between 50-55 MMcf/d gas from the Abenaki 5 interval. Seven delineation wells were subsequently drilled.

Since 1999, four more wildcats were drilled all in the vicinity of Deep Panuke targeting the Abenaki: two bank-edge wells - EnCana Musquodoboit E-23 and Canadian Superior Marquis L-35; one back-reef well EnCana F-09; and one fore-reef well, EnCana Queensland M-88. All were subsequently abandoned.

In summary, twenty-eight wells were drilled on the carbonate margin from Sable Island to the U.S. border. Of these, 10 were bank-edge wildcats, seven were field delineation wells (Deep Panuke) and 11 were off-reef wells. Of the seven exploration wells in the Acadia segment, three experienced lost circulation indicating well developed porosity and permeability. Of the eight bank margin wells in the Panuke segment, five had porosity. With one commercial gas development already established and good indications of reservoir potential along the margin, the carbonate bank is a play that encourages further exploration.

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# Syn- to Post-Rift Transitions on passive margins: The case of the western Iberian margin (NE Atlantic)

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*ABSTRACT*

*A comprehensive set of 2D seismic reflection lines, borehole data from Industry wells, stratigraphic information from key outcrops, and published DSDP/ODP data, was used in the analysis of syn-to post-rift transitions offshore West Iberia, Northeast Atlantic. Continental break-up in Southwest Iberia resulted in the sudden influx of siliciclastic material in onshore and shallow-offshore basins, interpreted to represent a forced regression (FRST) which was accompanied by: a) westward tilting of the proximal margin, which sourced westward-prograding units; b) complete abandonment of syn-rift depocentres, which were blanketed by post-rift successions. However, differences between the southern and northern sectors of West Iberia are observed, most likely reflecting changes in the geological processes that led to continental break-up. Thus, regions where continental break-up occurred relatively close to the rift-shoulder areas show widespread regional hiatuses and an abrupt shallowing of sedimentary facies across the break-up unconformity. Also, areas where break-up occurred closer to the rift-shoulder should contain the larger thickness of syn- and post-rift reservoirs, a character reflecting shorter distances between sediment source areas and adjacent depocentres on the continental margin. In contrast, deep-offshore regions will have diachronous break-up unconformities and will materialise different sedimentary responses that will depend on relative accommodation space, sediment influx and sediment capture by topographic features inherited from the syn-rift stages.*

*KEYWORDS: multiphased extension, rift migration, SW Iberia, North Atlantic.*

## 1. Introduction

As with syn-rift successions, the geometry of post-rift passive margins can vary across distinct crustal segments separated by transfer faults (see Tucholke et al, 2007). In this work, we chiefly use wireline, stratigraphic and seismic data to document the tectono-stratigraphic changes occurring when of continental break-up in strata below and above a regional 'break-up' unconformity. In this presentation are shown regional (2D) seismic-reflection profiles, outcrop and borehole data that indicate main depositional changes occurring when of (Aptian-Early Albian) continental break-up between northwest Iberia and Newfoundland. Statistical analyses are undertaken for key stratigraphic intervals identified on borehole data, not only in the west Iberian-Newfoundland conjugate pair of margins, but in other passive margins around the world. Direct comparisons with the deep-offshore Peniche Basin reveal that the significance of this break-up unconformity can vary across a continental margin, with break-up unconformities forming diachronous stratigraphic surfaces.

## 2. The stratigraphic significance of the 'break-up' unconformity on the proximal margin

One of the main aspects revealed on seismic data from multiple passive margins is the the presence of a widespread, ubiquitous seismic reflection marking the approximate end of syn-rift subsidence (e.g. Falvey, 1974). In West Iberia, a composite 'break-up unconformity' is observed in deep-offshore basins. Significantly, a period of widespread erosion is recorded at this time on the continental shelf and slope of southwest Iberia. In Northwest Iberia, a similar episode of progradation occurred in the Porto Basin during (Aptian) continental breakup. However, the inferred forced regression associated with the break-up unconformity is marked by prograding reflections of Albian age denoting shallow-marine environments, not continental deposits. Despite these differences, wireline data indicates that a sudden influx of siliciclastic material – over dark mudstones with source potential – marks the 'break-up unconformity'. This trend is maintained until a maximum flooding event of Cenomanian-Turonian age (Cacém formation).

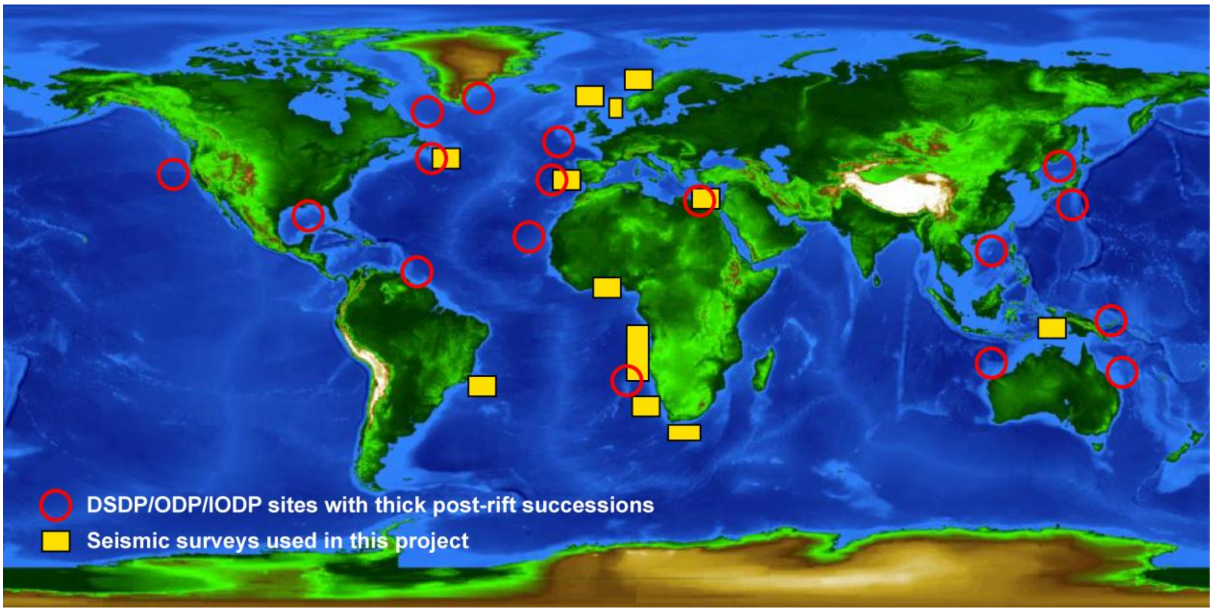


*FIG.1 – Seismic and borehole data set available for this study.*

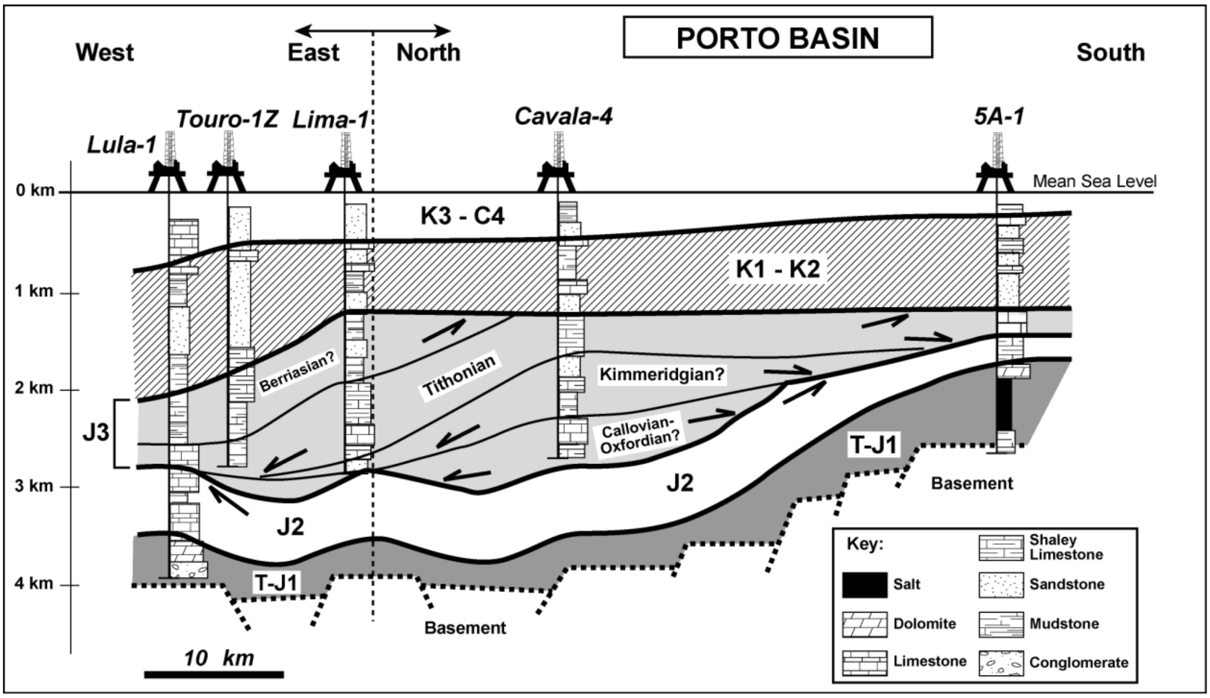


*FIG.2 – Example of the character of the break-up unconformity in the Porto Basin, West Iberia, the primary focus of our study when of the start of the project. Modified from Alves et al. (2006).*

We propose that in highly-segmented margins as West Iberia, sediment progradation on the inner proximal margin is not accompanied by the complete filling of deep-offshore depocentres, thus forming diachronous 'break-up unconformities' along the continental margins. The forced-regressive events observed in shallow-offshore basins should correlate with equivalent events on the continental slope, thus constituting more reliable markers that the interpretation of a 'break-up unconformity simply based on geometric criteria.

## 3. Conclusions

Main conclusions are:
- Aptian-early Albian and early Cretaceous break-up events are marked by forced-regressive episodes (FRST) on the proximal margins.
- From five regression episodes (S1 to S5) reflecting major tectonic events occurring on the deeper margin, some diachronicity should be expected from sub-basin to sub-basin, a function of sediment supply and accommodation space inherited from the rifting phases.

*Acknowledgements*
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# The Upper Jurassic Petroleum System: evidence of secondary migration in carbonate fractures of Cabaços Formation, Lusitanian Basin

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*ABSTRACT*

*The Lusitanian Basin has important source rocks intervals deposited mainly during the Jurassic. In the central sector, occur oil impregnations in carbonate fractures of Cabaços Formation. The aim of this work is to characterize geochemically the origin and thermal maturation of this oil and to correlate with the source rock. The geochemical results obtained for this oil indicate low thermal maturation and an anoxic marine carbonate source, which is compatible with the composition of organic extracts from Cabaços Formation (Oxfordian). The good oil-source rock correlation corroborates the existence of an Upper Jurassic Petroleum System in the Turcifal Sub-basin domain.*

*KEYWORDS: Lusitanian Basin, Upper Jurassic Petroleum System, marine carbonate source rock.*

## 1. Introduction

The Lusitanian Basin located along the western Iberian margin, is one of a family of Atlantic margin Mesozoic rift basins which formed as a response to Pangea fragmentation in the Late Triassic and subsequent opening of the North Atlantic (Wilson *et al.*, 1989; Pinheiro *et al.*, 1996; Pena dos Reis *et al*., 1999; Pena dos Reis *et al*., 2009). In its sedimentary record, occur marine source rocks with high organic content deposited predominantly in the Jurassic, during the rifting phase and under rapid subsidence.

The petroleum exploration in the Lusitanian Basin began in the last century, especially after 1938, when several geological and geophysical data were acquired. Occurrences of petroleum impregnating surface rocks (seeps), and other hydrocarbon shows in the subsurface indicate the presence of active petroleum systems, in both the northern and southern parts of the basin (Source: DPEP).

Two main source rock intervals are recognized in Lusitanian Basin, both having reached oil zone and gas zone: in the North part, occur marls and shales of Lower Jurassic (Sinemurian and Pliensbaquian), whereas in the South part, occur mainly organic rich black limestones of Upper Jurassic (Oxfordian) (BEICIP-FRANLAB, 1996; Spigolon, 2007).

The aim of this work is to characterize geochemically the origin and thermal maturation of oil impregnated in carbonate fractures of Cabaços Formation present in outcrops in the Torres Vedras region (Turcifal Sub-basin; FIG. 1) and then to associate the oil to a petroleum system based on oil-source rock correlation.

## 2. Analytical Methods

The oil samples collected from carbonate fractures were analyzed using traditional geochemical techniques, including whole oil stable carbon isotopic composition ($\delta^{13}C$ - MS Finnigan MAT 252), liquid chromatography (MPLC), whole oil gas chromatography (GC), and saturate biomarkers by gas chromatography coupled with a mass spectrometer (GC-MS, m/z 191 e m/z 217).

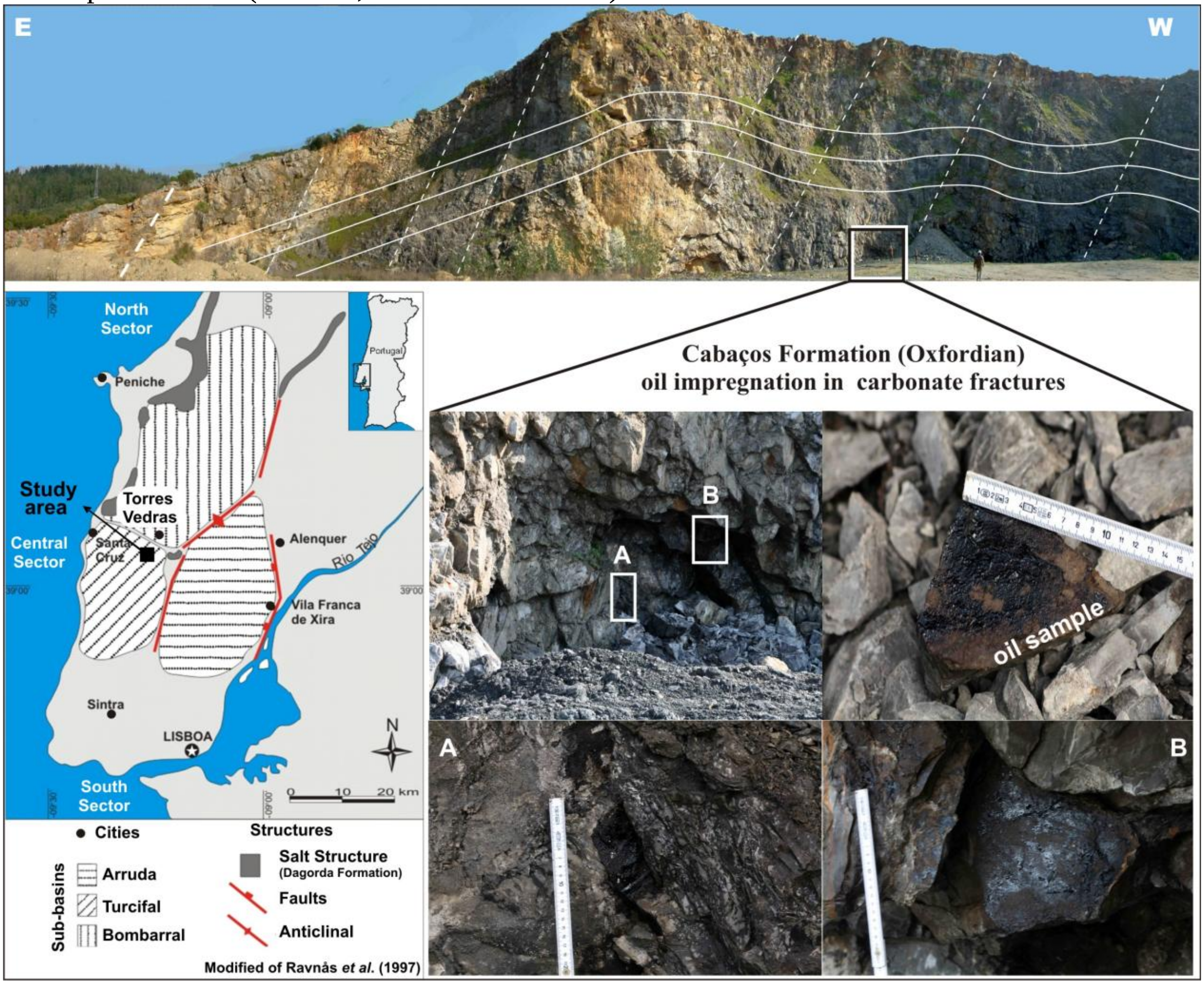


FIG. 1 – Regional and local contexts of the Torres Vedras oil impregnation, central sector of Lusitanian Basin.

## 3. Results and Discussions

The geochemical results of MPLC show a predominance of resins and asphaltenes with 51%, associated to 22% of saturates and 27% of aromatics. The values of $\delta^{13}C$ for whole oil are around -24.9‰ (FIG. 2).

According to gas chromatography data, the organic composition represents a typical signature of non-biodegraded oil, characterized by the abundance of *n*-alkanes and low pristane/*n*-$C_{17}$ and phytane/*n*-$C_{18}$ ratios. Sometimes, the absence of light *n*-alkanes and isoprenoids can be attributed to evaporation under conditions of prolonged exposure. Saturate biomarkers weren't affected by processes of secondary alteration. The relatively more abundant compounds among terpanes (m/z 191) are $C_{29}$ 17α(H)□□, 21β(H)-30-norhopane ($H_{29}$), $C_{30}$ 17α(H), 21β(H)-hopane ($H_{30}$), 17α(H)-22,29,30-trisnorhopane (Tm) and $C_{24}$ tetracyclic ($TET_{24}$). Moreover, the distribution of steranes (m/z 217) displays a predominance of $C_{29}$ steranes, pregnane ($C_{21}$) and homopregnane ($C_{22}$) (FIG. 2).

In agreement with Peters *et al.* (2005), the high relative abundances of $H_{29}$ and $TET_{24}$ compounds associated with the low concentration of diasteranes (DIA) and the high relative intensity of $C_{35}$ 17α(H)□□, 21β(H) homohopane (22S+22R) ($H_{35}$) between the homohopanes ($H_{31}$-$H_{35}$), represent a typical composition of source rocks deposited in an anoxic carbonate marine environment.

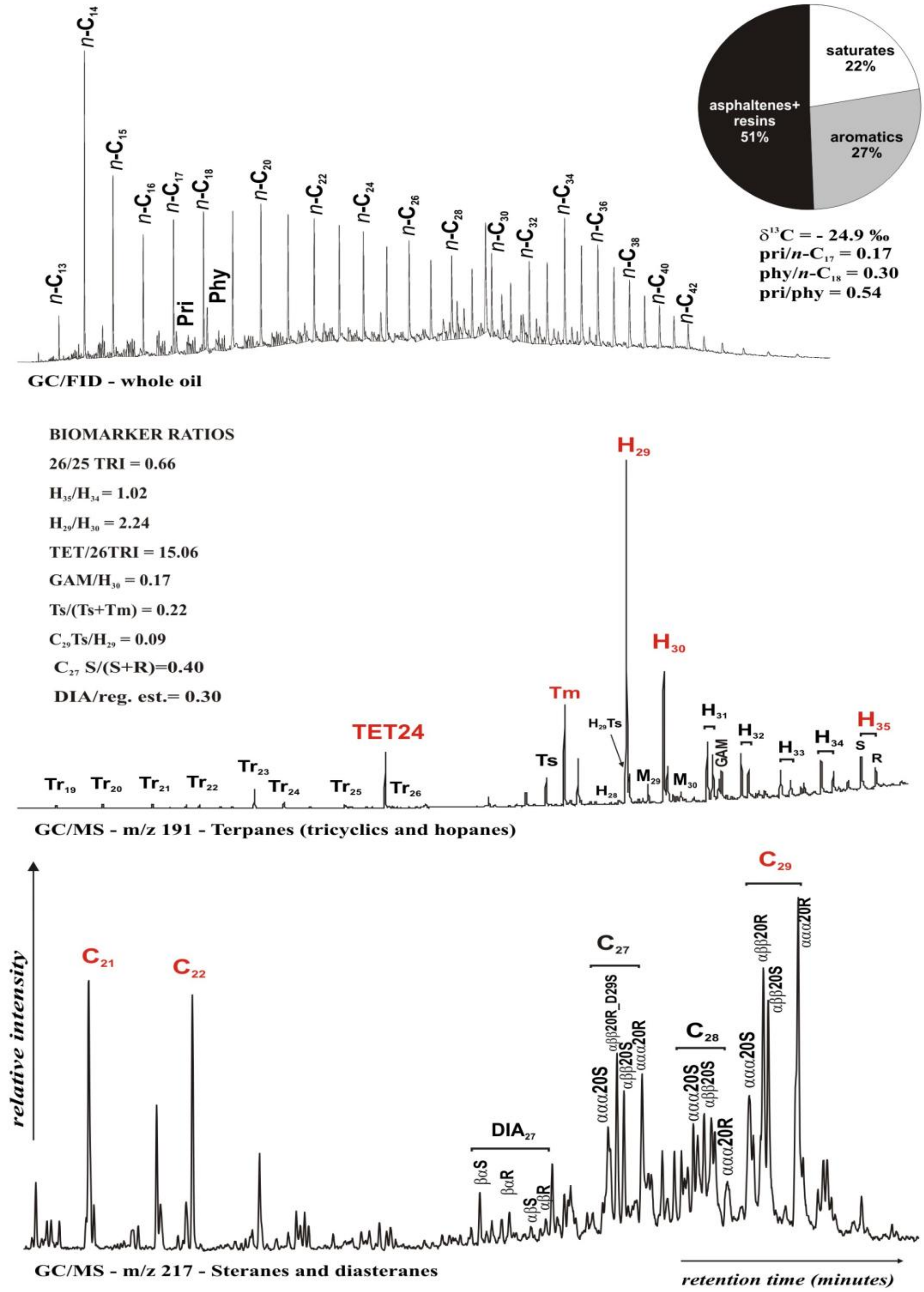


FIG. 2 – Composition and organic geochemistry parameters of Torres Vedras oil impregnation.

The organic geochemistry parameters of this oil, like low pristane/phytane and diasteranes/regular steranes ratios associated with high $H_{29}/H_{30}$, $TET_{24}/26$ Tri, $H_{35}/H_{34}$ ratios and carbon isotopic signature enriched in $^{13}C$, are compatible with the composition of extracts from Cabaços Formation, represented mainly by marine organic-rich black limestone intervals (Oxfordian) (FIGS. 2 and 3).

The good oil-source rock correlation corroborates the presence of an Upper Jurassic Petroleum System in the Turcifal Sub-basin domain, central sector of Lusitanian Basin. It is important to mention that the geochemical characteristics of the Upper Jurassic Petroleum System are easily recognizable when compared to Lower Jurassic Petroleum System (FIG. 3).

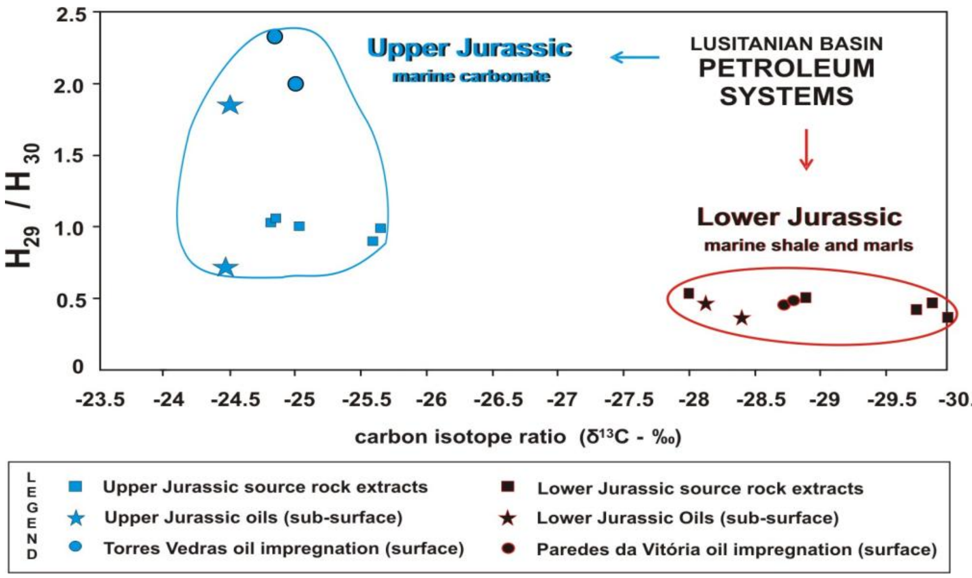


FIG. 3 – Oil-Source Rock and Oil-Oil correlations based on molecular and isotopic parameters of the Petroleum Systems from Lusitanian Basin.

The low thermal maturation found for this oil, based on low Ts/(Ts+Tm), $C_{29}Ts/H_{29}$ and $C_{29}$ S/(S+R) ratios, indicates that the kitchen area reached at least the beginning of the oil window (FIG. 2).

This type of occurrence suggests secondary migration via fractures probably associated with fissured carbonate reservoirs of Cabaços Formation. Similar reservoirs were tested in some wells drilled in the Torres Vedras region which recovered oil in fractures at the same formation (DPEP). Due to the short distance between source rock and reservoir, and also the network of fractures and faults observed in the outcrops, this petroleum system can be considered of high generation efficiency and drainage.

*Acknowledgements*
*The authors thank to PETROBRAS for authorization to publish this paper as well as Mário Duncan Rangel, José Roberto Cerqueira and Eugênio Vaz dos Santos Neto for the suggestions about the text.*

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# The Mesozoic Orpheus rift basin, offshore Nova Scotia and Newfoundland, Canada: Synrift and early postrift evolution of a well-imaged North Atlantic rift basin

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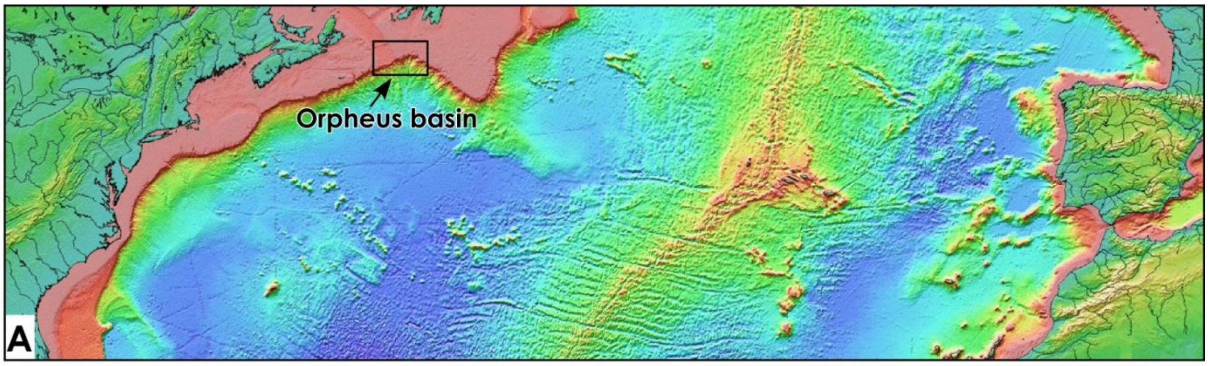
*ABSTRACT*
*The Orpheus basin of offshore eastern Canada formed before opening of the North Atlantic Ocean. We have identified four distinct tectonostratigraphic packages (A-D) associated with the basin's early development. Packages A, B, C, and D represent Paleozoic prerift strata and basement, Middle Triassic to Early Jurassic synrift strata, Early to Middle Jurassic postrift strata, and Middle to Late Jurassic postrift strata, respectively. The middle part of package B is likely salt. Rifting began by the Late Triassic and continued into the Early Jurassic. Regional shortening occurred after rifting (during the Early to Middle Jurassic), producing salt-cored detachment folds, detached thrust faults, and regional uplift and erosion. Tectonic quiescence followed shortening, leading to widespread deposition. Postrift salt movement resumed during the Middle to Late Jurassic.*
*KEYWORDS: Mesozoic rifting, Orpheus basin, tectonostratigraphic packages*

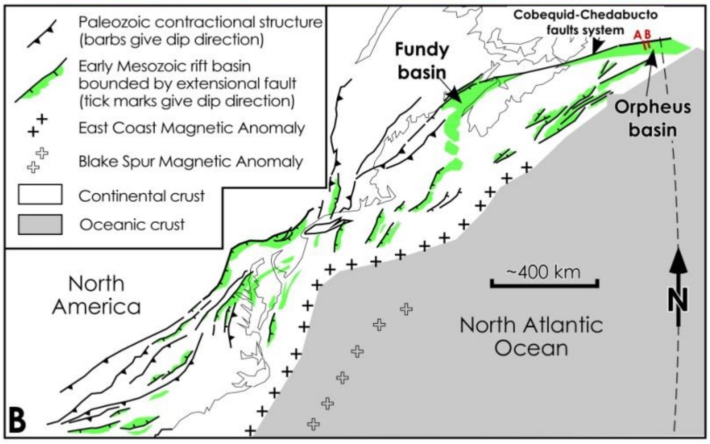
## 1. Introduction

A massive rift zone developed within the Pangean supercontinent during early Mesozoic time. Fragments of this extinct rift zone are now preserved on the conjugate passive margins of eastern North America, northwestern Africa, and southern Europe. The fragment on the North American margin, called the eastern North American rift system, consists of a series of exposed and buried rift basins extending from Florida to the Grand Banks (e.g., Withjack et al., 1998, 2010) (FIG. 1B). In this study, we focus on the synrift and early postrift evolution of one of these rift basins, the offshore Orpheus basin (FIG. 1A). To determine its evolution, we have interpreted newly reprocessed and recently acquired 2D seismic lines from offshore Nova Scotia, offshore Newfoundland, and the French territory of St. Pierre and Miquelon.

## 2. The Orpheus Basin

A series of E-striking, S-dipping faults define the northern margin of the east-plunging Orpheus basin (Fig. 1B). Most faults within this fault system (i.e. the Cobequid-Chedabucto fault system) likely formed during Paleozoic and older orogenic activity and were reactivated during early Mesozoic rifting (e.g. Withjack et al., 1998; Wade et al., 1996). During rifting, the Orpheus basin subsided and filled with several kilometers of clastic and evaporitic sedimentary rocks (e.g. Wade and MacLean, 1990; Tanner and Brown, 2003). After rifting, thick sequences of clastic and carbonate sedimentary rocks covered the Orpheus basin, filling the broad overlying depression known as the Scotian basin (e.g. Wade and MacLean, 1990; MacLean and Wade, 1992).



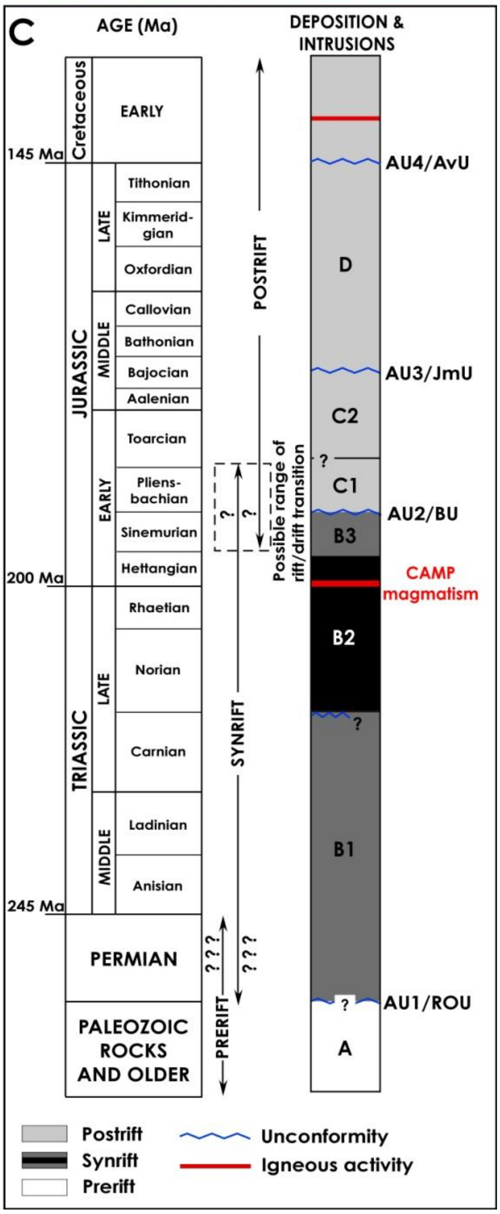




FIG.1 - A) Shaded-relief map of the conjugate continental margins of the North Atlantic Ocean. Black box indicates the study area. Modified from http://topex.ucsd.edu/marine_topo/gif_topo_track/topo8.gif. B) Major Paleozoic contractional structures, early Mesozoic rift basins, and key tectonic features of eastern North America (modified from Withjack and Schlische, 2005). The exact slip on most faults and the exact geometry and location of most subsurface rift basins is unknown. Red lines with letters refer to seismic lines used in FIG. 2. C) Generalized tectonostratigraphic packages of the Orpheus basin. Note that ages of the Triassic to Middle Jurassic packages are poorly constrained because well data are limited. AU = angular unconformity, ROU = rift-onset unconformity, BU = breakup unconformity, JmU = Middle Jurassic unconformity, AvU = Avalon unconformity.

### 3. Observations and Seismic Stratigraphy

Based on the seismic data, we have identified four distinct tectonostratigraphic packages (A-D) bounded by four major angular unconformities (AU1-AU4) associated with the Mesozoic development of the Orpheus basin (FIGS. 1C, 2). The oldest package, A, consists of tightly folded reflections. Unconformity 1 (AU1) separates

Packages A and B. Based on the internal character and geometry of seismic reflections, Package B is subdivided into three seismic units (B1-B3). The lower unit, B1, consist of subparallel and continuous reflections that are gently folded and faulted. The middle unit, B2, lacks internal reflections and has significant thickness variations. The upper unit, B3, consists of gently to tightly folded reflections. Reflections converge near the crests of some folds, indicating syndepositional folding. Reflections remain subparallel across the crest of others folds, indicating postdepositional folding. Numerous high-amplitude reflections, both concordant and discordant with other reflections, are present throughout Package B. Unconformity 2 (AU2) separates Packages B and C. Based on seismic internal reflections, Package C is further subdivided into a lower unit (C1) and an upper unit (C2). Reflections in unit C1 are subparallel, suggesting little deformation during its deposition. In unit C2, reflections locally onlap onto unit C1 and dip and diverge toward the south. Unconformity 3 (AU3) separates Package C and D. Package D consists of subparallel reflections that dip toward the south. A widespread angular unconformity, AU4, overlies packages A, B, C, and D.

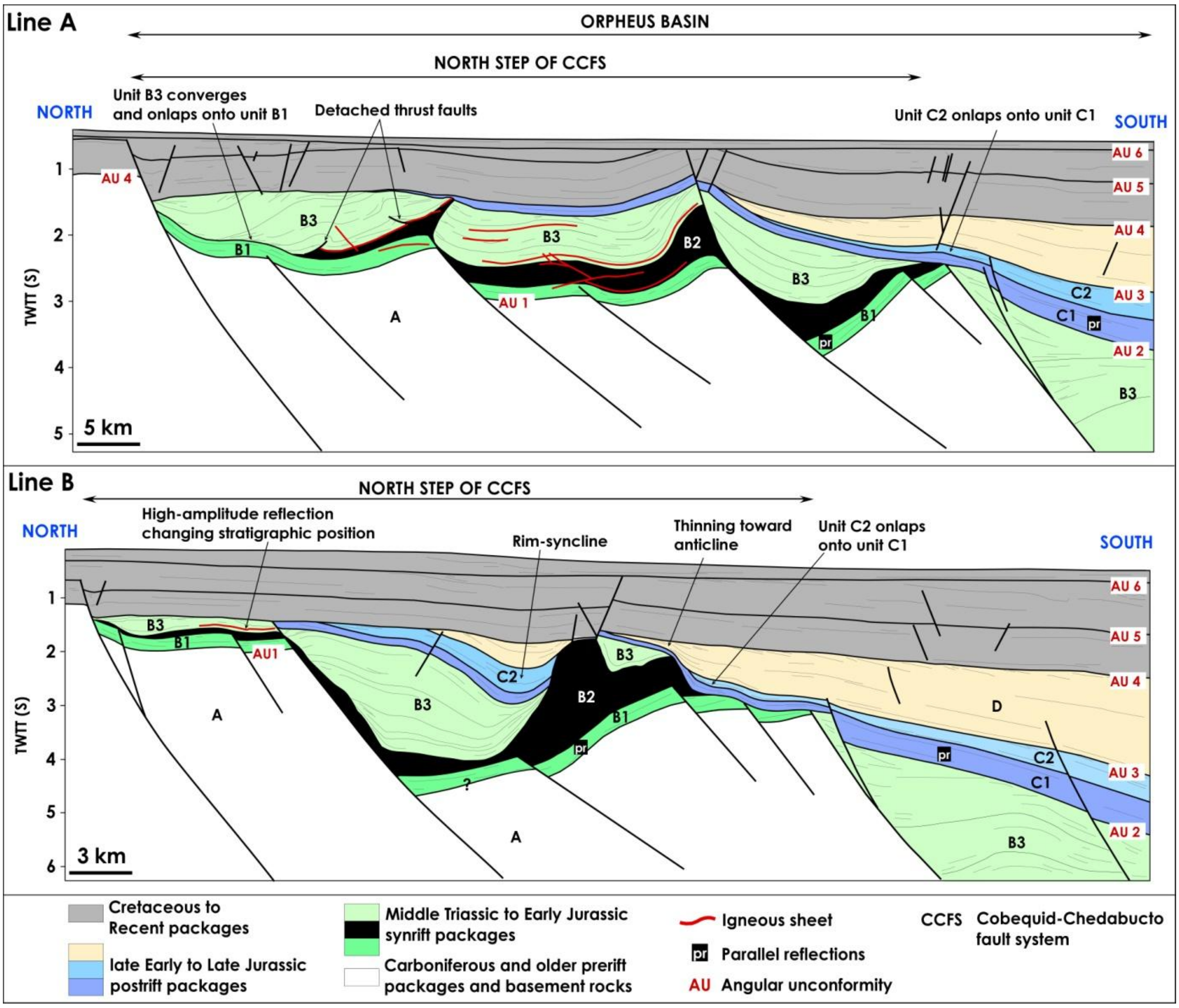



FIG. 2. – Interpreted line drawings of seismic lines A and B (see FIG. 1B for locations) showing unconformity-bounded packages within the Paleozoic – Mesozoic section of the Orpheus basin.

Information from nearby wells (albeit limited) and the onshore Fundy basin (FIG. 1B) suggests that packages A, B, C, and D represent Paleozoic prerift strata and basement, Middle Triassic to Early Jurassic synrift strata, Early to Middle Jurassic lower postrift strata, and Middle to Late Jurassic upper postrift strata, respectively (FIG. 1C). The Paleozoic strata of Package A contain Carboniferous salt (e.g., Pascucci et al., 1999). The middle unit of package B (B2) is likely halite associated with the Argo Formation. The high-amplitude reflections throughout package B are likely igneous sheets associated with the earliest Jurassic Central Atlantic Magmatic Province (CAMP). The angular unconformities that separate and bound the packages (AU1-AU4) are the rift-onset, breakup, Middle Jurassic, and Late Jurassic/Early Cretaceous (Avalon) unconformities, respectively (FIG. 1C).

## 4. Mesozoic Evolution of the Orpheus Basin

Both tectonic activity and the presence of salt affected the structural evolution of the Orpheus basin. Rifting began no later than the Late Triassic (MacLean and Wade, 1992; Wade et al., 1996; Tanner and Brown, 2003) or possibly earlier in Permian time (e.g., Olsen et al., 2000), producing a series of E-striking, S-dipping basement-involved faults with normal separation that bound the Orpheus basin on the north. During the early stages of rifting, the basin was broad with few faults. Most basement-involved faulting began during the deposition of the halite unit, causing pronounced thickening of the salt toward the south. The salt began to flow after its deposition, forming fault-parallel salt anticlines and salt-withdrawal synclines. Movement on basement-involved faults during rifting produced fault-propagation folds in the synrift section above the salt. Postrift shortening occurred during the Early to Middle Jurassic, producing salt-cored detachment folds, detached thrust faults, and regional uplift and erosion (FIG. 2). A period of tectonic quiescence followed shortening, leading to widespread deposition of unit C1 atop the breakup unconformity. In the Middle Jurassic, another episode of regional uplift and erosion affected the basin. Postrift salt movement resumed during the Middle to Late Jurassic, producing fault-parallel salt-cored highs and salt-withdrawal lows. Uplift and erosion during latest Jurassic to early Cretaceous produced a widespread unconformity.

*Acknowledgements*

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# Jurassic reef exploration play in the southern Lusitanian Basin, Portugal

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*ABSTRACT*

*A well-developed shelf-edge reef trend is observed on reprocessed 2-D and newly acquired 3-D seismic data from the western margin of the Turcifal sub-basin. Mohave Oil and Gas drilled a 1358m reef test based on the limited 2-D data and encountered Upper Jurassic lime mudstones and reef debris grainstones. Verification of reef facies led to acquisition of the 3-D seismic program which shows three stacked reef complexes ranging in age from Dogger to Oxfordian. Oxfordian and Kimmeridgian source rocks within the sub-basin range up to 6% TOC, and 25º API oil has been recovered from fractured, non-reef Oxfordian carbonates on the east side of the sub-basin. The Oxfordian reef tract is coeval with the productive Abenaki reef reservoir at Panuke Deep gas field, offshore eastern Canada.*

*KEYWORDS: Lusitanian, Portugal, Jurassic, reef, exploration.*

## 1. Introduction

Mohave Oil and Gas Corporation identified a Jurassic reef complex on limited 2-D seismic data along the western margin of the Turcifal sub-basin of the southern Lusitanian Basin, Portugal (FIG. 1). Mohave drilled a 1358m exploration well based on the 2-D data which encountered lime mudstones and tight reef debris grainstones in the Upper Jurassic section, but did not penetrate reef core facies. This verification of reef environment led to the proposed 117 km$^2$ 3-D seismic program over the reef trend currently in progress.

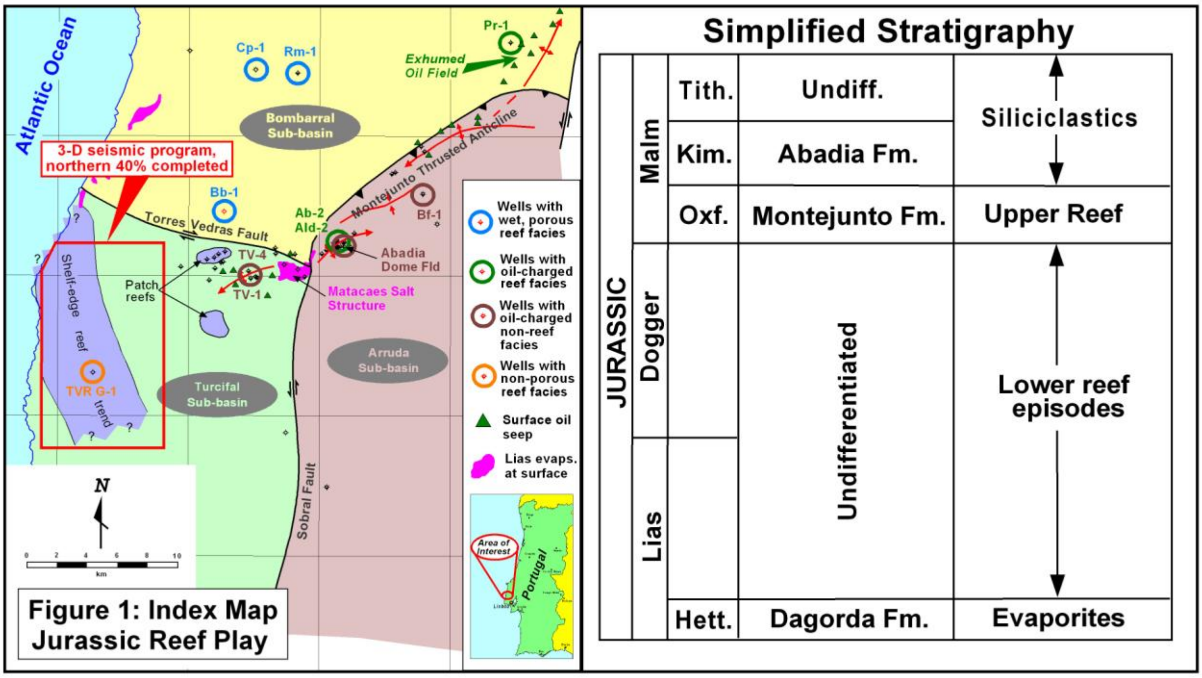


FIG. 1 - Location of reef trend, significant wells and simplified stratigraphy

## 2. Regional Stratigraphy and Structure

The region is divided into three sub-basins by the tripartite intersection of the Torres Vedras Fault, Montejunto Thrusted Anticline, and Sobral Fault (FIG. 1). The Bombarral sub-basin lies to the north of this "Y" intersection, the Arruda sub-basin to the southeast, and the Turcifal sub-basin to the southwest. The juncture of the three trends is marked by the Matacães Salt Structure, a probable diapir with Liassic Dagorda Fm. evaporites at the surface.

Lower and Middle Jurassic stratigraphy in this area is comprised of a basal Lias evaporite-bearing sequence overlain by Lias and Dogger carbonate rocks. The Malm is characterized by Oxfordian carbonates overlain by Kimmeridgian and Tithonian siliciclastics. Dogger-age reef facies have been described from outcrops in the Serra de Porto do Mós, north of the study area (Seifert, 1958) and from well samples from the Abadia-2 well at Abadia Dome (FIG.1). Upper Jurassic reefs are well documented from outcrops along the eastern margin of the Arruda sub-basin (e.g. Nose and Leinfelder, 1997) and have been penetrated in wells along the Montejunto Thrusted Anticline and in the Bombarral sub-basin.

## 3. Upper Jurassic Source Rocks

TOC values of both Oxfordian argillaceous carbonates and Kimmeridgian shales range up to 6%, with the maximum values for each occurring in the Turcifal sub-basin. Vitrinite reflectance values for outcrop and shallow well samples in the northeast Turcifal indicate early oil window maturity. Oil with ~$25^{o}$ API gravity has been recovered from Kimmeridgian sands and fractured, Oxfordian non-reef limestones in this area. No % Ro data are available from the Turcifal basin axis or western margin. Whole oil chromatograms for oils collected from the northeast Turcifal sub-basin and along the Montejunto Thrusted Anticline indicate two separate oil families, suggesting two petroleum systems have been active in the region.

## 4. Reef Reservoirs

The Campelos-1 well (Cp-1) and Bombarda-1 well (Bb-1) in the Bombarral sub-basin (FIG.1) both logged significant reef porosity with modern wireline tools. Cp-1 penetrated over 100m of water-bearing Oxfordian reef reservoir with porosity ranging from 10% to 18%. Bb-1 drilled 75m of oolitic and bioclastic grainstone/packstone with reef debris. The well penetrated a net 25m of porosity ranging from 10% to 14%. The Pragança-1 well (Pr-1) was drilled in 1959 on the northeast plunge of the Montejunto Thrusted anticline trend (FIG. 1). This well is located down dip of extensive tar accumulations in outcrops of Oxfordian reef and associated carbonate and overlying sandstone facies. Pr-1 penetrated 450m of interbedded Oxfordian reef boundstone, grainstone and mudstone with significant saturation of tar and heavy oil that became more liquid with depth.


FIG. 2 - Aldeia-2 reef facies core and analysis

On the Montejunto Anticline at Abadia Dome (FIG. 1), the Aldeia-2 well (Ald-2) cored 1m of oil-saturated Oxfordian reef facies (FIG. 2). Whole core analysis indicated 23% porosity and horizontal and vertical permeability of 1 Darcy. Additionally, the Abadia-2 well (Ab-2), the only deep well at Abadia Dome, penetrated upper Dogger carbonates described as reefal, algal and oolitic, with abundant sample oil shows. Microlog separation indicates over 100m of net porous and permeable zones within the upper 160m of the Dogger reefal facies.

## 5. New 3-D Seismic Data over the Turcifal Reef Trend

At present, 3-D seismic acquisition is complete over the northern 40% of the Turcifal shelf-edge reef trend (FIG. 1). An E-W inline from the current 3-D dataset that highlights important aspects of the Turcifal reef complex is shown as FIG. 3.

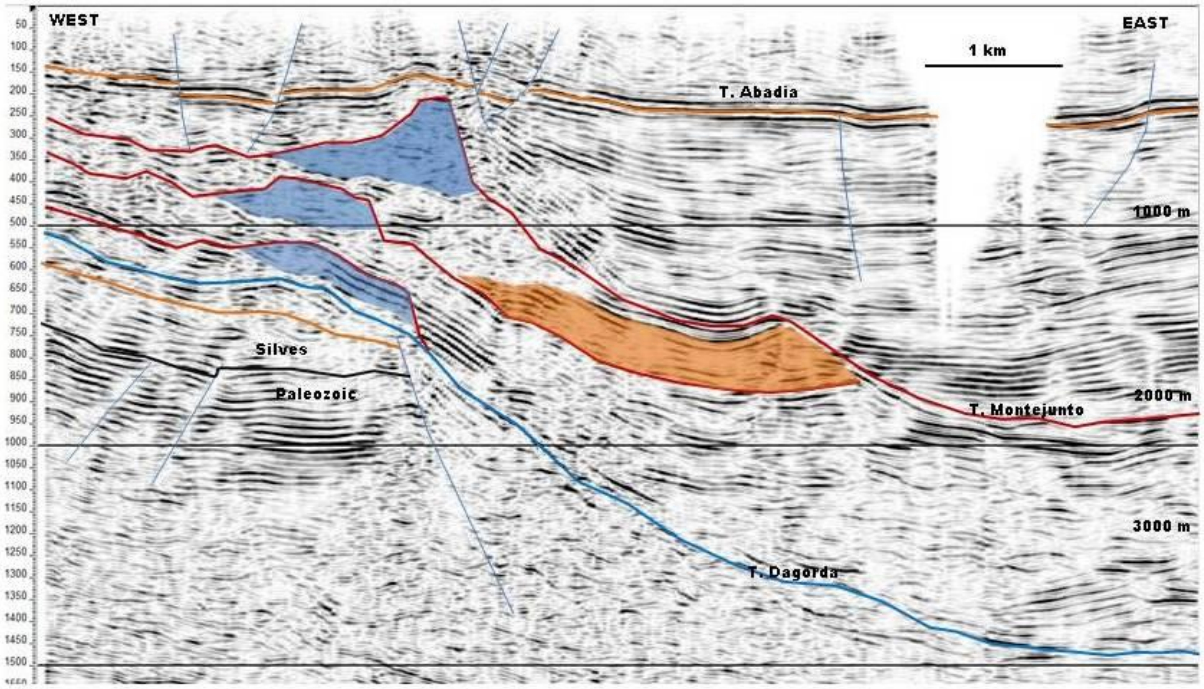


FIG. 3 - 3D inline 80 over the Turcifal sub-basin Jurassic reef trend. Interpreted reef bodies in blue and possible mass-wasting deposit in brown. Formation tops are indicated.

The seismic line shows how reefal development initiated in the Lower Jurassic, localized over a major rift fault. After the Dagorda evaporites were deposited, continuing post-rift sag draped them over the rift margin fault. The initial stage of carbonate deposition then occurred, including parallel trends of patch reefs and what appear to be shoaling episodes. The next stage of reefing appears to have been significantly exposed afterward, resulting in an interpreted mass-wasting deposit downdip. The final reefing episode took place through the end of Oxfordian (Montejunto Fm.). This reef has a greater areal extent than any of the previous episodes (FIG. 4), as well as the greatest height.

Overlying Kimmeridgian Abadia Fm. onlaps the reef front and covers the top. Where penetrated in the Mohave TVR G-1 well, the basal Abadia consists of 80m of intercalated, thin beds of silty shale, siltstone and silty, argillaceous micrite, characterized by high Gamma Ray values, largely in the 50 to 75 API unit range. Compaction folding over the reef bodies is well-exhibited, as is faulting in the Abadia clastics that does not appear to affect the underlying Montejunto carbonates. The essentially flat nature of the post-reef Upper Jurassic section indicates the reef trend has not been subjected to significant Cretaceous and Tertiary deformation which could breach reef reservoirs.

The recovery of live oil from fractured, non-reef Montejunto carbonates and overlying Abadia fine-grained sandstones at the northeast margin of the Turcifal sub-basin (FIG. 1) indicates the sub-basin has generated hydrocarbons. The reef trend along the western margin of the sub-basin is in an excellent position to receive a hydrocarbon charge and its structural history suggests little risk of subsequent breaching.

Data acquisition in the southern part of the 3-D survey which will tie the Mohave TVR G-1 well has not yet been completed.

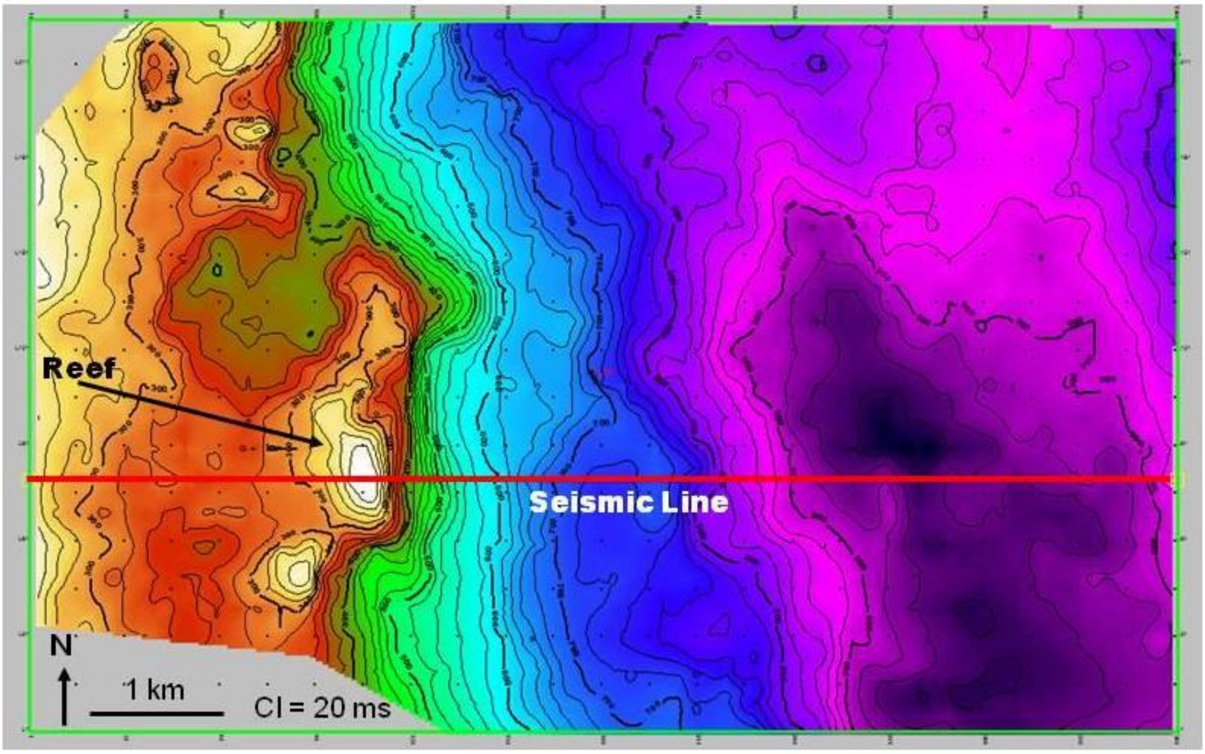


FIG. 4 - Time structure map on the top of the Montejunto Fm. showing shelf-edge reef development.

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*The authors thank Porto Energy Corp., Mohave Oil and Gas Corporation and Divisão Para a Pesquisa e Exploracão de Petróleo (D.P.E.P.) for permission to present this data.*

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# Sequence stratigraphy and evolution of the Tarfaya Basin, Morocco

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*ABSTRACT*

*The Mesozoic to Cenozoic evolution of the Tarfaya Basin includes five stages of tectonic evolution i) Permian to Pliensbachian rift- and sag, ii) Toarcian to Cenomanian drift, iii) Turonian to Early Eocene drift during initial Atlasian deformation, iv) Middle-Late Eocene drift with major Atlasian compression; v) Late Eocene to Early Miocene drift with major Atlasian uplift and inversion. At least one hundred thirteen sequences (third to fourth order) have been identified in the Lower Jurassic to recent Tarfaya shelf margin.*

*The Late Permian to Liassic rift, sag and early drift basin fill (260-180 Ma) includes alluvial, limnic, evaporite and carbonate ramp depositional environments. In the area of the central shelf the Lower Jurassic basin fill contains seven sequences showing coastal plain mudflats with alluvial intervals until the Early-Middle Toarcian and carbonate-evaporite ramps in the Late Toarcian. The Middle and Late Jurassic carbonate shelf ramp is subdivided by at least thirty-three sequences. Thirty Early Cretaceous and up to fifteen Late Cretaceous sequences comprise fluvio-deltaic and inner-outer shelf environments. Offshore, the Cretaceous is bounded by a major erosional unconformity, triggered by continental margin collapse. The Paleocene siliciclastic to carbonate and Eocene/Early Oligocene mainly clastic basin fill includes ten sequences. Significant sediment bypass across the shelf top and margin took place during this time. A major regression coincides with shelf margin and upper slope collapse in the Oligocene. The Neogene basin fill covers fourteen sequences. The resolution of the sequence stratigraphic model reaches reservoir-scale.*

*The sequence stratigraphic model of this contribution is based on i) well correlation,ii) seismo-/sequence stratigraphic interpretation and iii) data from outcrop analogues.*

*KEYWORDS: Tarfaya Basin, Sequence Stratigraphy, Morocco.*

## 1. Introduction

The Dhakla, Laayoune and Tarfaya Basins (TB) extend along the southern Moroccan continental shelf approximately to the town of Sidi Ifni, where a gradual transition to the Souss-Basin (SB) in the north takes place. Source areas of the TB include the Anti-Atlas, the Reguibate High and the western Zag Basin. The main objective of this study is placed on the TB between Tan-Tan and Cap Boujdour.

The development of the TB started with the opening of the Central Atlantic in the Late Permian to Triassic with continental extension (Le Roy & Piqué 2001). After rift climax in the Anisian/Ladinian, the sag basin development with thermal relaxation and high subsidence prevailed during the Carnian/Norian. A short-lived marine ingression and subsequent restriction resulted in thick evaporites in the northern offshore TB. Salt remobilisation started in the Early Cretaceous and represents the dominant structural driving force accompanied by far-field plate compression and uplift since Paleogene (first peak Atlasian orogeny) (Zühlke et al. 2004, Michard et al. 2008).

During the initial rift-, rift climax and sag basin stages (Late Permian to Early Pliensbachian), terrigeneous clastics were deposited in alluvial environments. Evaporites occurred in the Early Norian. Upper Norian basaltic extrusives and sills belong to the Central Atlantic Magmatic Province (CAMP). Initial open marine deposition after the rift basin stage took place in the Sinemurian (Zühlke et al. 2004, Davison 2005, Abou Ali et al. 2005). The Pliensbachian to Callovian is presented by an initial carbonate ramp followed by regressive marine sandstones and a renewed transgression led to deposition of open marine carbonates. The Upper Jurassic is represented by carbonate platforms of the Lower Puerto Cansado Fm. (Abou Ali et al. 2005, Michard et al. 2008). The platform margin consists of reefal build-ups. The former slope collapsed during Berriasian eustatic sea-level lowstand.

The Berriasian to Aptian in the northern part of the TB is dominated by the Tan Tan Delta which prograded to the NNE (Abou Ali et al. 2005). In the NW outer shelf area the Lower Cretaceous succession consists of carbonate to fine clastic deposits. The southern outer shelf is devided into a Berriasian to Mid-Barremian carbonate succession followed by clastic deposits of Upper Barremian to Aptian age. An open marine outer shelf to shelf margin environment developed in Albian age. Cenomanian to Coniacian increasing paleobathymetry coincided with oceanic anoxic conditions. As a result, organic rich clay- and marlstones of a deep open marine outer shelf environment represent the Lower Lebtaina Fm. (Abou Ali et al. 2005, Davison 2005).

An erosional unconformity truncates the Paleocene, Upper Cretaceous and parts of the Lower Cretaceous basin fill in the shelf-area. This multi-phase erosion took place between the Upper Santonian and Upper Paleogene (Davison 2005). Paleocene, Eocene and Miocene sediments are exposed onshore south of Laayoune to Smara. In the uplifted northern part of the TB, the Cenozoic succession was completely eroded. Sediment input from the eastern source areas was bypassed to the continued slope and rise. The Paleogene Samlat Fm. unconformably overlies the Upper Cretaceous basin fill. The Itgui and Gueran Members consist of predominantly marine sediments with siliceous chalks and chert concretions. The Oligocene Morcba Mb. shows continental environments with sandstones and conglomerates, but is only present in the southern onshore TB (Abou Ali et al. 2005).

## 2. Methods

The current sequence stratigraphic model is based on i) well log data, ii) 2D seismic surveys and, iii) outcrop analogue data in the Tarfaya and Zag Basins. Three dip line transects from shelf top to lower slope and basin margin have been studied.

1D pattern recognition has been applied on Gamma Ray and resistivity well log data in order to recognize parasequences, sequences and sequence sets (major T/R cycles). Flooding surfaces, sequence boundaries and T/R (Transgressive/Regressive) trend boundaries allow improved well correlation beyond biostratigraphic resolution and constrain seismostratigraphic interpretation.

2D sequence stratigraphic pattern recognition was done by interpretation of chronostratigraphic order of seismic reflectors using OpendTect®. As a result of sequence and system tract analysis, base level curves for outer and mid-shelf areas were generated. These curves were compared with Hardenbol's (1998) eustatic sea-level curve of European basins.

## 3. Results

Based on well log and 2D-seismic data, a high resolution sequence stratigraphic model has been developed. Third to fourth order sequences were identified based on the integrated analysis of well and seismic data (Fig. 1).

A Triassic rift and sag basin fill is followed by a Pliensbachian to Callovian prograding carbonate ramp containing intercalated clastic sediments of Toarcian age.

The Upper Jurassic carbonate platform shows long-term aggradation. Lower Berriasian base level fall led to a slope collapse. The Jurassic platform is bounded by reefal build-ups.

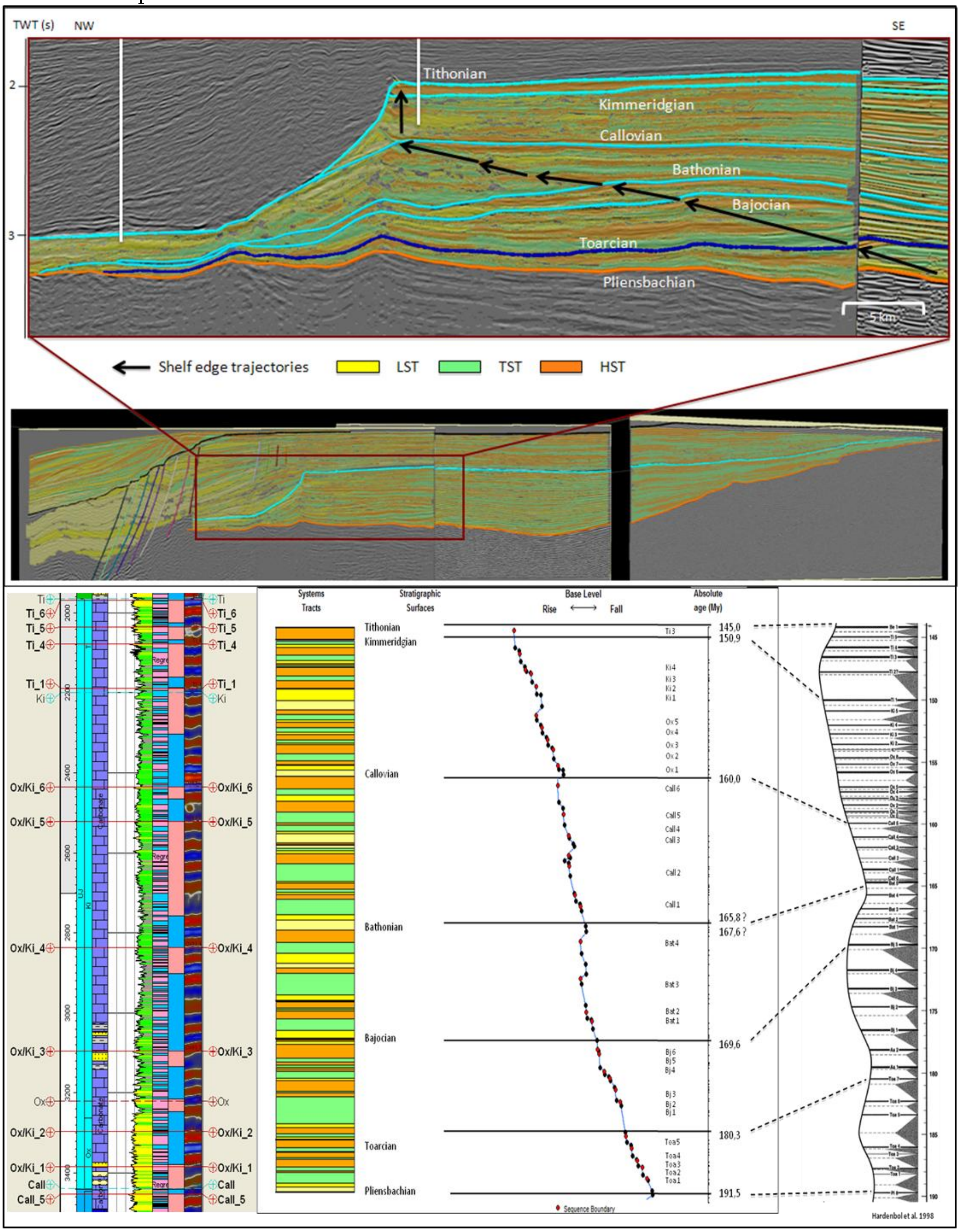


FIG.1 – Sequence stratigraphy of a seismic key transect (composite line with lateral offset) in the TB based on integrated well and seismic data (Pliensbachian to Tithonian interval as

example, see red dot in map window for location). Sequence and systems tract geometries are indicated in the upper image (yellow: LST, green: TST, orange: HST). Shelf edge trajectories follow progradation/aggradation trends (arrows). White lines show well positions on this transect. Major stratigraphic levels (reflectors) indicated have biostratigraphic control. 39 sequences were identified in the Jurassic basin fill. Example of logs and cyclostratigraphic interpretation of calibrating well on the lower left side, base level curve, system tracts and sequences in lower central position. Lower right side: Hardenbol's sea-level chart of European basins.

Berriasian deposition started with deep marine low stand fans followed by transgressive deposits which onlap against the Upper Jurassic collapsed platform margin. The Berriasian to Barremian unit is represented by progradation of the river-dominated lower Tan Tan Delta. During Barremian to Aptian the development of the upper Tan Tan Delta shifted to retrogradation with mainly coarse clastic basin fill. The Albian is represented by transgressive lagoonal, tidal and shallow marine muds. During the Cenomanian and Turonian, water depth increased and laminated, organic rich marls were deposited. They were identified at the recent shelf margin area of the northern key transect.

Up-section, a major regional unconformity cuts into the Albian to Lower Cretaceous basin fill. No post-Campanian sediments were preserved onshore. Paleogene and Neogene basin fill is restricted to the shelf margin and basin.

The generated base level curves of the Pliensbachian to recent basin fill show a plausible fit to Hardenbols sea level chart in terms of low order ($2^{nd}$) changes. Base level changes of higher order are modulated by regional subsidence trends.

## 4. Conclusions

The sequence stratigraphic model allows to subdivide the TB sediment infill in reservoir scale and far beyond the existing biostratigraphic resolution. Reservoir architecture and migration pathways from source rock to reservoir can be assessed.

Sequence stratigraphic analysis and generated base level curves show a plausible fit with Hardenbol's sea level chart of European basins in terms of low order (second to third) sea level changes. High order (third to fourth) changes in base level are modulated by regional subsidence trends.

Sequence stratigraphic models within a biostratigraphic framework provide essential input values for future reverse-basin, forward stratigraphic and hydrocarbon systems modelling.

*Acknowledgements*
*The first two authors are indebted to ONHYM, Rabat, and RWE Dea, Hamburg. Seismic and well data for this study have been made available by ONHYM. This study, as PhD project of Axel Wenke, has been funded by RWE Dea. Seismostratigraphic and well-log interpretation has been performed with Petrel® 2009 (Schlumberger), seismic system tract analysis with OpendTect 4.0 SSIS® (dGB Earth Sciences).*

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# Nova Scotia Play Fairway Analysis - Why and What for?

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*ABSTRACT*

*The Nova Scotia Department of Energy and Canada-Nova Scotia Offshore Petroleum Board have carried out a sound technical work program over many years to present potential licensees with the information to encourage them to participate in Nova Scotia. However, following some success, the result in terms of license bids in Nova Scotia's offshore, wells drilled and hydrocarbons won has proved disappointing. The value of the hydrocarbon province has not been fully unlocked. Although production and proven discoveries demonstrate that there is a working hydrocarbon system oil companies have left Nova Scotia in favour of other opportunities prior to completion of their exploration program. There is a view that in order to attract new investors it will be necessary to lower the barriers to entry. One of these is the ability of new investors to easily and quickly develop a good geological understanding of the Nova Scotia offshore basins and thus investment decisions. The province is conducting an industry standard sequence stratigraphic based play fairway analysis to a level of detail which is sufficient to give credibility to the outcome.*

*KEYWORDS: Nova Scotia, Canada, Play Fairway Analysis, PFA*

## 1. Introduction

The history of petroleum exploration offshore Nova Scotia spans more than 40 years with the first well drilled in 1967 and the first discovery in 1969. During this period more than 200 exploration, delineation and production wells have been drilled with discovered reserves in the range of 2.1 billion (boe). However it was not until 1992 that the first oil production took place at the Cohasset Panuke development, and first natural gas production in 1999 from the Sable Offshore Energy Project (SOEP). Most recently the discovery of commercial quantities of natural gas at Deep Panuke has resulted in the development of that field, with first gas expected in 2011. The remaining resource potential of the Nova Scotia offshore has been estimated by the Canada-Nova Scotia Offshore Petroleum Board (CNSOPB) to range from 12 to 39 tcf of natural gas and between 1.3 and 4.5 billion barrels of oil. In spite of what appears to be an attractive resource base, exploration activity has declined sharply over the last decade. Since 1998, a total of 29 exploration and delineation wells have been drilled at a cost of over $1 billion, but with only one commercial discovery, Deep Panuke in 1998. The lack of exploration drilling success is reflected in the decline in exploration licenses from a high of 59 in 2002 to only 10 in early 2008. Since then three new licenses have been issued as a result of a Call for Bids issued in mid-2008. Aside from these new licenses, many of the licenses existing at the beginning of 2008 have been relinquished at the end of the year resulting in a further decline in exploration licenses. As a result, there are only 8 active exploration licenses in 2009. Moreover, the number of active exploration licenses could drop to 2 in less than 5 years.

Royalties and other forms of government revenues from offshore petroleum production are extremely important to Nova Scotia. For the fiscal year ending March 31, 2008, Nova Scotia received approximately $540 million in direct revenues of various types from offshore petroleum activity, the third largest provincially generated source of government revenues. Royalties alone contributed $514 million in the 2008/09 fiscal year. In addition, petroleum activities have generated substantial economic activity in the Province, amounting to over $2.5 billion since the beginning of construction of the Sable Offshore Energy Project in 1996. It is clear that without an increase in exploration with commercial discoveries the fiscal and economic benefits that the Province has enjoyed will decline sharply. This provides a strong motivation for the provincial government to do whatever it can to address those issues that are within its ability to influence, particularly with respect to improving geoscience knowledge, the regulatory and fiscal regime, and targeted marketing of its resource potential.

A number of studies have been commissioned by the Province, the Atlantic Canada Opportunities Agency (ACOA) and others to better understand and address some of the key issues affecting offshore exploration. This paper elaborates on the business rational to conduct the Play Fairway Analysis (PFA) program in order to reinvigorate exploration interest.

***Exploration Overview***

The discovery history and the cumulative volumes discovered (creaming curve) are shown below. The key message from these figures is that ~2.1 bnboe in place was discovered by ~128 exploration wells over a period of some 40 years. Also from the point of view of prospective investors no significant discoveries have been made since 1998. 26 exploration wells have been drilled since 1999 and no new volumes booked. To an oil company with no or limited knowledge of Nova Scotia this raises some important questions:

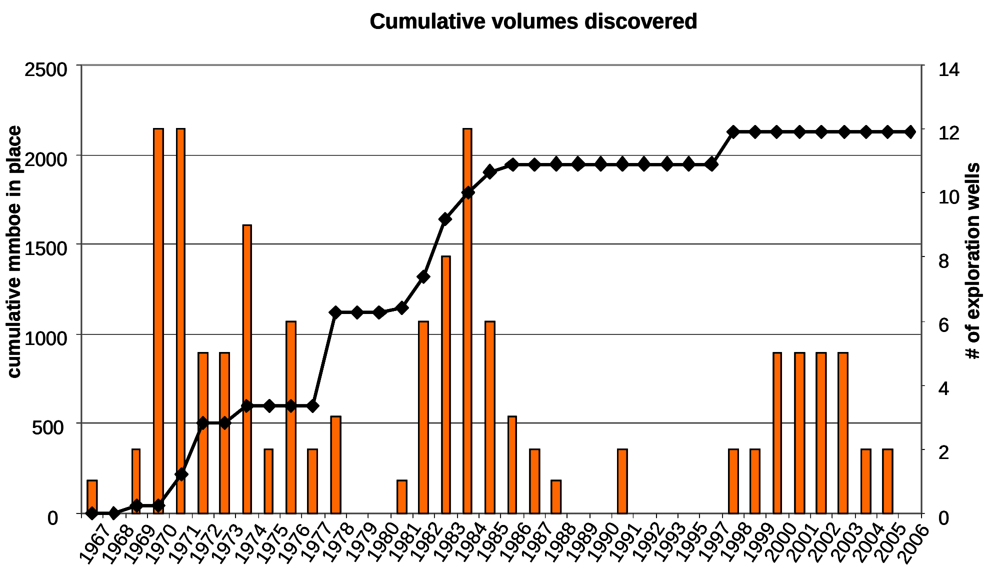


FIG.1 - Cumulative volumes discovered offshore Nova Scotia (By courtesy of NS Energy)

The commercial discoveries to date are on the Sable shelf and are not giant fields with the possible exception of Venture (defining a giant field as having >250 mmboe economic reserves).

What is limiting the scale of these discoveries?

Lack of reservoir? Lack of an effective charge system? Poor seal(s)? Or some combination?

The overall success rate is ~ 1:5. In the deep water it is arguably ~1:10 (allowing Annapolis as a "technical discovery").

This does not feel like a "world class system" at first sight.

To date there has been one "technical discovery" (Annapolis) in deep water and one gas show in the Newburn well.

When set against the high costs of exploring offshore Nova Scotia these impressions would understandably lead to reluctance to get engaged in the offshore province. A new entrant would see little evidence that there has been geological learning over the years that is showing an improvement in success rates.

## 2. External Studies Commissioned by the Province

Early in 2007 the Nova Scotia Department of Energy (NS Energy) commissioned a study by Gaffney Cline & Associates to assess Nova Scotia's position in the competitive arena for upstream petroleum investments. Gaffney Cline's study gave the following perceptions within the industry about Nova Scotia:

- High cost and difficult conditions
- Not super-major scale but has super-major costs and risks
- Disappointing exploration results
- Lack of basic geological framework which creates a high barrier to entry

Arguably the major concern raised in the Gaffney Cline review is the perception regarding resource scale and the geological risks. This necessarily underpins industry's appetite for engagement in any petroleum basin.

A Geoscience Gap Analysis study by Paras Ltd early 2008 reported the results of an analysis to identify gaps in geoscience understanding and data that may be contributing to investors' current reluctance to engage in exploration offshore Nova Scotia. The study concluded that although Nova Scotia is "data rich", much of the data that is fundamental to offshore explorers is not in the public domain. Furthermore there is no publicly available industry standard play fairway analysis for the Nova Scotia offshore. The primary recommendations arising from the Paras study were:

- Conduct an "industry standard" play fairway study which should be published as a play fairway atlas, and
- Build a geoscience data package that can be made publicly available along with PFA.

The Gap Analysis also concluded that in order to attract new investors it is necessary to lower the barriers to entry. One of these is the ability of new investors to easily and quickly develop a good geological understanding of the Nova Scotia offshore basins. The Geoscience Gap Analysis study was aimed at identifying geoscience activities that could help lower the barriers to entry.

## 3. Nova Scotia Government Funding

The results of the Geoscience Gap Analysis study triggered the NS Energy to make a case to the Province to provide funding for a comprehensive geoscience program to turn around current exploration interest trends. Companies aborted their exploration programs without completing them paying forfeiture penalties. Some of this forfeiture money is being used to fund the initiative to promote exploration activity on the margin.

In 2008 the Government of Nova Scotia committed funding of approximately $18 million to the OETR (Offshore Energy Technical Research) Association to enable it to undertake research to support offshore energy development. A significant portion of this (in the order of $15 million) is funding the PFA program, with the goal of stimulating renewed offshore petroleum exploration activity.

## 4. The PFA

In April 2009, after an extensive tendering process, the OETR Association awarded the contract to RPS Energy of the United Kingdom for program management services to co-ordinate an industry standard Play Fairway Analysis (PFA) project for offshore Nova Scotia.

The exploration history has shown the complex geological problems that need to be solved in order to demonstrate to the industry that there is a viable, attractive hydrocarbon region in offshore Nova Scotia. Several leading oil companies have determined that there is limited potential value in the shelf and have pulled out. The standard approaches to unlocking the hydrocarbon potential have failed.

The geoscience story is crucial. The key issues that will be addressed through the geoscience work include the following:

Showing that there is a route to reducing risk to acceptable levels with the fault seal capacity on the shelf to exploit the Sable Island play fairway.

Developing a model that can be used to predict reservoir presence on the slope. This will require understanding the interrelationship between salt movement and sediment transport and ponding.

Understanding the source rock story. There appear to be multiple source rock horizons with differing maturation timing and migration routes.

This work will show that the large undrilled features / structures that exist in the area could be hydrocarbon bearing and have substantial volumes. An understanding of the associated issues will be gained through innovative thinking based on a rigorous systematic approach to understanding the petroleum system.

Three important issues are being addressed as part of the overall play fairway program:

Plate Tectonic Reconstruction: there is a lack of understanding on the rift history of the margin and the timing of the final rift event. Understanding the relationship between rifting and salt deposition is critical in developing models for potential syn-rift and early post rift depositional environment and the development of source- rocks.

Forensic Geochemistry: although much geochemical data exists on the margin through the many hydrocarbon shows and discoveries, the source rock story is not understood. The program will undertake a systematic evaluation of geochemical source rock and hydrocarbon typing data. An important component of this work will include fluid inclusion studies from hydrocarbon traces found in the salt. An indication of lacustrine or restricted marine early Jurassic source rocks would considerably enhance the hydrocarbon potential of the area.

Sequence Stratigraphic Framework: there is no sequence stratigraphic framework for the margin. The program of work includes a re-evaluation of the biostratigraphy of several key wells which will be integrated with a seismic interpretation, and tectonic models, to build a comprehensive sequence framework.

### Program Components

The Play Fairway Program has evolved into a number of individual projects, including:

Plate Tectonics Modeling (described above)
Biostratigraphy
Geochemistry
Petroleum Systems Modeling
Seismic database preparation / Synthetics
Reprocessing of 7,500km 2D seismic lines
Seismic Rock Physics Review
Salt Structural Interpretation
Reservoir Quality
Play Fairway Evaluation

The projects are designed to incorporate the leading academic research being undertaken in Halifax into the overall PFA. Of particular note are the plate tectonic and salt modeling projects which build on work being done at Dalhousie University; and the biostratigraphy and reservoir quality projects which build on work being done at St. Mary's University. All projects will also build on the extensive high quality thinking and knowledge that exists in the Geological Survey of Canada (GSC) and the CNSOPB.

The Play Fairway Program integrates the results of these individual projects to develop an industry standard PFA and atlas. This will include the creation of Gross Depositional Environment (GDE), and Common Risk Segment (CRS) maps on each key sequence leading to the development of a final Yet-to-Find Analysis (YTF) by play segment.

The PFA is expected to be completed in March 2011 with the publication of a digital atlas that will be freely available to the exploration community.

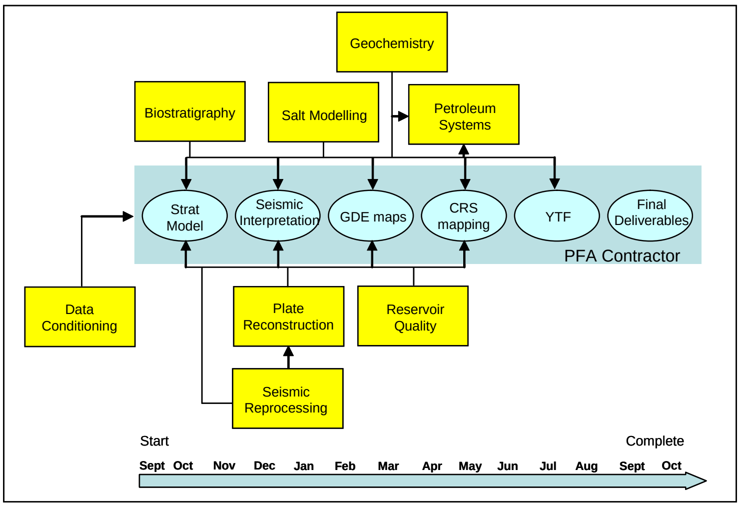


FIG.2 - Integration individual projects into the main PFA (RPS Energy proprietary document)

## 5. Marketing Plan for Ongoing Promotion

A marketing plan is currently being developed as a collaborative effort between the NS Energy, OETR Association, the CNSOPB and RPS Energy. A marketing plan will be an essential element to ensure the petro-technical results of the PFA are used effectively to promote offshore opportunities.

## 6. Conclusion

The current trend of oil & gas companies forfeiting their exploration licenses in favour of investment in more attractive basins elsewhere in the world has triggered the Nova Scotia government to make required funds available to the OETR Association to coordinate the PFA program. The goal of this work is to renew industry interest in developing Nova Scotia's offshore resources, increasing benefit to Nova Scotians through offshore royalty payments.

This PFA program is a major initiative that integrates expertise and knowledge of local academic and national research institutions working alongside some of the world's leading explorers. The intention of the program is also to work together with the seismic industry to make essential exploration-quality data available to this study. The assertion is that a publicly available PFA together with a package of geoscience data would enable investors to more easily appraise the risks and potential rewards of their investment.

As Nova Scotia is competing with more prolific basins in the world it will be necessary to promote PFA results through a variety of marketing activities which are aligned with other ongoing initiatives of the NS Energy.

*Acknowledgements*
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# Synsedimentary Tectonism on Wedge Top Basins: Offshore Rharb Basin (Northwestern Morocco)

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*ABSTRACT*

*The offshore area of the Rharb Basin is characterized by a series of mini-basins that evolve as shale withdrawal basins created on top of the Prerifaine Nappe. Deformation began during the Late Miocene-Pliocene as a consequence of sedimentary loading over the incompetent Prerif Nappe, that caused withdrawal and subsequence gravitationally collapse of the overlain Cenozoic stratigraphic levels. The extensional collapse created mixed extensional-compressional basins limited by normal listric faulting rooted in a detachment plane within the Nappe. Palinspastic restoration permits understanding of basin evolution and migration that together controlled the deposition of the deepwater turbidite succession.*

*KEYWORDS: Rharb basin, offshore, tectono-sedimentation, restoration.*

## 1. Introduction

The Rharb Basin is located onshore and offshore northwestern Morocco. The basin was created as result of the formation of the Gibraltar Arc and is the more external unit of the Rif Cordillera.

Northwestern Morocco evolved from a classic Mesozoic passive margin into an active margin due to the convergence of the Eurasia and African Plates and the westward escape of the Alborán microplate during Late Miocene time. The Gibraltar Arc represents the westernmost segment of the Alpine–Mediterranean Belt and connects the Betic Cordillera with the Rif Cordillera. The external domain includes sedimentary allochthonous units derived from the South Iberian and North African passive margins and results from a piggy-back sequence of emplacement from top to bottom and from hinterland to foreland.

The stratigraphy has been subdivided into pre-foredeep and foredeep successions (Flinch, 1993). The pre-foredeep corresponds to the infra-nappe formations unconformably overlying the Hercynian basement. The foredeep succession consists of Upper Miocene to Pliocene sediments that unconformably overlie the pre-foredeep succession by a basal unconformity. The Prerif Nappe was emplaced within the lower part of the foredeep succession and consists of Triassic to Miocene sediments whose stratigraphy is obscured by complex, compressional and gravity-driven tectonics (Feinberg, 1986).

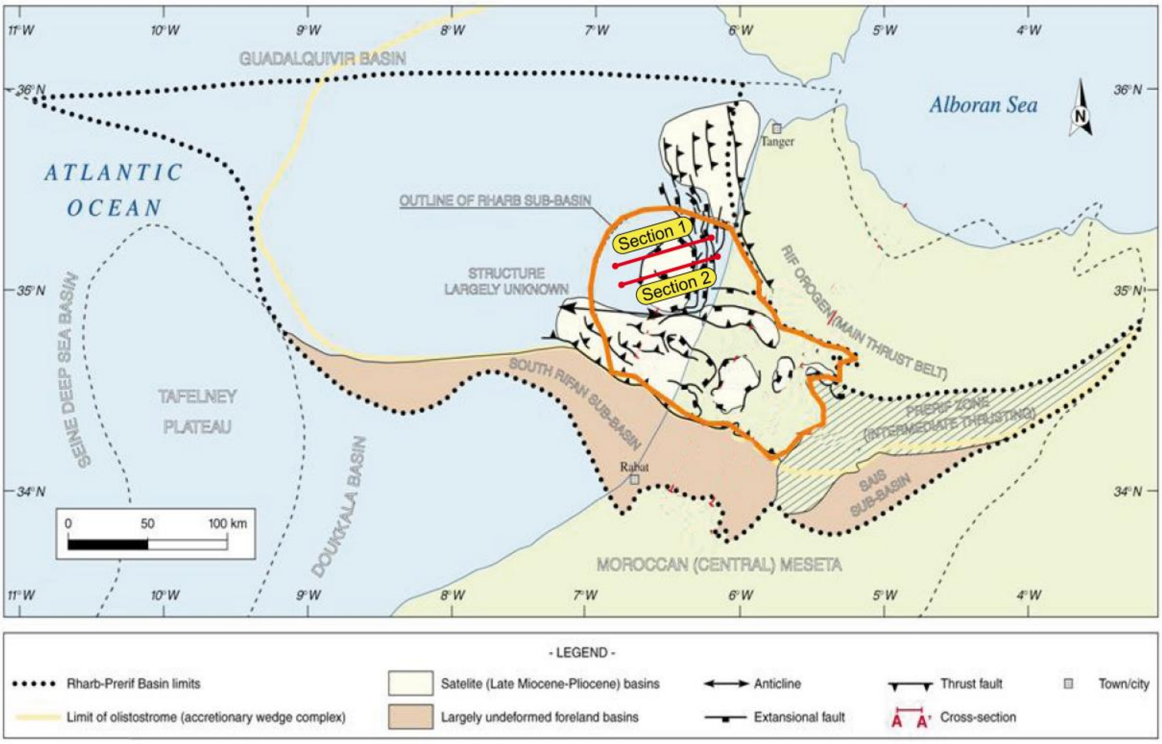


FIG.1 - Structural framework map.

## 2. Structure

Two regional northwest-southeast offshore seismic sections have been interpreted, converted to depth and restored to illustrate the evolution of the area (FIG.2). Seismic lines show a thick Tertiary section overlying the Prerif Nappe. This is an olistostrome sequence giving an irregular upper surface. This paleorelief was covered by a thick Miocene sedimentary sequence that produces instability of the incompetent Prerif Nappe. The extensional faults are rooted into the Prerif Nappe.

The restoration of the two lines (FIG.3) show that in the first stages the Miocene sediment loading triggered the extensional and gravitational processes. The Miocene depocentre is limited by a west-dipping master fault. Fault activity is more important in the south (Section 2) where it has also control the deposition of the base of the Lower Pliocene. To the north (Section 1), the activity of this fault decreases and deposition of the base of the Lower Pliocene seems to be controlled by differential compaction and subsidence (onlap relationships).

During the upper part of the Lower Pliocene and up to the Holocene, fault activity shifted to the west and the main depocentre, with sedimentation processes related to a master east dipping fault in Section 1. However, Section 2 shows that the sedimentation of the upper part of the Lower Pliocene is filling a small pod with onlap relationships on both sides.

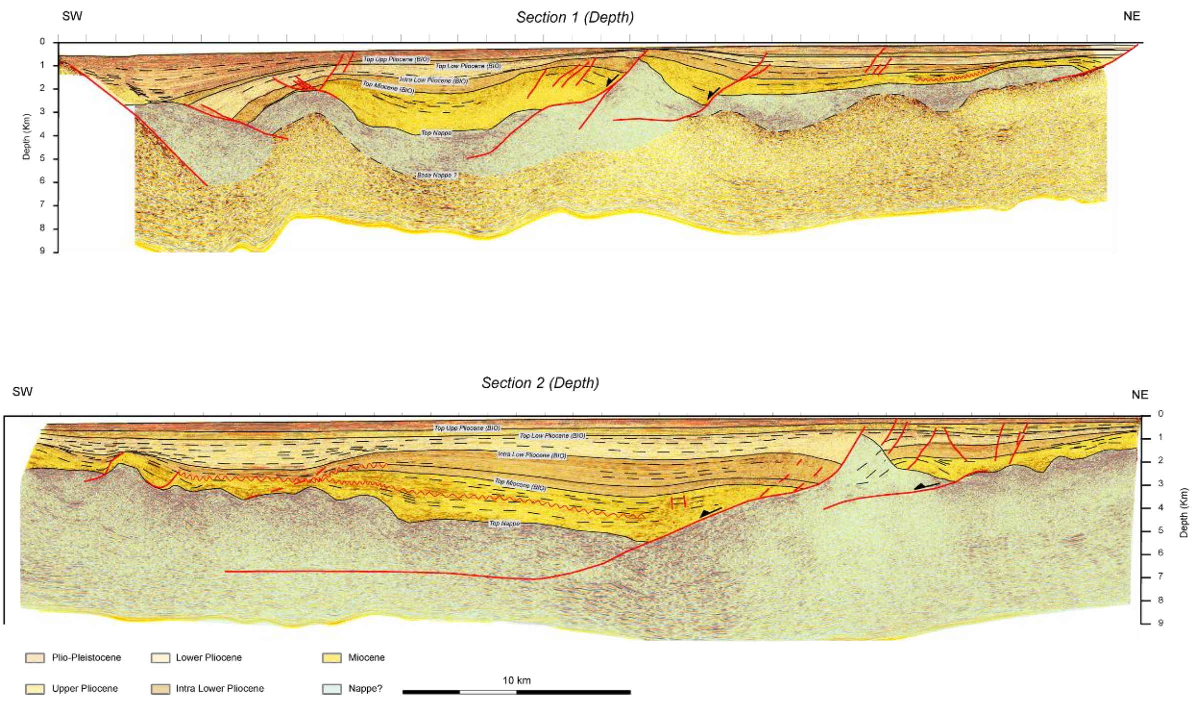


FIG.2 - Seismic lines used in this work. They were converted to depth; interpretation has well control.

## 3. Conclusions and discussion

Gravity spreading and extension began with the deposition of the Miocene sequence above the incompetent Prerif Nappe. Normal listric faults are rooted in this incompetent unit. Fault movement produced tilting and block rotation and probably toe thrust inside the Prerif Nappe. Sedimentation is mainly controlled by these normal faults and shifting of the sedimentation can be observed from east to west.

The palinspastic restoration has been very helpful to identify the movement and activity of the main faults present in the area. This activity controlled the accommodation space for the turbidite deposition, and knowing its evolution allows interpreting the location of the reservoir facies for the exploration prospects in the area.

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*The authors acknowledge Onhym, Gas Natural, Dana and Repsol the permission to publish the information and the results obtained.*

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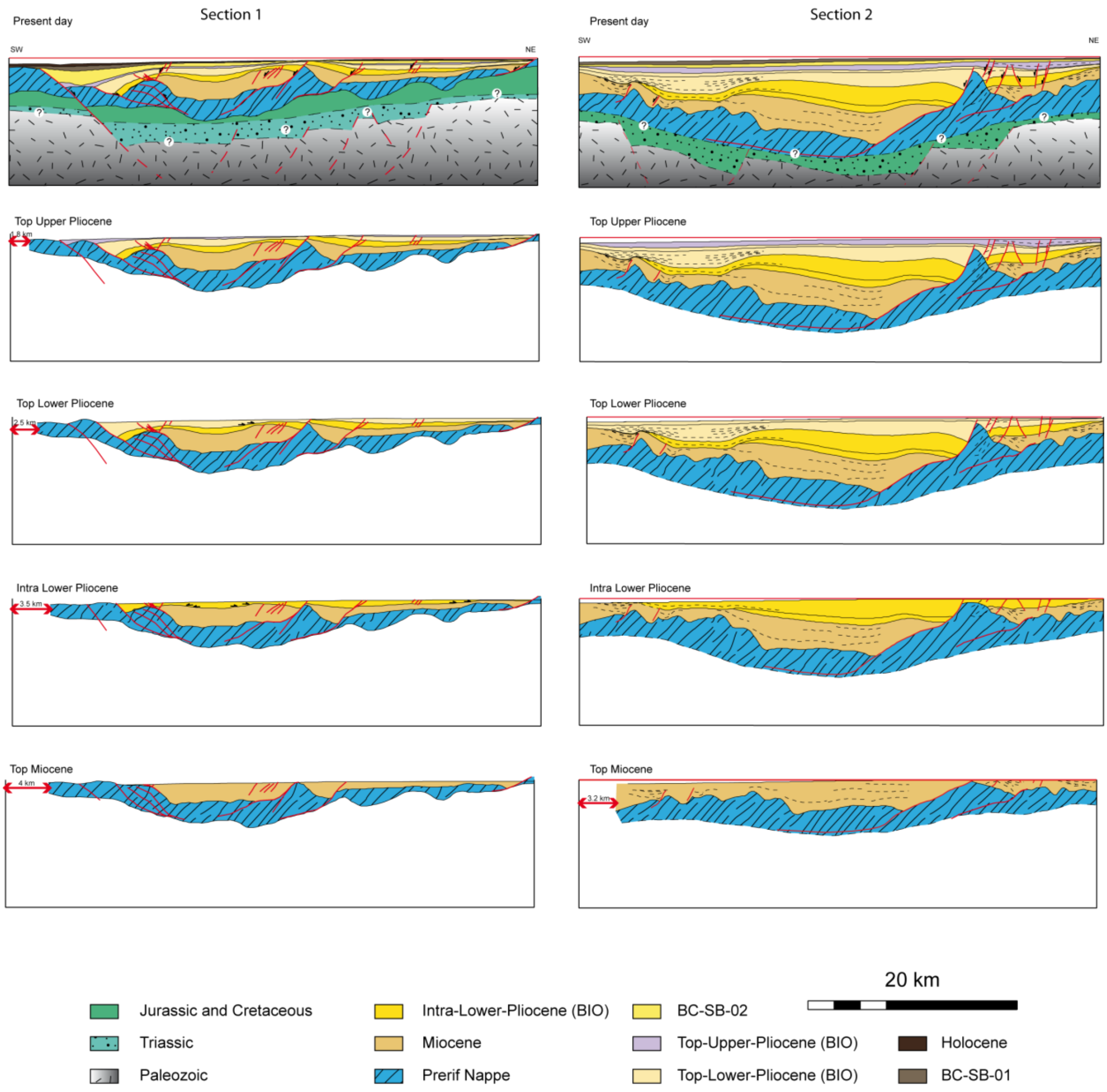


FIG.3 - Sections 1 & 2. These sections show the formation of the accommodation space through time and basin migration.