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Rediscovering the Atlantic: New Ideas for an old sea…

E&P IN ATLANTIC CONJUGATE MARGINS

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Foreword

A young ocean like the Atlantic is also a young realm in the quest for hydrocarbons. Newly conceived paradigms and models, old speculations, hopes and strong efforts are put together with edge technologies, testing some surprising discoveries and discovering more surprises.

These defying projects deal with many people mixing and boiling ideas, coming from many regions and countries, working together in companies, universities and other research institutions,.

The strategy is to assess existing models, to revisit some unhappy old proposals, to create unexpected roadmaps, to take a different place for an eye span and to travel and to dive inside the rocks.

Technologies must defy new performances and ideas must challenge the knowledge, putting in front of all, the doubt about the more solid theories.

New objects resemble surprising analogues where inspiration is obtained, old ideas deserve new harmonies, the most insignificant signs are put under the flashlights, and basins are more than treasures, waiting for our visit.

It is necessary to go deeper in our minds, to extend furthermore in our understanding and to fly faster beyond the hard summits. The Atlantic realm and his basins margins should conjugate as time goes back... Time slices, thick spaces, vanished distances and past landscapes must be our orientation. Science and Technology are the roads.

Manuel Ferreira de Oliveira

CEO Galp Energy

The world economic development and the population growth, which are expected to continue in the next decades, will present an increased challenge to the energy industry in general and the gas & oil industry in particular.

Up to now the energy industry has been able to meet the growing energy demands by discovering additional resources and maturing new or improve existing technologies to exploit these. Despite the growth of alternative energy sources, the world still relies on oil and gas for almost two thirds of its energy needs and this situation will not change dramatically in the next decade.

Global forecast studies indicate that the current oil field production will decline by 2/3 until the year 2030 but that this decline can be compensated by the increased oil production from offshore fields, which today represents around 1/3 of the world's supply.

In order to achieve this, the hydrocarbon industry has moved beyond the conventional to explore new frontiers. One of these new frontiers, which has been producing impressive results, is located in the deep (> ~ 200 m) and ultra deep (> 1500 m) waters of the oceans. These areas have yielded significant resources to date with exploration success rates superior to the ones in the onshore and shallow waters.

The technological progress has enabled to access these resources at an extraordinary speed, exemplified by the capabilities to drill in ever increasing water depths which in 1999, started at 1000 meters and reached 3000 meters in 2010. At these recent dephts even the supermajors have gained only a limited amount of expertise so far.

Ultra deep water requires stronger materials to e.g. withstand the enormous water pressures and more complex floating production systems. It is the latest new frontier posing a similar kind of challenge as putting a man on the moon. Costs are very high and, given the scale of understanding required, do demand a strong collaboration between the industries, the governments, research institutions and universities. In fact the latter two are very important industry allies to address these technological challenges.

Galp Energia ranks high among the E&P companies that believe firmly in the potential hidden below the oceans. This is also expressed by the fact that two thirds of the company´s portfolio consists of resources associated with attractive deep and ultra deep water acreages of this world.

António Costa e Silva

CEO Partex Oil and Gas

ATLANTIC CONJUGATE MARGINS

The organization of the conference on Atlantic Conjugate Margins in Lisbon is an honour for a city that launched many centuries ago bridges between the two sides of the Atlantic. We would like to thank the hard work of the organizers specially Dr. Nuno Pimentel from the Lisbon University and Dr. Pena Reis from Coimbra University, and also to all members of the Organizing Committee. We would like also to welcome all the experts and companies from different countries and we hope that the enlightened past of this city may inspire this conference with new ideas and concepts to build subsurface bridges between the two sides of the Atlantic that can help to understand better the geological correlations and similarities, the complex rifting and subsidence history and the combination of factors that lead to hydrocarbon generation and entrapment.

Around 200 Million years ago, the continental extension of North America and Eurasia started to develop the North Atlantic Margins. This separation took place in five major stages, beginning in the South and progressing to the North. But prior to the opening of the Atlantic, Portugal was joined to the Grand Banks area of present-day Canada. In this context, some analogues from the Eastern Basin of Canada can be expected in the Portuguese Deep-Offshore sedimentary basins, which may lead to important discoveries of Oil and Gas in this area. This is the fascination of the work done by geologists, geophysicists and geoscientists in general: they reconstruct the geological history and the complex evolution of the sedimentary basins, in order to identify the best leads and prospects with high potential for hydrocarbon presence.

In this endeavour many seismic profiles are analysed and many Geological and Geophysical Models are built. Nevertheless, as one of the leading Portuguese writers of the 20th Century, Virgílio Ferreira, put it: “When we are inside the house we cannot see the house and going out requires a lot of work”. The offshore geology of Portugal, located today at the South West margin of Europe, has been essentially controlled by three major events and displays a wide range of Play types. Tertiary Channel leads appear analogous to Oil and Gas fields in Mauritania and elsewhere, whilst Cretaceous and Jurassic plays may share common genesis with fields on the Western edge of the Atlantic Margin located in Newfoundland and Nova Scotia in Canada. This leitmotiv inspires the work of Geoscientists that build geological and geophysical models. In this side of the Atlantic, they need now to go out from the “house” in order to see the “house” and validate the assumptions. It is clear that without high quality 3D seismic no proper regional and prospect work can be done. It is also clear that future drilling is required in order to prove the validity of the postulated petroleum systems. Portuguese deep offshore basins were never drilled before. They remain large unexplored frontier acreage with the potential for hydrocarbon discoveries. We know that there is potential for both structural and stratigraphic traps and key exploration risks as source rock presence and maturity and occurrence of reservoir and seal rocks need to be addressed. But the potential is there, the adventure already started and the future is at our hands.

Partex is part of this adventure and is working with Petrobras, Galp and other partners in order to ensure success to this endeavour. Partex is an old petroleum company, it was founded in 1939 by Mr. Calouste Gulbenkian to manage its Oil and Gas participations in the Middle East. Mr. Gulbenkian is one of the “pioneers” of the oil industry and spent all his life trying to create bridges between the East and the West. He defined himself not as a “businessman” but as a “business architect”. Partex inherited this genetic mark from our founder and it is nowadays a Group that combines its traditional involvement in the United Arab Emirates and Oman with a modern approach based on the diversification of operations to other countries such as Kazakhstan, Brazil, Algeria and Angola. During its long history the Partex Oil and Gas Group has consolidated a well deserved reputation of being a reliable and discrete partner, with long-term vision and commitment to the countries where it is present, developing solid and lasting relationships with the national authorities and local companies. Partnership is the key that explains the success of the Group and no relationship can survive in the Oil industry without reliable partners, sound business ethics, confidence and a clear strategy for the future. In the Partex history this is the first time that the Group has decided to invest in Exploration Projects in Portugal. We know that the risks are high and must not be ignored or downplayed but the potential exists and the reward may be attractive.

The Oil industry is crossing today challenging times with major structural changes that will leave a major mark for the future. The growing difficulties to access new oil and gas reserves; the decline of production in North Sea, Alaska and elsewhere; the decline in the rhythm of new discoveries of significant size; the competition by new sources of energy; the resurgence of the resources nationalism - all these factors stress the importance of exploring and developing the deep offshore Oil and Gas reserves. However, as the tragic accident in the Macondo well in Gulf of Mexico has demonstrated, the industry needs to focus on ensuring safe and incident-free drilling operations. The short-term impact of the Gulf of Mexico tragic accident is just unfolding but it will range from new regulation to more detailed safety procedures, more adequate emergency plans, rising costs, more restrictive equipment inspections. On top of that, the medium and long-term impact may be even deeper and may reshape the existing oil corporate model, the type of organization, the culture and size of the companies. The need to move from monolithic centralized structures towards new approaches built on partnerships and joint ventures tuned to local needs, may also emerge. But, whatever the changes will be, one thing seems clear: in the medium term, once the economic development is back and recovery is stable, the world cannot avoid the exploration and development of the deep offshore oil and gas reserves given their impact to supply energy in order to meet the oil and gas demand. In this context, the Oil and Gas industry must extract all the learning lessons of the accident and improve the safety and reliability of the offshore operations. Partex will work with its partners, at our scale, to contribute to the success of these projects. The reinforcement of the cooperation among geoscientists working in both sides of the Atlantic and the reinforcement of cooperation among Oil Companies, Universities and Research Centers, will be a key element to ensure exploration and production success.

Francisco Nepomuceno[(1)] & Jose A. Cupertino[(2)]

(1) Manager of London Office
(2) General Manager of Exploration of the Eastern Brazilian Coast Basins

PETROBRAS AND THE RIFT RENAISSANCE

The Brazilian petroleum history related to the Atlantic margin began in the 1950's with the Recôncavo and Sergipe-Alagoas rift basins, located in onshore Northeastern Brazil. Afterwards, PETROBRAS turned the exploratory efforts to the offshore area, first in the Upper Cretaceous sequences where, based on the seismic stratigraphic concepts, significant giant oil fields in turbidite deposits were discovered.

Nowadays, PETROBRAS lives a new wave – the rift revival. The Company exploratory strategies are always looking for new frontiers, both in the geographic and/or in the geological meaning. The latest exploratory results led to an increased interest in the relationship between tectonics and sedimentation, as well as in the mechanical and thermal evolution of rift basins. In the Early Cretaceous (Neocomian), the central part of Gondwanaland was exposed due to a strong crustal extension process that caused the onset of NE rifts system. Part of those early rifts (e.g. Recôncavo Rift) was aborted before the Late Aptian continental breakup, whereas others (Campos and Santos Rifts Systems) evolved to a huge evaporitic basin in the Middle Aptian, which was followed by the development of passive marginal basins. The pre-evaporitic sequence has been our major recent targets, and the exploratory results have been the best!

On a broader scale, tectonics controls the formation of rift basins, but the deposition and distribution of the main reservoir facies occurred during the relatively quiescent periods, with a strong influence of climatic factors (e.g. provenance factors, carbonates vs. siliciclastics deposits). The search for a better understanding of the factors controlling structure and reservoir distribution in rifts is the reason to strengthen the symbiosis between academia and the oil companies aiming at the study of the concepts pertaining to the opening of the South and Central Atlantic. To understand the drilling results, one must know the asthenospheric behavior (thinning, cooling, mechanical responses, volcanism, heat flow history, etc), the formation of basinal space, the deposition and maturation of source rocks, the reservoirs depositional environment and paleogreographic facies distributions, and so on.

The understanding of the synchronous evolution of the eastern margin of South America and its West African counterpart is of utmost importance. The asymmetric nature of the breakup of the two conjugate margins caused an unequal distribution of both source rocks and reservoir units in the two sides of the South Atlantic. However, during the Early Cretaceous, we find similarities between the western branch of the modern East African Rifts Systems (EARS) and the western margin of the South Atlantic (passive margin, no volcanism as in the great African lakes). Additionally, some portions of the Brazilian South Atlantic margin in the Early Cretaceous also resemble the active, volcanic and anomalously hot Gregory Rift (EARS eastern branch). Keeping in mind the geotectonic evolution, PETROBRAS seeks, through its Exploration Department and Research Center, academic parties to recognize how tectonics controls the sedimentation to establish new models to support the exploratory strategies.

Bjørn A. Rasmussen

Country President, Statoil Angola

STATOIL – STRONG PRESENCE AND COMMITMENT AT BOTH MARGINS OF THE ATLANTICS

Statoil is an international energy company with operations in 40 countries and more than 35 years of experience from oil and gas production on the Norwegian continental shelf. We are headquartered in Norway with 29,000 employees worldwide, and are listed on the New York and Oslo stock exchanges. We were founded as The Norwegian State Oil Company, Statoil, in 1972. In October 2007, Statoil merged with Norsk Hydro's oil and gas division.

Facts about Statoil:

- Equity production of 1.962 million barrels of oil equivalent per day in 2009
- Operator for 39 producing oil and gas fields
- The second largest exporter of gas to Europe
- A world leader in the use of deepwater technology

International Exploration & Production is engaged in production from 12 countries: Canada, the USA, Venezuela, Algeria, Angola, Libya, Nigeria, the UK, Azerbaijan, Russia, Iran and China. International Exploration @ Production produce close to one third of Statoil's total equity production of oil and gas, and INT's share is expected to increase significantly in the future.

Statoil have a strong position at both sides of the Atlantic Ocean. We have exploration licences in North America (Canada and the USA), Latin America (Brazil, Cuba and Venezuela), Africa (Angola and Nigeria) and European area (the Faeroes, Ireland and the UK).

The main sanctioned development projects in which we are involved are in Canada, USA, Brazil and Angola, and we are well positioned for further growth through a substantial pre-sanctioned project portfolio.

Angola

The Angolan continental shelf is the largest contributor to Statoil's production outside Norway. It yielded approximately 200 mboe per day in equity production. Angola is a key building block in our international strategy and our ambition is to become an operator in the country.

Block 17 is operated by Total, and our interest is 23.33%. Production from the block currently comprises four development areas produced over two FPSOs. The Girassol, Jasmim and Rosa development areas are produced over the Girassol FPSO and the Dalia development area over the Dalia FPSO. The Pazflor project, which comprises the discoveries Perpetua, Acacia, Zinia and Hortensia, will be produced over a new FPSO with expected production capacity of 200 mboe per day and start-up scheduled for the end of 2011. The CLOV project, the fourth FPSO development in Block 17, consists of the discoveries Cravo, Lirio, Orchidea and Violeta. Basic engineering started in 2008. The project was sanctioned in July this year.

Block 15 is operated by Esso Angola. Our interest is 13.33%. Production from the block currently comes from five FPSOs; Kizomba A, Kizomba B, Xikomba, Kizomba C-Mondo and Kizomba C-Saxi Batuque. In addition, one satellite, Marimba, is producing through a tie-back to the Kizomba A FPSO. Kizomba satellites phase 1, consisting of two medium-sized discoveries - Clochas and Mavacola - was sanctioned by the partnership in 2009 and is scheduled to come on stream in 2012.

Block 31, an ultra-deepwater licence, is operated by BP, and our interest is 13.33%. The common development of the first four discoveries in the northern part of the block - Plutao, Saturno, Venus and Marte (PSVM) - was approved by the concessionaire in July 2008. PSVM will be developed via a new FPSO with a production capacity of 150,000 boe per day. Production start-up is expected in late 2011. Work is also ongoing to pursue the development of a second hub, comprising the Palas, Astraea, Juno and Dione discoveries.

Block 4/05 is operated by Sonangol P&P, and our interest is 20%. This block includes the Gimboa field. The average production has been 20 mboe per day since the FPSO commenced test production in April 2009.

Block 15/06 is operated by Eni. Our interest is 5%. Several discoveries have been made. Work is ongoing to assess a fast track development solution for the discoveries.

<u>Cooperation</u>

In Angola, Statoil have had a long-term cooperation with the national oil company Sonangol. We act as technical assistant in Block 34 and 4 where Sonangol is the Operator and have seconded personnel, provided training and technical services and shared best practises and management systems. Currently we also have a Technology Cooperation with Sonangol where we jointly develop new technology and knowledge.

Statoil also have a strong cooperation with academia. In Angola, one of our corporate social responsibility focus areas is higher education. We are involved in two Geoscience Master programs (University Agostinho Neto and the Private University in Lubango). The cooperation also encompasses guest lecturing, student internships and research projects. Statoil Angola also has an extensive international academic network. We have strong links to European universities in Rennes, Delft, Vrije, Trondheim, Barcelona and Coimbra. Through our office in Brazil we are establishing cooperation with UFF in Rio de Janeiro on seismic interpretation.

Nigeria

The Agbami field in deep waters off Nigeria has been developed with subsea wells connected to an FPSO. Production started in 2008. Agbami, which is operated by Chevron, is located in licences OML 127 and OML 128, approximately 110 kilometres off the Nigerian coast. Our interest in the unitised field is 18.85%. The Agbami field has a plateau production rate of 250 mboe per day.

Brazil

The Peregrino field is a heavy oil field located in approximately 120 metres of water in the prolific Campos Basin off the coast of Brazil, about 85 kilometres off the coast of Rio de Janeiro.

The field is being developed with a Floating Production Storage and Offloading Vessel (FPSO) and two wellhead platforms with drilling capability. The first oil production is planned to come on stream in early 2011 and we expect to reach plateau production within the first year of production. Design capacity is 100,000 boe per day. Installation of the wellhead platforms is completed and production drilling in progress.

Canada

Offshore, Statoil has interests in two crude oil producing fields: Hibernia (Statoil share 5%) and Terra Nova (15%), and in the two development projects; Hebron (9.7%) and Hibernia Southern Extension Unit (10.5%)

Hibernia, which was developed with a gravity base structure, is operated by Hibernia Management and Development Company Ltd (HMDC). The Hibernia field is in the initial stages of decline, with production rates averaging 125,000 barrels of oil per day. Terra Nova produces from a floating production, storage and offloading vessel and is operated by Suncor. The Terra Nova field is also in decline, with production rates averaging 80,000 barrels of oil per day.

The Hebron field, operated by ExxonMobil, will be developed with a gravity based structure. To date, the pre-engineering project studies have been completed. The Hibernia Southern Extension Unit, operated by ExxonMobil, comprises the development of resources in several fault blocks to the south of the existing Hibernia field. The field is planned for development as a satellite to the Hibernia field.

Ireland

Statoil has a 36.5% interest in the Corrib gas field, which lies on the Atlantic Margin north-west of Ireland. The Shell-operated Corrib field development was sanctioned in 2001, and work towards first gas is progressing. The development will comprise seven subsea wells, and the gas will be transported through a pipeline to an onshore gas processing terminal.

Technology

The Atlantic margin is a technically challenging area, with harsh environment, deep water and complex geology. The key to success is based on a good understanding of the geology, from large scale regional geology to reservoir scale.

In the South Atlantics, salt play an important role for exploration. Salt tectonics is a key element for understanding generation and retention of hydrocarbons. Even with high quality seismics, imaging of salt and presalt is difficult and requires use of advanced processing and imaging techniques. Understanding the tectonostratigraphic evolution and the similarities and differences between the conjugated margins helps identifying new plays and areas.

The Conjugated Margins is an important conference, where our researchers and explorationists meet others fellow colleagues to extend their knowledge and exchange ideas. We hope the conference will trigger discussions and stimulate creativity and look forward to many exciting presentations.

The Orphan Basin – a key to understanding the kinematic linkage between North and NE Atlantic Mesozoic rifting

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ABSTRACT

The Late Triassic to Early Cretaceous rifting in the N and NE Atlantic region formed a system of spatially and temporally overlapping rift zones. In this period the Orphan and Jeanne d'Arc basins, off Newfoundland, developed as the southern extremity of the Rockall Trough, and was formed contemporaneously with the Newfoundland-Iberia conjugate margin development. The complex structure of the Orphan Basin infers formation by two primary episodes of rifting. The total duration of extension lasted about 80 my, causing the Flemish Cap to wedge away from the Canadian shelf. Despite the long duration rifting and the magnitude of extension within the basin, the stage of seafloor spreading seems not to have been reached. The relative plate motion between the various structural elements makes it particularly evident that the northward decay in extension along the Newfoundland-Iberi rift is compensated by an oppositely directed decay in the width of the East Orphan and Jeanne d'Arc basin elements, and subsequently by the West Orphan Basin-Flemish Pass extension. The long duration extension and strain partitioning in the system argues for low strain rates, which is considered a main guiding factor for the mode of lithospheric deformation observed along different rift segments.
KEYWORDS: N Atlantic, NE Atlantic, Newfoundland, Iberia, rifting.

1. Introduction

The plate kinematics of the Central and North Atlantic Ocean have been mapped and described by several authors and a general consensus is largely reached with respect to both margin segmentation, timing of rifting, and continental break-up (e.g. Roest et al., 1992; Srivastava et al. 2000; Sibuet et al. 2007). In general the extensional deformation started in Late Triassic times and lasted until the Early Cretaceous when final separation between the Flemish Cap and Galicia Bank occurred. The Late Triassic rifting affected both the Central and North Atlantic regions, but while breakup between N America and NW Africa seems to have occurred as early as 184 Ma, the Newfoundland-Iberia (Nfl-Ib) breakup is described by a diachronic opening between 145 and 118 Ma (Srivastava et al., 2000). Between Newfoundland and Iberia the presence of serpentinized exhumed mantle, documented by ODP drilling (e.g. Whitmarsh et al., 1998; Tucholke et al., 2004), represents an important component in the understanding of the mode of lithospheric deformation taking place, as well as it questions some aspects of the nature of the continent-ocean transition development.

The aim of this paper is to re-evaluate the plate kinematic model, taking into account the structural setting in the Orphan Basin, and demonstrate how the linkage between Mesozoic rift development in the N and the NE Atlantic regions adds new insight on the overall N Atlantic rift to drift evolution. Particular focus is put on how strain partitioning enables the development of propagating and overlapping rift zones creating rapid changes in strain over relative short distances.

The plate reconstructions are made using in-house developed, proprietary software called the 4D Lithosphere Model (4DLM), which enables clipping and rotation of gridded data.

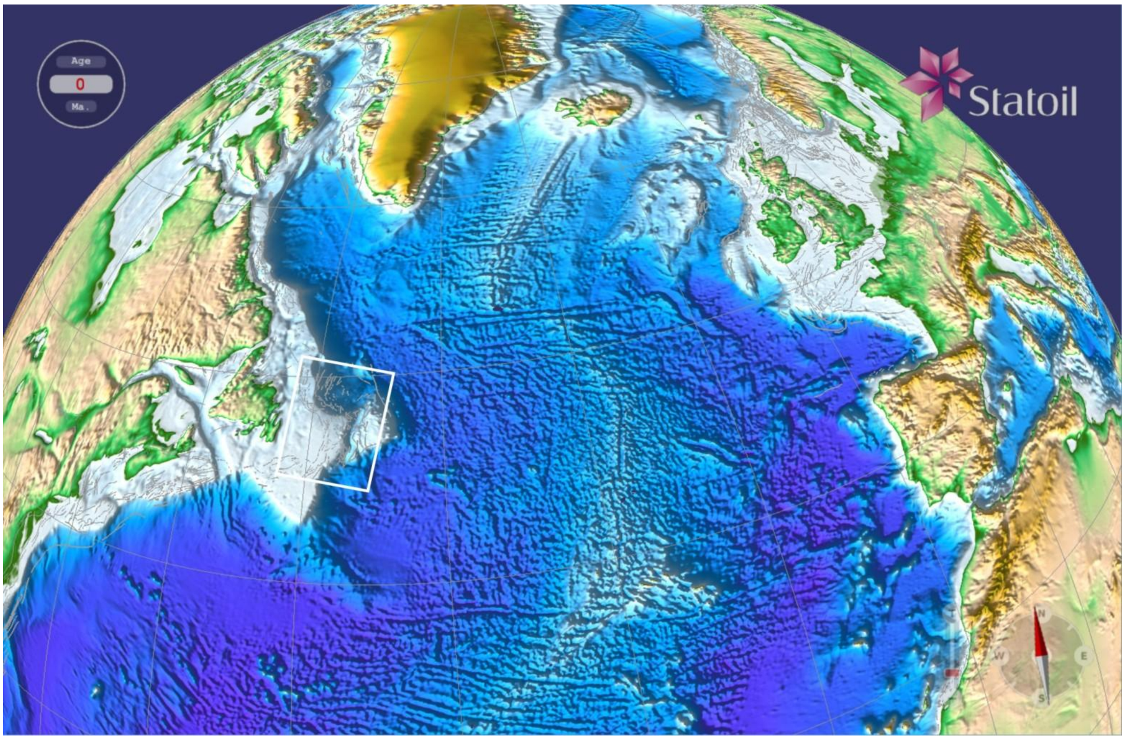


FIG.1 - North Atlantic Bathymetry/Topography map (Etopo2; NOOA) with location of the Grand Banks-Orphan Basin main study area (white rectangle). Structural lineamants (grey lines) are shown for genaral delineationof the main tectonic regions.

2. The Orphan Basin

The Orphan Basin represents a very broad rift zone, which in general is subdivided into a western and an eastern rift (FIGS.2 and 3). The East Orphan Basin predominantly reflects a Late Triassic-Jurassic rift development that links up with the development of the Jeanne d'Arc Basin to the south (FIG.2). Within the East Orphan Basin the Orphan Trough represents a particularly deep rift structure. From its seismically defined structure it demonstrates high degree of crustal (and lithospheric) thinning along its axial zone (FIG.4). The observed shallow Moho reflector from the seismic data correlates with a pronounced Bouguer gravity high implying an unusual up-warping of the crust-mantle density boundary. The formation of the trough appears to have taken place late during the formation of the East Orphan Basin, possibly as late as the Early Cretaceous.

The West Orphan Basin is interpreted to have formed as an Early Cretaceous rift basin, and it seems to lack a tectono-stratigraphic parallel to the Jeanne d'Arc Basin. The northern parts of the basin are characterized by a very wide, but apparently symmetric rift structure where large and rotated fault blocks dominate on both sides of the central rift zone. Some of the faults appear to be hundreds of km long and show heaves of several ten's of km (FIGS.2, 3 and 5).

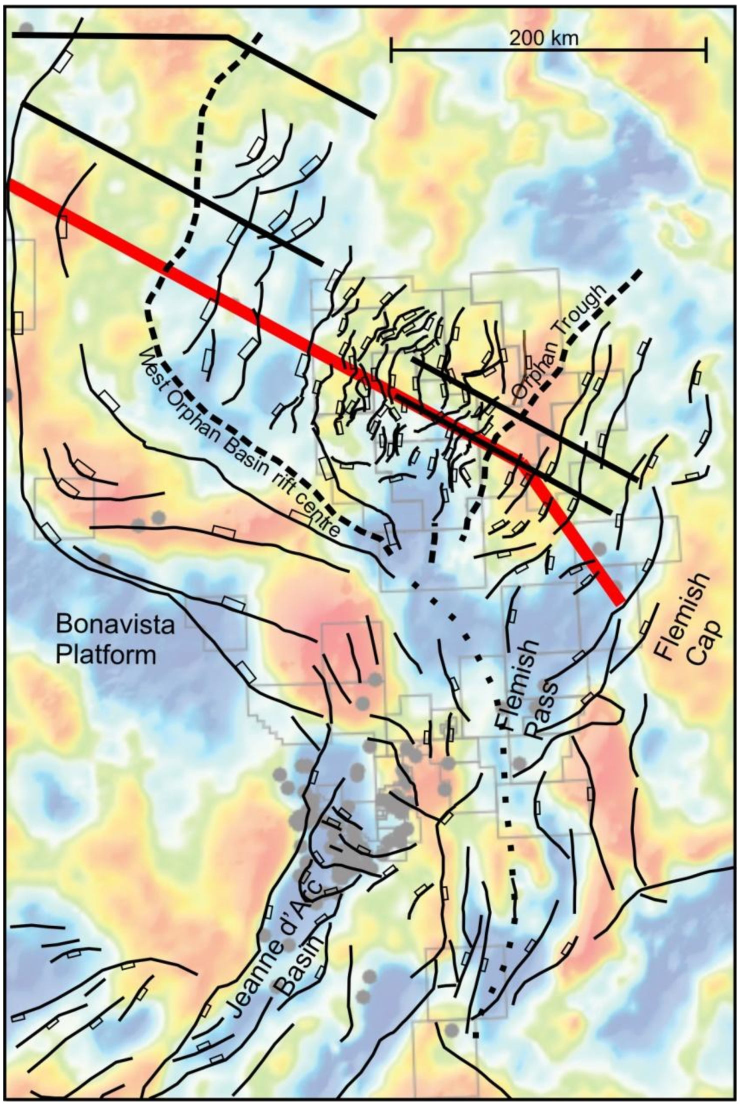


FIG.2 - Structural setting of the Orphan Basin plotted on top of a 200 km high pass filtered Bouguer gravity map. Location of seismic line drawings in FIGS.3 (bold red line), 4 (black lines across Orphan Trough) and 5 (black lines across northern West Orphan Basin rift Centre). Potential continuation of the West Orphan Basin rift Centre through the Flemish Pass is indicated by bold dotted line. Filled grey circles are pre 2003 exploration wells.

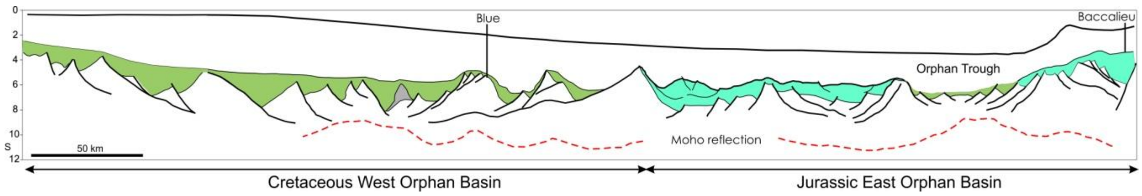


FIG.3 - Crustal cross section of the Orphan Basin (location in FIG.2) with pre Cretaceous sediment in the Jurassic East Orphan Basin (turquoise) and Lower Cretaceous sediment in the Cretaceous West Orphan Basin (green). Location of Blue and Baccalieu exploration wells shown for reference.

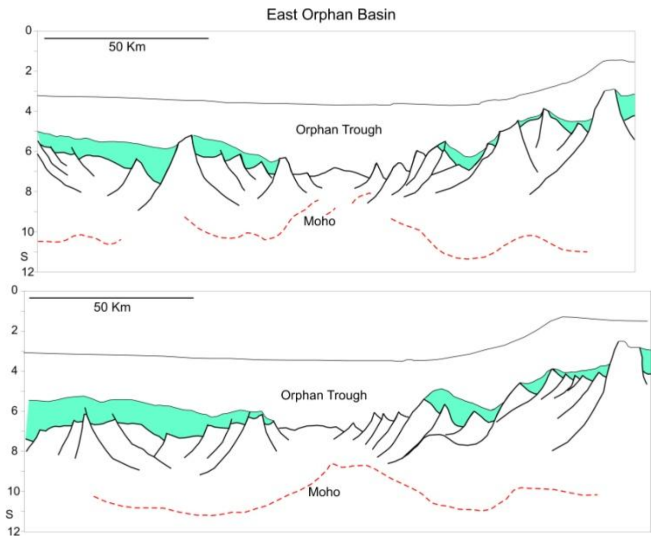


FIG.4 - Crustal structure of the Orphan Trough in the East Orphan Basin (location in FIG.2). Note the pronounced crustal thinning and shallow reflection Moho beneath the trough. Pre Cretaceous sediments in turquoise.

A probable Moho reflector can be interpreted, implying significant crustal thinning along the central rift zone. In addition, some seismic lines across the northern part of the rift show a possible volcanic structure near the rift axis indicating that the stage of seafloor spreading may almost have been reached before rifting ceased (FIG.5). The rift axis of the West Orphan Basin is structurally characterized by a close to 90 degree bend, from a NE-SW trend to the north, to a NW-SE trend towards the south, where the central rift zone narrows significantly and seems to be cross-cutting the southern portion of the Jurassic East Orphan Basin (FIG.2). Form the available seismic data it is not easy to document that the West Orphan Basin rift continues into the Flemish Pass, but the apparently contemporaneous rift development of the two, and the Bouguer gravity signature makes this interpretation a tempting solution (FIG.2).

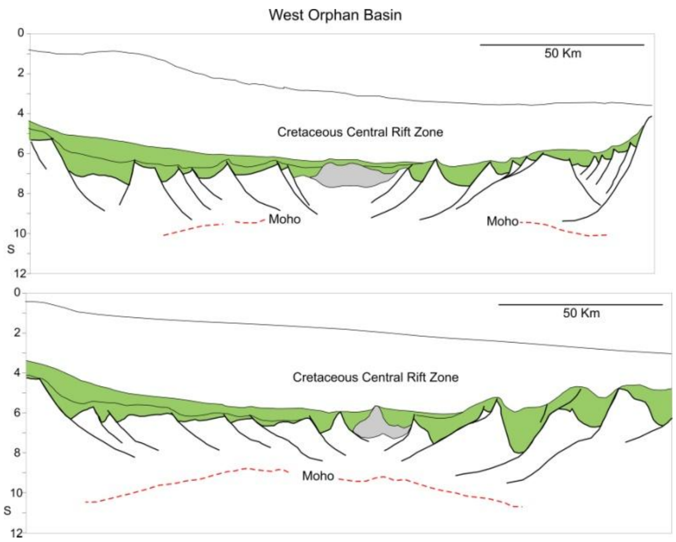


FIG.5 - Crustal structure of the West Orphan Basin (location in FIG.2) Note the pronounced crustal thinning and interpretation of a shallow reflection Moho beneath the central rift. Lower Cretaceous sediments in green.

3. The plate kinematics of N and NE Atlantic Mesozoic rifting

From a plate kinematic point of view previous models for the opening of the North Atlantic have largely overlooked the fact that the Orphan Basin plays an important role in the big scale picture. The two stage development of the basin, which implies a kinematic model where the Flemish Cap is rotated away from the Bonavista Platform has in fact large implication also for the understanding of the temporal development of the rifting to breakup between Newfoundland and Iberia, and thus links into the discussion of how to understand the formation of hyper-extensional rifted margins (e.g. Whitmarsh et al., 2001; Manatschal et al., 2001). Rotation of the Flemish Cap has been suggested by Srivastava et al (2000), Skogseid et al. (2003) and Sibuet et al (2007) but without fully addressing the magnitude of extension and the tectonic linkage between the Orphan Basin and its neighbouring tectonic elements. Here, a kinematic model is suggested that aims for an understanding of the tectonic linkage between N and NE Atlantic Mesozoic rifting, and by doing so also shedding some light on the variations in strain rates between rift zones and along rift segments.

Early North Atlantic rifting is described to have occurred episodically by one rift phase in the Late Triassic-Early Jurassic and a second in the Late Jurassic-Early Cretaceous (e.g. Tucholkie et al. (2007). It is known that the Late Triassic-Early Jurassic rifting also affected the Grand Banks basins, including the Jeanne d'Arc Basin, where Triassic salt locally was deposited. Similarly, Late Triassic-Earl Jurassic extension is reported from the Porto and Galicia Interior basins on the Iberian side (Murillas et al., 1990). However, Late Triassic extension is also mapped SW of Britain and in the Celtic Sea (Tankard and Welsink, 1989), which indicates that the extensional motion between North America and Africa/Iberia also included relative motion between North America and Eurasia at this time.

The North Sea rift , the Porcupine Basin and the Rockall Trough has been somewhat debated in terms of their age of early rifting, but it is generally assumed that the North Sea predominantly had a Late Jurassic development, whereas the two others formed over a longer time period with continued extension into the Early Cretaceous. Both the northward continuation of the Rockall Trough and the North Sea rift are, however, linked northward to the Late Jurassic-Early Cretaceous rift zones off mid Norway and into the SW Barents Sea.

In the plate reconstruction suggested here, where the opening of the Orphan Basin is quantified; there are a number of interesting observations. The reconstruction to 200 Ma (FIG.6a) shows the presumed pre-rift setting, where only little early rift development has taken place between N America and Africa/Iberia with links into the Celtic Sea and basins SW off Britain. The main uncertainty in this reconstruction is the position of the Iberian Plate and the degree of closure between Iberia and Newfoundland.

At 180 Ma (FIG.6b) early rift formation is established by a system of distributed and overlapping rift zones. Note that the Rockall Trough-East Orphan Basin is nicely aligned, and can be linked into the Jeanne d'Arc Basin. This rift zone spatially overlaps with both the Grand Banks Basin and, more importantly, with the Nfl-Ib rift zone, itself extending northward into the British/Celtic shelf and with a probable branch into the Porcupine Basin. Iberia is fixed to Eurasia, which means that in a cross section from N America to Iberia, across the Jeanne d'Arc and the Nfl-Iberia rifts, has an added rotation similar to a cross section over Rockall Trough, Porcupine Basin and the Celtic Sea. If the Jeanne d'Arc Basin actually formed as the tip of the southward propagating Rockall Trough, the presence of Triassic sediments in the Jeanne d'Arc Basin is indirect evidence that also the Rockall Trough has a Late Triassic rift initiation.

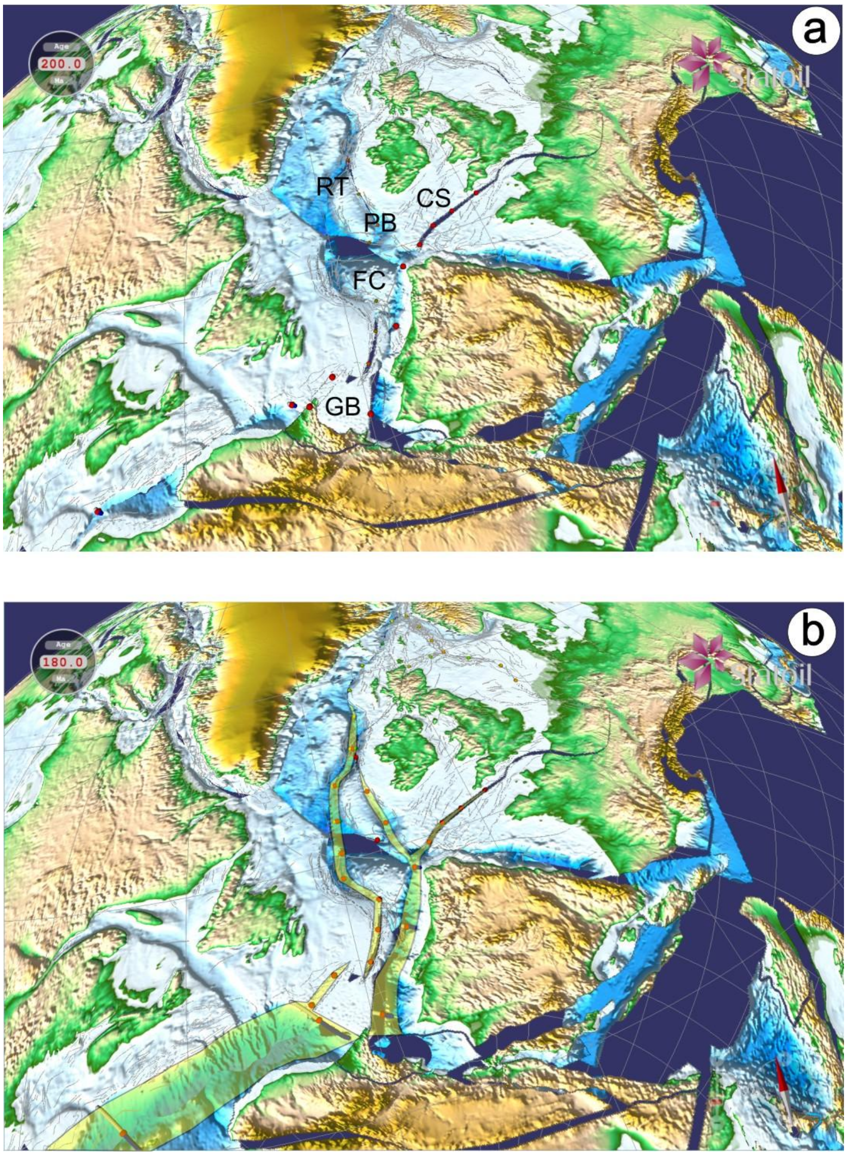
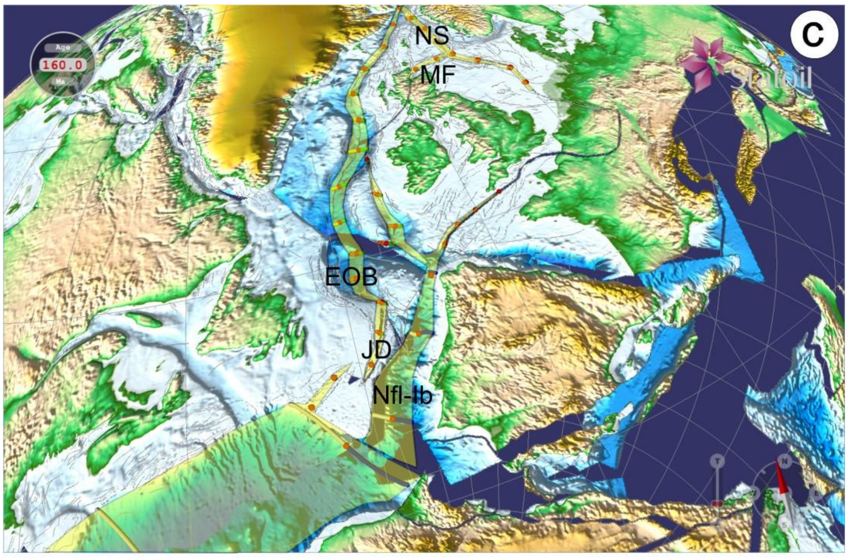


FIG.6 - Time steps in the plate kinematic model linking the Mesozoic N and NE Atlantic rifting. a) 200 Ma early rift configuration between N America and Africa/Iberia/Eurasia b) 180 Ma early basin formation establishing a system of distributed and overlapping rift zones. Total magnitude of extension along rift zones is shown by yellow shading. GB: Grand Banks; CS: Celtic Sea; FC: Flemish Cap; RT: Rockall Trough; PB: Porcupine Basin.

At 160 Ma (FIG.6c) rifting off SW Britain and in the Celtic Sea has ceased and deformation is centred along the Nfl-Iberia – Porcupine rift zone, overlapping with the Rockall Trough-East Orphan Basin-Jeanne d’Arc rift zone. Note that this early phase distributed deformation includes rifting in the North Sea and the Moray Firth Graben, which accounts for a part of the total N America–Eurasia relative plate motion, causing a relatively rapid northward decay in the width of the Rockall Trough.

At 140 Ma (FIG.6d) the eastward relative motion of the Flemish Cap and the East Orphan Basin with respect to the Eurasian side have caused the Rockall Trough to abandon the linkage with the East Orphan Basin. At this stage the West Orphan Basin is established by a westward rift axis jump and southward rift propagation, which cut across the East Orphan and Jeanne d’Arc basins, and continues through the Flemish Pass. Also the Nfl-Ib–Porcupine rift linkage now seems unfavoured, while the Porcupine Basin now seems to line up with the Orphan Trough within the East Orphan Basin.



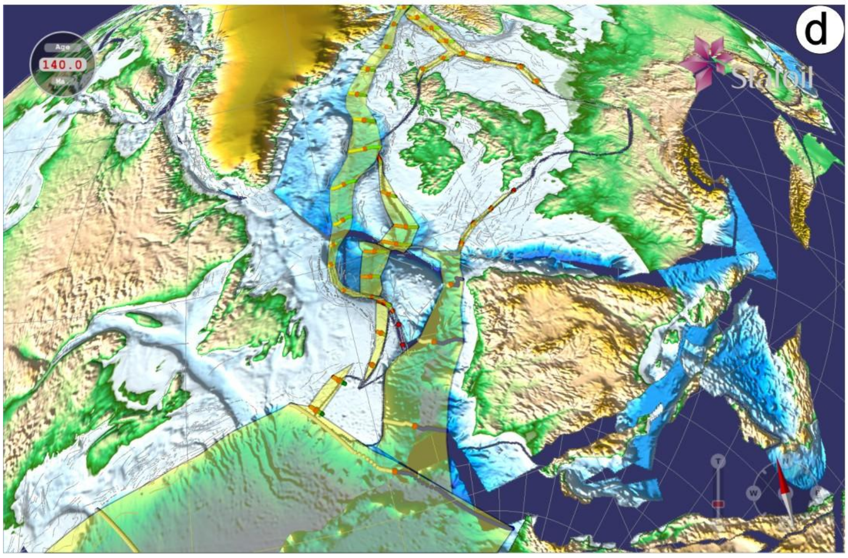


FIG.6 - continued: c) 160 Ma rifting off SW Britain and in the Celtic Sea has ceased and deformation is centred along Newfoundland-Iberia–Porcupine rift overlapping with the Rockall Trough-East Orphan Basin-Jeanne d'Arc rift zone. d) 140 Ma reconstruction where the Rockall Trough has abandoned the linkage with the East Orphan Basin and established the West Orphan Basin by a westward rift jump and a southward propagation cross-cutting the East Orphan and Jeanne d'Arc basins to continue through the Flemish Pass. Total magnitude of extension along rift zones is shown by yellow shading. GB: Grand Banks; CS: Celtic Sea; EOB: East Orphan Basin; FC: Flemish Cap; JD: Jeanne d'Arc Basin; MF: Moray Firth Basin; Nfl-Ib: Newfoundland-Iberia rift zone; NS: North Sea Basin; RT: Rockall Trough; PB: Porcupine Basin.

The 120 Ma reconstruction (FIG.7) shows the final stage in the tectonic development of the Orphan Basin. The map as such, resembles largely the M0 reconstruction by Srivastava and Verhoef (1992), while the flowlines of relative motion between pairs of plates demonstrate the magnitude (but not the spatial distribution) of extension within each basin element. It is particularly evident that the northward decay in extension between Newfoundland and Iberia is compensated by an oppositely directed decay in the width of the Orphan and Jeanne d'Arc basin elements. The shape of the West Orphan Basin-Flemish Pass rift and the angle of rotation chosen imply only a moderate N-S shear motion approaching the southern tip of the rift; a motion that causes little spatial complications with the respect to the ongoing opening between Newfoundland and Iberia. The Porqupine-East Orphan Basin alignment may have triggered renewed extension and formation of the Orphan Trough as part of the East Orphan Basin.

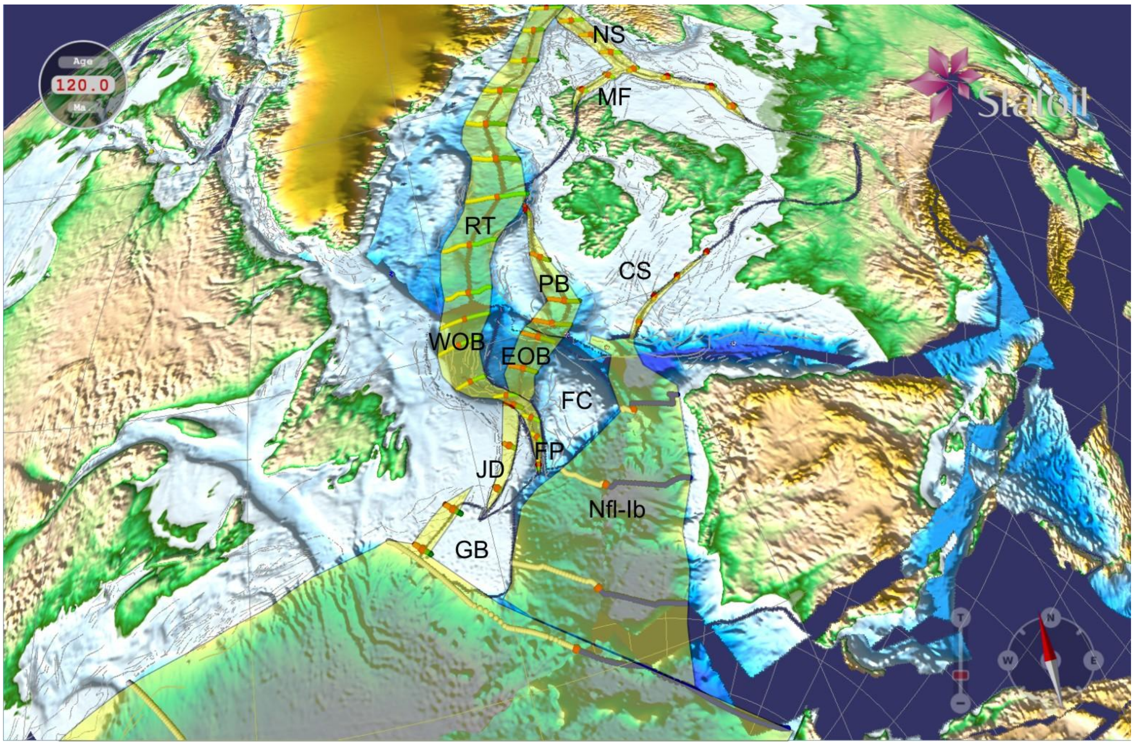


FIG.7 - 120 Ma reconstruction showing the final stage of Orphan Basin development with flowlines describing the relative motion between pairs of plates. Note that the width of the different rift zones (yellow shading) only represents the magnitude of extension as it is embedded in the rotation file, while the basin shapes and structural elements more reflect the distribution of the deformation. GB: Grand Banks; CS: Celtic Sea; EOB: East Orphan Basin; FC: Flemish Cap; FP: Flemish Pass; JD: Jeanne d'Arc Basin; MF: Morray Firth Basin; Nfl-Ib: Newfoundland-Iberia rift zone; NS: North Sea Basin; RT: Rockall Trough; PB: Porcupine Basin; WOB: West Orphan Basin.

4. Discussion

The Plate kinematic model presented here treats the relative motion between N America and Iberia/Eurasia as a continuous motion between 200 and 120 Ma. Thus, no attempt has been made to align with the model of episodic extension (e.g. suggested by Tucholke et al. 2007). The data from the Orphan Basin does not contain the stratigraphic information needed to do so, but multiple generation of faulting reflects that repeated extension has taken place. The large width of the basins and its long duration rifting makes it likely that strain partitioning in the different rift elements to some degree has developed independently. The observations Tucholke et al. (2007) based their conclusions on were primarily from the Newfoundland-Iberia rift zone, and should not necessarily be transferred to the Orphan rift system. On the other hand, with respect to the total stress and strain distribution during rifting, the Orphan Basin development needs be addressed when the Newfoundland-Iberia opening is discussed, and visa versa.

The main elements of uncertainty in the reconstruction seem to be the position of the Iberian Plate, both with respect to its N-S position between Eurasia and NW Africa, and to how tight the fit between Iberia and Flemish Cap should be made. Here a close fit with the Flemish Cap is suggested, leaving little space for the Galicia Bank, and indirectly suggesting that the bank has emerged beneath an intra crustal low angle detachment fault during extension. It should be stressed, though that the exact width of this pre-rift closure not represent an important element for the main conclusions made below.

In this plate model the assumption is made that the NE Atlantic, i.e. Rockall Trough-Orphan Basin, rift development ended at 120 Ma. This cessation of extension, i.e. approximately M0 time, correlates logically in time with that final separation and the establishment of seafloor spreading between the Galicia Bank and the Flemish Cap (e.g. Sibuet et al., 2007). The subsequent displacement in the N Atlantic was transferred into Labrador Sea rifting, cross-cutting the NE Atlantic rift elements.

The N Atlantic rift to drift development demonstrated here, shows that a number of spatially overlapping, and probably propagating rift zones, are accommodating the plate tectonic motion between N America on one side, and Africa, Iberia and Eurasia on the other. It seems evident that any attempt on dynamic modelling of lithospheric deformation, thus, will need 3D rather than a 2D approach. Rift propagation, in particular, is a deformation mechanism not possible to embed in a simple 2D rheology model. Realizing this is also reducing the predictive value of such models. In particular with respect to gaining knowledge of how strain is partitioned and what the resulting consequences are for the structural fabrics to be formed.

The duration of rifting embedded in the plate kinematic model implies low strain rates during extension. Between the Galicia Bank and Flemish Cap the extension velocities are in the order of 0.23 cm/y, in contrast to the region further south, between the Grand Banks and the southern tip of Iberia, with velocities of 0.63 cm/y. In the East Orphan Basin (<0,19 cm/y; assuming continuous development from 200 to 140 Ma), the Rockall Trough (0,28 cm/y; from 200 to 120 Ma) and the Porcupine Basin (<0,21 cm/y; from 200 to 140 Ma) similarly small extension rates apply. Strain rates of these magnitudes are interesting with respect to the thermal structure and rheology of the lithosphere during deformation. The low strain rate Nfl-Ib rift system caused hyperextension to develop, where the crust failed before the continental mantle leaving a somewhat asymmetric rift structure (e.g. Boillot et al., 1987; Whitmarsh et al., 2001; Manatschal et al., 2001; Shillington et al., 2006; Pe´ron-Pinvidic et al., 2007; Reston, 2009). In the Orphan Trough the thinnest ‘crust’ observed is only 4 km, which also imply that the crust has been thinned significantly more than the mantle. Here the Bouguer anomaly along the northern portion of the trough indicates a significant up-warping of the high density mantle. Low strain rates and syn-rift cooling efficiently truncate partial melting at the lithosphere-asthenosphere boundary (Pedersen and Ro, 1992), which neatly correlates with the apparent lack of igneous activity along the rift.

In the Rockall Trough very thin crust exists over a wide portion of the structure. Again the low strain rates seem to have allowed extreme extension without breakup (read decompression melting). Here a 7+ km/s velocity layer at the base of the crust is interpreted to represent serpentinized mantle (Shannon et al., 1999), to some extent resembling the discoveries off Iberia and Newfoundland. The presumed Late Jurassic-Early Cretaceous age of the Rockall Trough is, furtehmore, questioned by this model. E.g. if the Jeanne d’Arc basin is the southern tip of a propagating Rockall Trough, then the central Rockall Trough has to be slightly older than the Jeanne d’Arc basin, and as such must have started its development in Late Triassic time.

The Cretaceous West Orphan Basin, where some volcanic constructions along the central rift zone are inferred on the seismic data (FIG.5), extension velocities up to 0,6 cm/y are derived assuming extension between 150 and 120 Ma only. The structure of the northern parts of the West Orphan Basin shows a wide, near symmetric, rift development, and despite the relatively thin crust along the central rift zone, no distinct Bouguer gravity anomaly (similar to the Orphan Trough) is observed.

5. Conclusions

The main conclusion that is derived from this study is that there was a close link between N and NE Atlantic Mesozoic rifting. In fact, keeping Iberia fixed to Eurasia, the opening between N America and Iberia, and between N America/Greenland and Eurasia is defined by the same angle of rotation and spatially accounts for all the Mesozoic basin elements within the region. The Rockall Trough developed as the main Mesozoic NE Atlantic rift centre; is interpreted to have been directly linked into the two stage development of the Orphan Basin; and most importantly, to have developed in parallel, both in time and space, with the Newfoundland-Iberia rift.

The large scale structural picture of a series of overlapping and propagating rift zones neatly explains the rapid decay in width of individual rifts. The flowlines of relative motion demonstrate the magnitude (but not the spatial distribution) of extension within the basins. It is particularly evident that the northward decay in extension along the Nfl-Ib rift is compensated by an oppositely directed decay in the width of the East Orphan and Jeanne d'Arc basin elements, and subsequently by the West Orphan Basin-Flemish Pass extension.

The generally low strain rates likely explains the lack of melt formation by decompression melting, thus inhibiting the transition to seafloor spreading despite the total magnitude of extension, and the locally very thin remaining continental crust. The low strain rates are considered an important element controlling the mode of lithospheric deformation.

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Thermo-Mechanical Controls on Rifted Margin (De)formation

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Polyphase extensional and compressional reactivation of basins is a common feature in basin evolution. To differentiate between the different modes of basin formation and reactivation of passive margins and extensional basins, the development of innovative combinations of numerical and analogue modeling techniques is key. We present an overview of recent advancements in developing and applying analogue and numerical thermo-mechanical models to quantitatively asses the interplay of lithosphere dynamics and basin (de)formation.

Field studies of kinematic indicators and numerical modeling of present-day and paleo-stress fields in selected areas have yielded new constraints on the causes and the expression of intraplate stress fields in the lithosphere, driving basin (de)formation. Temporal and spatial variations in the level and magnitude of intraplate stress have a strong impact on the record of vertical motions in sedimentary basins. Over the last few years increasing attention has been directed to this topic advancing our understanding of the relationship between changes in plate motions, plate-interaction and the evolution of rifted basins.

The actual basin response to intraplate stress is strongly affected by the rheological structure of the underlying lithosphere, the basin geometry, fault dynamics and interplay with surface processes.

Integrated basin studies show that rheological layering and strength of the lithosphere plays an important role in the spatial and temporal distribution of stress-induced vertical motions, varying from subtle faulting to basin reactivation and large wavelength patterns of lithospheric folding, demonstrating that sedimentary basins are sensitive recorders to the intraplate stress field. The long lasting memory of the lithosphere, in terms of lithospheric scale weak zones, appears to play a far more important role in basin formation and reactivation than hitherto assumed. A better understanding of the 3-D linkage between basin formation and basin reactivation is, therefore, an essential step in research that aims at linking lithospheric forcing and upper mantle dynamics to crustal vertical motions, and their effect on sedimentary systems and heat flow.

Vertical motions in basins can become strongly enhanced, through coupled processes of surface erosion/sedimentation and lower crustal flow. Furthermore patterns of active thermal attenuation by mantle plumes can cause a significant spatial and modal redistribution of rifted margin deformation, as a result of changing patterns in lithospheric strength and rheological layering.

Novel insights from numerical and analogue modeling aid in quantitative assessment of basin history and shed new light on tectonic interpretation, providing helpful constraints for basin exploration, including understanding and predicting vertical motions (eroded sedimentation record), source fill relationships, and heat flow.

The lesson from the Iberia-Newfoundland rifted margins: how applicable is it to other rifted margins?

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ABSTRACT

The Iberia-Newfoundland rifted margins represent a unique data set to study the structure and processes related to rifting and continental breakup in magma-poor rifted margins. The major observations made along these margins show that: 1) rifting is polyphase and deformation localizes and migrates towards the area of final breakup, 2) the mantle consists of inherited, infiltrated and depleted domains, and 3) magmatism includes infiltration, underplating, diking and extrusion of MOR and alkaline magmas before, during and after continental breakup. This complex polyphase evolution is recorded in the migration of syn-tectonic sedimentary sequences and a subsidence history, which is yet little understood. These observations enable us to propose and test new models for the formation of deep-water rifted margins and continental break-up. A key question is to what extend the observations and models derived from the Iberia-Newfoundland rifted margins can be compared with less explored rift systems.

KEYWORDS: Iberia-Newfoundland, magma-poor deep water rifted margins, hyper-extended crust, mantle exhumation, detachment faulting.

1. Introduction

Research into the formation of deep-water rifted margins is incontestably undergoing a paradigm shift. The discovery of exhumed continental mantle, hyper-extended crust and top basement detachment faults directly overlain by extensional allochthons or syn- and post-rift sediments offshore Iberia and Newfoundland is at the origin of new concepts for the formation of rifted margins. Direct access to pertinent geological and geophysical data sets through deep-sea drilling and seismic surveys is fundamental in defining the processes that control continental lithospheric thinning and breakup in magma-poor rifted margins. However, complete datasets exist only from very few margins and it is unclear to what extend the lesson from the Iberia-Newfoundland rifted margins can be used to interpret other rifted margins such as the Central and Southern Atlantic, the Australian and Arctic rifted margins. Despite the lack of ultra deep-water industry and academic drilling along most of these margins, the increasing number of high-quality deep-penetrating multichannel seismic surveys indicates that these margins shear some first order similarities with the Iberia-Newfoundland rifted margins. This paper reviews the key structures, crustal architecture and rift processes proposed for the Iberia-Newfoundland rift system, which represents a benchmark dataset for less explored magma-poor rifted margins.

2. Geological context and data

The Iberia-Newfoundland rifted margins are conjugate, magma-poor rifted margins that resulted from the separation of the North America and Iberia plates (FIG.1). They belong to a Triassic to Lower Cretaceous rift system that includes several V-shaped hyper-extended rift basins such as Rockall Trough, Porcupine and Orphan basins. The importance of inherited Variscan and Caledonian structures as well as the polyphase nature of this rift system is discussed in Sibuet et al. (2007) and Péron-Pinvidic and Manatschal (2010). Rifting seems to have localized during Late Jurassic to

Early Cretaceous time within several basins resulting in thin, less than 10 km thick crust and locale mantle exhumation. The age of final break-up in the southern North Atlantic is proposed, based on stratigraphic arguments, to occur in late Aptian to earliest Albian time (112 Ma) (Péron-Pinvidic et al. 2007, Tucholke et al. 2007). One major question is how final breakup is related and controlled by the previous rift-event.

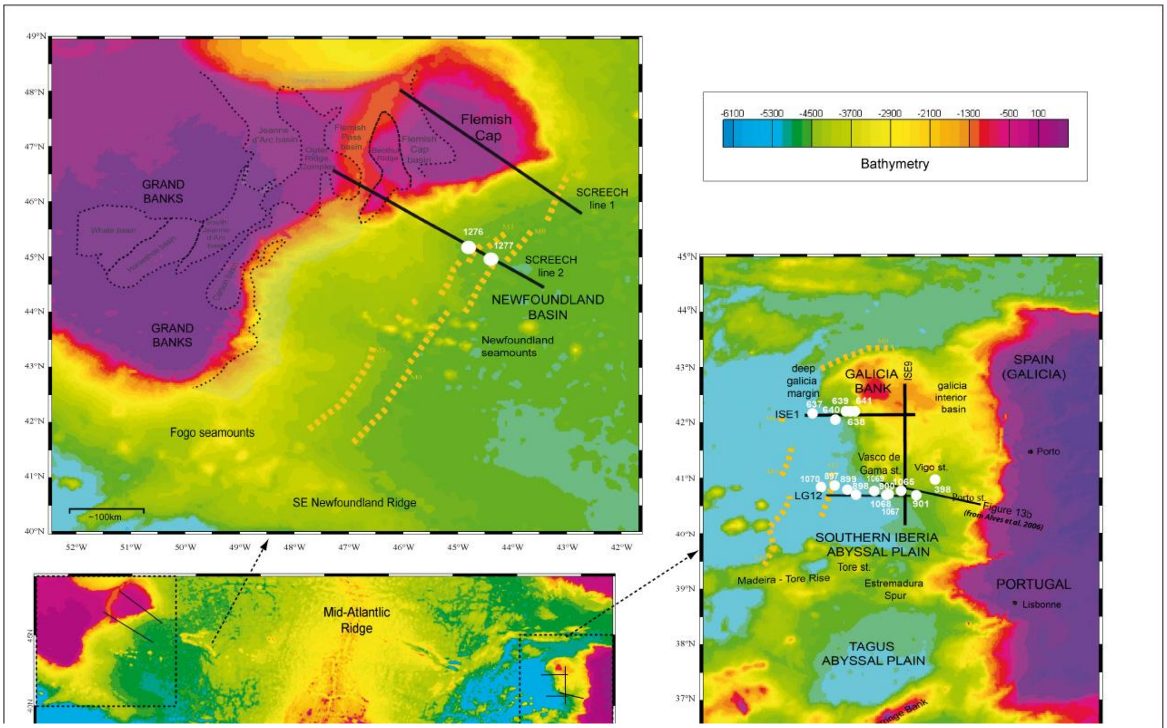

FIG.1 - Map of the southern North Atlantic showing the Iberia and Newfoundland rifted margins and the major seismic lines discussed in this paper.

In this paper we will mainly focus on the Iberia-Newfoundland rifted margins. These margins are at present the only ones where deep-sea drilling penetrated basement. 18 sites were drilled during DSDP Leg 47B and ODP Legs 103, 149, 173 and 210 (Sibuet, Ryan et al. 1979, Boillot et al. 1987, Sawyer, Whitmarsh, Klaus et al. 1994, Whitmarsh, Beslier and Wallace et al. 1998, Tucholke et al. 2007). These data combined with refraction and reflection seismic surveys (for a review see Shillington et al. 2006, van Avendonk et al. 2009, Péron-Pinvidic and Manatschal 2009) make that the Iberia-Newfoundland rifted margins are at present considered as the best studied rifted margins worldwide.

3. Key observations

The absence of important magmatic additions and salt, both of which can obscure the rift structures, enables to map rift structures and depositional systems using reflection and refraction seismic data. The nature of basement was determined based on ODP drill hole data. A first order observation that can be made along the Iberia-Newfoundland rifted margins is the occurrence of distinct domains referred to as the proximal margin, the necking zone, the distal margin, the ocean continent transition (OCT) and the oceanic crust. This contrasts to classical rift models, which distinguished only two major domains: a continental domain formed by tilted blocks and fault bounded rift basins and an oceanic domain formed by a classical three layered oceanic crust (FIG.2). The limit between the two was defined as a sharp contact, i.e. the ocean continent boundary (OCB), corresponding to the location where breakup occurred (FIG.2).

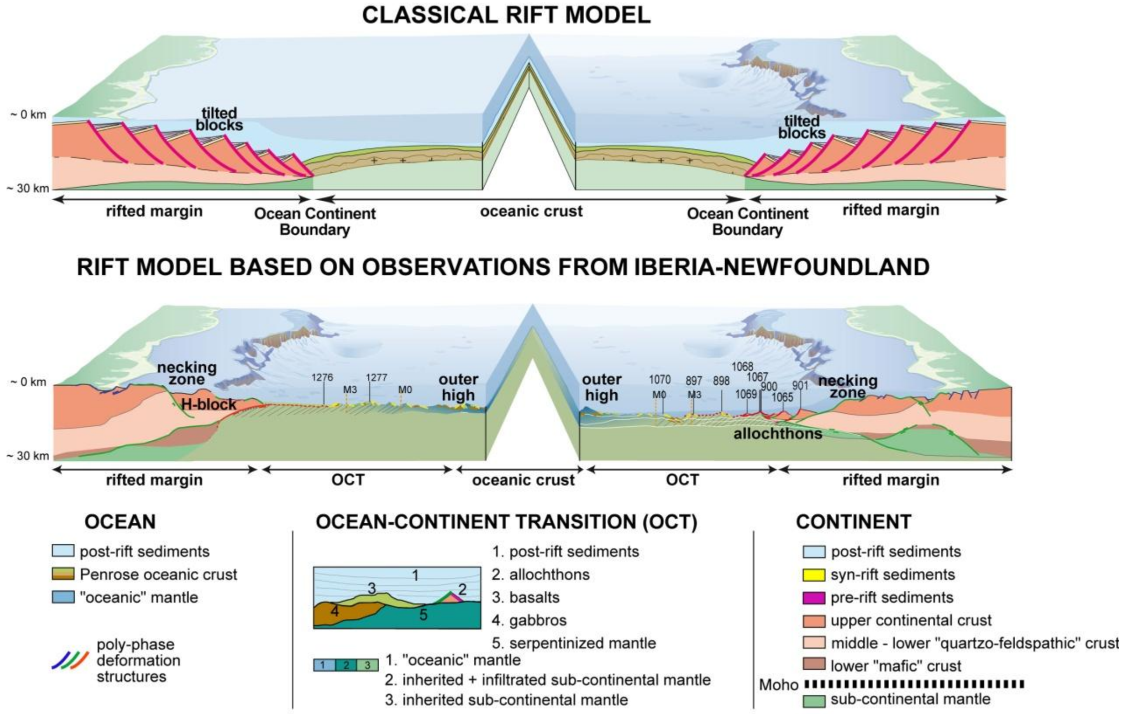

FIG.2 - Schematic three-dimensional representations of rifted margins: **(a)** Classical representation showing pre-, syn- and post-rift sediment architecture over uniformly stretched continental crust, affected by high-angle normal faults in the upper crust and ductile deformation in the lower crust, juxtaposed against a three layer Penrose type oceanic crust. **(b)** Representation of the structure of the Iberia-Newfoundland rifted margins as deduced from seismic sections and drill hole data. Major differences to the classical rift model are the occurrence of mantle exhumation along top-basement detachment faults in the OCT.

Rift domains observed along the Iberia-Newfoundland rifted margins (FIG.3)

The proximal margin is formed by fault bounded basins with normal faults soling out at mid-crustal levels indicating decoupling between upper crustal and mantle deformation. Moho topography is subdued and ß-factors are typically less than 2. This domain corresponds to the continental shelf and is characterized by shallow marine sediments.

The necking zone is defined as a localized area where the crust thins to less than 10 km. This domain is yet little explored and no drill hole recovered basement rocks from the necking zone of the Iberia-Newfoundland rift system. Therefore, the necking zone is so far only defined by refraction seismic data. Reflection seismic data from the necking zone often show strong reflections at the top, within and at the base of the crust converging oceanwards. If these reflections are related to crustal thinning is not yet clear.

The *distal margin* is formed by hyper-extended crust, often less than 10 km thick. A strong reflection referred to as the “S” reflection (de Charpal et al. 1992; Hoffmann and Reston 1992), in the Iberia Abyssal Plain also referred to as “H” reflector (Krawczyk et al. 1996), is the most prominent feature on seismic sections. This prominent reflector truncates tilted blocks suggesting that it acts as a detachment onto which the overlying fault blocks ride. Analysis of the physical properties of these strong reflections (Reston 1996) showed that they represent a relatively sharp boundary between fractured crustal rocks and partially serpentinized peridotites. In the Iberia Abyssal Plain, the "H" reflection points oceanwards towards the seafloor, which allowed this structure to be drilled (FIG.3). ODP Sites 900 and 1067 drilled into the hanging wall of the reflection and recovered hydrated mid to lower crustal rocks while ODP Site 1068 penetrated serpentinized mantle rocks in the footwall, which supports the idea that the "H" and "S" reflections define the boundary between exhumed crustal and mantle rocks. The interface between these reflections and the top of the basement represents therefore the continentward limit of exhumed mantle. Seismic reflection images from the Iberia-Newfoundland distal margins show that the continental basement is unevenly distributed (FIG.3). While the Newfoundland margin preserves a well-defined block (e.g. H-Block of Lavier and Manatschal 2006), the conjugate is made of thin allochthons and tilled blocks. Péron-Pinvidic and Manatschal (2010) interpreted the crustal bock on the Newfoundland margin as a residual block of a former H-Block and the tilted blocks on the Iberia margin as extensional allochthons resulting from the delamination of the H-Block during final mantle exhumation along top-basement detachment faults (for details and definition of the H-Block see FIG.4 in Péron-Pinvidic and Manatschal 2010). The top-basement detachment faults exhumed in their footwall lower crustal and mantle rocks to the seafloor. This is supported by ODP Sites 900, 1067, 1068 over Hobby High (FIG.3; see also for a review Manatschal et al. 2001). These drill hole data show that all basement and mantle rocks recovered from the distal margin are strongly altered, which is compatible with the low velocities obtained from the refraction seismic data from the Iberia margin (Chian et al. 1999).

The OCT is interpreted as the domain separating reflective hyper-extended continental crust and embryonic oceanic crust. The contact to the last identifiable continental crust corresponds to the location where the "S" and "H" type reflections (see above for discussion) intersect with the top of the basement. Oceanwards such strong intra-basement reflections are very rare. The contact to true oceanic crust occurs along a basement high referred to as outer high (for a definition see Péron-Pinvidic and Manatschal 2010). The basement in the OCT typically has a moderate velocity gradient (~0.2 s^{-1}) passing down from 5 km/s to close to 8 km/s and is characterized by weak ill-defined magnetic anomalies. Basement from the OCT has been sampled by dredging, by submersible and by drilling at ODP Sites 637, 897, 899, 1068 and 1070 on the Iberia margin and at ODP Site 1277 on the Newfoundland margin (for a review see Müntener and Manatschal 2006). The samples show that the anomalous crust in the OCT is formed by exhumed serpentinized subcontinental mantle that shows locally evidence for infiltration of the mantle by magmas. The observed downward increasing velocity gradient is therefore explained by downward decreasing serpentinization. However, velocities intermediate between 7 and 7.8 km/s occurring at the oceanward end of the OCT beneath the outer high at more than 6 km depth are too deep to be explained by serpentinization only. An alternative interpretation is that these domains at the transition between the OCT and the fist oceanic crust are formed by underplated bodies or may correspond to zones of partly serpentinized mantle intruded with mafic magmas related to excess magmatic activity during continental breakup (e.g. Péron-Pinvidic et al. 2007 and FIG.3 in Jagoutz et al. 2007). All drill holes penetrating basement in the OCT recovered tectono-sedimentary breccias at the top of the basement. These breccias range from sedimentary (debris flows, olistostromes) to tectonic (cataclasites and gouges) to ophicalcites, the latter resulting from reaction of tectonized exhumed mantle rocks with seawater. Although several hypotheses have been put forward to explain the occurrence of these breccias [Whitmarsh and Sawyer 1996], at present these breccias are interpreted as being related to the exhumation of crustal and mantle rocks along detachment faults. Drilling in the OCT also showed the existence of extensional allochthons made of continental crust (ODP Site 1069; Wilson et al. 2001). These extensional allochthons are interpreted to have formed while the mantle was pulled out from underneath the Newfoundland margin (for details see Péron-Pinvidic and Manatschal 2010). Important to note is also that magmatic rocks can locally occur in the OCT as MOR gabbros or basalts, the latter reworked in debris flows, or as alkaline magmas in veins and sills that pre-date as well as post-date continental breakup (Jagoutz et al. 2007).

The oceanic crust in the Iberia-Newfoundland rifted margins has not been drilled and therefore little is known about its nature. However, the nature of oceanic crust is well defined by reflection and refraction seismic data indicating that the oceanic crust is different and can therefore be distinguished from the crust forming the OCT (for more details see Whitmarsh et al. 2001).

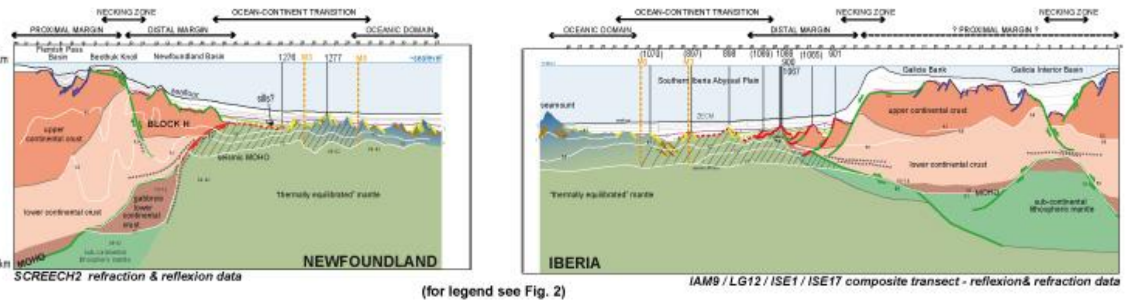

FIG.3 - Reconstructed section across the conjugate Iberia-Newfoundland rifted margins (modified from Péron-Pinvidic and Manatschal (2009). The Iberia - Newfoundland composite transect is based on geophysical data (*van Avendonk et al.* [2006], *Shillington et al.* [2006], *Pickup et al.* [1996], *Perez-Gussinyé et al.* [2001]) and drill hole data (ODP Legs 103, 149, 173 and 210 Scientific Results). The section coincides with the Screech 2 reflexion /refraction profiles on the Newfoundland margin and integrates the IAM9; LG12, ISE1 and ISE17 lines on the Iberia margin (for location of the transects see map in FIG.1).

Stratigraphic record of the deep Iberia-Newfoundland rifted margins

At present little is known about depositional environments, sedimentary facies, age and subsidence and thermal history of pre- to syn-rift sediments of deep water rifted margins. Based on the drilling results and in particular due to the surprising similarity between the Lower Cretaceous sediments drilled at Sites 398 and 1276 on the Iberia and Newfoundland margins respectively (see FIG.12 in Shipboard Scientific Party 2004) it is possible to map and date the major seismic formations in the Iberia-Newfoundland rifted margins (Péron-Pinvidic et al. 2007). However, as discussed by Wilson et al. (2001) and Peron-Pinvidic et al. (2007), the determination of syn-rift stratigraphic intervals is difficult and remains a major difficulty. This is mainly due to the fact that drilling targeted mainly basement highs, which explains that true “syn-rift sediments” were only recovered from very few places along the Iberia-Newfoundland rifted margins.

4. Processes controlling rifting and continental breakup

The spatial and temporal evolution of rifting observed in the Iberia-Newfoundland rift system, shows a progressive localization and migration of rifting towards areas where the crust is thinned to less than 10 km and where mantle is exhumed at the seafloor (Péron-Pinvidic and Manatschal 2010). This is well shown by the distribution of hyper-extended V-shaped rift basins in the southern North Atlantic. It is important to note that the subsequent continental breakup cross cut the previous rift structures. This leads to the question to what extend rifting controls continental breakup. In the Iberia-Newfoundland rift system it can be observed that deformation migrates and localizes during rifting. Lavier and Manatschal (2006) proposed that the migration and localization of rifting is related to a change in the mode of extension, which can also explain the different domains described in the previous chapter. While proximal margins are mainly affected by coupled pure shear extension (e.g. stretching phase of Lavier and Manatschal 2006), the evolution of the distal margins is more complex and controlled by thinning and exhumation processes involving detachment faulting. These structures, so far only drilled in the Iberia-Newfoundland rifted margins, are interpreted to result from the sequential overprint of stretching, thinning and exhumation phases (FIG.4).

In contrast to the stretching (pure shear) and exhumation (simple shear) modes that were defined by McKenzie (1978) and Wernicke (1985) the least understood processes that can not be explained by these two modes are related to the question of how the lithosphere thinned and finally ruptured.

Whitmarsh et al. (2001) showed evidence that major crustal thinning in the Iberia-Newfoundland rift system occurred during Late Jurassic (Tithonian). The major problem is that the thinning of the crust seems not to be accompanied directly by the expected subsidence as indicated by the relatively shallow water conditions indicated by the drilled Tithonian sediments (for more details see Wilson et al. 2001, Péron-Pinvidic and Manatschal 2009). A possible explanation could be that crustal thinning occurred simultaneously with the thermal uplift provided by the extreme thinning of the entire lithosphere (e.g. depth depended thinning of Kusznir and Karner 2007). In the case of the Iberia-Newfoundland rift system the distribution of subsidence during crustal thinning recorded in the Tithonian sediments may therefore provide indirect constraints on the amount of thinning of the lithosphere and the timing of infiltration in the lithospheric mantle described by Müntener and Manatschal (2006). However, in order to proof the link between magma infiltration during lithospheric thinning, strain localization, and the anomalous Tithonian subsidence history, further drilling along the Iberia and Newfoundland rifted margins is necessary.

Continental breakup occurs only after mantle rocks have been exhumed at the seafloor. In theory lithospheric stretching and thinning allows the underlying asthenospheric mantle to well up towards the surface, undergoing decompression melting according to the amount and rate of upwelling, coupled with the temperature and fertility of the asthenosphere (Bown and White 1995). In reality, this process may be more complex. During lithospheric thinning deformation processes may evolve as a function of changes in rheology due to changes in temperature and pressure or additions of magma and fluids (Pérez-Gussinyé and Reston 2001). This process may result in an increased coupling between crust and mantle, culminating in complete crustal embrittlement. Only when the entire crust becomes brittle, detachment faults can cut from the crust into mantle and exhume the latter at the seafloor. This happens in the Iberia-Newfoundland rift system when the crust is less than 10 km thick between Tithonian and Valanginian time (between 145 and 137 Ma). However, continental breakup occurs only in latest Aptian to earliest Albian time, i.e. at about 112 Ma, indicating a delay of 25 myr between first mantle exhumation and continental breakup. Classical rift models (FIG.1) can neither explain this delay, nor the existence of a wide OCT. This has major consequences for the interpretation of the breakup unconformity, magnetic anomalies and the occurrence of high-angle faults and sedimentary wedges in the OCT. The new observations show that non of them can be used as stand alone criteria to determine continental breakup or to map the oceanward limit of continental crust. Recurrence of distributed tectonic extension and magmatic activity after mantle exhumation and even after onset of localized seafloor spreading within the OCT suggests that continental breakup is more complex as previously suggested and that OCTs do not behave like oceanic domains.

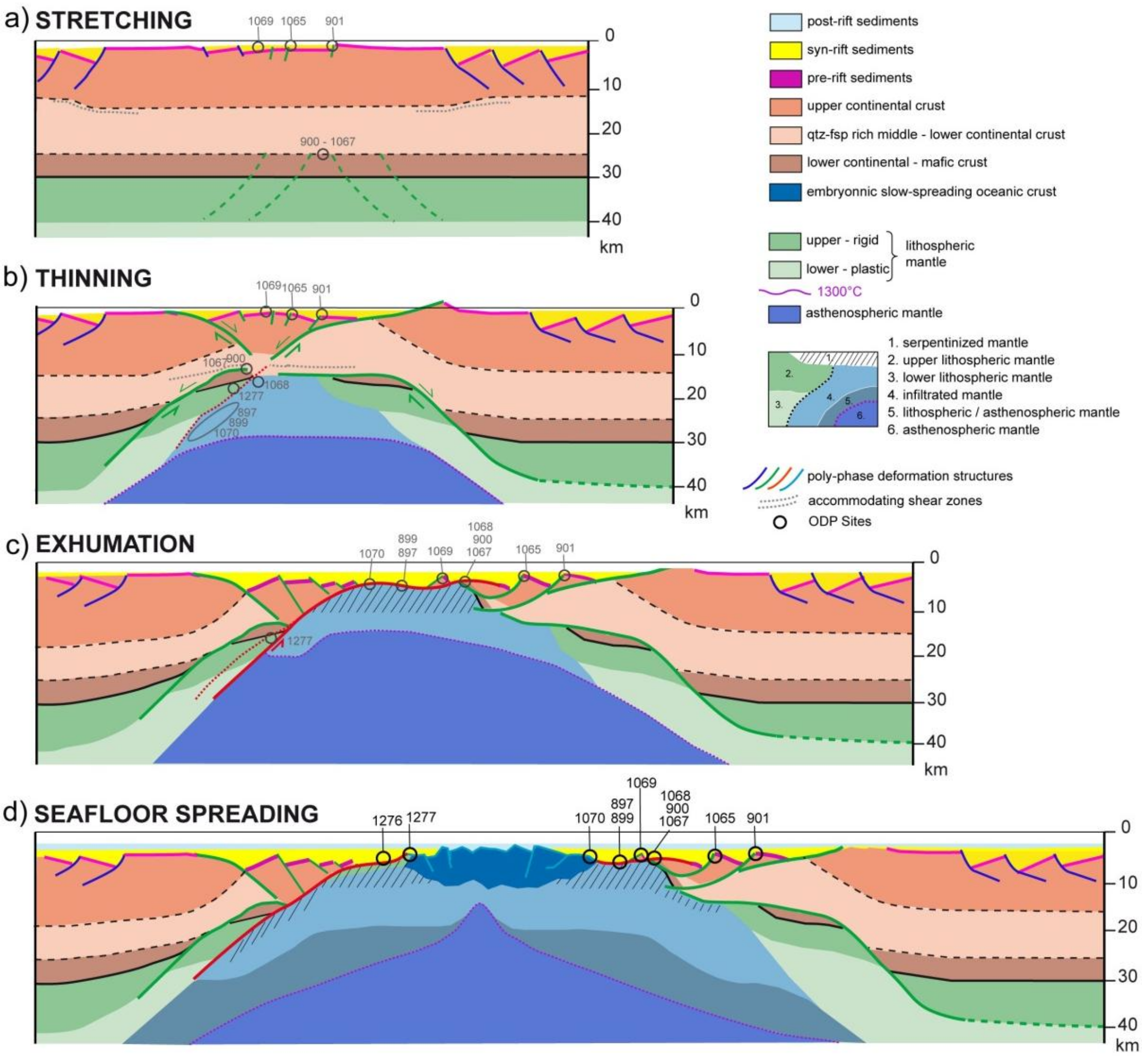

FIG.4 - Schematic conceptual model showing the evolution of rifting based on observations from the Iberia/Newfoundland rift system (modified from Péron-Pinvidic and Manatschal 2009). FIG.4.a. to 4.d. summarize the modes of extension leading to continental break-up. **(a)** The stretching mode is characterized by high-angle listric faulting associated with classical half-graben subsidence; continental crust is slightly stretched and sedimentary basins developed independently from each other, affecting a broad region. **(b)** The thinning mode is characterized by a conjugate decoupled system of detachment faults that accommodate exhumation of deeper crustal and/or mantle levels underneath Block H. The thinning mode is at the transition from distributed to localized extension. **(c)** The exhumation mode is characterized by detachment faults that cross cut the embrittled crust and exhume serpentinized mantle rocks at the seafloor. **(d)** Final seafloor spreading is defined by the irrevocable localization of thermal and mechanical processes in a narrow zone corresponding to a proto- ridge. (The numbers shown on top of each figure refer to ODP Sites).

5. Application of the lesson learned in Iberia-Newfoundland to other rifted margins

In the past, rifted margins have been classified as volcanic or non-volcanic rifted margins. These terms are a bit misleading as even non-volcanic rifted margins exhibit magmatism. The use of “magma-poor” and “magma-rich” may therefore be more appropriate for the description of rifted margins. However, given the difficulties in determining the thickness of igneous additions to the lithospheric mantle and crust, and to determine the precise rift duration, a practical definition of magma-poor margins may be the one where tectonic rather than magmatic processes dominate during final rifting. The Iberia-Newfoundland rifted margins can therefore be considered as the type example of a magma-poor rifted margin. Other examples of magma-poor rifted margins are found in every ocean. Reston and Manatschal (subm) estimate that they form more than 50% of the world rifted margins. Of particular interest is, due to its high potential in hydrocarbons, the South Atlantic rift system between Angola-Gabun and Brasilia. These margins are, however, poorly imaged. The thick sedimentary sequence and the occurrence of salt obscure the deeper parts of these margins. As a consequence, these margins are difficult to describe and interpretations of the crustal structures cannot be tested by drill hole data like in the case of the Iberia-Newfoundland rifted margins. Unternehr et al. (2010) showed by using reflection seismic sections that the S-Atlantic margins share many similarities with the Iberia-Newfoundland rifted margins suggesting that the underlying rift processes may be similar as well. The comparison of the published refraction seismic line of Contrucci et al. (2004) (FIG.5) with the section across the Iberia margin (FIG.3) also supports the similarity.

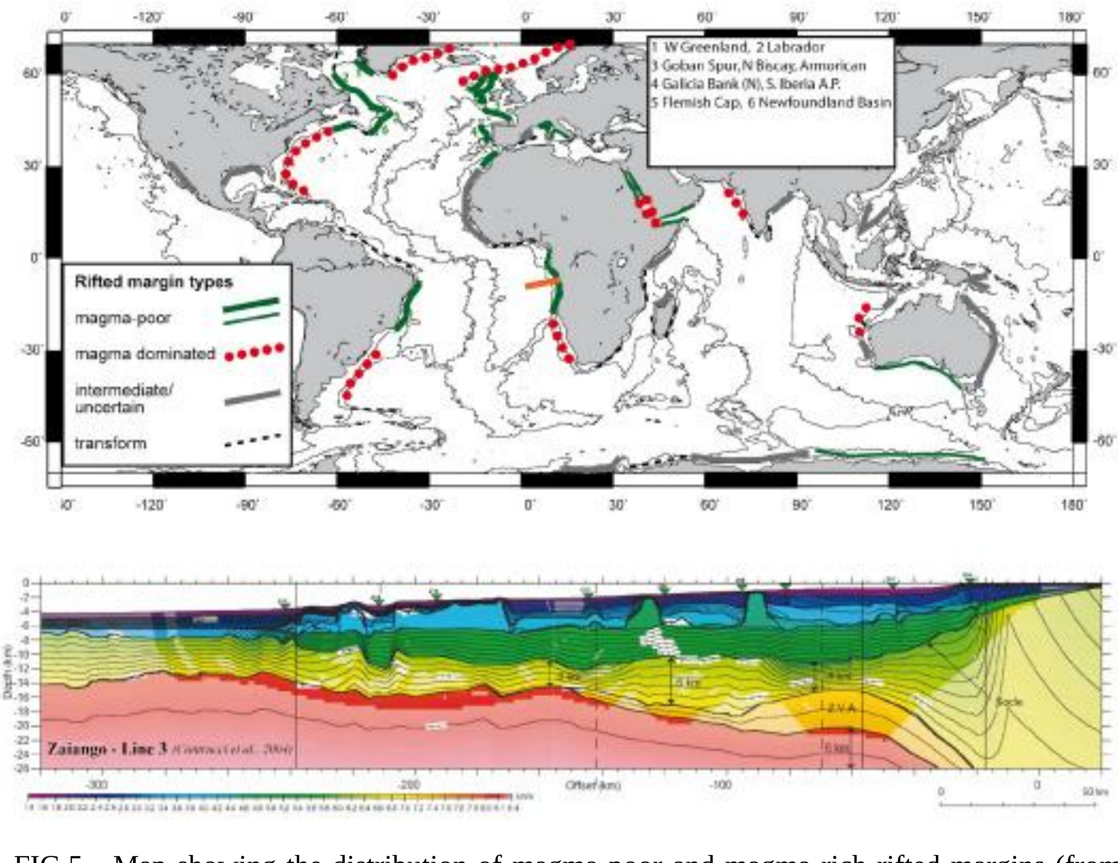

FIG.5 - Map showing the distribution of magma-poor and magma-rich rifted margins (from Reston and Manatschal subm) and seismic refraction line of Contrucci et al. (2004). Location is indicated in the map.

Although in detail it is difficult to interpret the nature of the crust and of the structures in a refraction seismic section, the line of Contrucci et al. (2004) shows a number of common features that are also characteristic for the Iberia margin. These similarities are: 1) extreme crustal thinning from ~30 km to a less than 10 km within a narrow necking zone; 2) subdued high-angle faulting over hyper-extended crust in the distal margin; 3) a zone of anomalous basement between continental crust and first true oceanic crust; 4) the existence of an outer high separating the oceanic crust from unequivocal continental crust; and 5) high velocity bodies in the necking zone and below the distal margin that may represent mafic lower crustal bodies.

6. Discussion and conclusions

This paper focused on the large-scale structure observed along the Iberia-Newfoundland rifted margins. The overall structure of this margin is interpreted to be the logical result of migration and localization of extension that is associated with a change in the mode of deformation from stretching to thinning to exhumation (FIG.4). The extreme thinning of the crust is interpreted to be the result of multiple phases of extension, some of which are difficult to be recognized on seismic data. This is particularly true for top-basement detachment faults. The localization of deformation is accompanied by complex mantle and magmatic processes that are identified along the Iberia-Newfoundland rifted margins by drill hole data. It is, however, difficult to link these processes with the overall strain and isostatic evolution of the margin during rifting. We belief, that many rifted margins may follow a similar pattern of development with two key differences:

1) The volume of melt during thinning may be different, in which case breakup may occur either earlier (the case of magma-rich margins) or fail (in cases of absence of magma). In the former case, the rift structures can develop in a different way and cannot be compared with structures observed along the Iberia-Newfoundland rifted margins.
2) The inheritance may be different, in which case the strain distribution and localization may evolve in a different way leading to wider or narrower necking zones and/or distal margins and OCT.

Other parameters may also control the rift evolution and final structure of rifted margins. However, despite the observed variability, it seems as if rift systems are formed by a limited number of architectural elements also referred to as building stones. These building stones show in many rifted margins very characteristic spatial and temporal relationships similar to those described from the Iberia-Newfoundland rifted margins.

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The Method of Sequence Stratigraphy

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ABSTRACT

Sequence stratigraphy highlights stratal stacking patterns and changes thereof in a time framework. Each stratal stacking pattern defines a particular genetic type of deposit with unique sediment dispersal patterns within the basin, including 'forced regressive', 'lowstand normal regressive', 'transgressive', and 'highstand normal regressive'. These genetic units consist of tracts of age-equivalent depositional systems (i.e., systems tracts), and are bounded by key sequence stratigraphic surfaces.

The optimal approach to the application of sequence stratigraphy relies on the integration of outcrop, core, well-log and seismic data. Each data set provides different insights toward the identification of stratal stacking patterns and key bounding surfaces, and mutual corroboration is important to reduce the error margin of interpretations. Not all data sets may be available in every case study, a factor which may limit the 'resolution' of the sequence stratigraphic interpretation. At the same time, not all types of data afford the recognition of all sequence stratigraphic surfaces, and not all sequence stratigraphic surfaces are present in every depositional setting. The area of transition between fluvial and shallow-water systems affords the formation of the entire array of sequence stratigraphic surfaces. In contrast, within fluvial and deep-water systems, conditions are favorable for the formation of fewer key bounding surfaces.

The existence of several competing approaches has prevented the inclusion of sequence stratigraphy in stratigraphic codes or guides. The various approaches differ in terms of (1) nomenclature of systems tracts and sequence stratigraphic surfaces, and (2) selection of surfaces which should be elevated to the rank of 'sequence boundary'. Both these aspects do not make a difference to the successful application of the sequence stratigraphic method. A standardized workflow requires the identification of all genetic units and bounding surfaces that are present in a stratigraphic succession. Beyond this framework of surfaces and systems tracts, the selection of sequence boundaries may vary with the approach, available data sets, and depositional setting.

1. Introduction

Definition

Sequence stratigraphy is uniquely focused on the analysis of stratal stacking patterns and changes thereof within a temporal framework. Stratal stacking patterns respond to the interplay of accommodation (space available for sediments to fill) and sedimentation, and reflect combinations of depositional trends that include progradation, retrogradation, aggradation and downcutting.

Data sets

The sequence stratigraphic method yields optimum results when information derived from multiple data sets, including seismic, outcrop, core, well log, biostratigraphic and geochemical, is integrated. Each data set provides different insights toward the identification of stratal stacking patterns and the identification of bounding surfaces, and mutual corroboration is important to reduce the error margin of interpretations. Notably, seismic data provide continuous coverage of relatively large areas at the expense of vertical resolution, whereas outcrops, core and well logs may provide the opportunity for more detailed studies in particular locations but within the context of a sparse and discontinuous data base. Not all data sets may be available in every case study, a factor which may limit the 'resolution' of the sequence stratigraphic interpretation. Working models are refined as more data become available, as, for example, when well logs and cores are added to the subsurface seismic data base following the initial seismic stratigraphic survey.

The need for formalization

In spite of its popularity among geoscientists in academia, industry and government organizations, sequence stratigraphy remains a stratigraphic method that has no formalized definitions in stratigraphic guides or codes. This reflects the existence of a variety of alternative approaches for applying sequence stratigraphy to the rock record (FIGS.1 and 2). Researchers usually choose the conceptual model and the nomenclature that is best adapted to the depositional system they are studying, which naturally leads to a multitude of different definitions of the sequence stratigraphic units and surfaces. However, the differences between these approaches are not significant enough to prevent the formal recognition of the method in stratigraphic guides and codes. Such differences revolve largely around nomenclatural preferences and arguments with respect to which stratigraphic surfaces hold the greatest utility to be elevated in importance to the rank of sequence boundary. Beyond these differences, all approaches share a common ground that justifies the formalization of sequence stratigraphy (Catuneanu et al., 2009, 2010).

Formalization is necessary if the present state of methodological and nomenclatural confusion is to be eliminated along with the uncoordinated effort in the development of the method. To acquire formalization, sequence stratigraphy requires the definition of a model-independent methodology that honors the various approaches but transcends their differences. A single set of terms also is required so as to facilitate communication between geoscientists adopting this method. In no way is formalization meant to be an obstacle that limits further conceptual development or prevents certain approaches to specific situations. The definition of the common ground in sequence stratigraphy should promote flexibility with respect to the choice of approach that is best suited to a specific set of conditions as defined by tectonic setting, depositional setting, data available, and scale of observation.

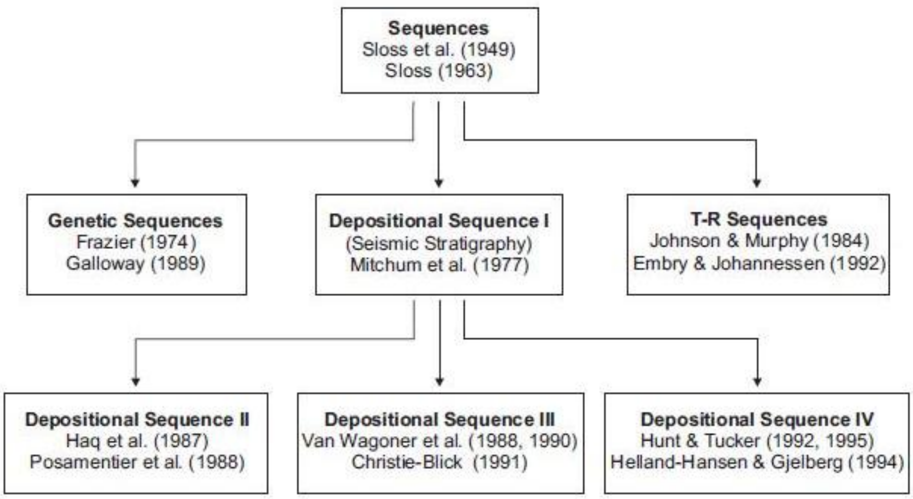

FIG.1 - . Evolution of sequence stratigraphic approaches (from Catuneanu et al., 2010).

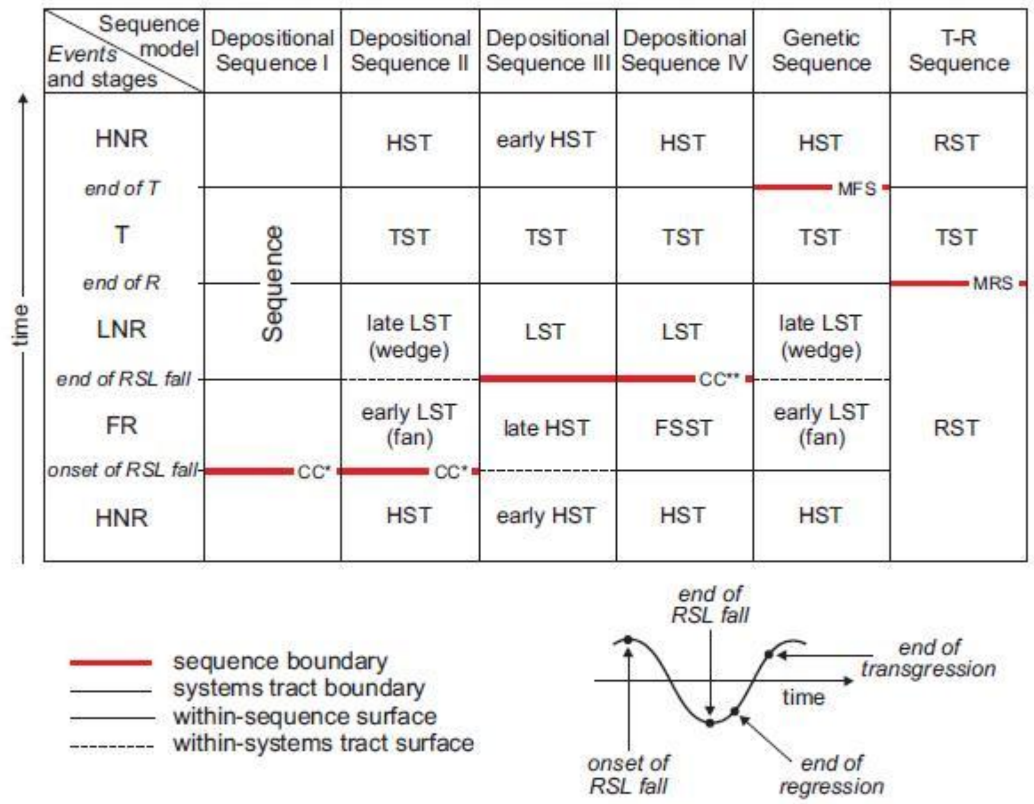

FIG.2 - Nomenclature of systems tracts, and timing of sequence boundaries for the various sequence stratigraphic approaches (modified from Catuneanu et al., 2010). Abbreviations: RSL – relative sea level; T – transgression; R – regression; FR – forced regression; LNR – lowstand normal regression; HNR – highstand normal regression; LST – lowstand systems tract; TST – transgressive systems tract; HST – highstand systems tract; FSST – falling-stage systems tract; RST – regressive systems tract; T-R – transgressive-regressive; CC* – correlative conformity in the sense of Posamentier and Allen (1999); CC** – correlative conformity in the sense of Hunt and Tucker (1992); MFS – maximum flooding surface; MRS – maximum regressive surface. References for the proponents of the various sequence models are provided in FIG.1.

Stratal stacking patterns

Stratal stacking patterns may be defined either in relation to or independently of shoreline trajectories. Criteria involved in the definition of stratal stacking patterns include geometries and facies relationships that emerge from the interplay of available accommodation and sediment supply at syn-depositional time.

Shoreline-related stacking patterns are defined by combinations of depositional trends that can be tied to specific types of shoreline trajectory: forced regression (forestepping and downstepping at the shoreline, interpreted as the result of negative accommodation); normal regression (forestepping and upstepping at the shoreline, interpreted as the result of positive and overfilled accommodation); and transgression (backstepping at the shoreline, interpreted as the result of positive and underfilled accommodation) (FIG.3). In the case of stratigraphic cycles that include a stage of forced regression as well as a stage of transgression, normal regressions can occur during both lowstands and highstands of relative sea level and, consequently, the products may be classified as ‘lowstand’ and ‘highstand’ deposits. In addition to regressive or transgressive shorelines, stable shorelines may also develop where accommodation and sediment supply are in balance. However, as accommodation and sediment supply are controlled independently by different mechanisms, stable shorelines are unlikely to be maintained for any significant periods of time.

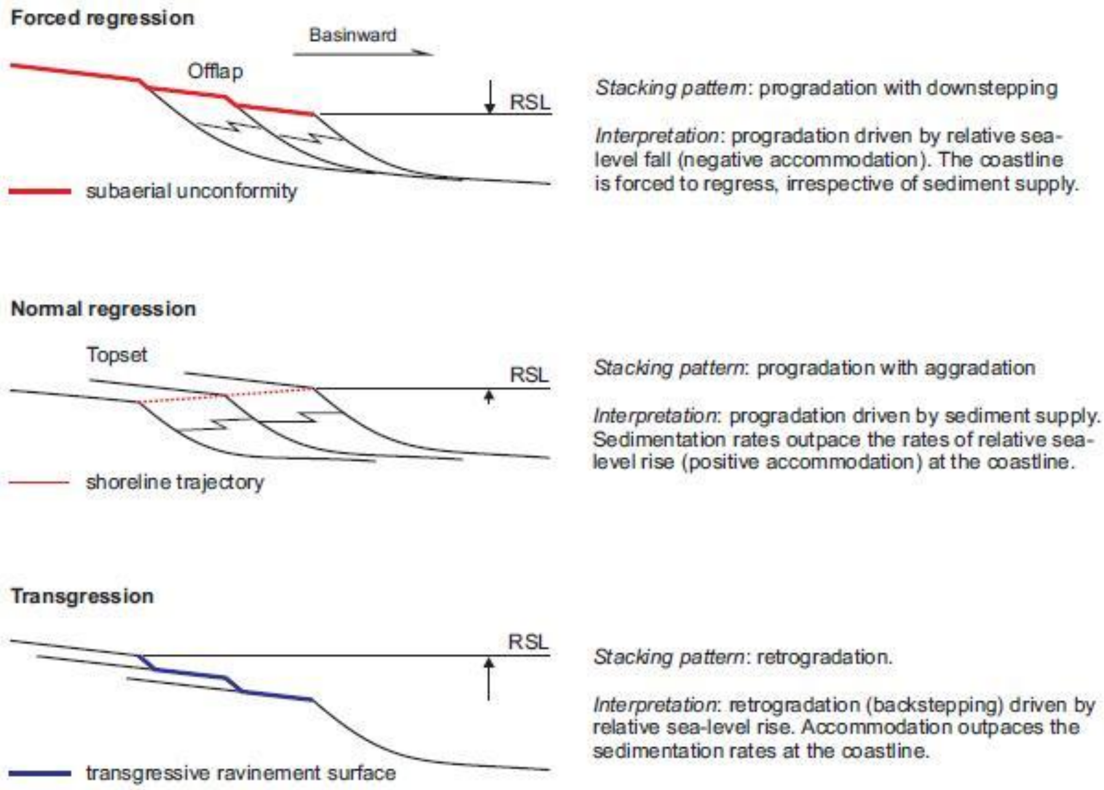

FIG.3 - Stratal stacking patterns related to shoreline trajectories (from Catuneanu et al., 2010): forced regression, normal regression, transgression. Zigzag lines indicate lateral changes of facies within individual sedimentary bodies. The diagram shows the possible types of shoreline trajectory during changes (rise or fall) in relative sea level. During a stillstand of relative sea level (not shown), the shoreline may undergo sediment-driven progradation (normal regression, where the topset is replaced by toplap), erosional transgression, or no movement at all. However, due to the complexity of independent variables that interplay to control relative sea-level change, it is unlikely to maintain stillstand conditions for any extended period of time. Abbreviation: RSL – relative sea level.

Shoreline-independent stacking patterns may develop in areas remote from coeval shorelines where sedimentation processes are unaffected by shoreline shifts. Such stratal stacking patters may be defined based on changes in depositional style that can be correlated regionally. Distinct depositional styles are characterized by specific types or combinations of depositional elements. In upstream-controlled fluvial settings, depositional styles may be defined by the degree of amalgamation of channel deposits, which may reflect syn-depositional conditions of available fluvial accommodation (i.e., low- versus high-accommodation settings; e.g., Shanley and McCabe, 1994; Boyd et al., 2000). In deep-water settings, depositional styles may be defined by the degree of channel confinement, which may reflect changes in accommodation on the shelf and/or variations in sediment supply in the staging area. Some of the deep-water stacking patters may be genetically related to shoreline trajectories, but there are also cases where offshore sub-basin tectonism may generate stacking patterns in a manner that is independent of changes in accommodation at the shoreline (e.g., Fiduk et al., 1999).

Each type of stratal stacking pattern defines a particular genetic type of deposit (e.g., FIG.3), with a distinct geometry and facies preservation style. These genetic units form the basic constituents of any sequence stratigraphic unit, from sequence to systems tract and parasequence (FIG.4; Catuneanu et al., 2010).

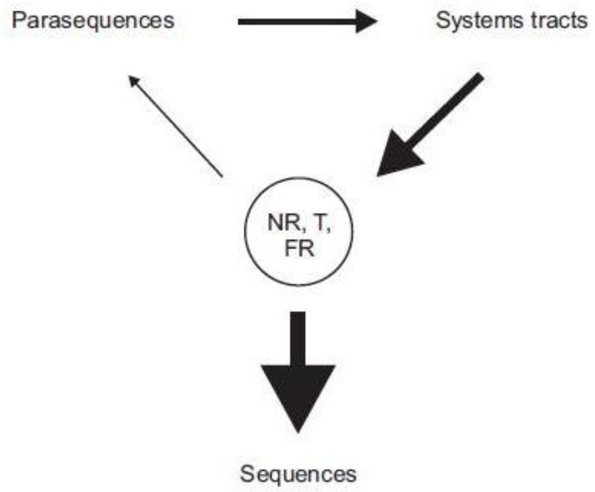

FIG.4 - Types of sequence stratigraphic unit: sequences, systems tracts, parasequences. Stratal stacking patterns are central to the definition of any kind of sequence stratigraphic unit, at any scale of observation. All sequence stratigraphic units the origin of which relates to changes in shoreline trajectory consist of a combination of forced regressive, normal regressive and transgressive deposits. Abbreviations: FR - forced regressive; NR - normal regressive; T - transgressive.

Sequence stratigraphic surfaces

Significant surfaces, called sequence stratigraphic surfaces, separate the different types of genetic units and include subaerial unconformities, correlative conformities, maximum flooding surfaces, maximum regressive surfaces, transgressive ravinement surfaces and regressive surfaces of marine erosion.

Sequence stratigraphic surfaces are surfaces that can serve, at least in part, as boundaries between different genetic types of deposit. Not all types of data afford the recognition of all sequence stratigraphic surfaces, and not all sequence stratigraphic surfaces are present in every depositional setting. The area of transition between fluvial and shallow-water systems affords the formation of the entire array of sequence stratigraphic surfaces. In contrast, within fluvial and deep-water systems, conditions are favorable for the formation of fewer key bounding surfaces.

The criteria that can be used to identify each sequence stratigraphic surface include: the conformable versus unconformable nature of the contact; the depositional systems below and above the contact; the depositional trends below and above the contact; the types of substrate-controlled ichnofacies associated with the contact; and stratal terminations associated with the contact (see FIG.4.9 in Catuneanu, 2006, for a review of criteria; Catuneanu et al., 2009, 2010).

Sequence models

Several different approaches (models) as to how the sequence stratigraphic method should be applied to the rock record have been proposed (FIGS.1 and 2), each with its own merits and pitfalls.

Depositional sequences

A depositional sequence forms during a full cycle of change in accommodation, which involves both an increase (positive) and decrease (negative) in the space available for sediments to fill. The formation of depositional sequence boundaries requires periods of negative accommodation. The dependency of depositional sequences on negative accommodation (whether in continental or marine settings), in addition to the nature of bounding surfaces, separates depositional sequences from other types of sequence stratigraphic unit, the formation of which may not require negative accommodation (i.e., parasequences, genetic stratigraphic sequences, transgressive-regressive sequences in the sense of Johnson and Murphy (1984), and systems tracts that form during positive accommodation).

Genetic stratigraphic sequences

The formation of genetic stratigraphic sequences depends on the development of maximum flooding surfaces, which form during times of positive accommodation. A genetic stratigraphic sequence may form during a full cycle of change in accommodation, as in the case of a depositional sequence, but it may also form during periods of positive accommodation in response to fluctuations in the rates of accommodation creation and/or sediment supply. Consequently, a genetic stratigraphic sequence may or may not include an internal subaerial unconformity, depending on whether or not the corresponding cycle includes a stage of negative accommodation. Maximum flooding surfaces may include unconformable portions expressed as "hiatal surfaces preserved as marine unconformities" (Galloway, 1989). Such unconformities may develop on the shelf and slope because of sediment starvation, shelf-edge instability and erosion during transgression. Where present, unconformable maximum flooding surfaces are included within but do not constitute the bounding surfaces defining depositional sequences and transgressive-regressive sequences.

Transgressive-regressive (T-R) sequences

The original T-R sequence of Johnson and Murphy (1984) depends on the development of maximum regressive surfaces, which form during times of positive accommodation. As in the case of genetic stratigraphic sequences, this type of sequence may form during a full cycle of change in accommodation, but it may also form during periods of positive accommodation as a result of fluctuations in the rates of accommodation and/or sediment supply. By contrast, the T-R sequence of Embry and Johannessen (1992) is dependent on negative accommodation, as it requires a subaerial unconformity at the sequence boundary. As the maximum regressive surface is younger than the subaerial unconformity, the marine portion of the maximum regressive surface may or may not meet with the basinward termination of the subaerial unconformity (Embry and Johannessen, 1992). The temporal and spatial offset between the two portions of the sequence boundary is increasingly evident at larger scales of observation (Catuneanu et al., 2009).

Model-independent methodology

The sequence stratigraphic surfaces that are selected as sequence boundaries vary from one sequence stratigraphic approach to another. In practice, the selection is often a function of which surfaces are best expressed within the context of each case study, depending upon tectonic setting, depositional setting, types of available data and the scale of observation. This high degree of variability in the expression of sequence stratigraphic units and bounding surfaces requires the adoption of a methodology that is sufficiently flexible to accommodate the wide range of possible scenarios in the rock record.

A model-independent methodology requires the identification of all sequence stratigraphic units and bounding surfaces, which can be delineated on the basis of facies relationships and stratal stacking patterns, using the available data. Construction of this framework ensures the success of the method in terms of its objectives to provide a process-based understanding of the stratigraphic architecture. Beyond this method-independent workflow, the interpreter may make model-dependent choices with respect to the selection of surfaces that should be elevated to the rank of sequence boundary (FIG.5). Such model-dependent choices are often guided by the particularities of each case study. This is because, in practice, the particular depositional setting commonly dictates the prominence (or obscurity) of any particular surface, whereas the data available typically dictate which of these surfaces are most readily observed and thus hold the greatest utility for defining sequence boundaries (Catuneanu et al., 2009, 2010).

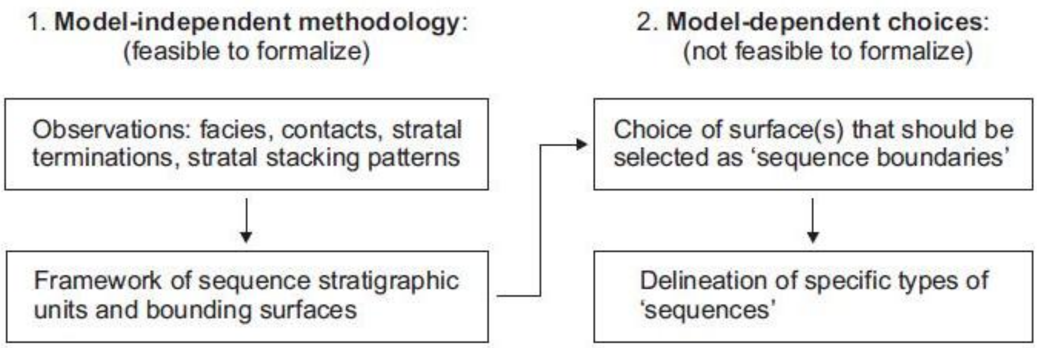

FIG.5 - Model-independent methodology versus model-dependent choices in sequence stratigraphy (modified from Catuneanu et al., 2009, 2010). The model-independent methodology starts with basic observations and leads to the construction of a sequence stratigraphic framework defined by specific stratal stacking patterns and bounding surfaces. The model-dependent choices refer to the selection of surfaces that should be elevated to the status of sequence boundary. This selection is commonly guided by how well the various surfaces are expressed with the available data in a given succession.

Conclusion: relevance of sequence stratigraphy to the petroleum industry

Sequence stratigraphy developed primarily as a new method for petroleum exploration in the 1970's (Payton, 1977). Subsequent refinements to the sequence stratigraphic methodology led to a gradual increase in the degree of stratigraphic detail that can be resolved with this method. The "high-resolution" sequence stratigraphy expanded the application of the method to petroleum production development as well.

As petroleum companies are running out of traditional structural traps, sequence stratigraphy provides a viable alternative for the identification of a new array of petroleum plays. Multiple data sets are integrated for this purpose (e.g., seismic, well-log, core and outcrop), and insights from several disciplines, including process sedimentology, biostratigraphy, geochemistry, geophysics and basin analysis, are required.

The predictive aspect of sequence stratigraphy is the key to its appeal and success, as models of temporal and spatial facies relationships can be constructed from local to regional scales. Depending on the scale of observation and the objective of each study, sequence stratigraphy can be used in exploration to predict the location of reservoir, source and seal facies, as well as in production to better understand the compartmentalization of reservoirs, the geometry of flow units and the distribution of facies that represent barriers to flow.

The versatility of sequence stratigraphy to resolve various practical issues related to petroleum exploration and production defines the method as an essential tool in the geoscience activities within the industry. The relevance of sequence stratigraphy to the understanding of the spatial and temporal relationships between reservoir, source and seal facies also renders the method an essential role to the definition of petroleum systems within a sedimentary basin.

Acknowledgements

This paper builds upon the work published by Catuneanu et al., 2009, 2010, and is the result of the continuing effort to identify a solution for the inclusion of sequence stratigraphy in international stratigraphic guides and codes. Contributions to the ideas presented in this papers were made by a large working group which includes V. Abreu, J.P. Bhattacharya, M.D. Blum, R.W. Dalrymple, P.G. Eriksson, C.R. Fielding, W.L. Fisher, W.E. Galloway, P. Gianolla, M.R. Gibling, K.A. Giles, J.M. Holbrook, R. Jordan, C.G.St.C. Kendall, B. Macurda, O.J. Martinsen, A.D. Miall, J.E. Neal, D. Nummedal, L. Pomar, H.W. Posamentier, B.R. Pratt, J.F. Sarg, K.W. Shanley, R.J. Steel, A. Strasser, M.E. Tucker and C. Winker.

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Late Jurassic Source Rock Super-Highway on Conjugate Margins of the North and Central Atlantic (offshore East Coast Canada, Ireland, Portugal, Spain and Morocco)

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Preamble

Canada possesses petroleum resources second only to Saudi Arabia: 178 Bbbls of oil and more than 60 Tcf of gas. The great majority of Canada's conventional and nonconventional petroleum resources are located in Western Canada Sedimentary Basin (WCSB) and the adjacent Thrust and Foreland belts. During the past decade Canada's contingent oil reserves have increased 36 fold due to inclusion of WCSB oil sand reserves that became technologically producible in 2003. A large quantity of other nonconventional oil and gas resources from sources such as coalbed methane, tight sands gas, gas shale and tight oil reservoirs were also added in the past decade to the basin's endowment.

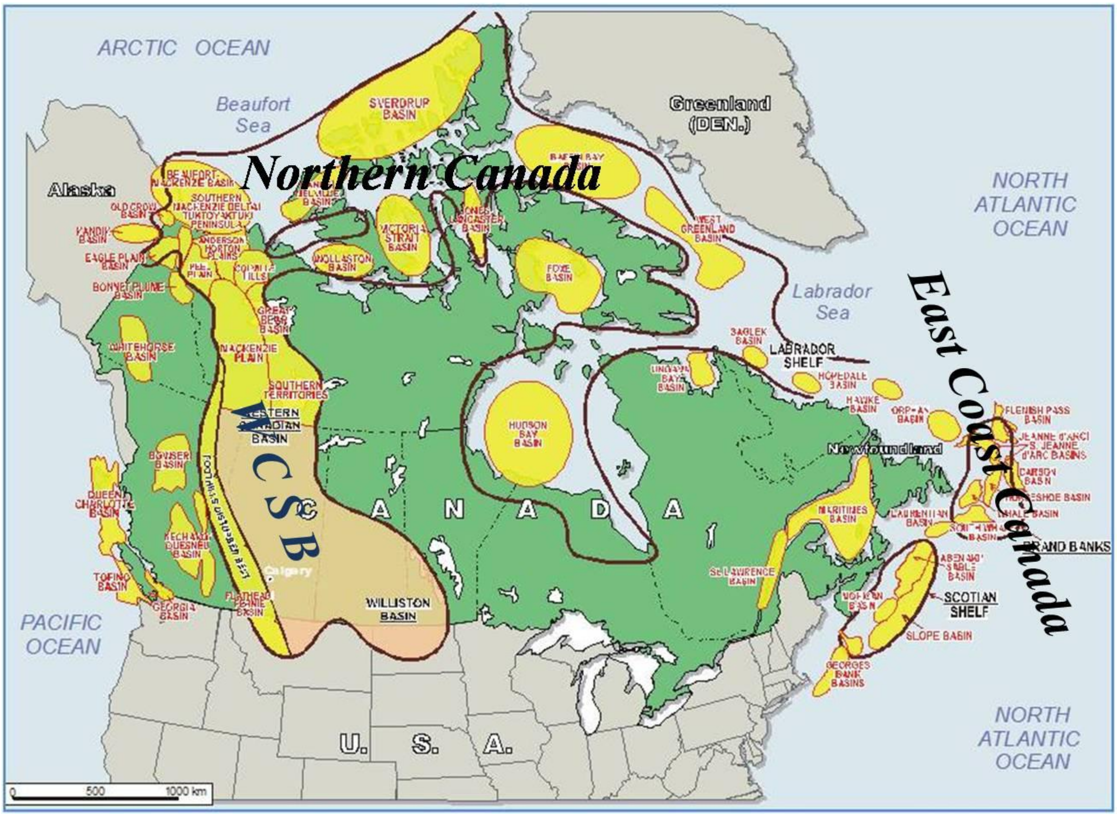

FIG.1 - Canada's sedimentary basins map including the East Coast basins.

In addition to Western Canada's resources, a large amount of Canada's new petroleum resources are found in the sedimentary basins located in the Atlantic Canada, the Arctic and in lesser known basins scattered onshore and offshore. These basins, commonly known as Frontier basins, are lightly explored and may contain further important petroleum reserves. Currently, only the East Coast offshore Mesozoic basins of Nova Scotia and Newfoundland contain producing oil and gas fields, most of which were discovered in the late 1970s to early 1980s when a Canadian Government exploration stimulus program - the National Energy Program (NEP) - was in place. Presently, Canada's only significant oil production outside Alberta, comes from offshore Newfoundland (350,000 bbl/d) and the only important natural gas production comes from Nova Scotia shelf (400 MMcf/d). Additionally, large gas discoveries located offshore Labrador and the Sverdrup basin of the eastern arctic await development.

The main ingredient of Canada's East Coast oil industry is the presence of widespread, high quality Late Jurassic source rocks that are mature in several basins and have generate large hydrocarbon accumulations.

1. Introduction.

One of the prime results of the energy industry sustained exploration efforts and the government targeted research in the Atlantic Canada basins was the birth of a truly Canadian offshore oil and gas industry, whose expertise is now applied around the world (Atkinson and Fagan, 2000; Enachescu and Lines, 2001; Hogg, 2002; Enachescu, 2005; Enachescu and Hogg, 2005; Hogg and Enachescu, 2007 and 2008; Kidston et al. 2002 and 2007).

The first commercial offshore oil development in Canada (1992-1999) was located at the now abandoned Cohasset-Panuke Project (COPAN) on the Scotian Shelf that produced 44.5 MMbbls of high, 50^0 API oil from Cretaceous sandstones. In the Scotian Basin off the east coast of Nova Scotia, the Sable Offshore Energy Project (SOEP), started to produce in 1999 from several gas fields with a total reserve estimated at 3 Tcf (CNSOPB). This is a multi-field development led by ExxonMobil, which has a production capacity of 400 MMcf/d of natural gas and 20,000 bbl/d of natural gas liquids (NGLs). The Deep Panuke field will start to be developed this year (2010) and is projected to produce at a rate of 300 MMcf/d from a 0.63 Tcf gas reserve in Jurassic reefal, dolomitized carbonate (CNSOPB). About 6 Tcf of gas from offshore Nova Scotia, contained in smaller fields remains undeveloped.

Starting in 1999 with the oil production at Hibernia, and later the development of the Terra Nova (2002) and White Rose (2004) fields, the Grand Banks of Newfoundland has become an important oil producing region. To date, more than 1.1 billion barrels have been produced from a total proven recoverable reserve of 3.2 billion barrels. This recoverable resource volume is contained in the three fields, their satellites, a series of smaller fields and the giant heavy and light oil Hebron field that will be developed starting in 2013. Production which now averages 350,000 bbls/d will increase with field satellite developments (N. Amethyst, S. Hibernia, W. White Rose) and when the large Hebron field will be brought on stream. More than 10 Tcf of associated and non-associated natural gas has been discovered in the Grand Banks of Newfoundland and the Labrador Sea but due to low gas price and distance to markets, there is no current natural gas production.

The Frontier basins of Eastern Canada occur in both the onshore and offshore of the four Atlantic Provinces (Nova Scotia, Newfoundland and Labrador, Prince Eduard Island and New Brunswick) and the eastern portion of Quebec. These sedimentary basins were formed during two successive Supercontinental (Wilson) cycles, which took place in:

1) Paleozoic (extensional-compressional) and

2) Late Triassic to present time (extensional).

The following section contains a concise geological overview of the Mesozoic East Coast offshore basins that were proactively targeted by oil and gas exploration companies and were the primary focus for federal and provincial government funded research through Geological Survey of Canada, Provincial Government Surveys and Canadian universities during the past 50 years.

2. East Coast Canada Basins

The basins associated with the Atlantic continental margin (FIG.2, in magenta) represent the Mesozoic-Tertiary Wilson cycle. The Canadian Atlantic continental margin comprises a network of interconnected shelf, slope and deep-water basins formed during the break-up of Pangea supercontinent and opening of the Atlantic Ocean. These basins developed during repeated rifting and thermal subsidence episodes during the Late Triassic to present day; they are mostly extensional in nature but some show a degree of inversion in certain area (e.g. Enachescu and Hogg, 2004; Enachescu, 2008). Over the length of the basin chain, water depth ranges between 10 to more than 4000 m.

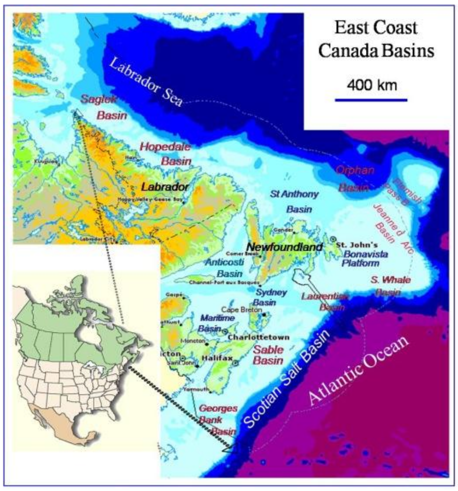

FIG.2 - Bathymetry and sedimentary basins of the East Coast. In blue type are Paleozoic basins and in magenta type the Mesozoic basins (after Enachescu, 2006c).

Atlantic oil and gas fields of national importance were discovered in the Sable sub-basin (gas), Jeanne d'Arc Basin (oil and gas) and Hopedale and Saglek basins (gas) (FIG.2). Almost three billion Canadian dollars were committed for East Coast exploration during the past decade. These expenditures included the extensive acquisition of 3-D seismic surveys, refinement in seismic and well data interpretation, application of reservoir fluids characterization methods (AVO, LMR, etc), use of controlled-source electromagnetic (CSEM) surveying, high resolution biostratigraphy, fluid inclusion analysis, 3D visualization of subsurface geology together with the development of safe technology that allowed for the expansion of oil and gas exploration into deeper water. During the past decade, oil and gas industry drilling, reflection seismic surveys, CSEM, geotechnical studies and geological investigations were carried out along a large portion of the Canadian Atlantic shelf and slope, from the southern tip of the province of Nova Scotia, to the Central Labrador Sea (FIGS.1 and 2). Only two small portions of the total Atlantic offshore with petroleum potential are currently under moratorium and off limits for oil exploration: Georges Bank and The Gully canyon in offshore Nova Scotia. Most of the exploration and research activity were carried out in basins with proven petroleum potential (Jeanne d'Arc, Sable) or unproven, underexplored basins (e.g. Scotian Slope, Laurentian, East Orphan, Hopedale basins).

Regionally, the continental margin of Eastern Canada is characterized by a series of thick sedimentary basins, bounded by faults and located above the thinned continental crust; faulting and folding style and basin geometry varies laterally along the margins (Umpleby, 1979; McWhae et al., 1980; Purcell et al., 1980; McWhae, 1981; Grant and McAlpine, 1986; Enachescu, 1987, 1988, 1992a and b, 2006a and b; Tankard and Welsink, 1987 and 1989; Grant (comp.), 1988; Balkwill and Legall, 1989; Austin et al., 1989; Welsink et al., 1989; Ziegler, 1989; Balkwill et al., 1990; Grant and McAlpine, 1990; Keen and Williams (eds.), 1990; Wade and MacLean, 1990a and b; Hiscott et al., 1990; McAlpine, 1990; MacLean and Wade, 1992 and 1993; Sinclair, 1988 and 1993; Srivastava and Verhoef, 1992; Foster and Robinson, 1993; Driscoll et al., 1995; Withjack et al., 1998; Desilva, 1999; Atkinson and Fagan, 2000; Louden, 2002; Kidston et al., 2002, 2003 and 2007; Smee, 2003; Shimeld, 2004; Enachescu and Fagan, 2005a and b; Enachescu et al., 2005a, b and c; Enachescu and Hogg, 2005; Louden et al. 2005; Shimeld, 2005a and b; Hardy, 2007; Fagan, 2010).

During the Late Mesozoic, the Atlantic margin contained a network of intra-connected rift basins where fine sediments with high organic content (*source rocks*) and porous fine to coarse-grained silisaclastics and carbonates (*reservoir rocks*) were deposited. Alluvial, deltaic, near shore and submarine fan deposition, faulting, folding and a significant amount of mobile salt have created subsurface configurations that can host both oil and gas fields within stratigraphic and structural traps.

2.1. Offshore Nova Scotia

The Scotian Basin, under Atlantic Canada's continental shelf and slope, encompasses a corridor 100 to 200 km wide and 900 km long on the southern margin of the province of Nova Scotia, Canada (FIG.3). Offshore Nova Scotia is an underexplored Atlantic-type rifted area with excellent gas potential. The basins and sub-basins forming the Scotian Shelf and Slope contain synrift and postrift sedimentary sediments deposited during the Late Triassic to Late Cretaceous period. From south to north, the large Scotian Basin includes the following structural elements: Georges Bank Basin, Shelburne Basin, Mohawk Ridge, Emerald Basin, Mohican Basin, Sable Basin, Abenaki Basin, southern Laurentian Basin and Scotian Salt Province. These basins are separated by highs known as ridges or platforms and by transfer faults. Two oblique mainly Triassic-Early Jurassic filled rifts, Fundy Basin and Orpheus Basin (Graben), are part of the Scotian Mesozoic extensional area (FIG.3). Deposition was dominated by terreginous deltaic and shelfal sedimentation with thicknesses up to 20 km in Sable and Laurentian fan areas (Wade et al. 1989; Welsink et al., 1989; Wade and MacLean, 1990a and b Drummond, 1990; Lewis et al., 1991; McLean and Wade, 1992 and 1993; Kidston et al., 2002, 2003 and 2007; Shimeld, 2004 and 2005a and b; Hogg, J. R. and M. E. Enachescu, 2007).

Exploration in the basin started in mid-1960s and intensified in late 1970s to early 1980s when most of the discoveries were made. A late 1990s to early 2000s exploration phase resulted in the discovery of the Deep Panuke gas field in Late Jurassic carbonates. Exploration on the slope and deepwater trend has been less successful resulting only in one non-commercial discovery at Annapolis G-24 (Hogg, 2002; Kidston et al., 2003; Hogg and Enachescu, 2003, 2004 and 2007; Enachescu and Hogg, 2005; Enachescu, 2006e).

The petroleum system of the Scotian Basin includes porous sandstone reservoirs of the Missisauga and Logan Canyon Formations and porous limestone reservoirs of the Late Jurassic Baccaro Member of the Abenaki Formation, organic rich source rocks early identified within shales of the Verrill Canyon Formation within a multitude of structural and stratigraphic traps (Barss et al., 1979; Purcell et al., 1979; Powell, 1982 and 1985; Welsink et al., 1989; Wade and MacLean, 1990a and b; Kidston et al., 2002, 2003 and 2007; Hogg, 2002; Enachescu, 2006e).

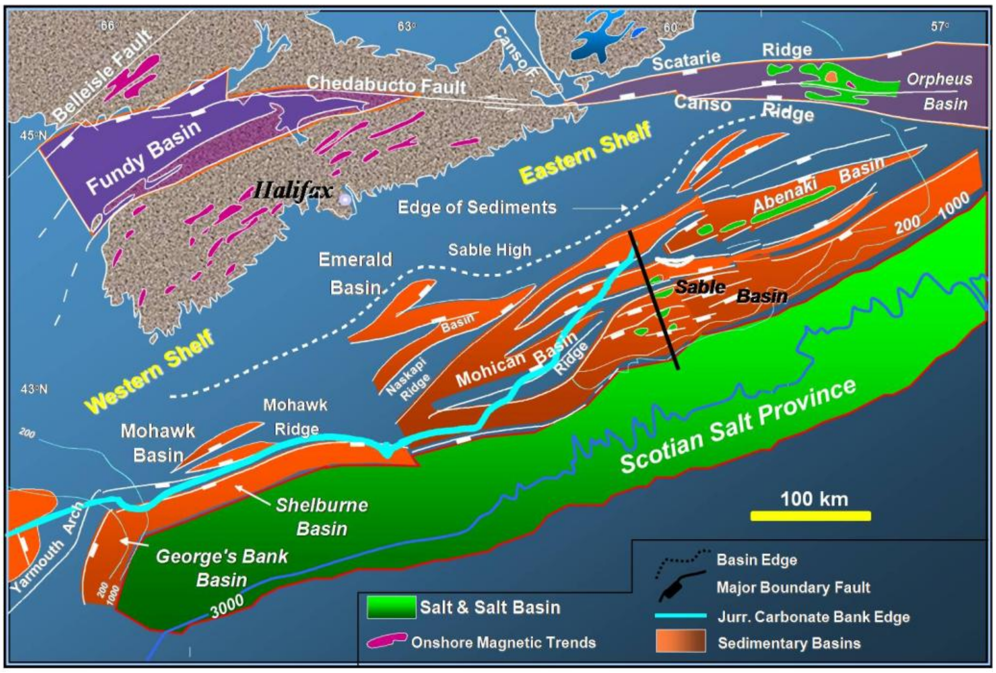

FIG.3 - Structural and tectonic framework of the Scotian Basin (Hogg and Enachescu, 2005; modified from Welsink et al., 1987). Black line shows geological cross-section in FIG.4.

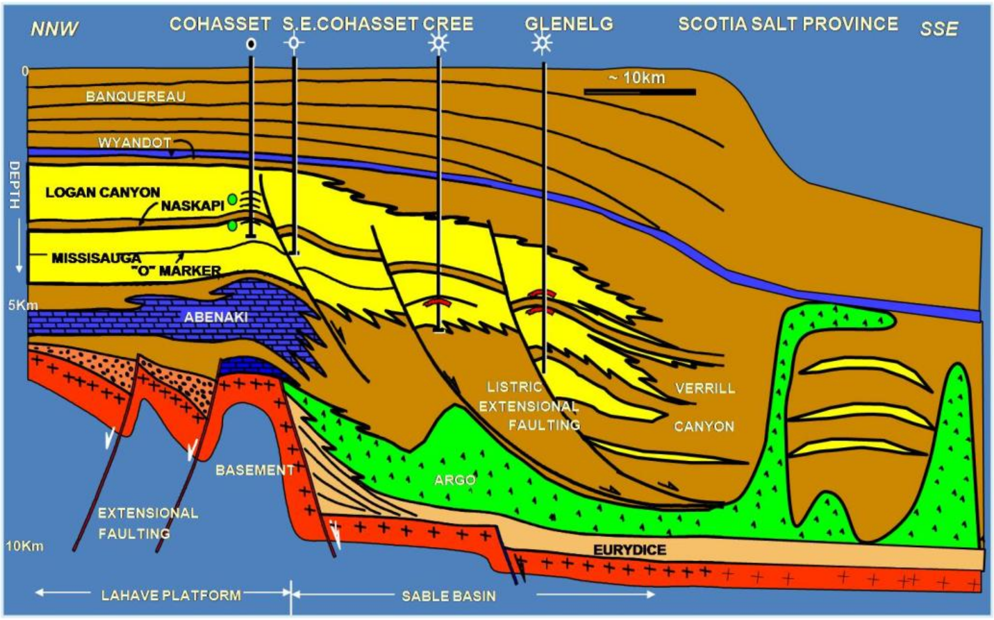

FIG.4 - Structural and stratigraphic cross-section of the Scotian Basin (after Hogg and Enachescu, 2005). Location of cross-section shown in FIG.3 (black line).

The majority of gas and condensate reserves have been discovered on the shelf, within Late Jurassic deltaic sandstones (FIG.4). To date, the total discovered basin resource, at the mean value, is estimated at 6 Tcf and 75 MMbbls of oil, discovered mainly in an area known as the Sable Basin.

Copan Project

A total of 45 MMbbls was produced from the abandoned Panuke, Balmoral and Cohasset fields situated in approximate 40 m of water, 250 km offshore (Hogg, 2002; Hogg and Enachescu, 2003). The three fields have produced light oil from shallow four-way anticlines with stacked porous sandstones of the Early Cretaceous Mississauga and

Logan Canyon formations. Wells in Panuke field were capable to flow more than 25,000 bopd. The COPAN Project was the earliest Atlantic Canada oil development and helped to build offshore petroleum infrastructure in the province. Gas resource estimates from various sources put the potential for the Scotian Shelf and slope at 20 to 40 Tcf.

Sable Offshore Energy Project (SOEP) is the first North American East Coast offshore gas development. It consists of a six field development with gas and condensate production from a central platform and five satellite fields: North Triumph, Venture and Thebaud, Alma and Glenelg. Production is from Jurassic and Cretaceous sandstones from an estimated reserve of about 3Tcf (Mudford and Best, 1989; Wade et al., 1995; Hogg and Enachescu, 2003). The production averages 450 MMcf/d with the majority moving to the US eastern seaboard though Duke Energy et al. Maritime & Northeast Pipeline.

Deep Panuke gas field was discovered by EnCana in 1998, when a well was drilled from the Panuke platform into a deeper seismic amplitude anomaly located at the edge of the Jurassic carbonate platform (Hogg, 2002; Hogg and Enachescu, 2003 and 2008; Enachescu and Hogg, 2005; Weissenberger et al., 2006; Eliuk, 2009). The field was subsequently delineated by five wells and was tested at an average gas rate of 55 MMcf/day from 69 m of net pay within the Abenaki carbonates. The Abenaki reservoir is a dolomitized reefal member with secondary vaggular porosity and may contain upward of 0.6 Tcf slightly sour (2000 ppm H_2S) gas. The field, operated by Encana (100%), is expected to deliver more 300 MMcf/d starting in 2011.

Several slope fan plays have been drilled in intermediate to deep water during the 1999-2005, with only one announced success at the Annapolis G-24 well. While source rocks have been intersected in all the wells that penetrated the Late Jurassic sequence, very little reservoir rock was encountered. The petroleum geology of the deeper water areas remains poorly understood and new paleogeographic models need to be developed to better position the reservoir fairway and distribution of low stand sediments on the slope and in deepwater. There is a need for new research, in plate tectonics setting, basin evolution and reservoir distribution studies to understand better the depositional systems in the deeper water Cretaceous and Tertiary sections.

2.2. Offshore Newfoundland and Labrador

For the past thirty years, the main focus of exploration has been the synrift sequence within the Jeanne d'Arc Basin that shown success in faulted anticline and structural-stratigraphic plays. More recently, similar hydrocarbon plays were pursued in Flemish Pass Basin (three wells), the Orphan Basin (two wells) and in the South Whale Basin (one well) (FIG.5 and 6). Only 17 exploratory wells were drilled in the entire offshore NL East Coast area since 1995, as risk management has become the new petroleum industry creed. This low drilling rate can only be increased by lowering the geological risk through detail petroleum system research and regional and 3D mapping. Some of the deep-water wells were costly disappointments, but they have tested new play concepts for the area with very little information on the nature and distribution of source and reservoir rocks. The only novel play type successfully drilled was tested by the Mizzen L-11 and the follow up Mizzen O-16 both located in the North Flemish Pass Basin in the 1100 m of water depth. The seismic and drilling focus of the past decade shifted to four practically unexplored basins: the Laurentian, Flemish Pass, East Orphan and Hopedale basins (Hogg and Enachescu, 2003, 2004 and 2008; Enachescu et al., 2005a and b; Enachescu and Hogg, 2005; Enachescu, 2005, 2006a and b).

The basins of the southern Grand Banks (Laurentian Basin and South Whale Basin) have had a common structural evolution with the Scotian Shelf and Slope during most of the Mesozoic era. These two rift basins are interconnected and show a strong imprint of salt tectonics, similar to the Sable Basin and to other basins along the southern margin of the Grand Banks/Scotian Shelf (FIG.5). These basins are located approximately 200 km south of Newfoundland, in shallow to deep-water depths and are free of the sporadic and seasonal iceberg traffic that is a factor on the Northern Grand Banks, Orphan Basin and Labrador Shelf.

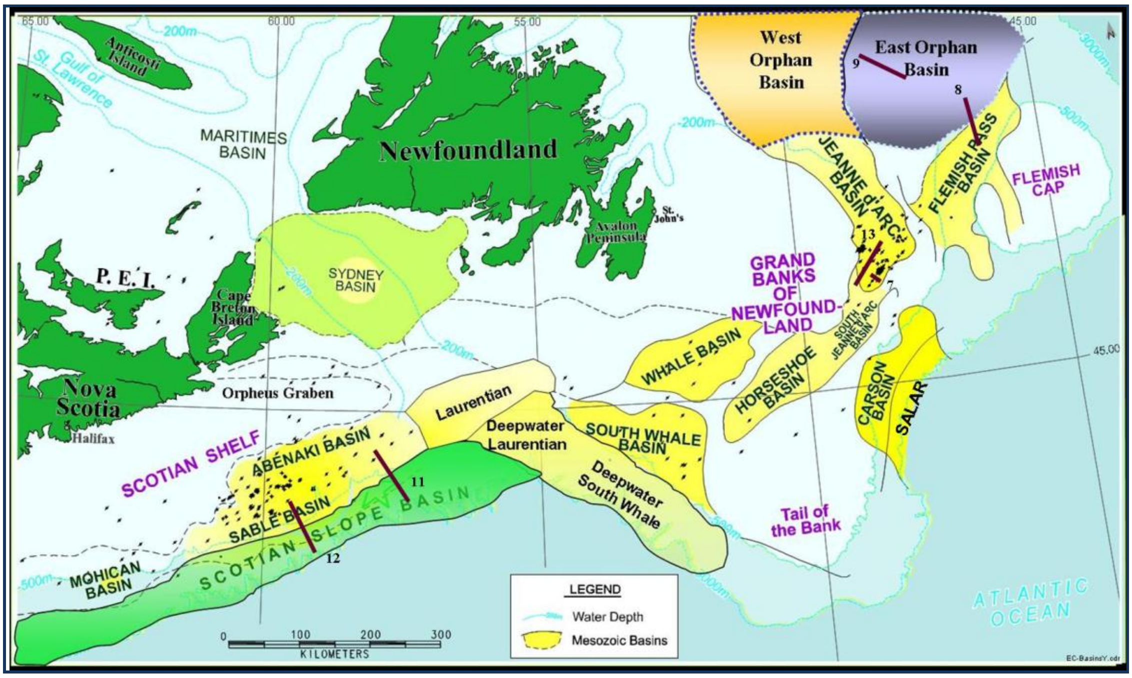

FIG.5 - Offshore Nova Scotia and Newfoundland basins with location of seismic sections shown in this paper (modified from Enachescu 1988 and 2006c). Seismic sections are indicated with brown lines and numbers corresponding to FIGS.7, 8, 9, 11, 12 and 13.

Laurentian Basin

This basin, situated in the south-westernmost Grand Banks, covers an area of 60,000 km^2 distributed between the Newfoundland and Cape Breton islands (FIG.5). Reports by the Geological Survey of Canada and the results of early seismic mapping have indicated a recoverable resource potential for this basin of 600 to 700 MMBbls of oil and 8 to 9 Tcf of natural gas (McLean and Wade, 1992).

A single well, Bandol #1, was drilled during 2001 in the French territorial waters by ExxonMobil, Gulf and partners. This dry hole has been reported to intersect several reservoir intervals that showed promise. Detailed results for this well will not be released until 2011. An inspection of available seismic data and older mapping clearly show that the Laurentian Basin is a typical Atlantic margin deep basin influenced by salt and extensional tectonics (Keen and Williams, (ed.), 1990; Maclean and Wade; 1992; Kidston et al., 2003; Hogg and Enachescu, 2007; Fagan and Enachescu, 2007 and 2008; Fagan and Enachescu, 2007; Enachescu and Fagan, 2009; Fagan, 2010). The potential hydrocarbon plays within this basin are similar to those encountered on the Scotian shelf and slope and include listric fault blocks, rollover anticlines and salt cored anticlines with Jurassic to Early Cretaceous sandstone reservoirs. There is possibility for development of the Jurassic Abenaki limestone porosity and presence on the slope of sandstone fans. Major Late Cretaceous-Tertiary mass transport deposits are also evident on seismic data in the deeper, younger portions of the basin. The current water bottom in the Laurentian Basin is strongly "canyonized". Submarine slides on the Laurentian slope have been previously recorded (Piper et al., 1985; Fagan, 2010).

The Laurentian Basin is presently in the first exploration round because of a long-lived moratorium stemming from a now settled international boundary dispute between France and Canada over the extent of the offshore entitlement of the French islands of St. Pierre and Miquelon that lie directly north of the basin. Once the international boundary was settled and before any lands could be let for exploration, the offshore inter-provincial boundary between Nova Scotia and Newfoundland and Labrador had to be defined. During the summer of 2004, existing federal permits, which had been frozen under the moratorium since the late 1960s, were renegotiated into Exploration Licenses under current legislation. Following exploration efforts on these blocks, at least two large prospects were identified. An unsuccessful exploration well, East Wolverine G-37, was drilled in early 2010, by ConocoPhillips and BHP Billiton, to test one of these deep-water prospects.

South Whale Basin

The South Whale Basin is a Mesozoic sedimentary depocentre situated mostly in the shallow and intermediate water depths of the southern Grand Banks, close to the Newfoundland Transfer Zone (FIG.5). This basin contains 5 to 8 km of Late Triassic to Mid-Cretaceous synrift sediments (akin to those on the Scotian Shelf). Due to the shallower water depths of the South Whale Basin and its generally ice free location, this basin was the first to be drilled in the Newfoundland offshore (Grant and McAlpine, 1986 and 1990; Grant et al., 1988; Balkwill and Legall, 1989; Wade and McLean, 1990b, McLean and Wade, 1992; Desilva, 1999; Enachescu, 2006c and d). The other basins located on the southern Grand Banks - Whale, Horseshoe, South Jeanne d'Arc and southern Carson basins have suffered intense erosion during the Early Cretaceous inversion of the Avalon Uplift. This has caused the removal of the Late Jurassic source rock members and the destruction of the possible petroleum system (Enachescu, 1988, 1992a and b).

The early stage plays in the South Whale Basin were based on drilling for oil on the shallower and crestal portions of the salt anticlines. All such wells were abandoned with only minor shows. Lately, the play concepts have shifted to prospects identified within the large fault bounded rollover anticlines and the rotated fault blocks within deeper synclines where Late Jurassic (Mic Mac sandstone and Abenaki carbonate) and Early Cretaceous (Logan Canyon sandstone) reservoirs form the potential targets. Additional targets may exist within sand-rich fans developed on the southern slope of the basin.

This basin was tested by 14 wells without success during the 1960's (2 wells), 1970's (11 wells) and 1980's (1 well) (Balkwill and Legall, 1989; Wade and MacLean, 1990b; Enachescu, 1988 and 1992b; Enachescu and Fagan, 2005b). During 2005, the Lewis Hill G-85 well, spudded in 100 m water depth, intersected several Late Cretaceous reservoir sandstones but was abandoned without testing. The petroleum system of the South Whale Basin is hypothesized to include ponds of Kimmeridgian – Oxfordian source rock (Verrill Canyon and/or Egret shales) localized within the mapped sink-synclines or mini-basins. Additional Mid to Late Cretaceous source rocks may be present on the slope (Enachescu, 2006c and d; Hogg and Enachescu, 2007).

Carson/Salar Basins

This is a complex basinal area located on the Grand Banks eastern divergent margin and extending from the continental shelf to water depths in the 4000 m range (Austin et al., 1989; FIG.5). Four exploration wells, drilled in the 1970's and 1980's, within the shallower portion of the basin, were abandoned. These wells found good potential reservoir zones but did not intersect the Kimmeridgian Egret Member source rock, probably due to wells position on highs (Enachescu, 1988 and 1992a and b; Louden, 2002; Enachescu, 2006c and d).

There may be significant hydrocarbon potential in the deeper parts of this basin (slope of the Grand Banks and deep water known as Salar), beyond the basement ridge that separates the shelf and slope basins, where an Egret equivalent source rock may be present. Potential Cretaceous source rock of Albian and Cenomanian to Touronian age was drilled during the ODP Leg 210. In the deep-water portion of the basin, Late Cretaceous and Early Tertiary slope fans and several anticlines have been identified on the seismic data and may constitute viable prospects. GSC Atlantic researchers performed several source maturation and geophysical studies during early 2000s to add exploration in this basin (Wielens et al., 2002 and 2006; Baur et al. 2009).

Jeanne d'Arc Basin

This basin is a fault-bounded, Late Jurassic-Early Cretaceous reactivated sector of the larger Late Triassic-Early Jurassic rifted area on the Grand Banks (Enachescu, 1987, 1988 and 1992; Tankard and Welsink, 1987 and 1989). The Jeanne d'Arc Basin is surrounded by the following structural units Bonavista Platform, Cumberland Belt, Central Ridge, Morgiana Anticlinorium and Flemish Pass Basin. Main tectonic lineaments are Murre, Egret and Mercury faults and Dominion Transfer Zone (FIG.5 and 6).

The Jeanne d'Arc Basin was primarily shaped by repeated extensional episodes and exhibits only minor inversion due to trans-tensional forces and salt diapirism. A proven rich petroleum system is present including: a) Kimmeridgian source rock (Egret Member of the Rankin Formation) and b) excellent reservoirs within the Late Jurassic Jeanne d'Arc, the Early Cretaceous Hibernia and Catalina, and the Mid-Cretaceous Avalon and Ben Nevis formations (Enachescu, 1987 and 1988; Tankard and Welsink, 1987; McAlpine, 1989 and 1990; Hiscott et al., 1990; Grant and McAlpine, 1990; Huang et al., 1994; Sinclair, 1995; Atkinson and Fagan, 2000; Fowler and Obermajer, 2001; Driscoll and Hogg, 1995; Ainsworth et al., 2005; Enachescu, 2006c and d).

To date 61 exploration wells have been drilled in the Jeanne d'Arc Basin, representing an exploratory well density of one well per 230 km^2 within the basin. All past exploration has been focused on the oil play, but this may change, as investigations are currently underway toward bringing Grand Banks gas to market. A more complete description of the Jeanne d'Arc Basin and its exploration history, main fields, structure, stratigraphy and petroleum systems was given by Bars et al. (1979); Enachescu (1987 and 1988); Tankard and Welsink (1987); Grant and McAlpine (1990); Sinclair (1993 and 1995); Desilva (1999); Atkinson and Fagan (2000); Enachescu and Fagan (2004); Enachescu (2006c and d) and more information is available from the NL Department of Resources website (http://www.nr.gov.nl.ca/mines&en/oil/).

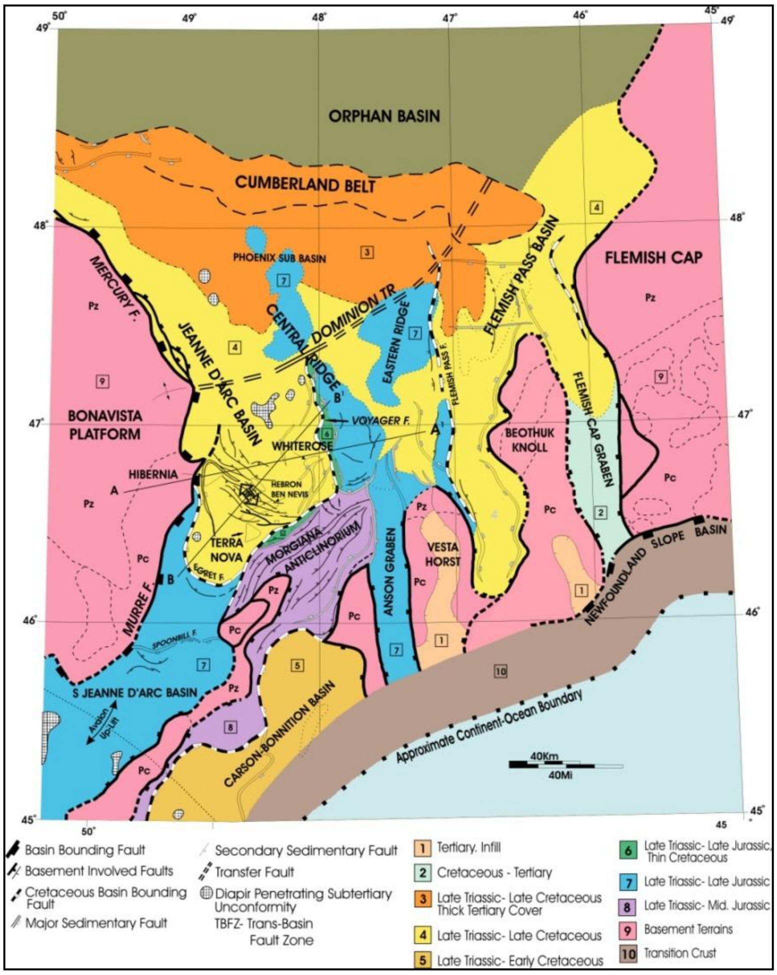

FIG.6 - Tectonic and structural framework of Northeastern Grand Banks and environs (modified after Enachescu 1987 and 1992).

After the Kimmeridgian-aged Egret source rock has been intersected in the Egret K-36 well, a seismic horizon was easily correlated to this member. Once geochemically recognized at this and several other well locations, the corresponding seismic marker was then regionally mapped using 2D and 3D seismic data sets. The maps have shown a widespread distribution of the Late Jurassic source rocks within the Jeanne d'Arc Basin and Central Ridge.

According to the Canada Newfoundland Offshore Petroleum Board (C-NLOPB), the discovered recoverable reserves and resources of the Jeanne d'Arc Basin are estimated to be 2.9 billion barrels oil and 6.6 Tcf of associated and non-associated gas with 356 MMbbls of associated liquids, but this number is set to increase due to continuous increase in the recovery rate for the offshore fields. The total recoverable reserves for this basin are estimated at over 5.3 billion barrels oil and 20 Tcf gas within the Hibernia, Terra Nova, White Rose and Hebron fields (some of the largest oil fields discovered in Canada). Smaller satellite fields and extensions of the producing fields were drilled in the last five years. Some are now developed as satellites to major fields (e.g. North Amethyst, South Hibernia). The Jeanne d'Arc Basin has future potential for oil discoveries in deeper structural and stratigraphic traps in the southern part, and combination traps in the eastern side of the basin. Gas plays within this basin remain undrilled.

Hibernia oil field

The Hibernia structure is a large anticline situated in the downthrown side of the Murre Fault and densely dissected by two sets of faults (Arthur et al., 1982; Enachescu, 1987; Tankard and Welsink, 1987; Mackey and Tankard, 1990; Ainsworth et al., 2005). The field was discovered in 1979 by the Chevron et al. Hibernia P-15. This was the 45th well in Grand Banks region, 10th well drilled in Jeanne d'Arc Basin and tested 800 bopd, 32^0 API on openhole test of Late Jurassic sandstones. High quality reservoirs were encountered in the Berriasian-aged Hibernia sandstone that is a high quality reservoir and contains the largest reserves. High quantity of oil was also found in the more heterogeneous Avalon sandstone (Aptian/Albian) and oil was subsequently tested from the Jeanne d'Arc and Catalina sandstones. The field was developed with a Gravity Based Structure (GBS) sitting in 80 m of water. The field started producing in 1997 from an initial estimated oil reserve of 550 MMbbls. The recoverable reserves have been recently increased to 1.24 Bbbls due to improved drilling technologies (deviated wells, long reach drilling, efficient reservoir monitoring, etc.) and discovery of additional reserves. Additionally the trap contains 1.3 Tcf of associated gas. Hibernia has pumped out 680 million barrels to summer 2010, with maximum output of over 200,000 bbls/d attained in May 2004. During summer 2010 Hibernia has reached payout of development costs and it is now providing larger royalty (30%) to Newfoundland and Labrador.

Terra Nova oil field

The Terra Nova field is contained in a structural-stratigraphic trap developed in the downthrown of the Voyager Fault, on the eastern margin of the Jeanne d'Arc Basin. The high quality reservoir is formed by onlap of Late Jurassic Jeanne d'Arc sandstone on a large structural nose (Enachescu, 1993; Enachescu et al., 1994). Only the Central Graben, Eastern Flank and the far-East Flank of the segmented structural have produced oil. The reservoir was deposited as a large paleodrainage fluvial system sourced from the southern Jeanne d'Arc Basin with sands reworked along a fluctuating Late Jurassic shore line (FIG.7). The field is segmented by two fault systems (N-S and E-W). On parts of the field the reservoir is juxtaposed on the Egret Member source rock. The field was discovered in 1984 by the Petro-Canada et al. Terra Nova K-08 and was developed in 95 m of water using a FPSO. The field has 419 MMbbls recoverable oil reserves. Production started in 2002 and attained over 100,000 bbls/d during June 2003.

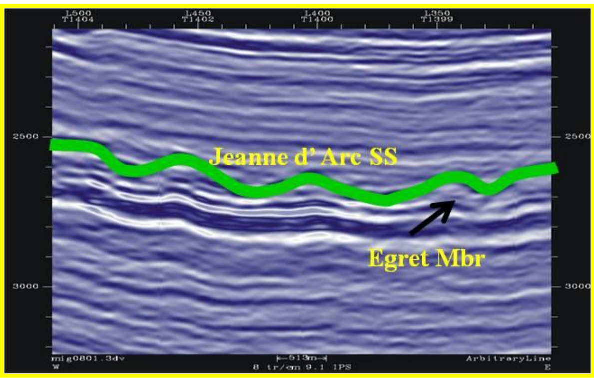

FIG.7 - Egret Source rock level indicated in green south of Terra Nova Oil field offshore Newfoundland. Location of seismic section is shown in FIG.5.

White Rose oil field

Several teaser wells (White Rose N-22, J-49 and L-61) were drilled in the on a large salt diapir induced structure located in the east-central Jeanne d'Arc Basin, before the true discovery well White Rose E-09 drilled in 1998 intersected a 90 m oil pay (Enachescu, 2006c). The field area consists of several oil and gas pools in the Avalon formation sandstones. This reservoir was formed by reworking older sandstones from the Central Ridge area and deposited during the late Early Cretaceous along an approximately north-south trending shoreline roughly paralleling the eastern margin of the Jeanne d'Arc Basin. The White Rose south pool, estimated to contain 305MMbbls was developed using a FPSO. The first oil was achieved in the fall of 2005. Maximum annual production was about 42.8 million barrels attained in 2007, while maximum daily production of 120,000 bpd was achieved during August 2007. White Rose has several satellite fields, the first of which - the North Amethyst field - has started production in 2010.

From the above discussion it is evident that the daily production of the Grand Banks oil field is down from its peak of 400,000 bopd attained in May 2007 and that new satellite field development, the future production from the Hebron complex and new discoveries are needed to maintain the health of NL oil industry.

Hebron oil field

This is a compartmentalized field discovered in 1981 and delineated during the next twenty years (Enachescu, 2006c and 2009). The field consists of the Hebron, Ben Nevis and West Ben Nevis oil accumulations located in several independent fault blocks situated in the central part of Jeanne d'Arc Basin in 90 to 100 m of water. Oil and gas are contained in the Ben Nevis, Hibernia and Jeanne d'Arc Formation sandstone reservoirs. The Hebron field faces challenges associated with the recovery of heavier gravity oil (~20^0 API) in the Hebron main pool, variability of oil quality within individual reservoirs and compartments. The Hebron complex is estimated to contain 731 MMbbls recoverable reserves/resources and is to be developed starting in 2012 with "first oil" production scheduled for 2017. Development will involve a concrete GBS to be built in Newfoundland and Labrador. It is projected that Hebron field will yield 120,000 - 176,000 bopd over 30 years.

Flemish Pass Basin

This is Mesozoic basin is partially located in a bathymetric low (roughly 1100 m of water) northeast of the Jeanne d'Arc Basin and west of the Flemish Cap bathymetric high (Enachescu, 1987 and 1992; Grant et al., 1988; Foster and Robinson 1993; Desilva, 1999; Atkinson and Fagan, 2000; McCracken et al., 2000; Enachescu et al., 2005a, b and c; Hogg and Enachescu, 2007 and 2008; Enachescu, 2009; FIGS.1, 5 and 6). Four older and three recently drilled wells have proven that the basin has excellent Late Jurassic Egret equivalent source rock and good, thick Late Jurassic – Early Cretaceous sandstone reservoirs. Modern 2D and 3D seismic surveys cover almost the entire basin and show large, complexly faulted extensional anticlines that were subsequently modified by several trans-tensional episodes. The basin is subdivided by transfer faults into several sub-basins that had relatively different depositional and structural histories (Desilva, 1999; Enachescu et al., 2005c).

Three recent wells, Mizzen L-11, Tuckamore B-27 and Mizzen O-16, were drilled in the northern Flemish Pass Basin. Non-commercial oil pay was discovered in Early Cretaceous sandstone in Mizzen L-11 (Hogg and Enachescu, 2007 and 2008; Enachescu, 2009). In the Mizzen O-16 well, drilled 10 km north of L-11, a Late Jurassic sandstone with good reservoir properties was found (FIG.8). This oil-filled unit was tested and subsequently a significant discovery was declared in 2010. In May 2004 the Canada-Newfoundland and Labrador Offshore Petroleum Board and the Geological Survey of Canada published a report that estimated the undiscovered recoverable petroleum resources in the Flemish Pass Basin at 273 million m^3 (1.7 Bbbls) at a 50 percent probability - with expected field sizes ranging from 528 to 44 MMbbls.

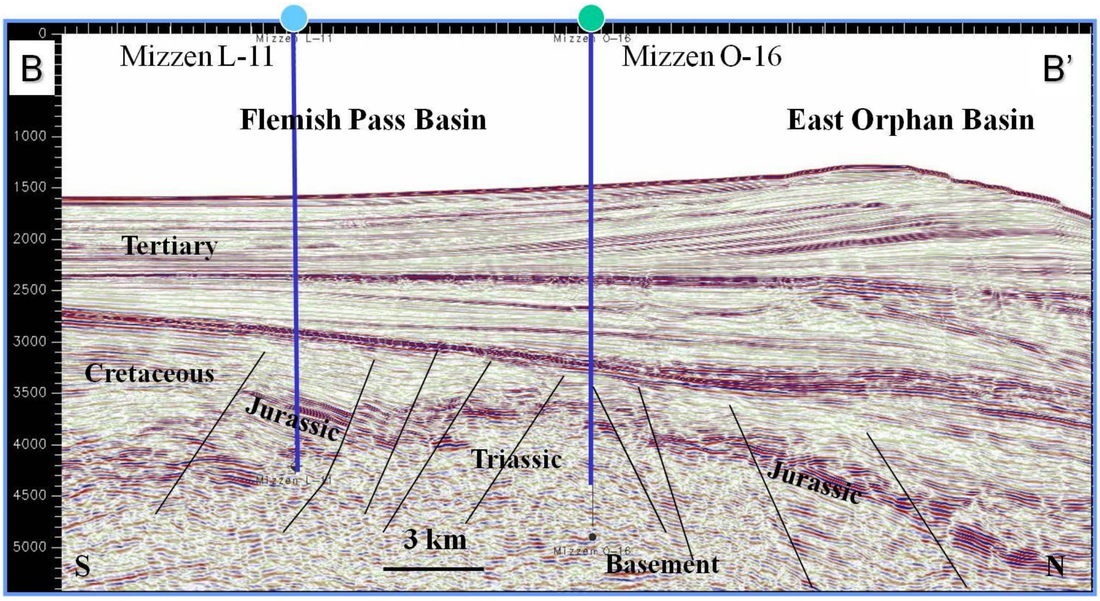

FIG.8 - Location of the two discovery wells Mizzen L-11 and Mizzen O-16 in Flemish Pass Basin (modified after Enachescu 2009). Location of seismic section is shown in FIG.5.

The Mizzen O-16 oil pays and the thick Late Jurassic source rock interval identified in Mizzen wells, bodes well for future exploration of this basin and its larger neighbour to the northwest - the East Orphan Basin (FIGS.5 and 8).

East Orphan Basin

The present major focus of exploration in Atlantic Canada is in the East Orphan Basin, a highly extended Mesozoic-Tertiary sedimentary area situated north and northeast of the Grand Banks of Newfoundland in water depths ranging between 1500 and 3500 m (FIGS.1, 5 and 8). With a long intra-continental rift evolution, shallow marine and restricted marine interludes where formed that allowed for source rocks deposition and numerous synrift structural and stratigraphic trapping configurations, the East Orphan Basin has the potential to become the first deep water producing area in Atlantic Canada (Enachescu et al., 2005a, b and c; Hogg and Enachescu, 2004 and 2007; Burton-Fergusson et al., 2006). Large and complex anticlines, rotated fault blocks and submarine fans can be mapped in the basin using present 2D and 3D coverage. According to recent published regional seismic studies, there are half dozen large structures in the basin, each with the potential to hold several billion barrels of oil-in-place (Smee, 2003; Enachescu et al., 2005c; Hogg and Enachescu, 2008; Enachescu, 2009).

Connected to the proven petroleum systems of the Jeanne d'Arc and Flemish Pass basins, the East Orphan Basin has the potential for several giant discoveries (FIGS.5 and 8; Enachescu et al., 2005c). The petroleum system of the East Orphan Basin should include: a) Kimmeridgian and probably Albian to Late Cretaceous source rocks; b) Late Jurassic, Early Cretaceous and Tertiary reservoirs; d) Source maturation, generation and short distance migration of oil and gas from large sub-basins into existing antiforms and submarine fans (Enachescu et al., 2005c; Hogg and Enachescu, 2007; Hardy, 2007). The Great Barasway F-66 drilled during 2006-2007 was dry but intersected good quality sandstone reservoirs and Late to Mid Jurassic age (FIGS.9 and 10). No paleogeographic description or geochemical information is available on the Late Jurassic source quality of the shales encountered in this well. A new deep-water well Lona O-55 was spudded in 2600m of water during spring of 2010. The quality and maturity of possible Late Jurassic source rocks and migration timing are topics that need to be research in this slightly explored basin.

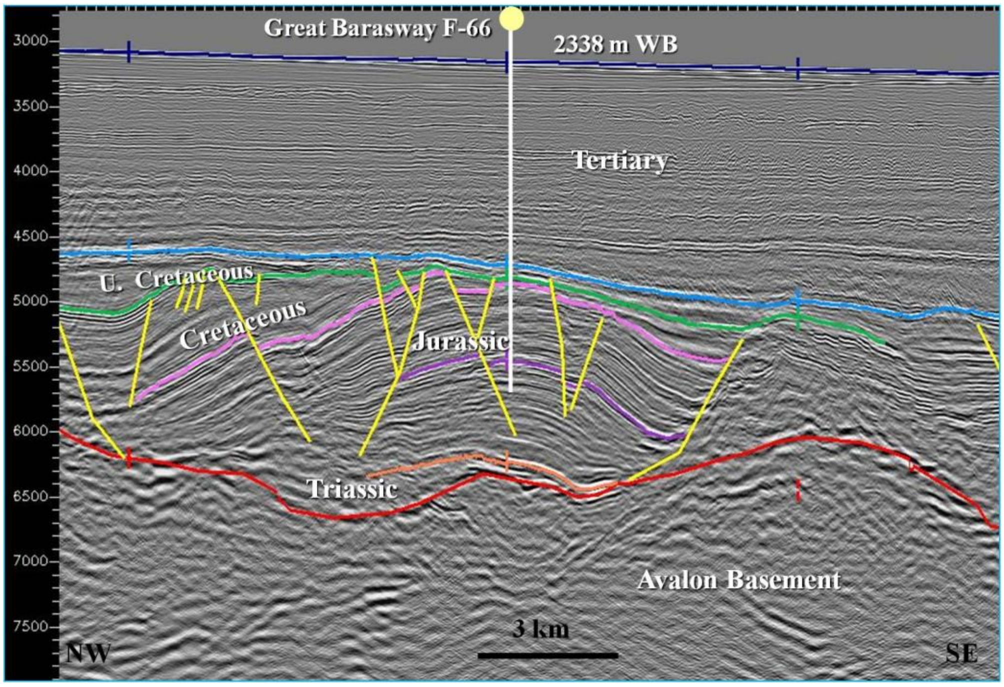

FIG.9 - Location of the abandoned Great Barasway F-66 well in East Orphan Basin (modified after Enachescu, 2009). Location of seismic section is shown in FIG.5.

West Orphan Basin

The West Orphan Basin is an area of approximately 60,000 sq km lying between the White Sail and Bonavista faults and located directly west from the current exploration in the East Orphan Basin (FIGS.1, 5 and 10). This basin is a younger rift basin than the East Orphan and the Jeanne d'Arc basins and was initiated during Cretaceous extensional stages of intra-continental rifting and inter-continental drifting (North Atlantic and Labrador rift stages). Landward rift migration produced a large area that filled with in excess of 7 km Cretaceous strata lying above and between large northeast-southwest trending rotated basement blocks (Enachescu et al., 2005a, b and c; Hogg and Enachescu; 2004 and 2007; Burton-Fergusson et al., Hardy, 2007). The Cretaceous strata are overlain by a thick Tertiary section ranging from 3000 m to 5000 m. It is possible that Jurassic sedimentary rocks may be present to some degree in several deep troughs in the West Orphan Basin, but current seismic imaging and lack of deeper well control do not allow a definitive conclusion (Enachescu et al., 2005a, b and c; Hogg and Enachescu; 2004 and 2007).

The Tertiary section is significantly thicker in the West Orphan Basin than in the East Orphan Basin, ranging from 3000 m to 5000 m in thickness. Below the Base of the Tertiary seismic marker, a thick Mesozoic section can be seen in the downthrown block of the basin-bounding Bonavista Fault. Some sedimentary troughs may contain in excess of 7 km of Cretaceous-aged sediments. It is also possible that Late Jurassic sediments may be present to some degree in several deep troughs in the West Orphan Basin, but current seismic imaging does not allow a definitive conclusion to this effect.

Existing 2D seismic data in the area show a significant number of potential hydrocarbon traps within the Cretaceous sediments, including tilted fault blocks, drape closures over basement highs and stratigraphic traps on the flanks of basement highs. Subaqueous fans and turbidites of Late Cretaceous and possibility Tertiary age derived from platform and ridges and sourced from a postulated Albian or Late Cretaceous source rock are the most obvious undrilled play-types in the West Orphan Basin. Several Late Cretaceous and Early Tertiary seismic sequences have characteristic aspects of marginal fans, but 3D mapping will be necessary to verify their areal extent, shape and trapping potential of this features. Some of these fans are associated with amplitude anomalies at various levels in the Cretaceous and Tertiary.

The West Orphan Basin contains seven dry holes drilled between 1974 and 1985 that targeted Mesozoic reservoirs. All wells were drilled on basement highs, with little preserved Cretaceous cover. While good reservoirs and very large structural traps were tested, no significant hydrocarbon flows were found. More importantly, no Kimmeridgian source rocks were encountered and this may account for the lack of Early Cretaceous hosted oil discoveries in this basin. Given the large size of the basin, and the fact that the drill bit has never tested most of the Mesozoic sequence, the West Orphan Basin deserves more research and a second round of exploration using modern seismic including 3D data, thermal modeling of possible Cretaceous source rocks and drilling for synrift, intra-graben Early Cretaceous reservoirs and for basin margin Late Cretaceous fans.

2.3. Labrador Sea

This area has seen an early exploration phase during the seventies and early eighties that resulted in significant gas finds (FIGS.1 and 7). The area of hydrocarbon potential is vast, encompassing 200,000 km^2 from 52 to 60 degrees north. The Labrador Sea contains a series of Early Cretaceous to Tertiary extensional and trans-tensional basins that were drilled during the seventies and early eighties, and resulted in five significant gas discoveries (Umpleby, 1979; McWhea, 1980; McMillan, 1982; Balkwill, 1987; Balkwill et al., 1990; Desilva, 1999; Enachescu, 2006, a and b, 2008). The source rock for these gas accumulations is the lacustrine shale intervals within the Bjarni Formation, which also contains the most important reservoir rock (Fowler et al., 2005; Enachescu, 2006a and b; Enachescu, 2008). The Labrador Sea has two main basins: Hopedale in the south and Saglek in the north.

There was a revival of exploration activity in the area marked by the 2007 landsale of 4 ELs and the acquisition of new seismic data during 2003-2008. Recently acquired regional seismic data tying some of the earlier 28 wells (gas discoveries included), and extends the Cretaceous play areas off-shelf into the deeper water. This renewed interest in the area is also a reflection of recent exploration activity taking place across the sea on Greenland’s continental margin where indications of older sequences, including Late Jurassic strata, have been observed on land in outcrop and on recently acquired seismic data.

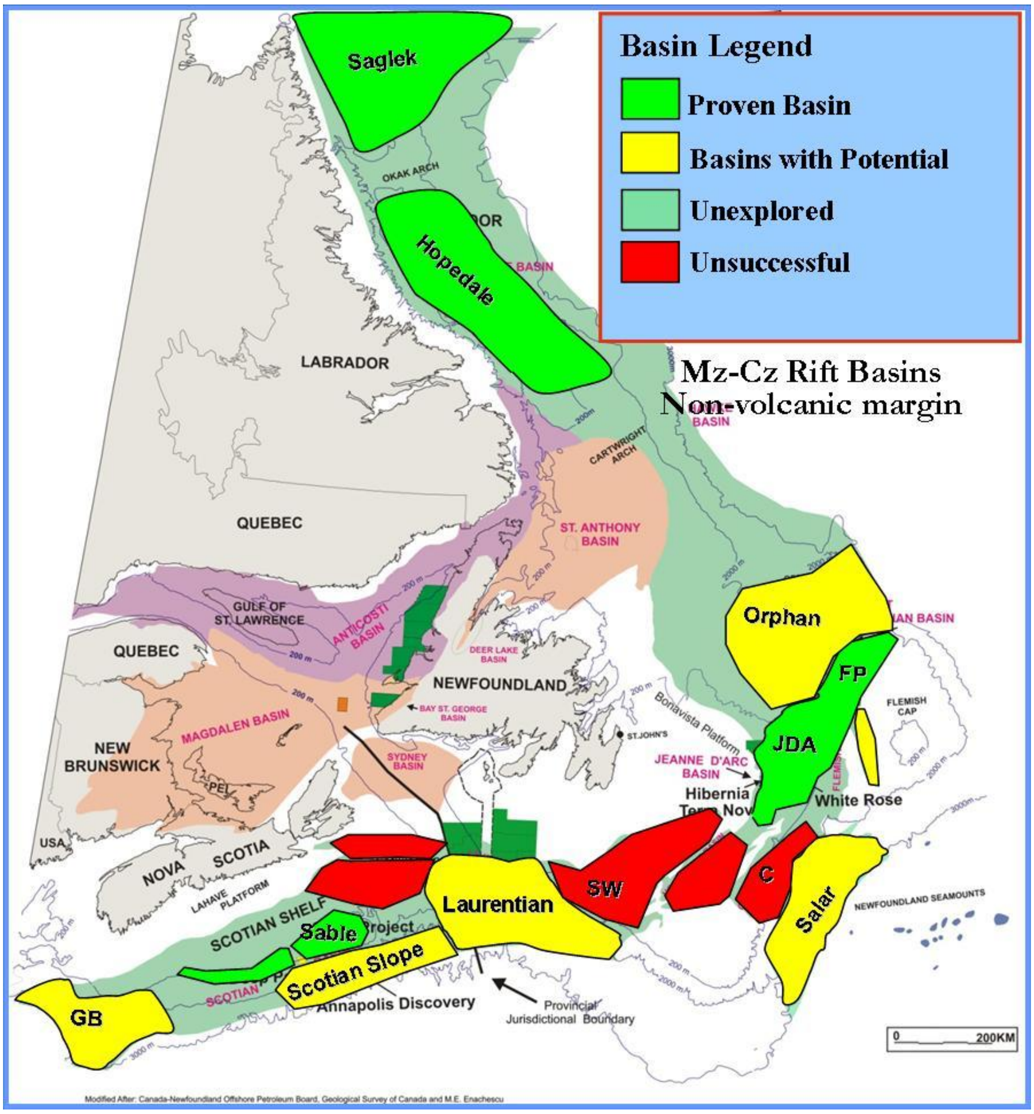

FIG.10 - Mesozoic East Coast Canada basins and their exploration ranking (regional map after NL Department of Natural Resources, GSC and from Hogg and Enachescu, 2008; Enachescu et al., 2008). Annotations are: GB = Georges Bank, SW = South Whale, C = Carson, JDA = Jeanne d'Arc and FP = Flemish Pass basins.

Hopedale Basin

The Hopedale Basin is located 80 and 150 kilometres off the coast of Labrador between in the southern part of Labrador Sea (FIGS.1 and 10). The basin has been tested by 21 wells (16 only reached target) between 1973 and 1983. No drilling has occurred in this basin since 1983 (Balkwill et al., 1990; Enachescu, 2006a and b; Hogg and Enachescu, 2007; Enachescu, 2008). According to the C-NLOPB, a total of 4.24 Tcf of gas resource and 123 million barrels of NGL's were found in the Hopedale Basin, between 80 and 150 km off the coast of Labrador in fields such as North Bjarni (2.2 Tcf), Bjarni (0.9 Tcf), Hopedale (0.1 Tcf), Gudrid (0.9 Tcf), and Snorri (.105 Tcf), but no drilling has occurred in the basin since 1983. Excellent quality reservoirs were encountered in Late Cretaceous-aged sandstones of the synrift sequence and in Ordovician pre-rift carbonates located at 2.5 to 3.5 km depth. Large structures such as horst and fault blocks are the usual exploration targets. Conceptual plays include the drape and onlap of the Bjarni sandstone on basement highs, rollover anticlines, fault blocks and Tertiary fan and turbidite sands. Several stratigraphic traps (pinch outs) were also drilled.

Significant Discovery Licences (SDLs) in the Hopedale Basin are held by several companies including Husky, Suncor, AGIP, ConocoPhillips and ChevronTexaco. These discoveries are currently at the edge of the technical and economical frontier, but new technologies and increasing demand for cleaner fossil fuels may accelerate their development. Given the large number of undrilled features and proven prospectivity, it is very likely that more reserves will be found in the large licensed area. There is new evidence of deep basins on the continental slope rise, increased prospectivity for oil in deepwater, where possible older basins containing Late Jurassic formations may exist.

Saglek Basin

The Saglek Basin is the most northerly Labrador Sea Basin (McWhea, 1980; Balkwill et al., 1990; Enachescu, 2006a and b; Jauer and Budkewitsch, 2010). It covers an area of 80,000 km^2 (FIGS.1 and 10). The six wells drilled in the basin during the 1970’s to early 1980’s has proved the presence of both source and reservoir rock within the basin. The Hekja O-71 well located in 350 m water depth, discovered natural gas (2.3 Tcf) and NGLs in Paleocene/Eocene sandstones. The basin has similar structural, tectonic and stratighraphic characteristics with the Hopedale Basin. However, considerable volumes of volcanic rocks are present in the Saglek Basin. Recent reprocessing of older seismic data, the identification of marine surface seeps from satellite data and the acquisition of some new regional seismic data has facilitated research into the basin’s geology and petroleum potential (Jauer and Budkewitsch, 2010). However, the Saglek Basin remains underexplored and one of the least understood basins on the Canadian margin. New seismic data has been recorded in the past years over the Saglek Basin, including lines tying the exploration wells and two trans-Labrador Sea lines (Enachescu et al., 2007; Enachescu, 2008).

3. Source Rocks

Nova Scotia Shelf and Slop

Most source rocks beneath the shallow water Scotian Shelf are dominated by terrestrial organic matter and hence are gas or gas- and condensate-prone (Purcell et al., 1979 and 1980; Powell, 1982 and 1985; Snowdon and Fowler, 1988; Wade and McAlpine, 1990; Wade and MacLean, 1990; Mukhopadhyay, 1990 and 2001; Kidston et al., 2003 and 2007; Hogg and Enachescu, 2007 and 2008). They were deposited in partially anoxic conditions in a shallow marine setting with major sediment input from a major deltaic system (Jurassic-Cretaceous age Sable Delta) and hence dominated by Types II and III kerogens though with some minor zones containing Types I and II oil-prone kerogens (Mukhopadhyay et al., 2003).

At least eight stratigraphic successions have been identified containing source rock facies (Mukhopadhyay et al., 1995 and 2006; Mukhopadhyay, 2001; Kidston et al., 2007). The Callovian (and possibly Bajocian) age black shales and carbonates are considered the major source interval, with the Berriasian-Valanginian as a subsidiary source though here are mostly gas-prone (P.K. Mukhopadhyay, pers. comm., 2010):

Age	Unit	Depositional Environments	Kerogen Types	Potential Hydrocarbons
E. Tertiary (Paleocene-Eocene	Banquereau	marine	I II-III	oil condensate-gas
M.-L. Cretaceous (Aptian-	Logan Canyon	terrestrial & lacustrine	II-III III	condensate gas

Cenomanian)				
E. Cretaceous (Aptian-Albian)	Verrill Canyon	marine	II II-III III	oil oil & gas gas
E. Cretaceous (Berriasian-Valanginian)	Verrill Canyon	marine	II-III	condensate & gas
L. Jurassic (Oxfordian-Kimmeridgian)	Verrill Canyon Misaine	marine	II II-III III	oil oil & gas gas
M. Jurassic (Callovian)	Misaine	marine	II-III	oil & gas
M. Jurassic (Aalenian-Bajocian)	Mohican	terrestrial & lacustrine	II-III III	condensate gas
L. Triassic to E. Jurassic	Eurydice & Mohican	lacustrine	I III	oil gas

TAB.1 - Compilation of Scotian Shelf source rock intervals (after Mukhopadhyay et al., 1995, and 2006; Mukhopadhyay, 2001).

Most of these source rocks are found within the Sable Subbasin and on the La Have platform, with commercial discoveries of gas, condensates and light oils limited to the former area. Geochemical analysis of the liquids reveals four hydrocarbon families as defined by Mukhopadhyay et al. (1995; 2001).

On deepwater Scotian Slope, there are limited (10) well penetrations, of which six are of recent vintage (2001-2004). Well targets in all but two wells were structural features containing interpreted deepwater turbidite and fan facies of Early to Late Cretaceous age. Non-commercial gas discoveries were made in the Annapolis G-24 well (27m net pay) and in the Newburn H-23 well (7m net pay). Although deepwater reservoirs were uncommon, where adequate porosity was developed the sands were gas-charged indicating an active petroleum system (Kidston et al., 2007). The paucity of wells precludes a comprehensive evaluation of the source rock sequences on the deepwater Slope and their spatial distribution, yet general trends can be determined. Mukhopadhyay et al. (2006) suggested that the source intervals shown Table X could be projected into the deepwater regime. Review of geochemistry studies from the recent wells (Kidston et al., 2007) for the region down-dip of the Sable Subbasin reveal that Tertiary source rocks are generally lean and composed of Type II and III organic matter. They are gas-prone, with TOCs from 0.5-2.0% (with some exceptions) and are mostly immature with some marginally mature. The Cretaceous-age source rocks have similar TOC ranges from Types IIB and III organic matter and are also gas- and condensate-prone with possible oil. Except for the uppermost part of the succession, Cretaceous source rocks are moderately mature to mature (oil window). In deeper water wells (e.g., Annapolis G-24) the equivalent stratigraphic succession is slightly more mature than wells on the upper slope (FIGS.11 and 12).

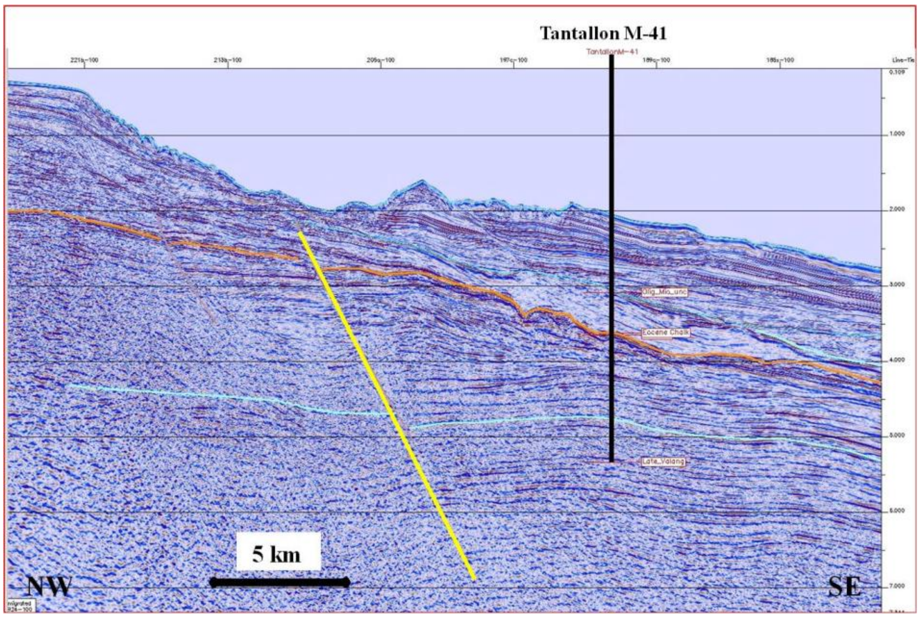

FIG.11 - Seismic dip profile through the Tantallon M-41 well, central Scotian Slope, drilled to test a large rollover anticline. No reservoir sands and hydrocarbons were encountered, but the well identified several source intervals in this slope setting (modified after Kidston et al., 2007). Location of seismic section is shown in FIG.5.

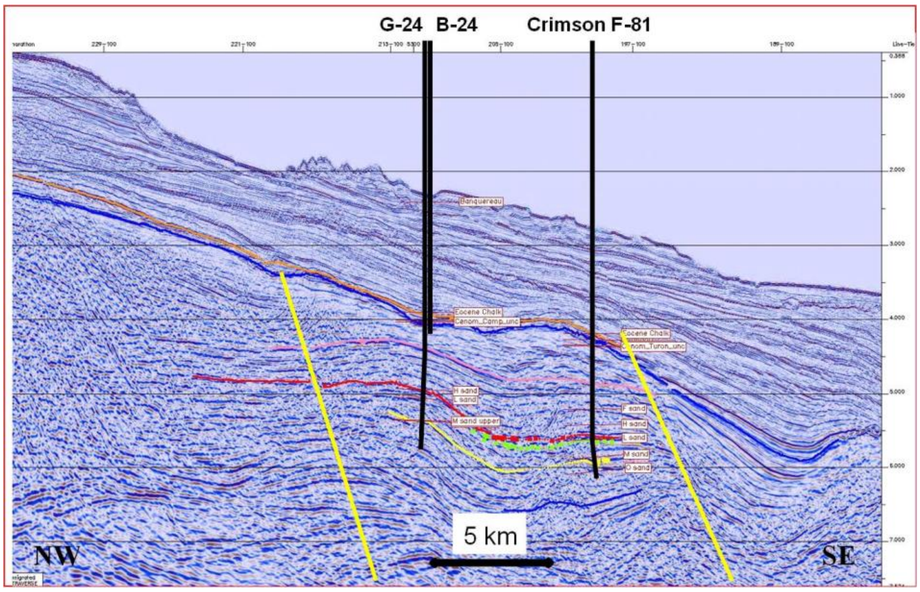

FIG.12 - Seismic dip profile through the Annapolis and Crimson wells, central Scotian Slope, drilled to test large salt-related slope detachment structures outboard of the Sable Subbasin (modified from Kidston et al., 2007). Location of seismic section is shown in FIG.5.

Age	**Unit**	**Depositional Environments**	**Kerogen Types**	**Ro**	**Maturation**	**Potential Hydrocarbons**
E. Tertiary (Paleocene-Eocene)	Banquereau	marine	I/II II-III	~0.2-0.4	immature-marginally mature	oil condensate-gas
L. Cretaceous (Cenomanian-Turonian)	Logan Canyon	marine	II IIB-III	~0.3-0.5	moderately immature-marginally mature	oil condensate-gas
E. Cretaceous	Verrill Canyon	marine	II-III	~0.4-	marginally	oil & gas

(Aptian-Albian)	(Missisauga Eq.)		III	0.6	mature- mature	gas
E. Cretaceous (M. Berriasian- L. Barremian)	Verrill Canyon (Missisauga Eq.)	marine	II II-III	~0.6- 1.0	mature- late mature	oil oil & gas

TAB.2 - Geochemical evaluation from four of the six most recent deepwater wells on the Scotian Slope reveals that Tertiary and Cretaceous source intervals, where penetrated, are broadly comparable to those defined by Mukhopadhyay et al. (1995 and 2006). Better sampling density indicates source intervals straddling the Neocomian (Early Berriasian to Late Barremian). No wells reached Jurassic age strata. A summary of well geochemical information and respective source documentation is presented in Kidston et al. (2007).

Offshore Newfoundland

The best characterized Kimmeridgian-aged source rock in offshore Atlantic Canada is the Egret Member of the Rankin Formation in the Jeanne d'Arc and Flemish Pass basins (Powell, 1985; Fowler and McAlpine, 1995; McCracken et al., 2000; Fowler and Obermajer, 2001). This has been proven to be the source for most of the discovered hydrocarbons within the Jeanne d'Arc Basin with minor contributions from other Late Jurassic intervals. The Egret source rock was first intersected in the basin at 2578 m subsea by the Egret K-36 well. This was the 26th well drilled in the Grand Banks and the 5th well in Jeanne d'Arc Basin (FIG.13; C-NLOPB, 2010).

The lithology of the Egret Member is interbedded shales and carbonates with the shales becoming more dominant toward the north east of the basin. The Egret Member ranges in thickness from 55 to in excess of 200 m, with an average TOC content of 4.5%. It contains Type II marine-derived organic matter. Hand-picking of samples (there are no cored intervals) has shown that dark brown shales are the best source lithology, with grey- to grey-brown shales and marlstones showing lesser potential, and claystones and sandstones constituting non-source lithologies. The Egret Member was probably deposited under relatively shallow water conditions in a semi- silled basin where periodically high planktonic productivity occurred in surface waters.

Potential source rocks, other than the Egret Member, that have been identified within the Jeanne d'Arc Basin include an interval of Callovian-Oxfordian age within the underlying Voyager Formation and a Tithonian aged interval within the overlying Jeanne d'Arc Formation, all deposited in a similar paleogeographic environment as the Egret Member.

The Egret Member is present in wells on the Outer Ridge Complex and in the Flemish Pass Basin to the east and north east where it appears to have similar characteristics (McCracken et al., 2000; Enachescu, 2006). Magoon et al. (2005) has reported geochemical and facies differences between the Egret Member deposited in the western part of Jeanne d'Arc Basin and the Egret Member deposited in the eastern part of the basin and in the Central Ridge/Flemish Pass area.

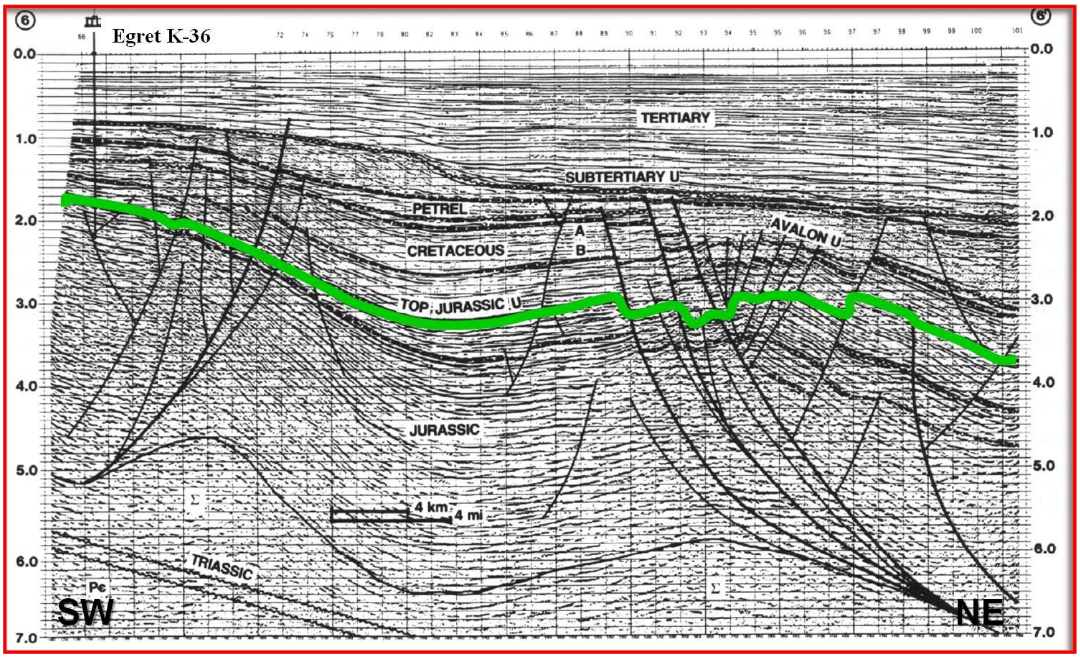

FIG.13 - Location of Egret K-36 the first well that intersected the prolific Egret Member source rock in Jeanne d'Arc Basin (after Enachescu, 1987)). Location of seismic section is shown in FIG.5.

While some oils in the Jeanne d'Arc Basin accumulations are biodegraded, they are also sourced from the Egret Member of the Rankin Formation (Shimeld et al., 2005). Although Kimmeridgian-aged source rocks have been proposed to be present in the Orphan Basin, to the north of the Jeanne d'Arc Basin, geochemical or well results published data to date has not corroborated this. Further north on the Labrador shelf (Hopedale Basin), Mesozoic sediments older than the Cretaceous, are not present where the wells have been drilled on the proximal margin of the basin. The major source rock in the Labrador basins is the Early Cretaceous Bjarni Formation shales.

No source rocks have yet been determined for the southern Grand Banks basins. Only in the South Whale Basin have shows been encountered. The oil at Heron H-73 has very different characteristics from any other Atlantic Margin oils and is thought to have a Cretaceous very sulphur-rich source. Based on drilling data, the Kimmeridgian source rocks are not thought to be present in this area either due to non-deposition or removal due to erosion at the Avalon Unconformity, which occurred prior to any hydrocarbon generation. However there are several small deep troughs within the shelfal and deepwater portions of the basin that may have preserved the Late Jurassic source rocks.

Offshore Ireland

The Late Jurassic Kimmeridge Clay has long been known to be the principle source rock for most North Sea oils. Equivalent intervals are also thought to be major source rocks for hydrocarbons west of Shetland and in the Porcupine Basin (FIG.14 and Crocker and Shannon 1987; Crocker and Shannon (eds.), 1987; Millson, 1987; Crocker and Klemperer, 1989; Pinheiro et al., 1996; Butterworth et al., 1999; Johnson et al., 2001; Robinson and Canham, 2001), although a Middle Jurassic contribution has also been suggested for oils in the latter basin. Based on the chemistry of the oils, Butterworth et al. (1999) suggested the Egret Member and Kimmeridge Clay Formation equivalent of the Porcupine Basin to be similar "unusual" marine source rocks that differ in organic facies from the North Sea units. Other Atlantic Margin basins north and west of Ireland, have Lower and Middle Jurassic source rocks and generate oils that differ compositionally from those with Kimmeridgian source rocks due to their greater non-marine/lacustrine nature.

Offshore Iberia (Portugal and Spain)

Petroleum geology of the Iberian basins and in especial the Lusitania Basin were described by Montenat et al. (1988); Wilson et al. (1989), Hiscott et al. (1990), Pinheiro et al. (1996), Alves et al. (2003a and b), Pena dos Reis and Pimentel (2009) and Pimentel et al. (2009). Rich, oil prone, marine shales have been identified in the Lower Jurassic Sinemurian - Toarcian, corresponding to the Brenha Formation in the northern Lusitanian basin, both in wells and in outcrop (DGGE, 2010 website). Source rock thickness is between 140 and 190 m, TOC values range up to 5.8 % and maturation levels. R_o values range from 0.7 to 2.0 %, placing these samples within both the oil and in some places the gas window (DGGE, 2010). These organic rich shales seem to have been deposited in significant thickness in the main depocenters where euxinic conditions prevailed, while being absent or thin elsewhere. Source rocks of about the same age and type have been observed in wells drilled in the Porto Basin; it is probable that these are richer and better developed off-structure.

Within the Late Jurassic there are rich, oil prone Oxfordian-aged source rocks in the southern Lusitanian Basin (DGGE, 2010). These source rocks occur as massive, deeper marine limestones and coastal to lacustrine bituminous limestones, both in wells and outcrops, with the latter ones better developed in the synclines. Geochemical analysis of samples from the South Lusitanian Basin show source rock thicknesses between 20 and 110 m, TOC values up to 3 % and maturation levels ranging from immature to over-mature.

Offshore Morocco

The source rock story of offshore Morocco, the conjugant margin of Nova Scotia, while more complex, is more similar to the Newfoundland’s margin than Nova Scotia’s. Recent geochemical surveys, shows that the Rif, Middle and High Atlas basins contain rich Early Jurassic source rock with organic facies being predominantly amorphous type II kerogene with TOC values up to 10% and with R_o values within the oil window in most places (ONAREP, 2010).

The petroliferous character of the Jurassic source rock facies may have a widespread distribution. The oil in Sidi Rhalem field in Essaouira Basin is produced from Oxfordian shales that have TOC up to 4 % (ONAREP, 2010). The oils discovered in the onshore/offshore Tarfaya Basin in southwestern Morocco are probably sourced from Jurassic marly facies. In the Tarfaya-Layoune-Dakhla Basin Lower to Middle Jurassic source rocks have TOC value ranging up to 2.49 % (ONAREP, 2010).

In the Cretaceous, marine source rocks of Aptian-Albian and Cenomanian-Turonian age are by far, the richest organic matter with TOC value up to 20 % (ONAREP, 2010). These facies are widespread over most of Moroccan sedimentary basins. Also, in the Miocene and Oligocene marls and shale have TOC value of up to 7 % in the offshore Atlantic basins and up to 2 % in the Mediterranean offshore area (ONAREP, 2010).

4. Late Jurassic source rock Super-highway

In the past decade, offshore Atlantic Canada has become an important petroleum province producing from Late Jurassic-Early Cretaceous synrift structures associated with Pangea breakup and opening of the North and Central Atlantic. The region’s offshore basins had a complex geodynamic evolution including Mesozoic extension, salt tectonism, subsidence and localized compression and exhumation that have created numerous hydrocarbon trapping styles.

The largest hydrocarbon discoveries were made during the 1979-1984 period, when drilling in the high-risk, high-cost Atlantic waters was stimulated by the Canadian federal government's Petroleum Incentive Program (PIP). Currently, 55646 m^3/d (350,000 bopd) are produced from three oil fields of the Jeanne d'Arc Basin offshore Newfoundland, while 12.7 MM m^3/d (450 MM ft^3/d) flow daily from the five gas fields of the Sable Subbasin offshore Nova Scotia. The Hebron giant oil field on the Grand Banks and the large Deep Panuke gas field on Nova Scotia shelf are future petroleum developments on the Canadian margin adding to the region's daily oil and gas production.

The distribution of Central and North Atlantic sedimentary basins and their petroleum geology in context of Mesozoic plate tectonic evolution was a long-lived preoccupation of geoscientists on both side of the Atlantic (e.g., Mason and Miles, 1984; Keen et al., 1989; Ziegler, 1989; Verhoef and Srivastava, 1989; Srivastava et al., 2000; Srivastava and Verhoef, 1992; Olsen et al., 2000; Kearsey and Enachescu, 2005; Enachescu et al., 2005c; Hopper et al., 2006; Sibuet et al., 2007a and b; Pena dos Reis and Pimentel, 2009 and FIG.14).

The most important component of the Atlantic Canada's petroleum system is the organic rich Kimmeridgian-aged source rock. Due to deposition in different paleogeographic conditions, it is predominantly a restricted marine source in the Grand Banks basins and a terrestrial derived, open marine, on the Scotian Shelf and Slope basins.

Initially indicated by wildcat wells, seismic mapping and basin-to-basin correlations, the presence of Late Jurassic rock successions in other Newfoundland offshore basins (Flemish Pass, East Orphan basins) was recently confirmed by drilling. In the Flemish Pass Basin the 2003 Mizzen L-11 well has intersected a Late Jurassic source rock and discovered reservoired oil, while in 2008 the Mizzen O-16 well, drilled 10 km to the north, was recently declared a significant oil discovery. The 2007 Great Barasway F-66 well in the East Orphan Basin intersected a Late Jurassic sequence that might also contain Mid to Late Jurasic source rocks. A second deep water well Lona O-55 was spudded during spring 2010 in the East Orphan Basin, and its results will bring new information on the Late Jurassic depositional environments. No geochemical results from these wells will be publically available for a few years. This well is the nearest well to the Mizzen O-16 and paleogeographically, the closest well to the Porcupine Basin deep side at the Late Jurassic time.

Moreover, the location of the Mizzen O-16 on the last basinal high bordering the East Orphan Basin proves that northern Flemish Pass and East Orphan basins were not isolated, and thus, were part of the Kimmeridgian-aged source rock super-highway (FIG.14). This highway partially followed the Atlantic rift trend connecting the Scotian Basin to offshore Newfoundland basins and extended into the Porcupine, Rockall Trough and Slyne basins, West of Ireland and from there into the North Sea and Norwegian Sea basins and subbasins. On the conjugate margin this source rock freeway, through a parallel lane, connected offshore Morocco to Lusitania Basin and from here to the Aquitaine Basin.

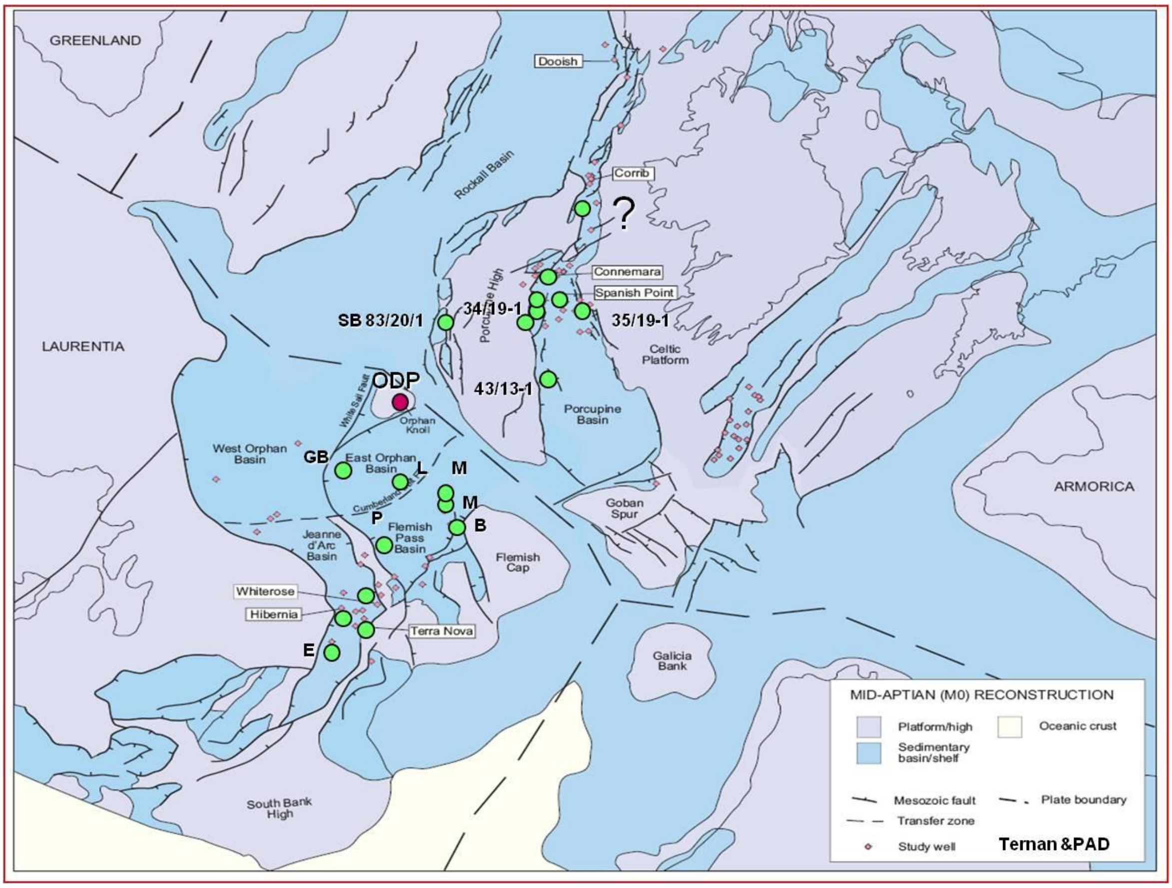

FIG.14 - Location of wells that have either intersected Late Jurassic source rocks, Late Jurassic terrestrial rocks or contain Jurassic sourced oil accumulations. (M0 plate reconstruction from PGL Ternan Ltd. and Irish Petroleum Affairs Directorate 2007; well locations after Enachescu, 2009).

While not directly proven by drilling, it is hypothesized that arms of this Kimmeridgian Sea extended into the Carson and Salar basins on the eastern Grand Banks divergent margin and from there into the Iberia conjugate margin basins. Moreover, during the Late Jurassic prerift stage, arms of the sea may have extended into Labrador Sea basins situated now on the slope and deep waters of both the Greenland and Labrador margins. In other words, the Late Jurassic source rock highway the we envisage starting in Georges Bank area and extending all the way to Europe, had several lanes (the most unexplored one being the Carson/Salar-Lusitanian basins connections) and probably a few other cul-de-sacs (South Whale, eastern East Orphan Basin, deepwater Labrador?).

Due to asymmetric rifting in the south (Nova Scotia-Morocco) coupled with differences in sediment supply and quality and size of mid-Jurassic carbonate bank, significant variation in the characteristics of source rock exist on the conjugate margins.

Detrimental to area's petroleum geology, after the Late Jurassic source rock deposition, the freeway was segmented by further rifting and modified by erosion during events such as the Cretaceous Avalon Uplift on the Grand Banks and Alpine inversion in the Morocco and Iberia margins.

5. Recommendations

Only 17 deepwater wells have been drilled offshore Newfoundland and Labrador and 10 offshore Nova Scotia. For the benefit of all Canada's East Coast stakeholders and of Eastern Atlantic margin explorers it is necessary that this deepwater drilling program be thoroughly analyzed and results be largely disseminated. Once dated, the geological formations containing reservoir and source rocks and all major unconformities need to be tied to regional seismic reflection grids on the NE Atlantic margin before connecting to grids from across Atlantic conjugate margin basins.

We have stressed in the past and continue to do so, the importance for petroleum exploration of: a) studying the region's Late Jurassic paleogeography, b) performing geophysically based plate tectonic reconstructions of the oceanic (Nova Scotia, Morocco) and intra-continental (Newfoundland, Iberia, Ireland, Labrador) rifting and c) undertaking detail petroleum geochemistry study including compilation of older research results supplemented with new work performed on recent discoveries and onshore outcrop studies. All pertinent countries should be involved in this research that must engage geoscientists from government departments, universities, oil and gas industry and expert consultants.

Keys to further oil and gas discoveries on conjugate margins of the North and Central Atlantic are:

- Reconstructing the paleogeography of the intra-continental rifting in the north and oceanic rifting in the south;
- Identifying and mapping, with regional seismic grids, the Late Jurassic source rock super-highway; and
- Characterizing, typing and connecting source rocks to crude oil in discoveries, shows and outcrops and correlating along and across the Atlantic margins.

Geodynamic evolution studies should use regional-conjugate reflection and refraction lines, accurate potential field maps and high resolution biostratigraphy study in representative wells. Plate reconstruction must account for mantle exhumation prior to initiation of oceanic rifting. Oil-source rock correlations need be performed on the latest deepwater wells and results should be included in the paleo-reconstruction of the Late Jurassic basin network.

6. Conclusions

The on-margin and conjugate Central and North Atlantic basins shared a common origin and early geodynamic evolution. While they have many common traits, they are not similar from a petroleum geology point of view. Differences have emerged due to asymmetric rifting, diverse paleogeographic conditions, existence and duration of lacustrine and anoxic sea stages versus open marine stage, variability of sediment supply, size of carbonate platform and post rift history that might include inversion and compression. Oil and gas exploration success within the Central and Northern Atlantic margin requires presence of Late Jurassic source rocks. A large numbers of wells were required to drill the first occurrence of oil source rock and then the first economic size field offshore Newfoundland. The key to economic success is the identification of areas where source rocks were deposited, survived erosion and is in the mature range. Recognizing source rock seismic signature and its seismic mapping is critical for any exploration program on the conjugate Atlantic margins. Typing of oils and geochemical analysis of intersected Jurassic sequences are needed as a cross-Atlantic collaborative effort, by countries sharing the Late Jurassic paleogeography (Canada, Ireland, Denmark, Island, UK, France, Norway, Spain, Portugal and Morocco). Therefore, petroleum exploration requires proper reconstruction of the Late Jurassic intra-continental rifting and epicontinental sea distribution and a collaborative source rock/oil geochemistry research project. We have no doubts that these efforts will generate new information and ideas and ultimately conduce to new oil and gas discoveries on both Atlantic margins.

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