Petroleum Systems of the Central Atlantic Margins, from Outcrop and Subsurface Data

Wach, Grant
Dalhousie University
1355 Oxford Street
Halifax, Nova Scotia, Canada, B3H 4R2
e-mail: Grant.Wach@dal.ca

Pimentel, Nuno
Centro de Geologia, Faculdade de Ciências da Universidade Lisboa
Campo Grande C-6
1749-016 Lisboa, Portugal
e-mail: Pimentel@fc.ul.pt

Pena dos Reis, Rui
Centro de Geociências, Faculdade de Ciências e Tecnologia da Universidade de Coimbra
Lg Marquês de Pombal
3000-272 Coimbra, Portugal
e-mail: penareis@dct.uc.pt

Abstract

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

Introduction

Outcrops from analogous outcrop sections along the UK and European margins may provide new play opportunities when the petroleum systems of the Central Atlantic margin are explored and developed (Fig. 1). These outlier basins typically are marked by significant unconformities that can mark key intervals for reservoir generation and reservoir distribution, and hiatal surfaces that may provide key data on condensed and sediment starved intervals. These basins have relatively complex geological histories, multiple sources of sediment input, source rock analogs, and variable depositional settings. The Wessex-Channel basins of southern England and the Lusitanian basin of Portugal provide excellent outcrops to examine these intervals and develop new concepts that can be applied to the Western Margin where there are wells and significant production, but no outcrops of producing intervals (Fig. 1).

The Wessex and Channel basins lie on Paleozoic basement deformed during the Variscan Orogeny, which culminated during the late Carboniferous. In early Mesozoic, north-south extension created a series of east-west faults possibly related to reactivation of Variscan thrusts. Extensional activity lasted until the end of Barremian times and possibly well into the Aptian, while thermal relaxation continued until the end of the Cretaceous.

The Lusitanian basin is an epeiric basin on the coastal areas and offshore western Portugal. It is bounded to the east and west by emergent Paleozoic highlands that provide the source of siliciclastic sediments to the basin. The basin provides good outcrop analogs for a range of depositional environments ranging from fluvial to estuarine mixed sediments and coastal platform carbonates.

Background and Previous Work

Srivastava and Verhoef (1992) established boundaries for the basins of the Central Atlantic that remain valid today with minor modifications. Hiscott *et al.* (1978) helped to establish the tectono-stratigraphic events between the Moroccan margin and eastern North America and determined that rates of sedimentation were relatively constant along the basin margins but there was some increase in rifting along the Newfoundland margin (Hiscott *et al.*, 1990). Sinclair *et al.* (1994) and Shannon *et al*. (1995) examined wells from the Jeanne d'Arc basin offshore Newfoundland with those of the Porcupine and Moray Firth basins with the objective of determining similarities in basin fill and the tectonic controls on reservoir architecture. Wu's (2007, 2013) work on crustal structure of the Scotian margin correlated the refraction seismic data from the Scotian and Moroccan margins, noting the similarities and key differences between the margins. The Channel and Wessex basin outcrops have been investigated in several studies (*e.g.* Channel basin - Ruffell and Wach, 1991; Wessex Basin - Hesselbo *et al.* 1990). Lusitanian basin studies include those of Cunha and Pena dos Reis (1995), and Dinis *et al.,* (2008 and references therein).

Petroleum Systems

An understanding of basin evolution is crucial to deciphering the petroleum systems and controls on sedimentation and the depositional history of the Eastern margin basins. Regional tectonic events coupled with eustatic variations had direct impact on the petroleum systems.

Wessex and Channel Basins

Three major fault zones divided the Wessex basin into five subbasins, including the southernmost Channel basin (Fig. 2). Lower sea level in the latest Jurassic to Early Cretaceous created two depocenters separated by the London Brabant massif but with slower sedimentation rates in the northern basins. Within the basin there were minor unconformities and non-sequences due to eustatic changes and variable rates of local tectonic and regional tectonism. These were superseded by a major unconformity cutting the Mesozoic section in southern England associated with later Cimmerian tectonism; the unconformity formed in a late extensional setting. The deposition of the Aptian-Albian Lower Greensand in southern England marked the end of the late Cimmerian event.

Source rock, maturity and migration

Bray *et al.* (1998) recognized four major heating events in the Wessex basin complex (Fig. 2): mid-Triassic to early Jurassic, early Cretaceous, mid-Tertiary, and late Tertiary. Due to basin tectonics (periods of uplift and burial), maturity levels vary within different subbasins of the Wessex. There are two potential (depending upon maturity) Jurassic source rocks; the lower Oxfordian Clay and Kimmeridge Clay, and a proven source rock in the Lower Jurassic Lias Group. The Kimmeridge Clay consists of the Type II and III kerogen whereas the Oxfordian and Lower Lias consists of Type II, III, and IV (Ebukanson and Kinghorn, 1985). The Kimmeridge and Oxford Clay have high total organic carbon (TOC) content (up to 20%) however these rocks are not sufficiently buried to become mature (Farrimond *et al.,* 1984 cited in Underhill and Stoneley, 1998). TOC values in the black shales of the Lower Lias have values recorded up to 8% in a Type II kerogen (Ebukanson and Kinghorn, 1985).

The Lias Group shows large variations in maturation along the basin due to regional tectonics and subsequent compartmentalization of the hydrocarbon systems. This compartmentalization is apparent in the Kimmeridge-5 well which experienced source rock generation in the early Cretaceous to mid-Tertiary (Bray *et al*., 1998). It is during this interval within the early Cretaceous that these hydrocarbons entered the oil window; *i.e.*, the critical moment (Fig. 2). Underhill and Stoneley (1998) suggest that peak generation is around middle to late Cretaceous. Other areas of the basin, for example the Wytch Farm Block, does not reach maturity at any time during the Jurassic and early Cretaceous due to shallow burial.

Reservoir rock

Within the Wessex basin, siliciclastic units have the highest reservoir rock potential (Underhill and Stoneley, 1998) having high primary porosities, high net:gross values, and sufficient lateral extent to hold commercial oil accumulations. Examples of potential and producing reservoirs are the lower Triassic Sherwood Sandstone with variable porosity that are facies dependent: fluvial channel sands (6-18%), sheet flood deposits (14-22%) and eolian sandstones (14-27%). The thick, fine-grained early Jurassic Bridport Sands have porosities up to 15% based on outcrop exposure and up to 32% in the Wytch Farm field based on core data.

There are other units having higher reservoir risk due to the reduction in permeability, limited lateral extent (*e.g.,* Permian eolian sandstone), or a high content of fine-grained material (*e.g.,* Thorncombe Sandstone), or the fractured mid-Jurassic Frome Clay. Some carbonate units also act as good reservoirs when secondary porosities are created by fracturing and/or dissolution of cement. These include the Middle Jurassic Inferior Oolite and Portland Limestone.

Trap

The traps in the Wessex basin were primarily structural rather than stratigraphic and can be divided into two major tectonics events: extensional in the Mesozoic and compressional (basin inversion) during the Cenozoic. Extensional faulting began during the Paleozoic Variscan fold and thrust belt, progressing to the Late Cretaceous (Underhill and Stoneley, 1998). The extensional tectonics subdivided the basin into several fault blocks, tilting the strata, and thus creating potential traps, similar to fields on the Grand Banks. Hydrocarbon exploration shifted to these buried and tilted extensional blocks which are related to the structural plays in the Wytch Farm and Wareham oil fields, whereas structures related to the Cenozoic-based inversion are periclinal traps developed from the late Cretaceous to early Cenozoic (Underhill and Stoneley 1998).

Seal

Most of the reservoir rocks are sealed by the presence of thick shale intervals or by thin, impermeable layers. Some examples of these are the Triassic Aylesbeare Mudstone Group overlying Permian eolian sandstone, Mercia Mudstone overlying the Sherwood Sandstone, and potentially the Kimmeridge Clay overlying the lower Jurassic reservoirs. Structural tilting of the blocks during extensional tectonics (Permian to Cretaceous) and later by structural inversion (Cenozoic) may have contributed to the sealing of the reservoirs. In these cases, lateral traps which developed are dependent on lithology, thickness (sand:shale ratio), and the amount of fault displacement. Inversion could initiate remigration of hydrocarbon into shallower reservoirs, but drilling to target these plays suggests the faulting (which acted previously as conduits for the migration of hydrocarbon) became barriers or seals as a result of compressional forces (Selley and Stoneley 1987) and perhaps cementing of fault traces through diagenesis.

Portuguese Margin

Portuguese margin basins

The Lusitanian basin is bounded to the east and west by emergent Paleozoic highlands that provide the source of siliciclastic sediments to the basin (Fig. 3). The Berlengas highlands separate the Peniche basin offshore, to the west from the Lusitanian basin. The Peniche basin is open to the Atlantic, has no wells, and has limited proprietary seismic data in the region. It is expected that the geology progresses from non-marine and littoral environments to shelf, slope, and basin floor settings. There may be similar basins outboard, west of the Peniche basin.

Source rock and maturity

The Lusitanian basin geological record contains different units having source-rock potential, including basement Paleozoic deep-marine black-shales, and turbidites, with hydrocarbon generation and migration into Mesozoic reservoirs (Uphoff, 2005; Pena dos Reis and Pimentel, 2010a, 2010b). Lower Jurassic (Sinemurian-Pliensbachian) marls and Upper Jurassic (Oxfordian) laminated marly limestones are the two major units having high TOC; however, Hettangian (Dagorda Formation), Kimmeridgian (Abadia Formation), and Cenomanian-Turonian (Cacém Formation) should also be considered (Spigolon *et al*., 2011).

The Lower Jurassic marine marly black shales (Duarte and Soares, 2002) up to one hundred meters thick, are the lower part of the Brenha Group, which extends across the basin and contains a highly variable TOC (up to 22.5 wt%; Duarte *et al*., 2012) of kerogen Types I-II (Spigolon *et al*, 2010). These homoclinal carbonate ramp deposits dip to the northwest and are related to the initial opening of the Lusitanian basin to marine influences. Two significant organic-rich maximum flooding surface intervals (Água de Madeiros Formation and Vale das Fontes Formation) have been studied in detail, regarding their TOC values, isotopes, palynofacies, etc. (Duarte *et al*., 2010, 2012; Silva *et al*., 2010, 2011; Poças Ribeiro *et al*., 2013).

The Upper Jurassic source rock (Cabaços Formation) is composed of marly limestones deposited in lacustrine to lagoonal and coastal environments (Spigolon *et al*. 2011; Silva *et al*. 2013). TOC values in darker layers usually range from 2 to 5 wt%; kerogen types are variable, but there is a predominance of Type II-III. Their deposition overlies a major regional Callovian unconformity and records the early syn-rift transgressive interval during the Oxfordian. The prevailing paleogeographic conditions were controlled by a north-northeast/south-southwest oriented depression, fed by a fluviodeltaic network from the north-northeast, towards the deepening areas developing more to the south-southeast (Pena dos Reis *et al*., 2011). The richest intervals are not strictly synchronic, but they are widespread basin-wide, and have no preferential sectors (Silva *et al*., 2013).

Maturation of both source rocks has been modeled, based in lithology and thickness well data, calibrated by vitrinite reflectance data (Teixeira *et al*., 2012, 2014). Both Jurassic source rocks have attained the hydrocarbon generation window, although not everywhere in the basin as a result of the highly heterogeneous basin's subsidence and overburden, especially in the Late Jurassic.

Non-mature Lower Jurassic source rocks are known in outcrop, namely at the Peniche, Montemor-o-Velho and São Pedro de Muel sections (Oliveira *et al*., 2006; Silva *et al*., 2010; Spigolon *et al*., 2011; Duarte *et al*., 2012), but the same units have reached maturity in several exploration wells in the basin (Teixeira *et al*., 2012, 2014). Also, non-mature Upper Jurassic source-rocks are known in different outcrops, such as Cabo Mondego or Montejunto (Spigolon *et al*., 2011), whereas they reached the oil window in nearby wells such as SB-1, FX-1 and CP-1 (Teixeira *et al*., 2012, 2014). This situation points to a very important role of differential subsidence along the basin, both in time and space.

As a general statement, it may be considered that the Lower Jurassic source rock is mature for oil in the north sector of the basin and mature for gas in the south sector, whereas the Upper Jurassic source rocks may be not mature in the north sector and are mostly mature in the south sector (Teixeira *et al*., 2012, 2014).

The different geological setting of these two Jurassic organic-rich intervals, has generated geochemically distinct types of hydrocarbons. Therefore, detailed studies of oil seeps and oil shows have revealed the presence of mature oils from both source rocks, in different depositional and tectonic settings. Good examples are the presence of Lower Jurassic related oils identified in Cretaceous sandstones close to diapir walls at Praia da Vitória and Leiria, as well as Upper Jurassic related oils identified in Oxfordian limestones close to a diapir wall at Torres Vedras (Spigolon *et al*., 2010).

Reservoir rock

Several siliciclastic and carbonate units have good reservoir potential in the Lusitanian basin. These include Late Triassic alluvial-fan to fluvial red beds (Silves Group), Middle Jurassic (Candeeiros Group) and Late Jurassic (Montejunto Formation) fractured carbonates and biohermal build-ups, Late Jurassic turbiditic (Abadia Formation), and fluviodeltaic (Lourinhã Formation) sandy lobes and channels. Moreover, the sedimentary infill of the basin presents at its uppermost section abundant Cretaceous fluvio-estuarine sandy deposits (Torres Vedras Group) related to the breakup unconformities (Dinis *et al*., 2008).

These Cretaceous units have very good reservoir properties but have been disregarded as a potential reservoir due to their high stratigraphic position and lack of apparent seal. However, these same units are expected to be present in offshore areas, namely in the deep offshore Peniche basin where the more distal location could provide adequate seal facies. Current exploration in these areas make it increasingly important to understand the reservoir potential. Two analogous outcrops have been studied in detail to understand facies relationships and heterogeneities – the Ericeira outcrop, 35 km northwest of Lisbon, and the Crismina outcrop, 30 km west of Lisbon.

The outcrop at Ericeira lies along the western part of the outcropping Lusitanian basin. The succession comprises the unconformity-bounded surface of Late Aptian age (Rey *et al*., 2006). This unconformity is marked by the abrupt shift from highstand carbonates in the Aptian (Crismina Formation) to terrestrial low gradient coastal sediments (Rodízio Formation) comprising red and grey mottled silt and clays and fluvial channels consisting of fine-grained to pebble-sized sediments. The coarser grain size may reflect reactivation of faults along the western margin of the basin (Dinis *et al*., 2008); basin margin syndepositional faults are visible in the Ericeira section. The succession abruptly fines up into medium to dark grey shales before the resumption of small channel deposition, marking a forced regression at the base of the Albian.

The section at Crismina, is located along the southwestern edge of the Lusitanian basin. The section is similar to Ericeira, also representing the Late Aptian breakup unconformity, but between more distal facies of the two aforementioned formations (Rey *et al*., 2006). The outcrop shows an abrupt transition from shallow marine and lagoonal carbonates in a highstand during which there was limited siliciclastic sediment input to the basin. There is an erosive surface and an abrupt transition to clean white quartzose sands deposited in estuarine conditions, with evidence of subtidal channels and barforms. The succession rapidly shallows, and coarser grained sediment and trough cross bedding reflect further progradation of sediment into the basin and deposition of fluvially derived sediments sourced from the Paleozoic highlands that bounded the basin to the west (Dinis *et al*., 2008). These highlands separate the Peniche basin from the most southern sectors of the Lusitanian basin (south of the Lousã-Caldas fault) and their erosional remnants are expressed today as the Berlengas Islands.

Trap

The traps in the Lusitanian basin are predominantly structural. The Late Jurassic rifting phase and the Late Cretaceous–Eocene alpine inversion, followed by the Miocene Betic inversion due to Iberia-Africa collision, caused a significant structural complexity and created a tectonic block puzzle and both local subsidence and later uplift with movement of salt. This structural framework allowed the contact of different source rocks, migration pathways, and reservoir units, sometimes not completely sealed. Some major folding, induced by deep salt doming combined with clay-rich capping units, is likely to have trapped late Jurassic hydrocarbons in fractured limestones, and coarse-grained Kimmeridgian turbidites. Salt movement also has had an important role in hydrocarbons accumulation, focusing the vertical migration of Early Jurassic hydrocarbons upwards into Cretaceous siliciclastics around the diapirs. These traps are proven by some hydrocarbons staining and fracture oil seeps associated with salt walls related to reactivation of deep basement faults.

Seal

Fine-grained clays and evaporates of the Hettangian Dagorda Formation (Palain, 1976) and thick clays of the Maastrichtian Taveiro Formation (Pena dos Reis, 2000) are certainly the most effective seals in the basin. The Dagorda Formation consists of compacted red clays containing variable amounts of gypsum, halite, and dolomite, up to hundreds of meters thick. It is intensely deformed in areas closer to basement faults. The clayey Taveiro Formation, up to 200 m thick, includes sandstone and carbonate, capping the Mesozoic areas north of the Lousã-Caldas fault.

There are several other clay-rich units, but they rarely act as a perfect seal due to their frequent intercalation with sandy layers as is the case of the Upper Jurassic and Lower Cretaceous units. However, Upper Cretaceous and Cenozoic shale units may have acted as important seals, particularly in more subsiding or distal areas of the basin.

Newfoundland Margin–Grand Banks

Recent discoveries by Statoil in the deep-water basins of the Flemish Pass have expanded the exploration potential and proven viable petroleum systems outside the traditional areas of the Grand Banks where exploration success has driven development for nearly four decades (Fig. 4). The Jeanne d'Arc Basin includes production from the Hibernia, Terra Nova, White Rose, and Hebron fields. Hebron has been the latest field development with estimates of three billion barrels in place but of a heavier grade oil (21 degree API) (Enachescu 2006). Baur *et al*. (2009) suggest that the Jeanne d'Arc basin formed as failed rift basin, first by a Late Triassic event and then slow stretching from the Late Jurassic though to the Early Cretaceous, although the latter did not have a significant impact on thermal maturity. Immediately to the south of the Jeanne d'Arc basin are the Carson basin and to the east of the Carson is the Salar basin on along the eastern edge of the Grand Banks. These basins lie on the present-day slope of the Grand Banks and began as a network of interconnected rift basins (Enachescu, 2006), that formed with the opening of the Atlantic Ocean and break-up of Pangea in the early Mesozoic.

The Mesozoic and Cenozoic sedimentary fill of the Carson basin on the eastern Grand Banks of Newfoundland has been penetrated by four wells. Wielens *et al.* (2006) indicate that the Salar and Carson basins are underlain by thicknesses of earliest Jurassic salt (Argo Formation), thicker on the on the western margins of the basins. They recognize that stratigraphic units could be correlated between the Carson and Jeanne d'Arc basins and that there are clear eustatic overprints across both basins. In the Jurassic, depositional conditions are inner neritic to marginal marine based on palynomorph, foraminiferal, and ostracod data.

Source rock, maturity and migration

In the Jeanne d'Arc basin the Egret Member of Kimmeridgian age is a mature marine source rock containing some terrigenous material and having TOC values between 4-6% and Hydrogen Index from 100-610 mgHC/ gTOC (Baur *et al*. 2010). Modelling of the petroleum systems of the Terra Nova oil field suggests, rather than one source from the Egret Member as previously thought, that there is potential for an additional kitchen area between the Terra Nova and Hibernia oil fields. This could impact understanding of the petroleum systems of the Mara, Hebron, Ben Nevis, Springdale, and White Rose fields. In the Carson basin, the Mesozoic section includes reservoir and seals but source rocks similar to the Jeanne d'Arc Basin have not been proven (Wielens *et al.*, 2006). Bauer *et al*. (2009) modeled a source rock in the deeper regions of the Carson basin that would be equivalent to the Egret in the Jeanne d'Arc basin and postulate that hydrocarbons could be generated and be trapped in Lower Cretaceous or Cenozoic reservoirs.

Reservoir rock

Siliciclastic deposition from highlands bordering the Jeanne d'Arc basin are the source of the majority of the reservoir prone sediments, which have porosities ranging between 15-25% and permeabilities to 100md (Baur *et al.*, 2009). The formation of traps was during the Berriasian (140 ma) during deposition of the Hibernia Formation; a second phase occurred during the Paleocene (53 ma) followed by a constant pattern of migration for the remainder of the Cenozoic (Baur *et al.,* 2009).There are several reservoir and seal pairs. The most effective seal, the Fortune shale unit, deposited during the latest Tithonian, represents a transgressive succession, capping the coarser grained Jeanne d'Arc reservoirs.

Trap

The formation of fault-bounded anticlinal traps was during the Berriasian (140 ma) during deposition of the Hibernia Formation; a second phase occurred during the Paleocene (53 ma) and then with a constant pattern of migration for the remainder of the Cenozoic (Baur *et al.,* 2009).

Seal

There are several reservoir and seal pairs. The most effective seal, the Fortune shale unit, deposited during the latest Tithonian, represents a transgressive succession, capping the coarser grained Jeanne d'Arc Basin siliciclastic reservoirs.

Enachescu (2006) reports potential petroleum plays in sandstone trapped in fault blocks of the Jeanne d'Arc, Hibernia, and Avalon/Ben Nevis units. The Jeanne d'Arc Formation sandstones have been deposited during Late Kimmeridgian-Tithonian in stacked incised valley systems and inner neritic environment. This play has been successful at the Terra Nova and Hebron fields and it is expected to extend to other areas in the south-eastern Jeanne d'Arc basin. Oil pay is found in the Hibernia sandstone reservoir in several of the fields surrounding the parcels. Similarly, Avalon and Ben Nevis sandstones contain oil and gas in several of the fields, and petroleum potential is also recognized in the Upper Cretaceous- Late Cenozoic sandstone members.

Scotian Basin

The Mesozoic to Cenozoic Scotian basin was initiated during the Triassic syn-rift to lower Jurassic post-rift phase on the Atlantic margin; terrestrial siliciclastic sediments and evaporites mark this phase (Fig. 5). In the Middle Jurassic, the Abenaki carbonate platform developed as an enigmatic succession of platform carbonates juxtaposed with sands and shale of the Sable Delta complex (Eliuk and Wach, 2008). The majority of the succession is a passive margin basin fill of sand and shale sequences deposited in response to global relative changes in sea level. In the later Jurassic and Cretaceous, the Sable and Laurentian deltas produce transgressive and regressive packages of deltaic, shelf margin, and slope deposits (Wade and MacLean 1990; Kidston *et al.,* 2002).

There are two active petroleum systems currently producing in the Scotian basin, both gas prone. The five field ExxonMobil Sable project (1999-present) produces from siliciclastic deltaic and shallow marine reservoirs having some condensate; production is scheduled to end later this decade. The Encana Deep Panuke project (2013) has begun production of gas from the Late Jurassic Abenaki carbonate margin and full production is scheduled for the year-end. A third is the light oil and condensate production from deltaic and shallow marine reservoirs in the now decommissioned Lasmo (later PanCanadian-Encana) Cohasset-Panuke project (1992-99); Panuke directly overlies the Deep Panuke field.

The western Shelburne subbasin is located in deep water and remains essentially untested for hydrocarbons, with but a single well drilled to test a shallow (Cenozoic) stratigraphic anomaly on the deep water Scotian Slope. An untested delta prism is interpreted in deep water on the western margin (Wade and MacLean, 1990). The subbasin is on track for future exploratory drilling following completion by Shell (2013) of a large (~8100 km^2) regional WAP 3D seismic program.

Source rock and maturity

Precisely identifying all source rocks on the Scotian Margin is a significant challenge with a mix of known and suspected intervals (OETRA, 2011). The Late Triassic rift syn-rift successions remains unproven but hold potential for Type I kerogens from lacustrine sources facies. Similarly, there are thick, late pre-rift evaporate deposits (Hettangian Argo Formation) that in addition to creating numerous structural configurations and traps may cap a hypersaline shallow marine succession (Type II). A lower Jurassic (Pleinsbachian-Toarcian) earliest post-rift marine source rock (Type II) is postulated but remains unproven. Potential exists for a Middle Jurassic Verrill (Callovian) source interval (Type II-III), although due to limited data its extent and thickness is unknown. Better known is the Late Jurassic to Late Cretaceous Verrill Canyon Formation assumed to be the source of most hydrocarbons encountered so far (gas). Its main source intervals are in the Tithonian (Type II-III), Valanginian (Type III), and Aptian (Type III); terrigenous detritus from the Sable Delta provides significant organic content. Note that the source of the high gravity Cohasset-Panuke oils, and those of other oil shows and discoveries (*e.g.,* Penobscot field), remain unknown.

Reservoir distribution

Understanding the linkages between shelf sediment capture/delivery, the role of shelf margin deltas, sea level, and slope processes is critical to detecting reservoir rock distribution in deep and ultra-deep water (Mosher *et al.* 2010). Thick Jurassic and Cretaceous fluviodeltaic to shallow marine sands of the Mic Mac, Missisauga, and Logan Canyon formations are common on the Scotian Shelf, and depending on location have very high sand:shale ratios. Better ratios are found in the middle and distal portions of the respective formations. The deep water Scotian Slope demonstrates a history of canyon and channel cut and fill and sediment mass transport. Significantly, results from a recent (2000-2004) phase of deep-water exploration (2D and 3D seismic) and drilling has confirmed the margin is a by-pass zone, as coarse siliciclastics have been transported into the salt-dominated region down slope (Kidston *et al.,* 2007; Deptuck, 2010; 2011a; 2011b). These processes link to relative sea level in combination with sediment volume, seismicity, and other causative factors.

Trap

Although the Sable Delta represents an active petroleum system associated with many significant gas shows in the Upper Jurassic to Lower Cretaceous delta, economic hydrocarbon accumulations have been limited (structural trap risk). Incised valleys, cut into shelf deposits during sea level lowstands, are recognized on 3D data and indicate potential reservoirs when calibrated to well data. The dominant (and most successful) trap styles are rollover anticlines in which sand-shale ratios range from 15-30% and there is limited crestal faulting (Richards *et al.,* 2008). Potential exists for stratigraphic traps (but seal risk is high due to an overall high net-to-gross section). Several traps styles are set up by the movement of the underlying latest Triassic-earliest Jurassic salt, particularly in deep water, but only a few have been tested and most by a single well: only one subsalt play has been drilled to-date.

Seal

Within the Sable subbasin, variable scale (field to regional) transgressive events developed "tongues" of the Verrill Canyon Formation shales that provide excellent seals to the reservoirs in the Sable Delta.

Discussion

Reservoir distribution

Shelf margin deltaic sequences are difficult to correlate in the subsurface (Fig. 6). Delta lobe switching contributes to stratigraphic complexity. Numerous permeability baffles and barriers create complex reservoir heterogeneities. For example, an extensive network of non-marine channels and incised valleys cut into deltaic and shelf deposits during the falling stage and lowstand systems tracts at multiple stratigraphic levels in the Sable Delta complex. Progradation of the Sable Delta to the shelf edge is constrained by localized accommodation controls from differential mobilization of underlying salt. Shelf margin sediments can be trapped at the margin or may contribute directly to downslope fans.

A significant issue in recent hydrocarbon exploration in the deep water on the Scotian and Moroccan margins is the detection of reservoir rock. Existing models of deep-water sedimentation have underestimated the links between shelf and slope sedimentation and the roles of sea level, salt tectonism, and canyon formation as sediment transport pathways. Mass failure and along-slope sediment transport processes are also significant processes in passive continental margin development. The consequence of these sedimentary processes is the inherent complexities of shelf to slope sedimentation patterns and movement of potential reservoir rock to greater depths than previously anticipated.

In the middle of the Cretaceous, rifting slowed or ceased and wider continental shelves developed. Lateral facies relationships along these shelf systems could create stratigraphic pinch-outs to reservoir continuity in addition to faults that could act as transmissive conduits or barriers, creating further reservoir compartmentalization. Condensed sections and transgressive intervals of shales, diastems, hiatal surfaces, firm grounds, and hard grounds (Ruffell and Wach, 1998) formed that created potential significant barriers and baffles to permeability and overall reservoir performance. These surfaces were apparent in outcrops in the Wessex and Channel basins, in the Jeanne d'Arc, and even in the mid-Cretaceous oil sands of Western Canada.

Tectonic influences on sedimentation, migration and maturation

Sinclair *et al*. (1994) and Shannon *et al*. (1995) demonstrate there are tectonic influences on basin infill and reservoir architecture. In the Wessex basin, there are minor unconformities and non-sequences that are due to eustatic changes and variable rates of local tectonic subsidence. These subsequently have been superseded in the Late Jurassic and Early Cretaceous times by a major unconformity associated with late Cimmerian tectonism, cutting the Mesozoic sequence in southern England, the Lusitanian basin, Grand Banks, and the Scotian basins. This period of extensive erosion is referred to as the late Cimmerian unconformity. The late Cimmerian unconformity has formed in an extensional setting by the combined effects of isostatic footwall block uplift and a contemporaneous eustatic lowering. This has produced a syn-extensional or early post-extensional isostatic disequilibrium that can be recognized throughout southern England. Only in small areas of rapid basin subsidence are the effects of the unconformity minimized, but the extent of this is not clearly known.

The deposition of the Lower Greensand in southern England marks the end of the late Cimmerian event. Only in areas of rapid crustal subsidence are the erosional effects minimized. These areas are the central part of the Weald and Channel basins (Chadwick, 1986). The Lower Greensand thins and pinches out to the north against the London platform and along the western margins of the Wessex basin, overstepping progressively older sediments. In turn, the Lower Greensand is succeeded by the Gault and Upper Greensand. The Gault marks the second mid-Cretaceous marine transgression. The dark grey mudstone of the Gault oversteps the Lower Greensand to lie unconformably on Lower Paleozoic strata of the London platform. The Portsdown anticline and to a lesser degree the Isle of Wight fault act as structural controls to sedimentation and have restricted the influence of the Boreal Sea from the north and the Tethys Sea to the south and east. Abundant Upper Jurassic clasts in pebble beds of the Lower Greensand Group suggest contemporaneous erosion of shore lines along the margins of the Cretaceous depositional basin (Ruffell and Wach, 1991). In the Lower Cretaceous, no sediments of pre-Albian age are preserved north of the fault where Albian Carstone sediments rest unconformably on Jurassic.

The Late Cimmerian unconformity was compared between the Jeanne d'Arc Basin of the Grand Banks and the Outer Moray Firth in the North Sea by Sinclair and Riley (1995). Early in the exploration of the southern Grand Banks, dry wells in the basin were attributed to an unproven source rock and breaching of the traps at the basal Aptian (Avalon) unconformity (Enachescu, 2006).

Basin accommodation space, shifting depocenters and inversion

In the outlier basins examined in this study, there is evidence of shifting basin depocenters initially controlled by local and regional tectonic events. Early rift basins are filled with evaporite and red shales (Fig. 6). As basins fill, eustatic controls overprint the tectonic events, accommodation space is diminished, and depositional environments reflect slower rates of sediment influx into a basin, often associated with erosion and denudation of surrounding highlands sourcing sediment into the basin. At the end of the basin cycle, the studied basins have been inverted in response to Alpine orogenic activity and compression along the eastern Atlantic margin, particularly during the Oligocene through Miocene. It is interesting that in the latest Cretaceous through early Cenozoic there is thermal evidence of uplift along the Scotian margin (Grist *et al*., 1995; Grist and Zentilli 2003).

Depocenters "shift" through the stratigraphic succession in response to tectonic and eustatic controls controlling accommodation space within the basins. Identifying the primary and secondary controls within a basin on sediment influx and distribution can help in the prediction of sediment conduits and fairways for the distribution of reservoir quality sediments.

During early Wessex Basin development, the rate of Permo-Triassic sedimentation kept pace with basement subsidence (Chadwick, 1986). Compaction became a factor later in the basin development as loading allowed sediment accommodation to exceed the rate of basin subsidence. For example, fluvial conditions were maintained during the deposition of the Wealden Group in the beginning of the Lower Cretaceous, despite rapid basin subsidence because of abundant sediment supply from the erosion of the proximal massifs.

Lowering of sea level in the latest Jurassic to Early Cretaceous created two distinct depocenters separated by the London-Brabant massif. The northern basin was characterized by relatively slow subsidence and low rates of sediment infill. In contrast, southern England received significant sediment supply from the erosion of nearby massifs, and coupled with rapid subsidence rates, the basin was rapidly filled.

The Variscan fold belts across the Wessex basin begin as thrust or reverse faults (Whittaker, 1985). The depth to the top of the Variscan basement on the Isle of Wight ranges from 1400-1600m north of the monocline, to 2000m on the southwestern side, deepening to 2200m on the central and southeastern area of the island. This deepening of accommodation space to the island's south-central area coincides with the thickest deposit of Lower Greensand sediment in this region.

A half-graben may have formed during the Permian (Chadwick, 1986) to late Cretaceous. The Chalk facies shows evidence of reworking on the margins of the Central Downs and possible hard grounds near the top of the strata, in the middle of the Central Downs; combined with thinning of the Chalk strata across the Central Downs, this suggests syntectonic activity. Movement is concentrated during the Mesozoic with an interval of relative quiescence during the mid to late Cretaceous. Mesozoic movement was followed by inversion at the end of the Cretaceous (Stoneley, 1982), which resulted in further development of steeply folded strata as a result of movement along pre-existing structures in the Paleozoic basement.

The basins distributed along the conjugate margin of the Central Atlantic, although with similarities, also demonstrate some marked differences; for example the location of the (relatively younger) Atlas Mountains along the northwest African coast compared to the Appalachians. What is the significance of the greater distance from North America to the Mid-Atlantic Rift compared to the distance from Africa and the breaks with the anomalies on both sides of the Atlantic?

Evidence of active petroleum systems–Oil seeps on basin margins

Oil seeps within the Lusitanian and Wessex basins are stratigraphically located in the upper Mesozoic, usually Cretaceous and Cenozoic strata. The accumulations and active and paleo-oil seeps reflect past and present petroleum systems that appear to have migration pathways associated with faults bounding the basin margins. Seeps are present in Cretaceous sediments at Mupe Bay and in Cenozoic sediments at Henigstbury Head. In the Lusitanian basin, there are paleo- or active oil seeps at Vale Furado (Nazaré) and Leiria.

Conclusions

The key elements in producing effective petroleum systems (Fig. 6) in the Central Atlantic conjugate margins are the presence of source rock and reservoir. Trap formation and migration are less of a risk as active tectonics occurred along the margin. The Wessex (Channel) and Lusitanian basins are appropriate outcrop analogs for basins along the Atlantic margin that have relatively complex geological histories, multiple sources of sediment into the basin, and restricted depositional settings to deeper marine settings. The Lusitanian basin is a good analog for basins that transition from continental to deep basin marine settings. There is more carbonate in the Lusitanian basin, perhaps reflecting more southern latitudes of the basin during the Mesozoic compared to the Wessex and Channel basins. The Lusitanian basin provides analogs for potential source rock facies, although maturity of these is unlikely with the burial history of the basin less than 500m.

Depocenters "shift" throughout the stratigraphic succession in response to tectonic and eustatic controls controlling accommodation space within these basins. Identifying the primary and secondary controls within a basin is dependent on sediment influx. Sediment conduits and fairways control the distribution of reservoir quality sediments. Eustatic controls in the Portugal basins appear to be less of a factor compared to other basins along the margins, perhaps due to a greater tectonic overprint.

What new exploration concepts and play types are possible? A confirmed petroleum system is present in the Flemish Pass basin on the Newfoundland Margin which should decrease exploration risk in the adjacent Orphan basin to the north. Exploration potential is often contingent on the presence of source rock. We can point to downdip deeper water reservoirs that may be sourced from updip deltaic systems; *e.g.,* the Sable and Morocco delta systems. These deeper water reservoirs are often encased by excellent seal rocks and within the fetch of condensed sequences that may form potential source rocks.

Deciphering forcing functions, sediment pathways and depositional processes will improve exploration models for passive clastic margins and suggests that exploration must move to deeper water where shelf-equivalent rocks are transported and deposited. These constraints can be expected in similar depositional settings in other margin basins. If there is salt influence in the basin, new play concepts can be generated with new trap configurations and the potential for trapping sediment.

There is a need to define basin-wide unconformities with greater precision. A number of unconformities are not resolvable on seismic and may be interpreted as one unconformity. These unmapped unconformities are significant and mark the potential for downdip transport of reservoir quality sediments in to the basin. Seismic data can help predict reservoir but seldom aids in defining reservoir quality. There is growing tendency for plate reconstructions to rely solely on subsurface data, particularly seismic and derivatives of the seismic data used for modeling. John Dewey (1983) reflected on his research and attributed many of the concepts he developed on plate tectonics, to outcrop studies he completed in Ireland and Nova Scotia. We propose that we need to keep looking at the rocks to be able to discern many of the complexities along the margins. The Wessex-Channel and Lusitanian basins provide excellent outcrops to examine these and develop new analysis of petroleum systems for petroleum exploration and development of fields and basins of the Central Atlantic margin.

Acknowledgments

It is with great appreciation that we thank the following individuals for discussions throughout the years both in the field and at conferences, particularly the Conjugate Margins conferences: David E. Brown, Ian Davison, Paul J. Post, Iain Sinclair, Ian Atkinson, Michael Enachescu, Webster Mohriak, Bernardo Teixeira, Stephen Hesselbo, and Alastair Ruffell. David E Brown provided valuable comments on the manuscript. Carla Dickson, Trudy Lewis, Kristie McVicar, and Carlos Wong assisted with the preparation of this paper. We would like to thank Jim Pindell and Brian Horn as conference organizers and particularly Norm Rosen who each year continues to shepherd through a timely conference confronting key issues facing the industry.

References

Azeredo, A.C., L.V. Duarte, M.H. Henriques, and G. Manuppella, 2003, Da dinâmica continental no Triásico aos mares do Jurássico Inferior e Médio: Cadernos de Geologia de Portugal, Instituto Geológico e Mineiro.

Baur, F., R. Littke, H. Wielens, C. Lampe, and T. Fuchs, 2010, Basin modeling meets rift analysis: a numerical modeling study from the Jeanne d'Arc Basin, offshore Newfoundland, Canada: Marine and Petroleum Geology, v.27, no.3, p.585-599.

Baur, F., H. Wielens, and R. Littke, 2009, Basin and petroleum systems modeling at the Jeanne d'Arc and Carson Basin, offshore Newfoundland, Canada: Canadian Society of Exploration Geophysicists (CSEG) Recorder, September 2009, p.24-31, 36.

Bray, R.J., I.R. Duddy, and P.F. Green, 1998, Multiple heating episodes in the Wessex Basin: implications for geological evaluation and hydrocarbon generation, *in* J.R. Underhill and R.C. Stonely, eds., The development, evolution, and petroleum geology of the Wessex Basin: Geological Society of London Special Publication 133, p. 199-213.

Boudreau, R.R. and H.A. Wishart, 1990, Comparative stratigraphy and subsidence history of Mesozoic rift basins of North Atlantic: AAPG Bulletin, v.74, p.60-76.

Chadwick R.A., 1986, Extensional tectonics in the Wessex Basin, southern England: Journal of the Geological Society, London v.143, p.465–488.

Cunha, P.P., and R.P. Rena dos Reis, 1995, Cretaceous sedimentary and tectonic evolution of the northern sector of the Lusitanian Basin (Portugal): Cretaceous Research, v.16, p.155-170.

Cox, B.M., M.G. Sumbler, and H.C. Ivimey-Cook, 1999, A formational framework for the Lower Jurassic of England and Wales (onshore area). Keyworth, Nottingham: British Geological Survey, 25p. (RR/99/001)

Dercourt, J., M. B. Gaetani, E. Vrielinck, B. Barriers, M.F. Biju-Duval, J.P. Bruner, S. Cadet, S. Crasquin and M. Sandulescu, eds., 2000, Atlas Peri-Tethys, Palaeogeographical Maps: CCGM/CGMW, Paris.

Deptuck, M. E., 2010, The 'slope detachment zone' on the western Scotian Slope, offshore Nova Scotia: structural style, timing and implications for margin evolution: Central and North Atlantic Conjugate Margins Conference, Lisbon 2010, Metedo Directo, vol.IV, p.87-95, ISBN: 978-989-96923-1-2 http://www.cnsopb.ns.ca/geoscience

Deptuck, M.E., 2011a, Proximal to distal post rift structural provinces on the western Scotian Margin, offshore Eastern Canada: Geological context and parcel prospectivity for Call-for-Bids NS11-1: Canada-Nova Scotia Offshore Petroleum Board, Geoscience Open File Report (GOFR) 2011-001MF, 42p. http://www.cnsopb.ns.ca/sites/default/files/pdfs/gofr__2011_001mf.pdf

Deptuck, M.E., 2011b, Potential shelf sources for deepwater reservoirs along the southwestern Scotian margin, and the impact of a hybrid 'bypass-ponded' slope on reservoir distribution: Seminar delivered at the American Association of Petroleum Geologists International Conference & Exhibition, Milan, Italy. Available at http://www.novascotiaoffshore.com/data

Dewey, J., 1983, Lyell Medal acceptance speech: Journal Geological Society.

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

DPEP, 2013, Petroleum Exploration in Portugal: http://www.dgeg.pt/dpep/en/history.htm

Duarte L.V., R.L. Silva, L.C.V. Oliveira, M.J. Comas-Rengifo and F. Silva, 2010, Organic-rich facies in the Sinemurian and Pliensbachian of the Lusitanian Basin, Portugal: total organic carbon distribution and relation to transgressive-regressive facies cycles: Geologica Acta v. 8, p. 325–340. doi:10.1344/105.000001536.

Duarte, L.V. and A.F. Soares, 2002, Litostratigrafia das séries margo-calcárias do Jurássico Inferior da Bacia Lusitânica (Portugal): Com. Instituto Geológico e Mineiro, v. 89, p. 135–154.

Duarte, L.V., R.L. Silva, J.G. Mendonça Filho, N. Poças Ribeiro and R.B.A. Chagas, 2012, High-resolution stratigraphy, palynofacies and source rock potential of the Água de Madeiros Formation (Upper Sinemurian) of the Lusitanian Basin, Portugal: Journal Petroleum Geology v. 35, p. 105–126.

Ebukanson, E.J., and R.R.F. Kinghorn, 1985, Kerogen Facies in the Major Mudrock Formations of Southern England and the Implication on the Depositional Environments of their Precursors: Journal of Petroleum Geology, v.8, p.435–462.

Eliuk, L.S. and G. Wach, 2008, Carbonate and Siliciclastic Sequence Stratigraphy - Examples from the Late Jurassic Abenaki Limestone and West Venture Deltaic Beds, Offshore Nova Scotia, Canada, *in* D.E. Brown, ed., Extended Abstracts Volume: Central Atlantic Conjugate Margins Conference, Halifax, p.450-477, ISBN:0-9810595-1.

Enachescu, M.E., 2006, Newfoundland and Labrador Call for Bids NL)-1 Jeanne d'Arc Basin: Government of

Newfoundland and Labrador Department of Natural Resources, 55pp.

Farrimond P., P. Comet, G. Eglington, R.P. Evershed, M.A. Hall, D.W. Park, and A.M.K. Wardroper, 1984, Organic Geochemical study of the Upper Kimmeridge Clay of the Dorset type area: Marine and Petroleum Geology, v.1, p.340–354.

Grant, A.C. and K.D. McAlpine, 1990, The Continental Margin around Newfoundland, Chapter 6, *in* M.J. Keen, and G.L. Williams, Geology of the Continental Margin of Eastern Canada, Geology of Canada, No. 2: Geological Survey Canada, p. 239–292.

Grist, A., R.J. Ryan, and M. Zentilli, 1995, The thermal evolution and timing of hydrocarbon generation in the Maritimes Basin of eastern Canada, from apatite fission track data: Bulletin Canadian Society of Petroleum Geologists, v.43, no.2, p.145-155.

Grist, A.M. and M. Zentilli, 2003, Post-Paleocene Cooling in the Southern Canadian Atlantic Region: Evidence from Apatite Fission Track Models: Canadian Journal of Earth Sciences, v. 40, no. 9 p. 1279-1297.

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

Hiscott, R.N., R.C.L Wilson, F.M. Gradstein, V. Pujalte, J. Garcia-Mondejar, W. Manspeizer, J. H. Puffer, and H. L. Cousminer, 1978, Separation of Morocco and eastern North America: a Triassic-Liassic stratigraphic record: Geological Society of America Bulletin, v.89, p.901-920.

Hiscott, R.N., R.C.L. Wilson, F.M. Gradstein, V. Pujalte, J. Garcia-Mondejar, R.R. Boudreau, and H.A. Wishart, 1990, Comparative stratigraphy and subsidence history of Mesozoic rift basins of North Atlantic: AAPG Bulletin, v.74, p.60-76.

Hopson, Peter, 2005, A stratigraphical framework for the Upper Cretaceous Chalk of England and Scotland with statements on the Chalk of Northern Ireland and the UK offshore sector. Keyworth, Nottingham: British Geological Survey, 90 p. (RR/05/001)

Kidston, A.G., D.E. Brown, B.M. Smith, and B. Altheim, 2002, Hydrocarbon Potential of the Deep-Water Scotian Slope: Canada-Nova Scotia Offshore Petroleum Board, Halifax, 111p.

Louden, K., Y. Wu, and G. Tari, 2012, Systematic variations In basement morphology and rifting geometry along the Nova Scotia and Morocco conjugate margins, *in* W.U. Mohriak, A. Danforth, P. Post, D. Brown, G. Tari, M. Nemcok, and S.T. Sina, eds., Conjugate Divergent Margins: Geological Society of London Special Publications, 369, doi 10.1144/SP369.9

Mosher, D.C., G.D. Wach, D.C. Campbell, M.K. Giles, and V.I. Brake, 2010, Continental slope sediment distribution and characterization: case studies from the Scotian and Suriname margins, *in* R. Reis, and N. Pimentel, eds., Program and Abstracts II Central and North Atlantic Conjugate Margins Conference- Lisbon 2010 Re-Discovering the Atlantic, New Ideas for an old sea: ISBN: 97-989-96923-4-3September 29-October 1, 2010, p.68.

Kidston, A.G., B. Smith, D.E. Brown, C. Makrides, and B. Altheim, 2007, Nova Scotia Deep Water Offshore Post-Drill Analysis – 1982-2004: Canada-Nova Scotia Offshore Petroleum Board, Halifax, Nova Scotia, 181p.

Offshore Energy Technical Research Association (OETR Association), 2011, Play Fairway Analysis Atlas - Offshore Nova Scotia: Nova Scotia Department of Energy Report, NSDOE Records Storage File No. 88-11-0004-01, 347p.

OLIVEIRA, L.C.V., R. RODRIGUES, L.V. DUARTE AND V. LEMOS, 2006, Avaliação do potencial gerador de petróleo e interpretação paleoambiental com base em biomarcadores e isotopos estáveis de Carbono na seção Pliensbaquiano-Toarciano inferior (Jurássico inferior) da região de Peniche (Bacia Lusitânica, Portugal): Boletim Geociências Petrobras, v. 14 no. 2, p. 207-234.

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

Pais, João, Pedro P. Cunha, Diamantino Pereira, Paulo Legoinha, Rúben Dias, Delminda Moura, António Brum da Silveira, J. C. Kullberg and J. A. González-Delgado, 2012, The Paleogene and Neogene of Western Iberia (Portugal): A Cenozoic Record in the European Atlantic Domain: Springer, 138 p.

PALAIN, C., 1976, Une série détritique terrigène. Les "Grès de Silves": Trias et Lias inférieur du Portugal: Memórias dos Serviços Geológicos de Portugal, N.S. 25, 377 p.

Pena dos Reis, R., 2000, Depositional systems and sequences in a geological setting displaying variable sedimentary geometries and controls: example of the Late Cretaceous Lusitanian Basin (Central Portugal): Comunicações do Instituto Geológico e Mineiro, v. 87, p. 63-76.

PENA DOS REIS, R. AND N. PIMENTEL, 2010a, A evolução da Bacia Lusitânica (Portugal) e dos sistemas petrolíferos associados: VII Congr.Nac.Geologia, e - Terra 19 (4). metododirecto.pt/CNG2010/index.php/vol/article/download/70/345

PENA DOS REIS, R. AND N. PIMENTEL, 2010b, Sistemas petrolíferos no onshore da Bacia Lusitânica, uma visão geológica integradora *in* F. Noronha and A. Ribeiro, eds., Ciências Geológicas, Ensino, Investigação e sua História: Assoc.Port.Geólogos, v. 2, p. 143-156.

Pena dos Reis, R. and N. Pimentel, 2011, Sedimentation, Source-rocks and Reservoirs in Upper Jurassic sin-rift deposits of the Lusitanian Basin (Portugal). Abstracts 28th IAS Meeting of Sedimentology, Zaragoza.

Pena dos Reis, R., P.P. Cunha, J.L. Dinis and P.R. Trincão, 2000, Geological evolution of the Lusitanian Basin (Portugal) during the Late Jurassic: GeoResearch Forum, v. 6, p. 345-356.

Poças Ribeiro, N., J.G. Mendonça Filho, L.V. Duarte, R.L. Silva, J.O. Mendonça, and T.F. Silva, 2013, Palynofacies and organic geochemistry of the Sinemurian carbonate deposits in the western Lusitanian Basin (Portugal): Coimbra and Água de Madeiros formations: International Journal of Coal Geology 111, 37-54.

Rey, J., 1972, Recherches géologiques sur le Crétacé inférieur de l'Estremadura (Portugal): Ministerio da Economia, Secretaria de Estado da Indústria, Direcção-Geral de Minas e Serviços Geológicos, Serviços Geológicos de Portugal.

Rey, J., J.L. Dinis, P. Callapez and P.P. Cunha, 2006, Da roturacontinental à margem passiva. Composição e evolução do Cretácico de Portugal: Cadernos de Geologia de Portugal. INETI, Lisbon, 53 p. (in Portuguese, English abstract) + 10 plates.

Richards, B., L.H. Fairchild, P.J. Vrolojk, and S.J. Hippler, 2008, Reservoir connectivity analysis, hydrocarbon distribution, resource potential and production performance in the clastic plays of the Sable Subbasin, Scotian Shelf, *in* D.E. Brown, ed., Extended Abstracts Volume: Central Atlantic Conjugate Margins Conference, Halifax, p.165-185, ISBN:0-9810595-1.

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

Ruffell, A.H., and G.D. Wach, 1998, Hardgrounds, firmgrounds and softgrounds: Sedimentology, v.45, p. 91-107.

Shannon, P.M., B.P.J. Williams, and I.K. Sinclair, 1995, Tectonic controls on Upper Jurassic to Lower Cretaceous reservoir architecture in the Jeanne d'Arc Basin, with some comparisons from the Porcupine and Moray Firth Basins, *in* P.F. Croker, and P.M. Shannon, eds., The Petroleum Geology of Ireland's Offshore Basins: Geological Society Special Publication 93, 467-490.

Silva, F., L.V. Duarte, L.C. Oliveira, R. Rodrigues, and M.J. Comas-Rengifo, 2010, Contribution to the knowledge of petroleum generative potential of Late Sinemurian – Pliensbachian of the Lusitanian basin - northern sector (Portugal), *in* R. Pena dos Reis, and N. Pimentel, eds., Extended Abstracts II: Central & North Atlantic Conjugate Margins Conference., v. III, 256–260.

Silva, R.L., L.V. Duarte, M.J. Comas-Rengifo, J.G. Mendonça-Filho and A.C. Azerêdo, 2011, Update of the carbon and oxygen isotopic records of the Early–Late Pliensbachian (Early Jurassic, c.187 Ma): insights from the organic-rich hemipelagic series of the Lusitanian Basin (Portugal): Chemical Geology v. 283, p. 177–184.

Silva, R.L., J.G. Mendonça FIlho, A.C. Azerêdo and L.V.Duarte, 2013, Palynofacies and TOC analysis of marine and non-marine sediments across the Middle–Upper Jurassic boundary in the central-northern Lusitanian Basin (Portugal): Facies, doi: 10.1007/s10347-013-0369-x.

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

Sinclair, I.K. and LA. Riley, 1995, Separation of Late Cimmerian rift and post-rift megasequences: a comparison of the Jeanne d'Arc Basin, Grand Banks and the Outer Moray Firth, North Sea, *in* R. Stee;. ed., Sequence Stratigraphy: Advances and Applications for Exploration and Production in North West Europe: Proceedings of the Norwegian Petroleum Society Conference, Stavanger, February 1993.

Selley, R.C. and R. Stoneley, 1987, Petroleum Habitat in South Dorset, In: J. Brooks and K. W. Glennie (eds.), Petroleum Geology of North West Europe: Graham and Trotman, London, p.139–148.

SPIGOLON, A.L.D, R. PENA DOS REIS, N. PIMENTEL AND V. MATOS, 2011, Geoquímica organica de rochas potencialmente geradoras de petróleo no contexto evolutivo da Bacia Lusitânica: Bol.Geociências da Petrobras, v. 19, no. 1/2, p.131-162.

Spigolon, A.L.D., G.V. Bueno, R.P. Pena dos Reis, N.L. Pimentel and V. Matos, 2010, The Upper Jurassic Petroleum System: evidence of secondary migration in carbonate fractures of Cabaços Formation, Lusitanian Basin (Portugal): Ext. Abstr. II Central & North Atlantic Conjugate Margins Conference, Lisbon, v. III, p. 274-278.

Srivastava, S.P. and J. Verhoef, 1992, Evolution of Mesozoic sedimentary basins around the North Central Atlantic - a preliminary plate kinematic solution. In: Parnell, J, (ed.) Basins on the Atlantic Seaboard Petroleum Geology, Sedimentology and Basin Evolution: Geological Society of London Special Publication 62, p.397-420.

Stoneley, R., 1982, The structural Development of the Wessex Basin: Implications for Exploration: Proceedings of the Ussher Society, v.8, p.1–6.

Tankard, A.J., and H.R. Balkwill, 1989, Extensional Tectonics, Structural Styles and Stratigraphy of the North Atlantic Margins: Introduction, *in* A.J. Tankard and H.R. Balkwill, eds., Extensional Tectonics and Stratigraphy of the North Atlantic Margins: AAPG Memoir 46, p. 1-6.

Teixeira, B.A., N. Pimentel, and R. Pena dos Reis, 2012, Regional variations in Source Rock maturation in the Lusitanian Basin (Portugal) – the role of rift events, subsidence, sedimentation rate, uplift and erosion: Abstracts III Atlantic Conjugate Margins Conference, p. 91-92.

Teixeira, B. A., N. Pimentel, and R. Pena dos Reis, 2014 (in press), Thermal modeling and maturation of Jurassic source rocks in the Lusitanian Basin (North East Atlantic, Portugal): Journal of Petroleum Geology.

Underhill, J.R. and R.C. Stoneley, 1998, Introduction to the development, evolution and petroleum geology of the Wessex Basin, *in* J.R. Underhill and R.C. Stonley, eds., The development, evolution, and petroleum geology of the Wessex Basin: Geological Society of London Special Publication 133, p.1-18.

UPHOFF, T. L., 2005, Subsalt (pre-Jurassic) exploration play in the northern Lusitanian basin of Portugal: AAPG Bulletin, v. 89, no. 6, p. 699-714.

Wade, J. A., and B. C. MacLean, 1990, The geology of the southeastern margin of Canada. Geology of the continental margin of eastern Canada: Geological Survey of Canada, Geology of Canada, v.2, p.167-238.

Wielens, J.B.W., C.D. Jauer and G.L. Williams, 2006, Is there a viable petroleum system in the Carson and Salar Basins, offshore Newfoundland, Journal of Petroleum Geology, 29 (4) 303-326.

Witt, W.G., 1977, Stratigraphy of the Lusitanian Basin: Shell Prospex Portuguesa, Unpublished report, 61p.

Whittaker, A., 1985, Atlas of Onshore Sedimentary Basins in England and Wales: Post-Carboniferous tectonics and stratigraphy: Blackie, Glasgow and London.

Wilson, R.C.L., R.N. Hiscott, M.G. Willis, and F.M. Gradstein, 1989, The Lusitanian Basin of West-Central Portugal - Mesozoic and Tertiary Tectonic, Stratigraphic, and Subsidence History: Chapter 22: European-African Margins: AAPG Memoir 46, p.341-361.

Wu, Y., 2007, Crustal structure of the central Nova Scotia margin and the transition from volcanic to non-volcanic rifting off eastern Canada: Ph.D. dissertation, Dalhousie University, Halifax, 341p.

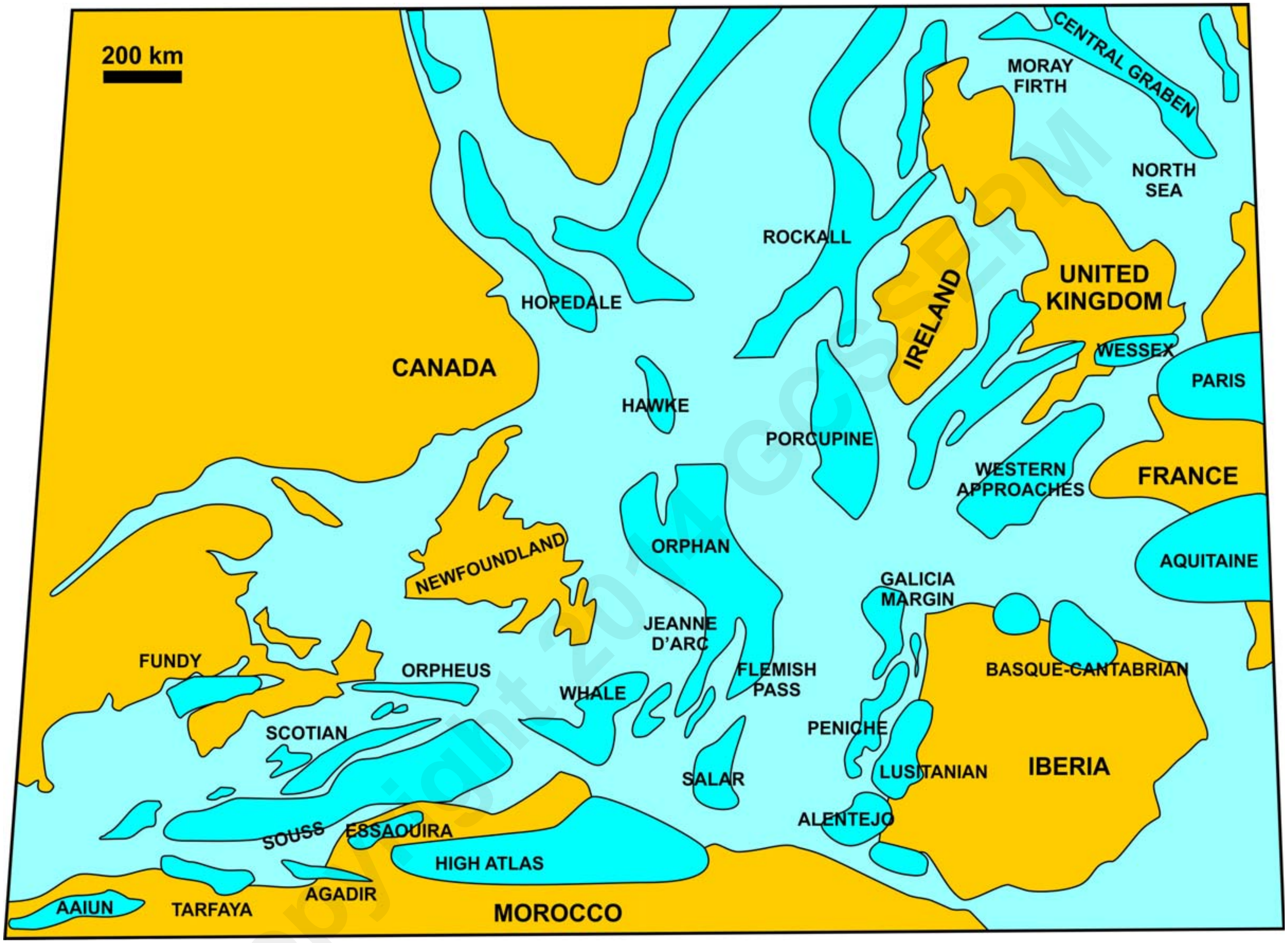

Figure 1. Location of several sedimentary basins formed by the rifting and sea-floor spreading that began in the Late Triassic, leading to the opening of the Atlantic Ocean (modified from Tankard and Balkwill, 1989; Decourt *et al.*, 2000, among others).

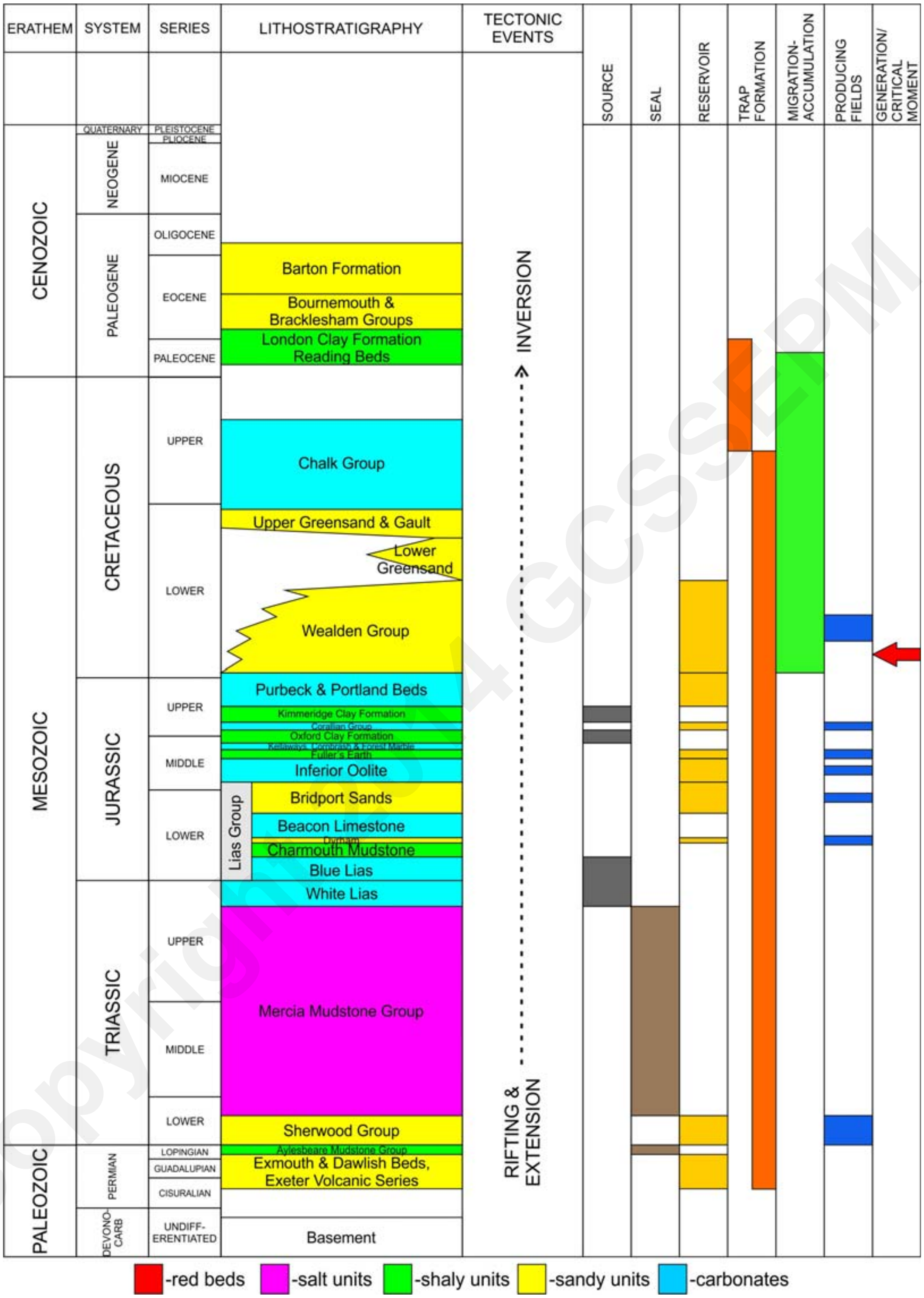

Figure 2. Petroleum systems chart of the Wessex basin (based on Underhill and Stoneley, 1998; Cox *et al.*, 1999; Hopson, 2005, among others).

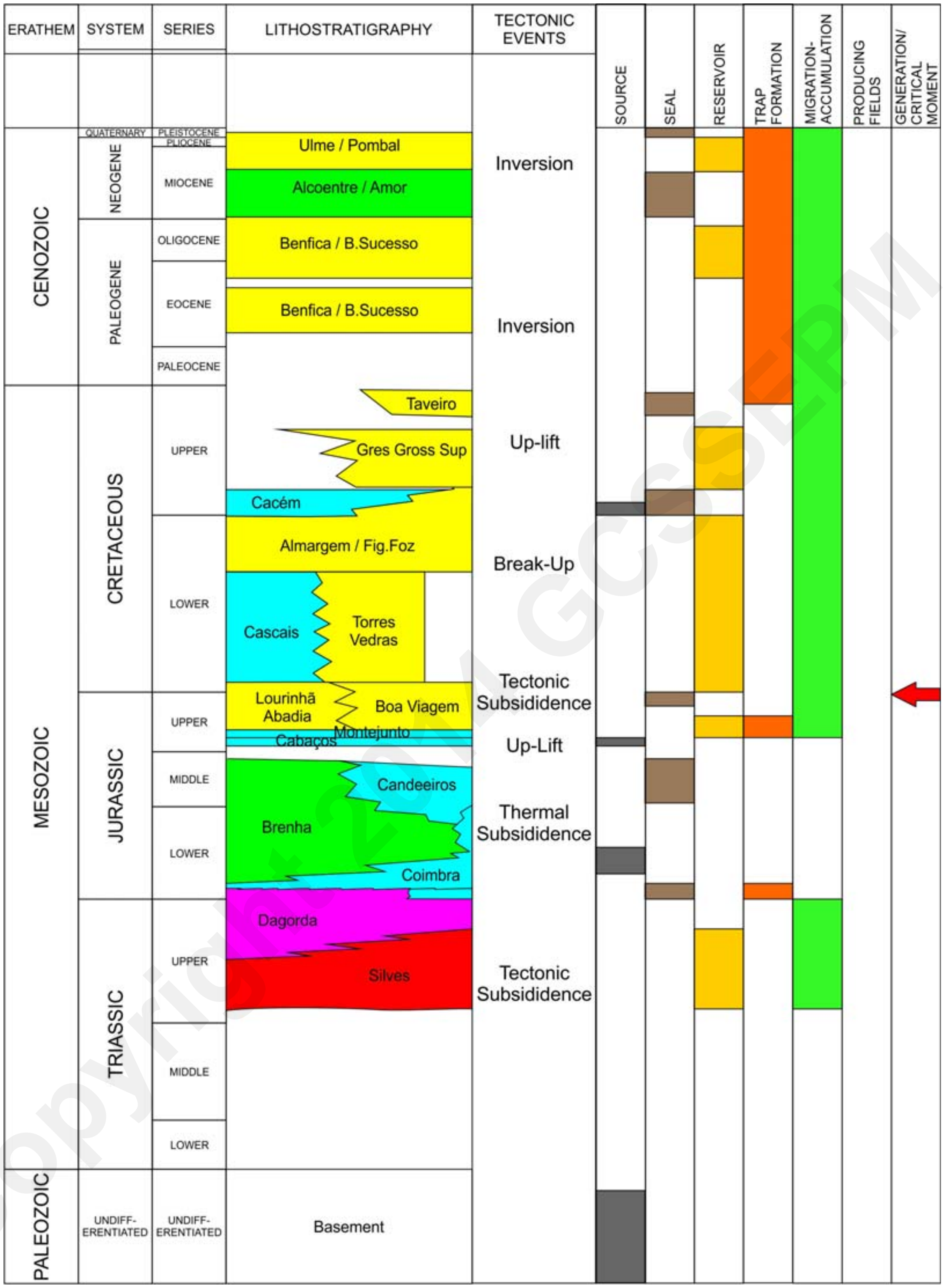

Figure 3. Petroleum systems chart of Central Portugal (based in Azerêdo *et al.*, 2003; Rey *et al.*, 2006; Witt, 1977, Pais *et al.*, 2012, among others).

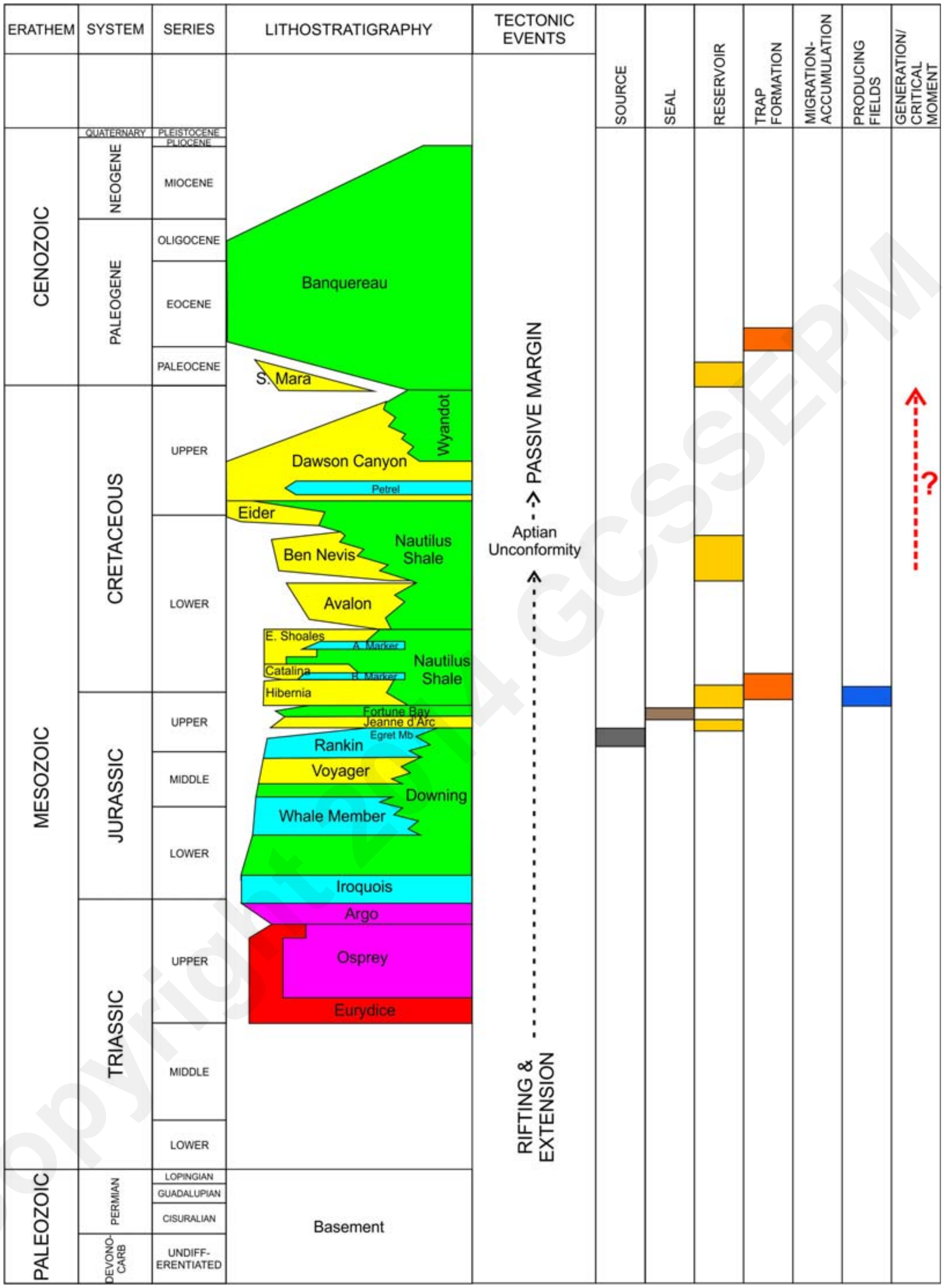

Figure 4. Petroleum systems chart of the Grand Banks- Jeanne d'Arc basin (based on Grant and McAlpine, 1990; Sinclair *et al.*, 1994; and Enachescu, 2006).

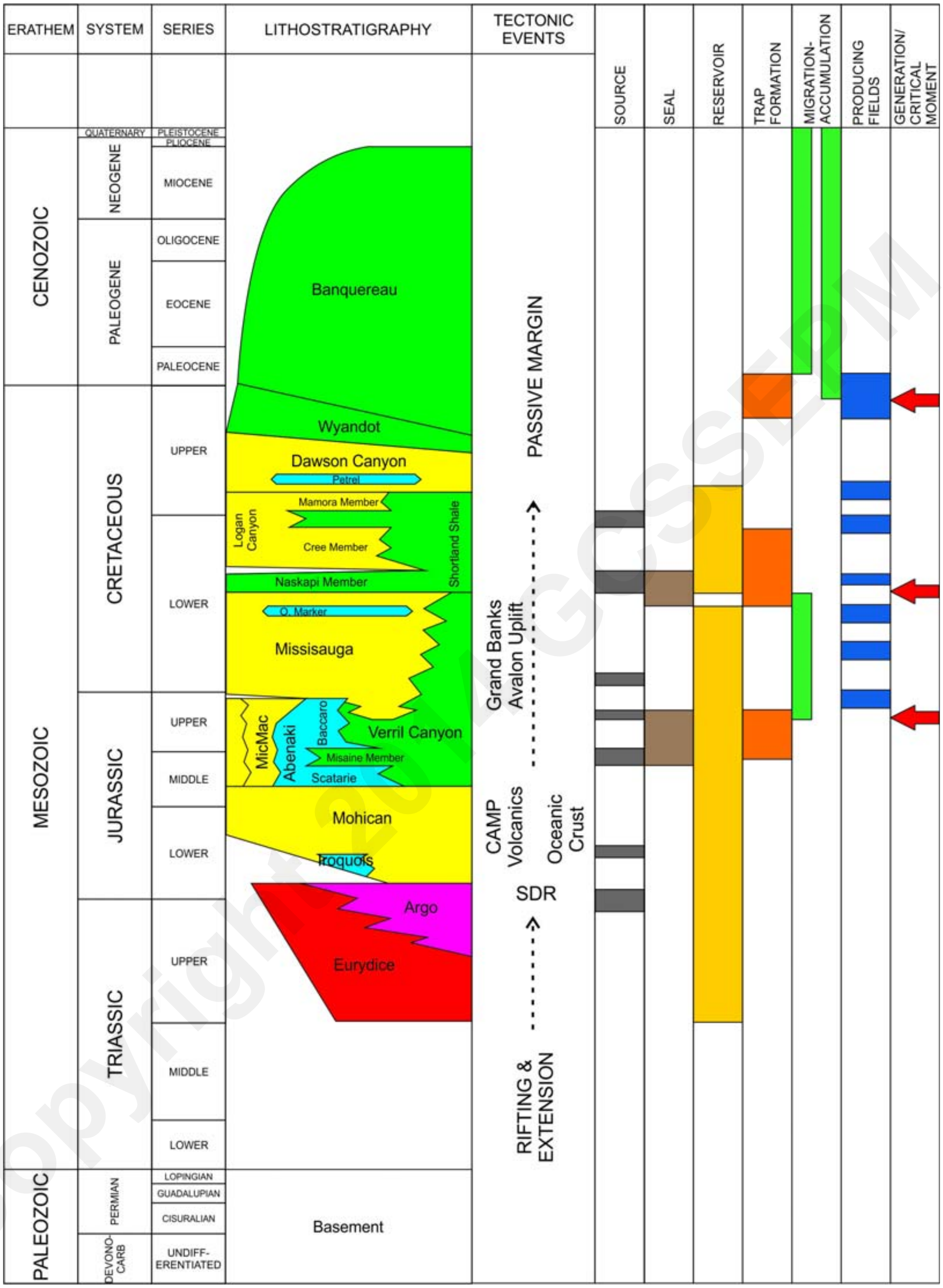

Figure 5. Petroleum systems chart of the Scotian basin (after Wade and MacLean, 1990).

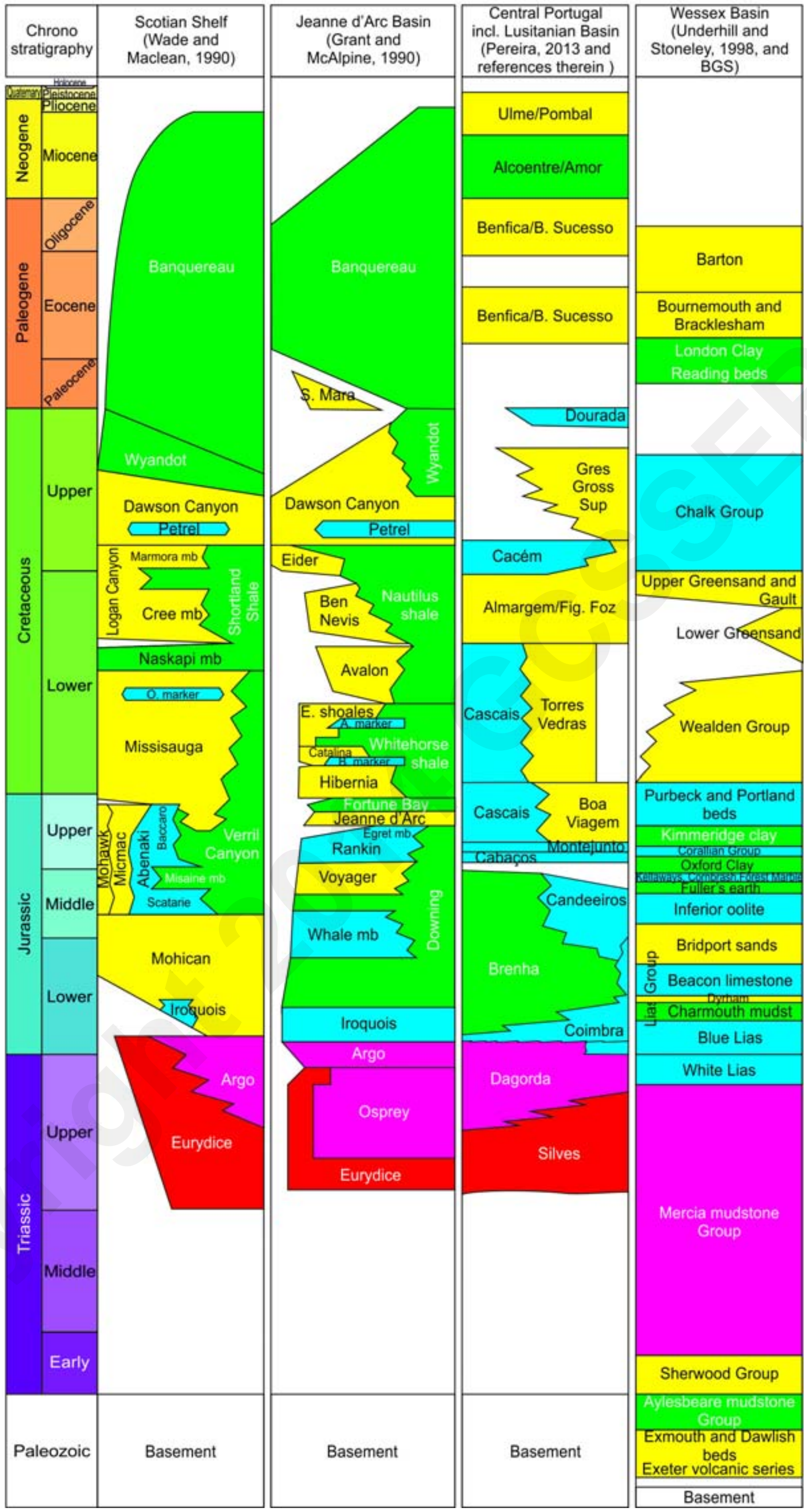

Figure 6. Simplified lithostratigraphic schemes of the Scotian Shelf basins (after Wade and MacLean, 1990), Jeanne d'Arc basin (Grant and McAlpine, 1990), Central Portugal (based in Azerêdo *et al.*, 2003; Rey *et al.*, 2006; Witt, 1977, Pais *et al.*, 2012, among others), and Wessex basin (based on Underhill and Stoneley, 1998; Cox *et al.*, 1999; Hopson, 2005, among others).