

ISPSG Project No: IS07/02

Second (Final) Annual Report

Regional Jurassic-Lower Cretaceous tectono-stratigraphy of the conjugate North Atlantic margins

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Executive Summary

The overall aim of the project is to provide an improved regional understanding of the Jurassic to Early Cretaceous facies, structure and development in the North Atlantic region. The results of the project will set the regional setting for the detailed work of the PhD project of Cédric Bulois (ISPSG Project ISO4/04) on the Late Jurassic – Early Cretaceous development in the northern Porcupine Basin region. They will also provide critical regional constraints on potential provenance sources and sediment transport pathways being examined in the PhD project of Áine McElhinney (ISO6/09).

The main scientific focus of the second (final) year of the project, was on reviewing models and data on regional North Atlantic Jurassic to Early Cretaceous development, and on re-interpreting available seismic data. While the conventional interpretation of the Jurassic-Lower Cretaceous succession in the region suggests an exclusively extensional setting, seismic and well data suggest that transpressional/compressional-driven uplift and erosion may have played a role in the shaping of the depositional and structural architecture of the basins.

The Base Cretaceous unconformity (sometimes several unconformities) marks an event of regional magnitude and can be followed along the Atlantic margin. The shape of the unconformity is likely to reflect the interplay of primary topography, compressional/transpressional tectonics, sediment compaction and loading, and later Cretaceous/Cenozoic thermal subsidence.

Significant inversion and erosion is interpreted for the Erris, Slyne and other small basins along the Rockall Basin, as well as locally within the Porcupine Basin. Flank uplift, magnified by compressional/transpressional deformation caused by the changing extensional directions between late Jurassic and early Cretaceous times resulted in the formation of a series of anticlinal and synclinal structures trending parallel to the Rockall margins. Their formation was also facilitated by presence of somewhat thinned (and weaker) continental crust in the basinal areas containing Permo-Triassic and Jurassic rift sediments buttressed between the thicker crust of the Erris Ridge, Porcupine High and Irish Mainland Platform.

1. Summary of work

Within the past year the following work has been carried out on the project:

Well and seismic interpretation. While the first year (summarised in the first annual report of February 2010) concentrated upon analysis of well and seismic data from the northern half of the Porcupine Basin, the main emphasis in the second year has been on expanding this to the remainder of the Porcupine Basin and to other parts of the Atlantic margin. Data from all available wells were reviewed and several thousand km of seismic profiles were examined and re-interpreted.

Regional tectono-stratigraphic analysis. A regional geological analysis of the uppermost Jurassic to lowermost Cretaceous succession of the Atlantic margin was carried out. This involved integration of all relevant published literature and available reports, combined with reinterpretation of seismic profiles and integrated with well data. Selected seismic lines in the Erris, Slyne and other smaller 'perched' basins along the Rockall Basin were examined and reinterpreted. Regional data from the Goban- Fastnet-Celtic margin, together with synthesis of data and work from the Porcupine Basin. Some comparisons with the Canadian and the Iberian conjugate margins were also included in the work. However, the general non-availability of seismic data from these areas meant that the data from these regions were limited to published data and reports.

Conference and other presentations. Yang presented one talk and two posters at the Atlantic Ireland 2010 Conference in November 2010 (abstracts included in Appendix 1). Yang also received permission from ISPSG to submit a single-author manuscript to a peer-reviewed journal for publication consideration.

Report preparation and submission. Yang wrote an initial draft of this report prior to his departure from the project and from UCD at the end of December 2010 to return to China. Shannon revised and provided additional written material and regional interpretations to the report. The following report presents the results of the regional analysis.

2. Regional Geological Introduction

The Base Cretaceous Unconformity is a feature of regional importance in many basins along both sides of the North Atlantic margin (Fig. 1) and is typically characterised by an angular unconformity or a major change in structural and depositional style across the latest Jurassic to the earliest Cretaceous interval. Ziegler (1982, 1989) attributed its formation mainly to thermal doming during the earliest Cretaceous Late Cimmerian major rifting period. He suggested that in northwest Europe, this tectonic pulse was accompanied by an intra-Berriasian eustatic sea-level fall, causing the emergence of large areas and restriction of marine sedimentation to the deeper parts of the North Sea Rift, Porcupine Basin and other areas.

However, several publications have shown significant tectonically-related structures formed during the latest Jurassic-earliest Cretaceous development of a number of basins in NW Europe, implying that the forming mechanisms of the Base Cretaceous Unconformity might have been more complex than suggested by Ziegler (1982, 1989). During Late Jurassic-Early Cretaceous, widespread strike-slip faults and related pop-up structures formed in the North Sea Rift (Bartholomew et al., 1993; Sears et al., 1993; Sundsbo and Megson, 1993; Eggink et al., 1996). Further west, Tate (1993) attributed a series of conspicuous north-south ridges in the northeastern

part of the Porcupine Basin to transpressional inversion across the Jurassic-Cretaceous boundary. To the northeast of the Porcupine basin the uplift and consequent erosion on the western margin of the Erris Basin was attributed to the effects of rifting and resultant footwall flank uplift in the Rockall Basin during the earliest Cretaceous (Chapman et al., 1999). Corcoran & Mecklenburgh (2005) suggested that the rift shoulder uplift caused by the Rockall extension resulted in the regional exhumation of 800-1700 m in the Slyne Basin during the Berriasian-Valanginian. Thomson and McWilliam (2001) interpreted a compressive pulse in latest Jurassic to earlier Cretaceous times in the North and South Bróna basins, responsible for giving the basins their characteristic appearance with fault reversal and north-south anticlines developed along the western margin. They suggested that the folding was the result of approximately east-west directed compression but did not discuss the causal mechanism for the compression.

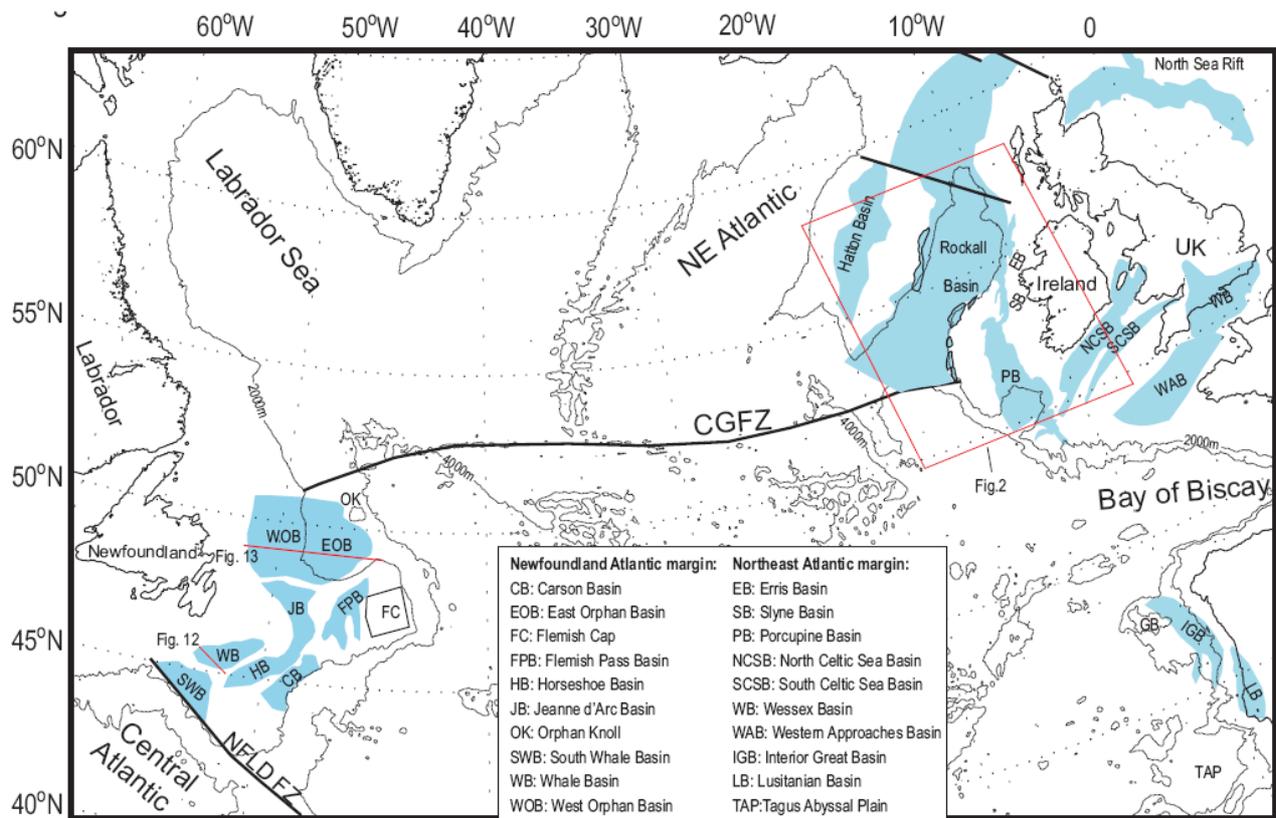


Figure 1. Mesozoic basins on the eastern North Atlantic margin and on the Newfoundland Atlantic margin. The locations of Figures 2, 12 and 13 are shown.

Turner and Williams (2004) suggested that exhumation of sedimentary basins is mainly driven by epeirogeny and basin inversion. Epeirogeny is a regional process in continental interiors, probably driven by plumes, basaltic underplating, mantle delamination, post-glacial isostasy, intra-plate stress and thermal-isostatic effects associated with rifting and/or oceanic opening. It has been generally accepted that horizontal plate movement (e.g. plate collision and ridge push) is the main mechanism that cause shortening and inversion of rift basins (Coward, 1994; Withjack et al., 1995). However, some inverted structures in continental rift basins are interpreted to result from extension (Buchanan and McClay, 1992). Therefore, separating the mechanisms of exhumation between epeirogeny and basin inversion within intra-plate regions located at a distance from active plate boundaries remains an outstanding and important problem (Turner and Williams, 2004).

This report evaluates and reinterprets some latest Jurassic-earliest Cretaceous deformation styles in basins along the European (largely Irish) Atlantic margins, in order to understand the tectono-stratigraphic evolution in the north Atlantic margin during the Jurassic-Cretaceous transition, and clarify the nature and mechanisms of the Base Cretaceous Unconformity. It also makes comparisons with depositional and structural styles on part of the conjugate North American (largely Newfoundland) margin. However, due to the non-availability of significant seismic and well data from this region the assessment and comparison is based largely on published work from the Newfoundland margin. Because structural evolution controls the style and timing of trap formation, and the deposition and burial history of source rocks, reservoirs and seals, a better understanding of the regional development across this interval is an important ingredient in de-risking exploration along the Irish Atlantic margin.

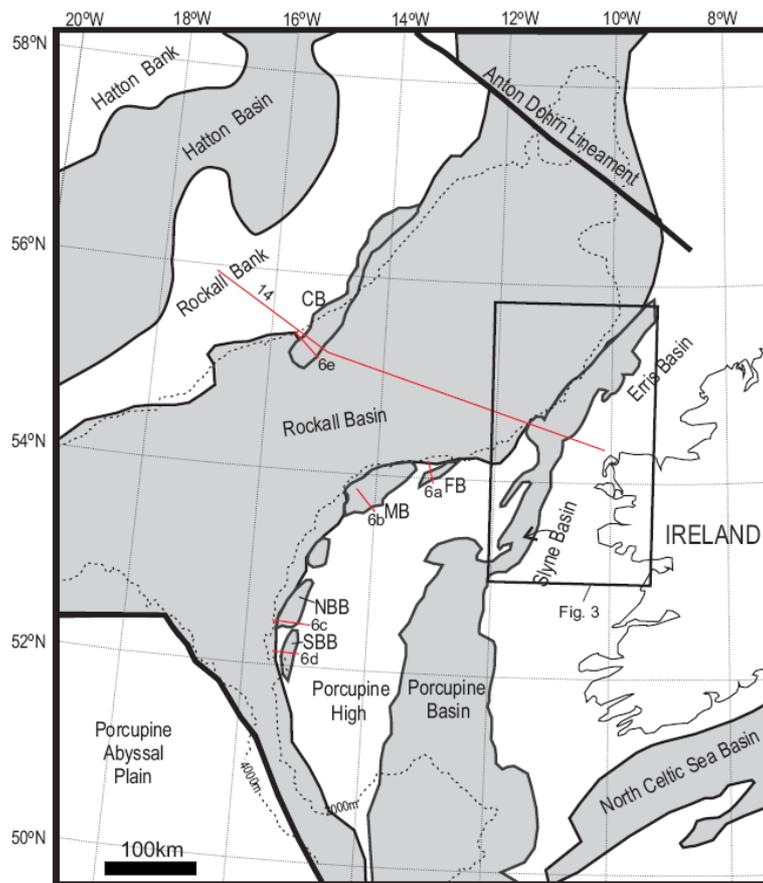


Figure 2. Mesozoic basins on the Irish Atlantic margin (modified from Naylor et al., 2002), showing the locations of Fig. 3, Figs 6a-6e and Fig. 14. CB: Conall Basin. FB: Fursa Basin. MB: Macdara Basin. NBB: North Bróna Basin. SBB: South Bróna Basin.

3. Late Jurassic – Early Cretaceous tectono-stratigraphic evolution of the Irish Atlantic margin

3.1 Basins along the Rockall margin

3.1.1 Erris Basin

In the Erris Basin, wells 19/5-1 and 12/13-1A encountered a succession of Cenozoic, Cretaceous, Early Jurassic, Permo-Triassic and Carboniferous age (Fig. 3). Latest Jurassic and/or Early

Cretaceous erosion likely removed originally deposited Middle-Upper Jurassic sequence in the Erris Basin (Morton, 1992). In a detailed structural and stratigraphic study of the region, based largely on seismic data, Chapman et al. (1999) suggested that the basin underwent major rifting during the Permo-Triassic and Middle-Late Jurassic periods and minor rifting during the late Early Cretaceous. Significantly, they interpreted a major inversion during the latest Jurassic-earliest Cretaceous, resulting in extensive uplift and erosion (2-4 km) of the western margin of the Erris Basin and the formation of the Base Cretaceous Unconformity regionally throughout the basin (Fig. 4). This inversion episode was attributed to the rifting of the Rockall Basin. They reaffirmed the model of Cunningham and Shannon (1987) who attributed the uplift and inversion along the Erris margin to rift shoulder uplift along the eastern margin of the Rockall Basin, which underwent more significant extension and crustal thinning than the smaller and narrower Slyne-Erris basins. During the Early Cretaceous, sedimentation in the Slyne-Erris basins was restricted to a NE-SW trending depozone to the east of the uplifted western margin, cored by the Erris Ridge, and strata bidirectionally overlapped the Base Cretaceous topography (Fig. 5).

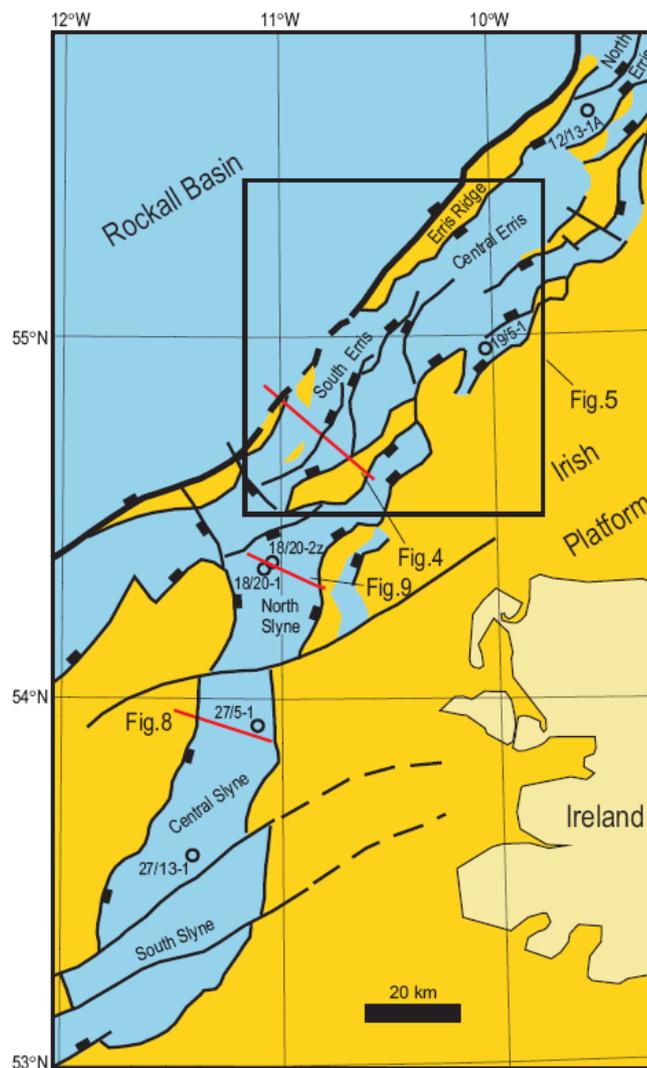


Figure 3. Location of the Erris Basin and Slyne Basin (modified from Chapman et al., 1999 and Dancer et al., 2005), showing locations of Figs 4, 5, 8 and 9.

Based on the structural and stratigraphic architecture in the Erris Basin, described by Chapman et al. (1999), it appears likely that the basin experienced a compressive phase during latest Jurassic-earliest Cretaceous time. The structural architecture of the basin does not conform to the geometries predicted from simple rift shoulder uplift models: thermal uplift of rift margins as a result of depth-dependent stretching (White and McKenzie, 1988) and flexural footwall uplift as a mechanical response to faulting (Kusznir et al., 1991). The western margin of the Erris Basin was uplifted, centred on the thick Erris Ridge that acted as a buttress and the eastern part of the basin was tilted oceanwards, forming a syncline in the central basin. The early Cretaceous sediments were deposited in the synclinal depozone formed during the latest Jurassic-earliest Cretaceous and overlapped two limbs of the syncline, forming a prominent bidirectional onlap pattern as Chapman et al. (1999) mentioned. In places, this is interpreted to reflect the ponding of marine strata (probably submarine fan clastics characterised by the succession encountered in the 12/13-1A well in the Erris Basin).

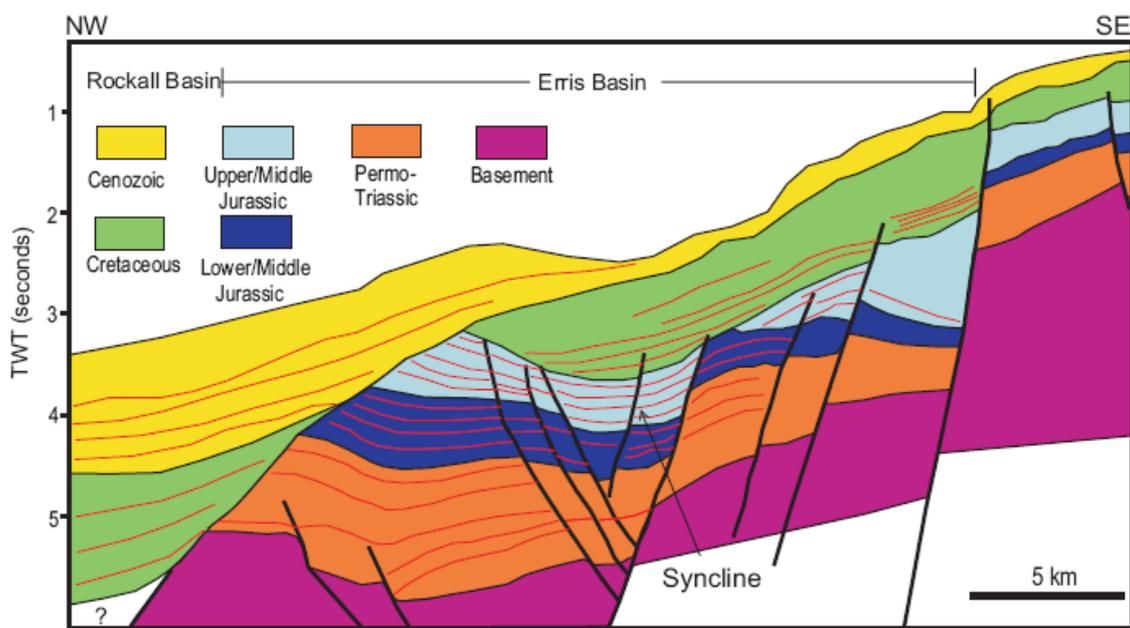


Figure 4. Cross-section across the southern Erris Basin, based on the seismic section in Chapman et al. (1999). See location in Fig. 3.

3.1.2 ‘Perched’ basins

A suite of small, generally elongate, basins lie at a high structural level along both the western and especially the eastern margins of the Rockall Basin. These ‘perched’ basins (Fig. 2) include the South Bróna, North Bróna, Macdara and Fursa basins on the eastern margin of the Rockall Basin, and the Conall and Rónán basins on the western side (Corfield et al., 1999; Naylor et al., 1999; Naylor and Shannon, 2005). Based mainly on comparison with seismic profiles of the Erris and Slyne basins, the interpreted Mesozoic stratigraphic fill of these basins was divided into several seismic sequences: Permian-Triassic sequence, Lower-Middle Jurassic pre-rift sequence, Middle-Upper Jurassic syn-rift sequence and Cretaceous sequence overlying the syn-rift wedge (Corfield et al., 1999; Naylor et al., 1999; Shannon et al., 1999) (Fig. 6). Several shallow boreholes penetrated Cenozoic, Cretaceous and Late Jurassic strata on the eastern margin of the Rockall Basin to constrain the Mesozoic and Cenozoic stratigraphic development of the region. Two of these (83/20-sb01 on the eastern margin of the North Bróna Basin and 83/24-sb02 on the western margin of the South Bróna Basin encountered Cretaceous and Upper Jurassic strata (Haughton et al., 2005).

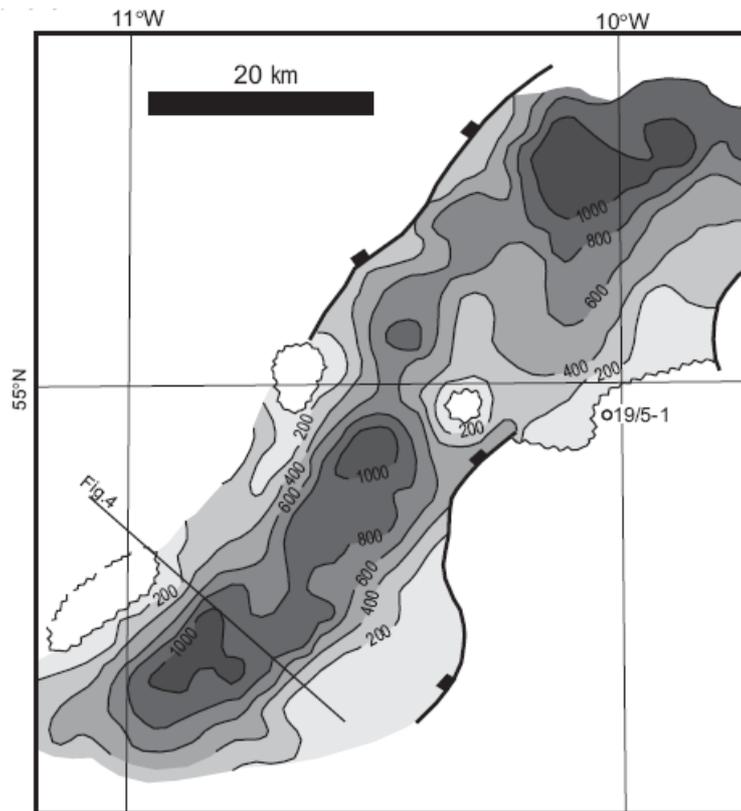


Figure 5. Cretaceous isochron map (contours in milliseconds) over part of the Erris Basin (Chapman et al., 1999). See location in Fig. 3.

The structural evolution and stratigraphic fill in these small basins during the Late Jurassic to Early Cretaceous transitional interval has been interpreted in different ways in the published literature prior to the drilling of the stratigraphic boreholes. Corfield et al. (1999) suggested that the Cretaceous sediments were deposited in compactional synclines of pre-Cretaceous strata on both flanks of the Rockall Basin, while Shannon et al. (1999) interpreted them as rift-related incised valley-fill deposits. Thomson and McWilliam (2001) proposed that the Bróna Basin experienced the main rift phase during the Late Jurassic followed by a compressional phase during the latest Jurassic-earliest Cretaceous, resulting in fault reversal and folding of pre-Cretaceous strata (Figs 6c, 6d). The approximate east-west-directed compression led to the development of north-south-trending anticlines along the western margin of the basin and the formation of synclines to the east which were filled by the Lower Cretaceous sediments. On a regional scale, Naylor and Shannon (2005) argued that the eastern margin of the Rockall Basin experienced flank uplift and erosion caused by the extension of the Rockall Basin during the Late Jurassic. However, the shallow borehole data on the eastern margin (in the Bróna basins) has provided better constraints on depositional setting and on the local structuring in the perched basins. The Upper Jurassic succession drilled in the 83/20-sb01 borehole suggests deposition of a mixed clastic/carbonate succession, with deposition taking place in an area of weak currents in shelf or possibly deeper water below wave base. Unfortunately, while seismic data from the region suggests an unconformity between the Jurassic and Cretaceous succession, this basal unconformity itself was not cored by the borehole. However, the borehole proved the overlying succession to contain poorly dated Cretaceous 'brownsands' with a basal algal limestone unit. The succession is interpreted as constituting a condensed, high-energy inner shelf succession, and is of indeterminate but probably Early Cretaceous age (Haughton et al., 2005). Based upon a combination of seismic

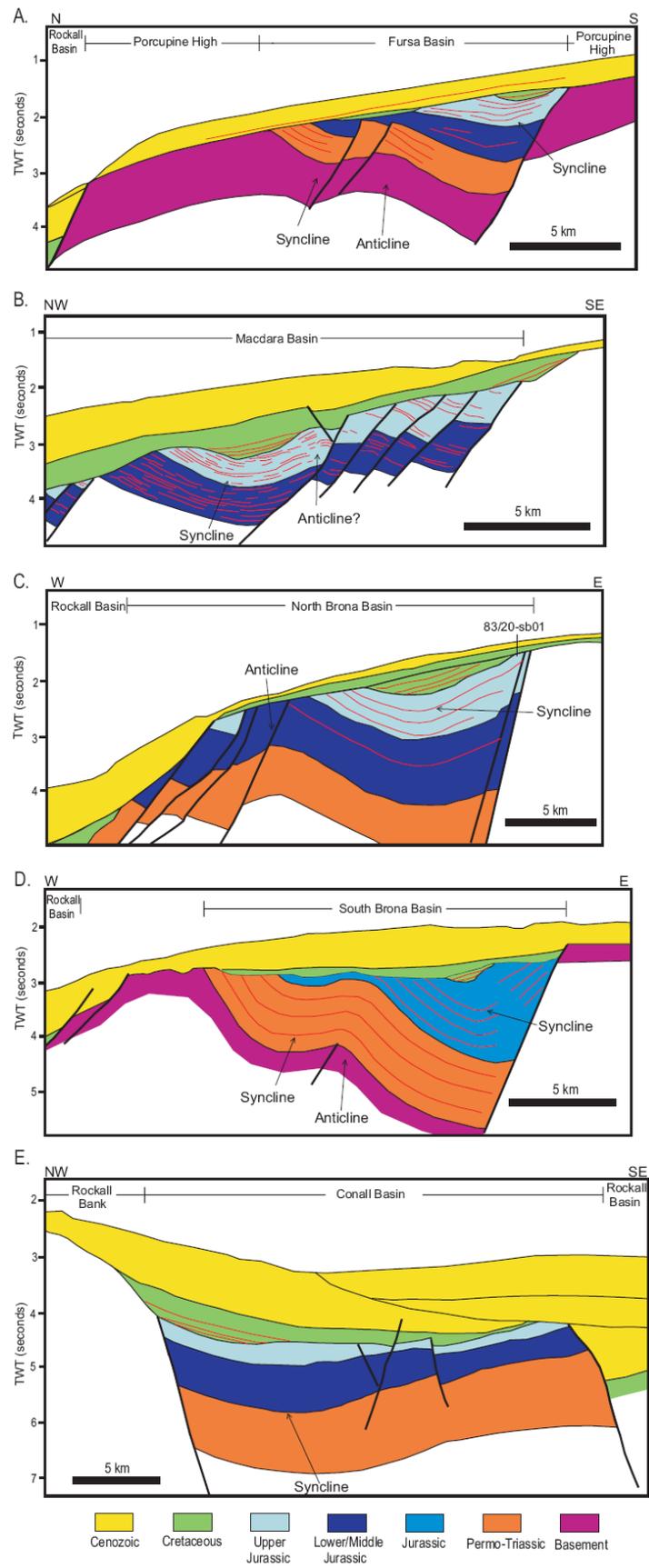


Figure 6. Cross-sections through 'perched' basins on the margins of the Rockall Basin (modified from Corfield et al., 1999; Naylor et al., 1999; Shannon et al., 1999). See locations in Fig. 2.

and borehole data, including the observation of small reverse faults displacing laminations in the Upper Jurassic succession, Haughton et al. (2005) demonstrated that the Jurassic strata are truncated by a prominent angular unconformity overlain in places by a condensed Cretaceous succession, and by Cenozoic strata in other places. The unconformity was interpreted to record a major Late Jurassic and /or Early Cretaceous inversion episode along the eastern margin of the Rockall Basin.

Re-examination and re-interpretation of seismic data from the perched basins in the present project confirms the regional extent of an inversion episode in latest Jurassic to earliest Cretaceous times. The large-scale geometry of the Jurassic succession shows a landward (eastward) dip, away from the Rockall Basin on the eastern perched basins, mirrored by a westward dip in the western basins. However, the Cretaceous proven and interpreted successions dip in the opposite direction, towards the centre of the main Rockall Basin. This is compatible with footwall uplift, erosion, deposition and collapse towards the Rockall centre. However, the fold structures (synclines and anticlines) seen in the Jurassic and older sections of the basins (Fig. 6), suggest an episode of compression accompanying the inversion. The fact that the Cretaceous strata onlap and downlap irregularities in the unconformity surface, resulting in ponded-like depocentres, and show no evidence of similar folding, helps to constrain the timing of the inversion/compressional event as latest Jurassic to early Cretaceous. This episode, resulting in regional uplift and folding of both margins strongly modified the structure of the Permo-Triassic and Jurassic rifted basins in these areas (Figs 4, 6). Cretaceous sediments were first deposited in the synclines. Shannon et al. (1999) interpreted the Cretaceous strata as rift-related incised valley fill deposits on the flanks of the Rockall Basin. However, in the light of the present study this interpretation requires modification. The presence of the major angular unconformity and overlying folded strata points towards the development of the depocentres as erosionally-modified compressional synclines rather than purely erosionally-created valley-like depocentres. Furthermore, classical incised valleys, created in response to a relative fall in sea level (*sensu* Posamentier and Vail, 1988), usually extend basinward from continental margins. While the available seismic data are insufficiently close-spaced to map the geometry of the Cretaceous depocentres in detail, they appear to be separated by uplifted areas from the Rockall Basin and have trends approximately parallel to the margins of the Rockall Basin (Figs 4-6). This is suggestive of a structural control on the geometry of the depositional basins, which downlapping and infilling the depocentres. Furthermore, the Base Cretaceous Unconformity shows a variable geometry, relatively parallel to the underlying pre-Cretaceous strata in some of the synclines (e.g. Fig. 6C), at a slight angle in others (e.g. Fig. 6A, 6E) and severely truncating the pre-Cretaceous at the structural highs. This points to a complex origin. It is therefore suggested that, in addition to the rift shoulder uplift model suggested by previous authors, a significant compressional component, with modification by erosion, is required to best explain the geometry of the early Cretaceous strata. This model also predicts the possibility of reservoir potential in some of the downlapping fills of the depocentres in contrast to the condensed successions that were drilled on the extreme margin of the North Bróna Basin.

3.1.3 Slyne Basin

The Slyne Basin is composed of three half-grabens which are separated from each other by complex transfer zones (Trueblood and Morton, 1991) (Fig. 3). In the central and southern Slyne half-grabens, a succession of Permo-Triassic and Early-Middle Jurassic sediments are unconformably overlain by a relatively thin Cenozoic section (Scotchman and Thomas, 1995; Dancer et al., 1999) (Fig. 7). A series of monoclines (locally anticlines) formed along the western margin of the central Slyne half-graben (Dancer et al., 1999) (Fig. 8). The parallelism of the Lower Jurassic and Triassic strata in these structures and the thinning of the Middle Jurassic onto them indicate that they formed during the Middle Jurassic period. Dancer et al. (1999) suggested that the

formation of these monocline structures is related to the movement of salt-detached extensional faults along the Permian Zechstein halite detachment layer during the Middle Jurassic extensional phase. In the northern Slyne half-graben, several wells have been drilled since the 18/20-1 Corrib gas discovery in the Lower Triassic Sherwood sandstone (Figs 3, 7, 9). The structural evolution model of the Corrib Field proposed by Corcoran and Mecklenburgh (Fig. 6, 2005) and Dancer et al. (Fig. 4, 2005) consists of several stages. During the Early-Middle Jurassic, a major syn-sedimentary westerly dipping listric fault developed above a Carboniferous horst block, possibly triggered by doming of Permian Zechstein salt. In the late Middle Jurassic-Late Jurassic, an easterly dipping listric fault which detaches on the Upper Triassic halite layer developed, forming a crestal collapsed rollover anticline in the hanging wall of the fault. A major phase of exhumation during the Ryazanian-Valanginian time resulted in an average gross exhumation of 1429-1482 m for the Base Cretaceous Unconformity, attributed to the superposition of regional exhumation related to lithospheric extension of the Rockall Basin during the Early Jurassic and local extensional fault movements.

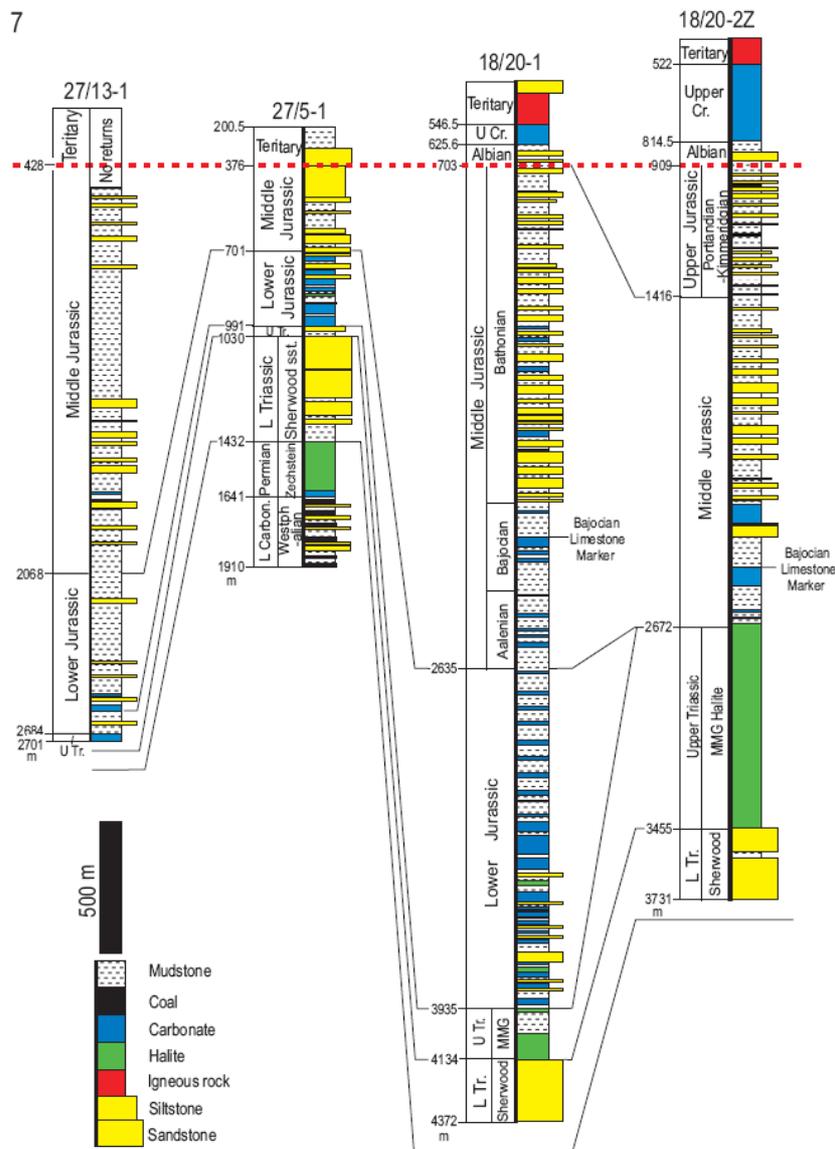


Figure 7. Lithological columns of wells in the Slyne Basin. Well locations are shown in Fig. 3. Wells are all sub-RKB depths with depth in metres. The stratigraphic subdivision of the well 27/13-1 is based on Scotchman and Thomas (1995).

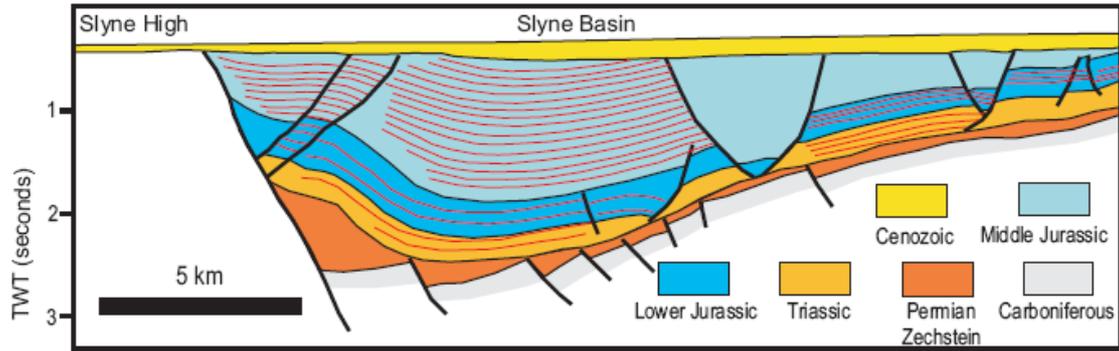


Figure 8. Cross-section in the Slyne Basin, based on the seismic section in Dancer et al. (1999). See location in Fig. 3.

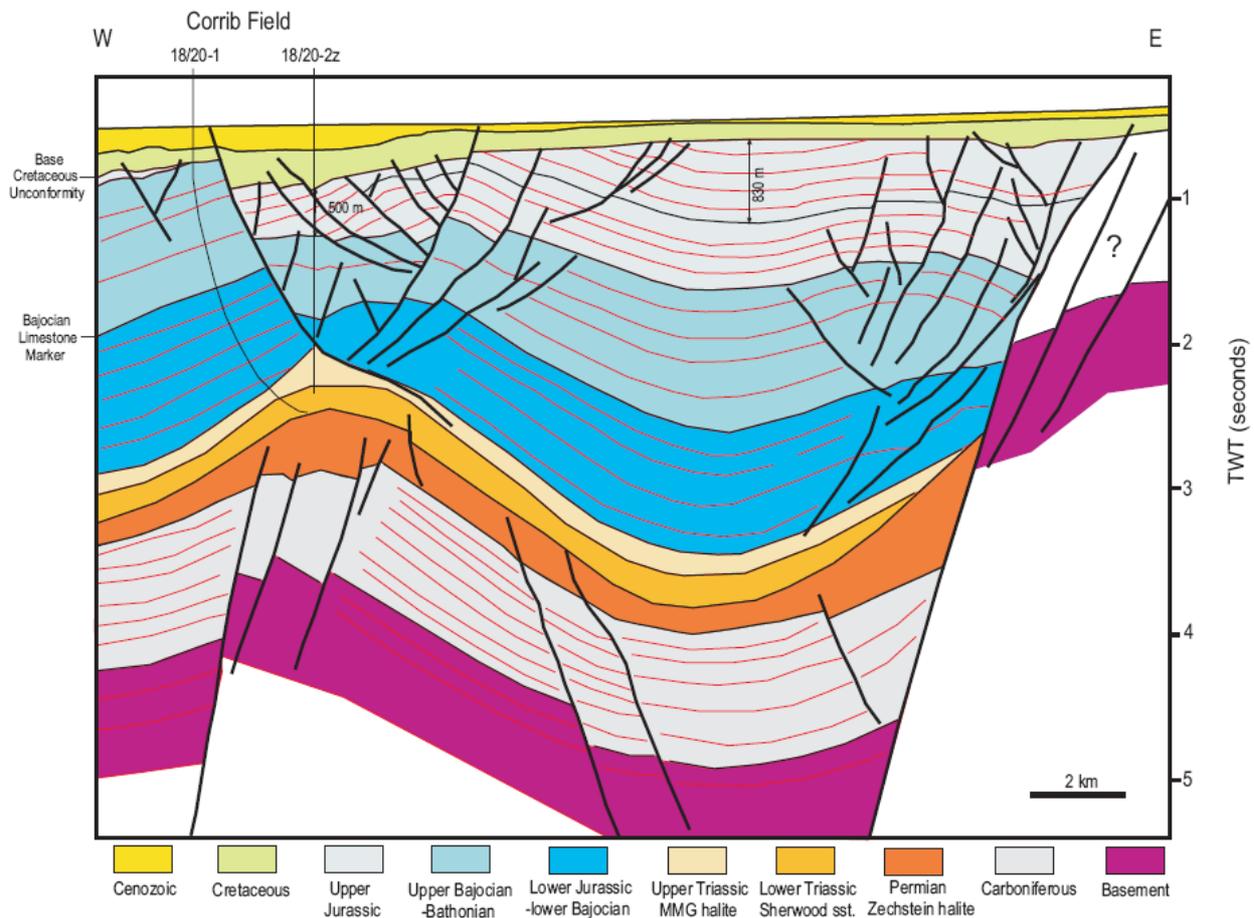


Figure 9. Cross-section across the Corrib Gas Field, based on the seismic section in Corcoran and Mecklenburgh (2005). See location in Fig. 3.

Although the structural evolution model of the Corrib anticline (Corcoran and Mecklenburgh, 2005; Dancer et al., 2005) provides an interpretation for some structural features of the Corrib Gas Field, it is quite problematic when several important stratigraphic features in the northern Slyne sub-basin (Fig. 9) are considered.

- (1) If there was a Carboniferous horst block at the present Corrib anticline area before the deposition of the Permian Zechstein halite, it is difficult to understand how relatively uniform or thicker Permian-Triassic sediments were deposited above the uplifted area which was several kilometers higher than the surrounding low areas. Moreover, the relative parallelism of the Carboniferous strata at both limbs of the interpreted horst block to the overlying Permian-Jurassic succession also questions the existence of a Carboniferous horst block.
- (2) If the main east-dipping listric detachment fault was a syn-sedimentary fault during late Middle Jurassic-Late Jurassic time, the Upper Bajocian-Bathonian and Upper Jurassic strata close the fault in the hanging wall would be expected to be much thicker than those in the footwall and those at the eastern limb of the anticline. However, the late Middle Jurassic strata in the hanging wall are much thinner than those in the footwall and those at the eastern limb of the anticline. The time-equivalent Upper Jurassic section of 500 m drilled by 18/20-2z has a relatively uniform thickness from the east-dipping listric fault eastward to the west-dipping basin boundary fault (Corcoran and Mecklenburgh, 2005), suggesting that the main listric fault and the series of synthetic and antithetic secondary faults to its east might have not been active during the Late Jurassic.
- (3) It is very clear there is a syncline folding the pre-Cretaceous strata between the Corrib anticline and the basin-bounding fault to the east of the gas field. This was not described by Corcoran and Mecklenburgh (2005) or Dancer et al. (2005). According to Corcoran and Mecklenburgh (2005), extensional rollover anticlines developed in the hanging wall of the main listric fault and the eastern basin-bounding fault during the late Middle Jurassic-Late Jurassic, implying that uplift of the rollover anticlines resulted in formation of the syncline. However, the formation of rollover anticlines in the Middle-Upper Jurassic strata could not influence the folding of the underlying strata. Secondly, it is difficult to see how such a high-amplitude syncline could develop between rollover anticlines during faulting of two listric faults with reverse dip directions (Xiao and Suppe, 1992; Withjack and Schlische, 2006). In this scenario, a relatively uplifted area may be produced between the rollover anticlines. In addition, a rollover anticline would not be anticipated to be developed in response to movement on to steep-dipping fault (see Xiao and Suppe, 1992; Withjack and Schlische, 2006), such as the eastern boundary fault in the northern Slyne sub-graben.
- (4) According to Corcoran and Mecklenburgh (2005), major exhumation during the Early Cretaceous resulted in erosion of Upper Jurassic strata of at least 830 m at the 18/20-2z well location, equivalent to the thickness of the undrilled Upper Jurassic section in the syncline. However, if the basin evolution is rolled back and restored, placing the eroded strata back above the putative collapsed graben, it would appear, prior to the major inversion and exhumation, there was a high at the hanging wall of the east-dipping listric fault. Normal faulting of the main listric fault and a number of secondary faults would be unable to produce an uplifted area during the late Middle Jurassic-Late Jurassic. Additionally, exhumation of mainly Upper Jurassic strata of 1330-1705 m occurred for the Base Cretaceous Unconformity at the 18/20-1 location (Corcoran and Mecklenburgh, 2005). It is also unlikely that sediments with a similar or larger thickness were deposited at the footwall of the main east-dipping listric fault than those at the hanging wall.
- (5) While it is plausible to attribute major uplift along the margins of the Erris Basin to flank uplift linked to the Rockall Basin, the Slyne Basin is located in a more inboard position, being 20-150 km from the eastern margin of the Rockall Basin and separated from it by the Porcupine

High (Figs 2, 3). This makes it more difficult to attribute the major uplift entire to such flank uplift linked to rifting in the Rockall Basin.

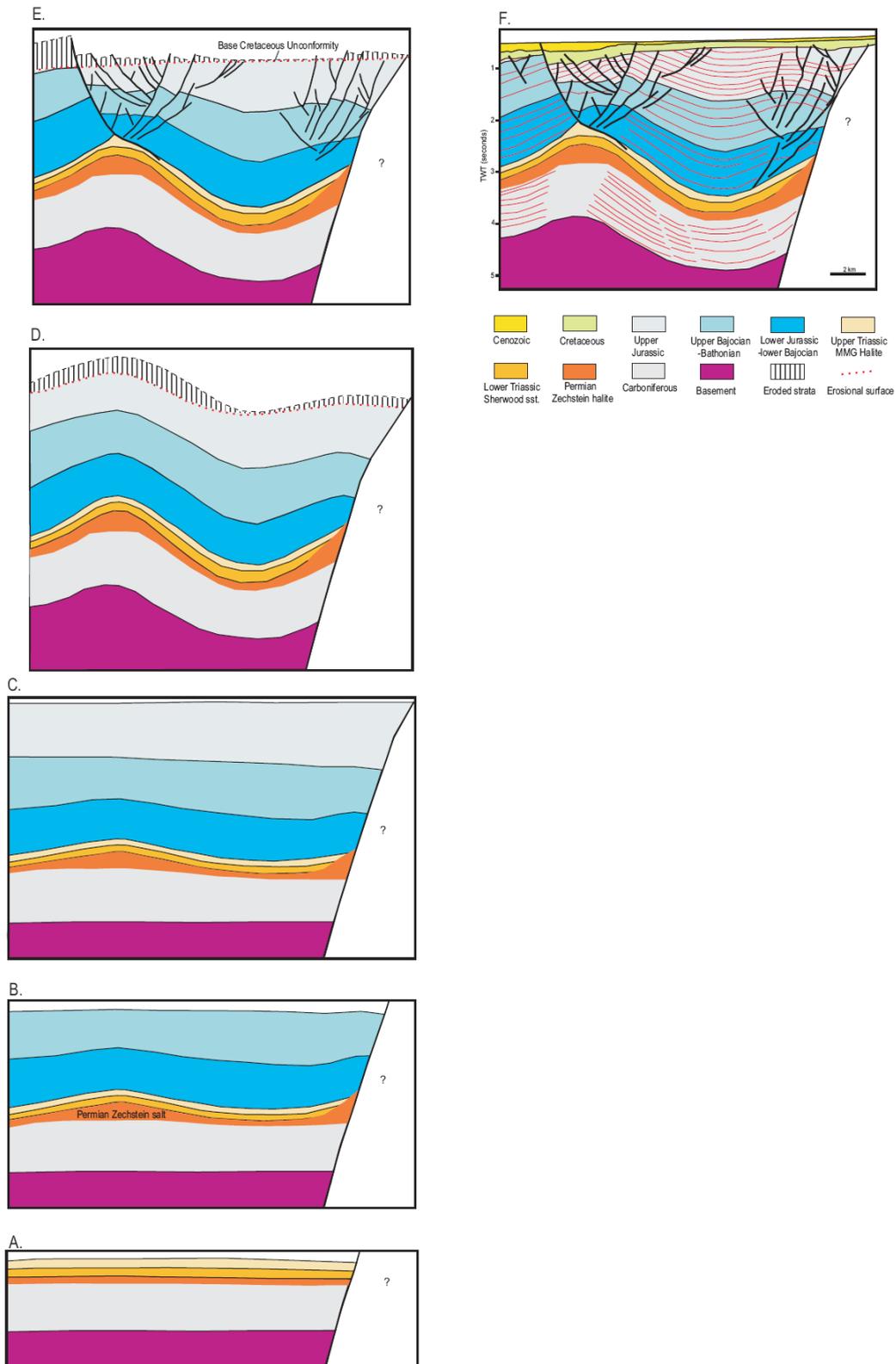


Figure 10. A schematic evolution of the Corrib structure: (A) during the Permian-Triassic; (b) during the late Early Jurassic-Middle Jurassic; (c) during the Late Jurassic; (d) during the latest Jurassic-earliest Cretaceous; (e) during the Early Cretaceous; (F) at the present.

Based on the structural and stratigraphic features observed in the Slyne Basin, together with the arguments presented above, a revised interpretation of the tectono-stratigraphic development of the northern Slyne Basin is proposed. During the Permian-Triassic (Fig. 10a), sediments with a relatively uniform thickness were deposited above the relatively planar top Carboniferous surface. This region is located a considerable distance from the Variscan Front and the effects of the Variscan Orogeny are thought to be very slight. This is confirmed by both seismic and well data in the region. During the late Early Jurassic-Middle Jurassic (Fig. 10b), the Slyne Basin underwent a major phase of rifting, which triggered Zechstein salt diapirism. This suggestion is consistent with the analogue modelling results that regional extension is the most common initiator of salt upwelling (Jackson & Vendeville 1994). Zechstein salt doming occurred at the present Corrib Field location, resulting in the formation of a symmetric anticline in the Triassic strata and deposition of relatively thin syn-uplift upper Lower Jurassic-Middle Jurassic sediments. The salt diapirism along the eastern boundary fault of the basin also led to deposition of relatively thin syn-uplift sediments at the hanging wall of the fault. This event may have been of regional extent in the Slyne Basin, resulting in the formation of the monoclines (locally anticlines) along the western margin of the central Slyne half-graben (Fig. 8). During the Late Jurassic (Fig. 10c), salt diapirism ceased but the eastern boundary fault continued to be active, resulting in the deposition of relatively thick sediments at the hanging wall.

Unfortunately, the general absence of Cretaceous strata through much of the basin makes it difficult to be confident of the precise age of much of the late Mesozoic and early Cenozoic structuring in the basin. The Cretaceous succession, where present, is invariably thin. In the 27/13-1 well in the south Slyne Basin possible Quaternary sediments rest upon Bathonian strata (Trueblood, 1992). The sequence in the Corrib Field region at the northern end of the Slyne Basin (Dancer et al., 2005) comprises 50-96 m of Albian marine claystones and glauconitic sandstones passing upwards to sandy claystones with occasional limestones. This thin Cretaceous succession rests unconformably on Middle to Upper Jurassic strata. Lower Cretaceous strata appear to be restricted to a relatively thin layer in the northern part of the Slyne Basin (Dancer et al., 1999). During the latest Jurassic-earliest Cretaceous (Fig. 10d), compression resulted in wide-amplitude fold structures and inversion of the pre-Cretaceous strata within the basin, and at the same time, the basin strata especially at the uplifted areas experienced a certain extent of exhumation.

Folding occurred at the present Corrib Field, significantly increasing the amplitude of the pre-Upper Jurassic structure. Folding also led to the formation of an anticlinal flexure adjacent to the eastern boundary fault. Between the anticline at the Corrib Field and the anticline at the hanging wall of the eastern boundary fault, a high-amplitude syncline was produced. However, the magnitude of the uplift and erosion is uncertain and it is unknown if uplift exhumed the succession to produce a non-marine setting as the thin Cretaceous succession, where penetrated, is always non-marine in its setting. A reduced Upper Cretaceous succession is present in the northern part of the Slyne Basin but it is absent elsewhere due to subsequent (probably early Cenozoic) erosion. In the Corrib Field area the Upper Cretaceous succession contains chalk and interbedded claystones, ranges up to 293 m in thickness and rests unconformably on the Lower Cretaceous. However, the Upper Cretaceous is thicker and more continuous in the Erris Basin, suggesting that the magnitude of the later (early Cenozoic) inversion and erosion was less pronounced in the latter basin. Therefore it is suggested that the Early Cretaceous structuring represented the first of a number of distinct uplift and exhumation events that occurred in the Slyne Basin in the Cretaceous to Neogene time period. (Figs 7, 8). The entire Upper Jurassic section and part of the Middle Jurassic section were eroded, and a gross exhumation of 1625 m occurred at the 27/5-1 location (Corcoran and Mecklenburgh, 2005). Therefore, it is very difficult to reconstruct the detailed geological evolution with confidence. Nonetheless, the nature and age of the patchily preserved strata are

compatible with a phase of compressional deformation and inversion during the latest Jurassic-earliest Cretaceous in the southern and central Slyne Basin.

During the Early Cretaceous (Fig. 10e), with the gradual disappearance of compressional stresses, local extensional stresses were produced at the top of uplifted anticlines, compatible with the model of small-scale lateral density contrasts causing local stress perturbation (Zoback, 1992). The main east-dipping listric fault, which detaches on the Upper Triassic halite layer, and a series of synthetic and antithetic secondary faults developed at the top of the Corrib anticline. A Triassic MMG halite diapir formed at the footwall face of the listric detachment fault. A set of minor normal faults were also formed at the top of anticline at the hanging wall of the eastern boundary fault. Due to the regional uplift of the whole Slyne Basin during the latest Jurassic-earliest Cretaceous, the extensional areas still experienced erosion. However, the compressional deformation and subsequent normal faulting resulted in local differential exhumation. Before the Cretaceous deposition, a sharp Base Cretaceous Unconformity formed and the footwall of the main listric fault experienced more intense erosion than the hanging wall (Corcoran and Mecklenburgh, 2005). Renewed deposition took place in the northern Slyne Basin at the Albian time (Figs 7, 10F), but the normal faults at the top of two anticlines, especially the main listric fault, continued to undergo syn-depositional growth beyond Albian times.

3.2 Porcupine Basin

The succession in the Porcupine Basin was the subject of the first year annual report of this project (Yang and Shannon, 2010). The reader is referred to this report for details. Yang also received approval from ISPSG to submit a sole-author manuscript on aspects of this work, and on his interpretations and conclusions, for publication. Only a summary of the material in the report, together with some subsequent alternative reinterpretations, are provided here for comparative purposes in the regional review.

A regional and topographically variable Base Cretaceous unconformity can be mapped throughout the basin. Evidence for a series of NNE-trending fold structures (synclines and anticlines) and accompanying inversion, most pronounced towards the basin margins, were presented by Yang and Shannon (2010). It was argued that these structural highs and lows in the pre-Cretaceous succession, represented the response to a phase of latest Jurassic to earliest Cretaceous compression or transpression. While the seismic data quality of the available data was not optimum at the critical level in many areas, and some of the fold structures could be alternatively interpreted as the combined response to syn-rift footwall uplift and hangingwall subsidence with sedimentary compactional effects, the magnitude of some of the structures appear to be too great to be solely accounted for by these mechanisms. Some of the structures appear to have a spatial association with major structural features that cross the basin, suggesting a transpressional component on the formation of the structures. It is also tempting to link some of the structures to the development of the interpreted major early Cretaceous igneous features identified in the basin centre (see Naylor et al., 2002). Overall therefore, a number of the structures appear to be most plausibly interpreted as the result of a component of latest Jurassic to earliest Cretaceous compression or transpression.

The irregular topographic nature of the Base Cretaceous unconformity throughout the basin is may be interpreted largely as the result of sediment compactional effects together with later structuring. However, the question of whether the unconformity represents subaerial erosion is worthy of some further discussion. While a hiatus in deposition occurs across the unconformity with earliest Cretaceous sediment missing and later Early Cretaceous strata onlapping the unconformity, no evidence is seen in any of the wells drilled in the basin to confirm subaerial exposure in earliest

Cretaceous times. The earliest Early Cretaceous strata throughout the basin are invariably of marine origin and, although phases of local uplift (probably rift-related) have been documented in the deltaic deposits of Aptian-Albian age in the northern flank regions of the basin, burial history plots for the basin (e.g. Naeth et al., 2005) suggest a period of initial rapid subsidence in the early Cretaceous, with no evidence of major uplift. This may point to the erosional nature of the Base Cretaceous unconformity being the result of pronounced submarine erosion, created in deep water, rather than by subaerial exposure and erosion. In such instances, the early Cretaceous infill of the topographic lows are likely to comprise ponded turbidites with the potential for stratigraphic traps. However, further detailed mapping would be required in order to define the 3D configuration of such bodies, as well as to predict with confidence the nature of the ponded bodies and the likelihood of their containing sandstones (e.g. tracking sediment fairways from eroded sand-prone Jurassic and older highs). Some detailed work of this type is being carried out by Cedric Bulois (ISPSG Project ISO4/04).

3.3 Celtic Sea margin

While the Celtic Sea region is beyond the main focus of project, a brief review of the latest Jurassic – earliest Cretaceous succession and development is included for comparison with the Atlantic margin. It is hoped this will provide some constraints on the nature and causes of the Jurassic-Cretaceous boundary. This is an important region in that it trends at a high angle to the Atlantic margin trend and extends from the eastern edge of the Atlantic margin in the Goban-Fastnet region inboard towards the Irish Sea region.

Throughout the Goban Spur to Celtic Sea region there is consistent variation in the amount of Jurassic strata missing at the Jurassic-Cretaceous boundary, while there is also a marked change in the nature of the earliest Cretaceous succession. In the Goban Spur 62/7-1 well marine sandstones and cherty limestones of possible Neocomian age, containing terrestrial palynomorphs, are overlain by shallow marine Barremian to lower Aptian limestones and claystones. They overlie a marked unconformity with Callovian to Bathonian basalts. Upper Jurassic strata were not encountered in the well and are suggested on seismic data (see Cook, 1987) as being absent except only locally. Naylor et al. (2002) interpreted possible localized deposits of Upper Jurassic strata beneath a pronounced Base Cretaceous unconformity. This suggests a significant period of uplift or non-deposition during late Jurassic times with collapse of the high areas and the onset of marine sedimentation in early Cretaceous times. Further westwards, in the Fastnet Basin a broadly similar pattern is observed of thin to absent Upper Jurassic, overlain by an angular Base Cretaceous unconformity, suggestive of inversion and erosion. Extensive uplift and erosion in the basin is indicated by the Base Cretaceous unconformity. In the deeper part of the basin erosion cuts down to the lower Bajocian, while on the basin margins the erosion extended as deep as the Aalenian or Toarcian. There were a few intra-basinal depocentres where Upper Jurassic strata were preserved (e.g. Ranger 63/8-1 well), suggestive of the irregular fault-controlled nature of the basin. The nature and thickness of the overlying Lower Cretaceous strata point to a pronounced topography, interpreted by Robinson et al. (1981) as the response to basin inversion in latest Jurassic to early Cretaceous times. Thick Cretaceous strata rest upon thin Jurassic strata in places, while elsewhere thin early Cretaceous strata rest on thick Early Jurassic successions. However, in contrast to the successions along the Atlantic margin described above, the Lower Cretaceous succession is non-marine fluvial (Wealden facies) in origin (Robinson et al., 1981). This is clearly indicative of a subaerial setting for much of the pre-Aptian succession in the basin and indeed for the Celtic Sea region.

Further east in the North Celtic Sea Basin, the Base Cretaceous unconformity can be mapped with confidence through much of the basin. However, Upper Jurassic strata are present, especially in the

deeper parts of the basin, although pinching out towards the basin margins where progressively older Jurassic strata are overlapped by Lower Cretaceous sediments. In common with the Fastnet Basin, the Lower Cretaceous strata are of Wealden facies, a pattern that is seen throughout the parallel basins south of England (e.g. the Wessex Basin).

Therefore, while there is a consistency in the regional extent of the Base Cretaceous unconformity (or unconformities – there is a cluster of unconformities in many areas), and in the erosional nature of the unconformity, frequently cutting deep into the earlier Mesozoic succession, there is a marked change in the nature of the earliest Cretaceous succession eastwards away from the Atlantic margin. Towards the Atlantic margin (e.g. in the Goban Spur) the Cretaceous succession is marine in nature while further inboard, in the Fastnet, Celtic Sea and Wessex basins the early Cretaceous strata are typically non-marine. This indicates either differences in the cause of the Base Cretaceous unconformity or in the tectono-sedimentary response to the basin inversion. Rotation of Iberia, immediately prior to the onset of seafloor spreading may have induced a dextral rotational simple shear regime on the Celtic Sea region (see Robinson et al., 1981), causing inversion and erosion while maintaining a structurally high, subaerial position for much of Early Cretaceous time.

4. Late Jurassic – Early Cretaceous tectono-stratigraphic evolution of the conjugate Newfoundland and Iberian margins

The evolution of basins between Newfoundland and Iberia began with a Late Triassic-earliest Jurassic rifting phase, followed by relatively tectonic quiescence during the Early and Middle Jurassic (Masson and Miles, 1986; Tankard and Welsink, 1987) (Figs 1, 11). A second extensional phase occurred generally from Late Jurassic to Early Cretaceous times, followed by post-rift thermal subsidence during the Late Cretaceous and Cenozoic. The basins experienced uplift and erosion during the late Kimmeridgian and late Tithonian, respectively (Hubbard, 1988) (Figs 1, 11).

The thick Bajocian/Bathonian to late Kimmeridgian strata and the sparsely distributed late Kimmeridgian to late Tithonian strata in the Whale Basin may be interpreted to represent moderate/intense rifting and minor rifting, respectively (Balkwill and Legall, 1989) (Fig. 11). A conspicuous Tithonian to early Aptian unconformity separates the structurally-disrupted, salt-pierced Jurassic and Triassic strata from the overlying Cretaceous succession in the Whale Basin (Fig. 12). Sediment eroded from parts of the uplifted Whale Basin was transported southwestwards to the South Whale Basin and redeposited as a prograding clastic wedge (Balkwill and Legall, 1989; Hubbard, 1988).

The Jeanne d' Arc Basin underwent (a) late Callovian-middle Kimmeridgian onset of rifting, (b) late Kimmeridgian-early Valanginian climax of rifting and (c) late Valanginian-early Aptian decrease of rifting (Tankard and Welsink, 1987; Tankard et al., 1989) (Fig. 11). Shannon et al. (1995) showed that the sedimentological response to the initiation of the major phase of rifting in the Tithonian varied between various basins, although some common lithofacies stacking patterns were recognised. Variably thick conglomerates and/or sandstones were widely deposited at the start of rift deformation, although palaeoenvironments varied from alluvial fans, fluvial braid plains and lakes to submarine fans, even within a single basin such as the Jeanne d'Arc Basin. During the late Kimmeridgian to early Tithonian, uplift of the southern portion of the Jeanne d'Arc Basin led to incision of 100-400 m deep into the Kimmeridgian carbonate facies, marking a general change from a carbonate shelf and restricted intrashelf basin setting of the initial onset warp phase of basin development, to an initial non-marine, clastic-dominated facies at the base of

the syn-rift phase. Synchronously the northern part of the basin underwent intense rifting (Hubbard, 1988; Tankard et al., 1989; Sinclair et al., 1994). The Jurassic-Cretaceous contact is slightly unconformable along the edges of fault blocks (Tankard and Welsink, 1987), while Sinclair et al. (1994) suggested that it is otherwise generally conformable and is represented by a gradual migration of delta front sandstones over pro-delta shales.

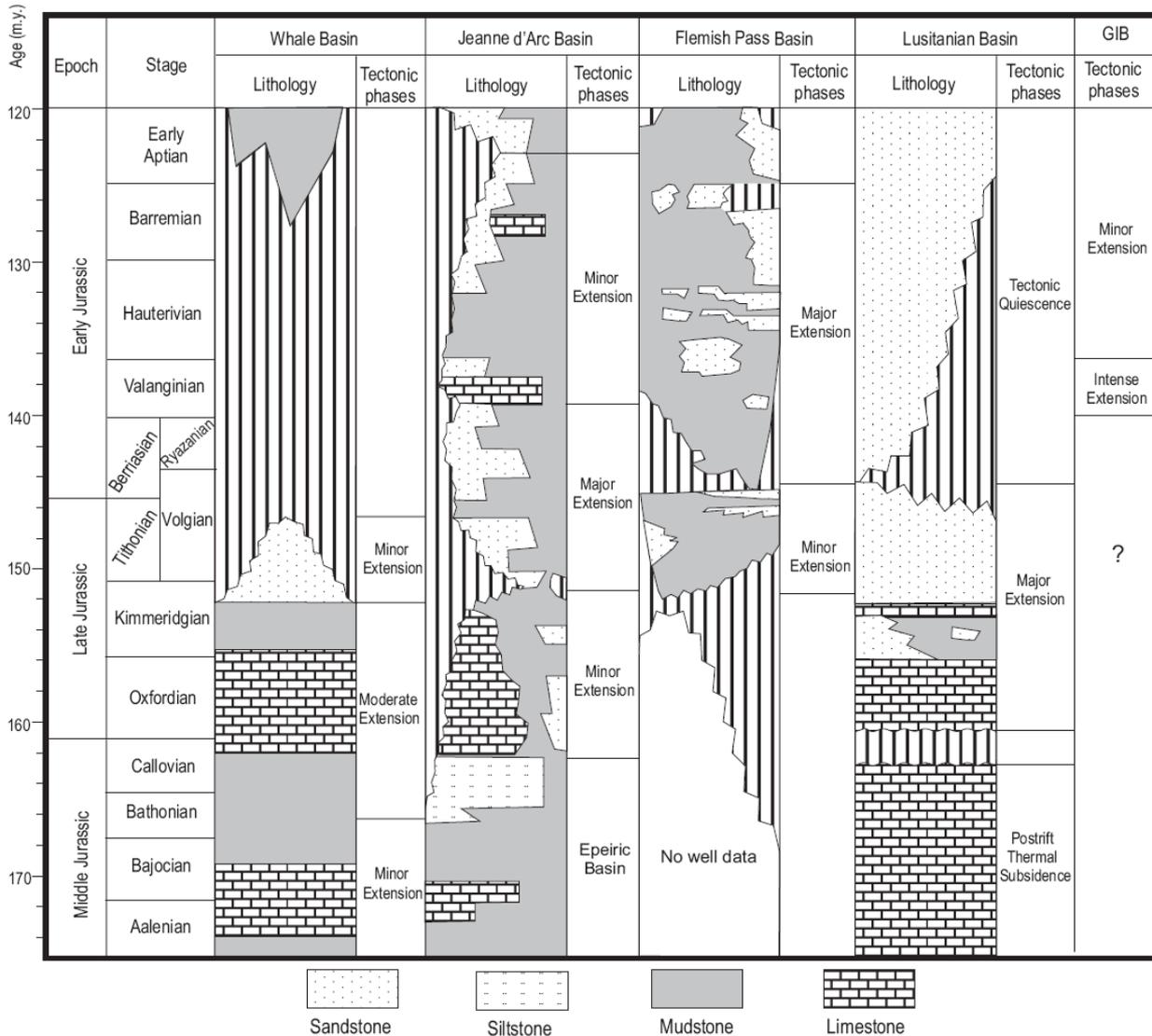


Figure 11. Stratigraphic columns and tectonic phases in basins between Newfoundland and Iberia. The Whale Basin is based on Balkwill and Legall (1989). The Jeanne d'Arc Basin is based on Tankard and Welsink (1987) and Sinclair et al. (1994). The Flemish Pass Basin is based on Foster and Robinson (1993). The Lusitanian Basin is based on Wilson et al. (1989) and Rasmussen et al. (1998). The Great Interior Basin is based on Murillas et al. (1990).

In the Flemish Pass Basin, the Lower Kimmeridgian to Lower Berriasian strata onlap the lower Kimmeridgian unconformity which, however, has not been penetrated by wells (Foster and Robinson, 1993). Major rifting led to regional deepening and deposition of clastic sediments from the early Berriasian to late Barremian. The latest Jurassic-earliest Cretaceous unconformity, with no evidence of major erosion, represents the onset of major faulting and regional deepening in the early Berriasian, demonstrated by deposition of deepwater marine mudstones and locally turbidites

over large parts of the basin, and by widespread onlap onto the basin margins (Foster and Robinson, 1993).

Recently, mainly based on seismic reflection profiles, it was proposed that the East Orphan Basin mainly experienced rifting during Jurassic (and probably Triassic), while the West Orphan Basin contains mostly Late Cretaceous sedimentary fill (Smee et al., 2003; Enachescu, 2006) (Figs 1, 13), draped by an eastward thinning Cenozoic (Tertiary) succession. In the latter basin there is no substantial evidence to indicate the presence of Early Cretaceous or older Mesozoic strata, while the Late Cretaceous succession is significantly thicker than in the East Orphan Basin

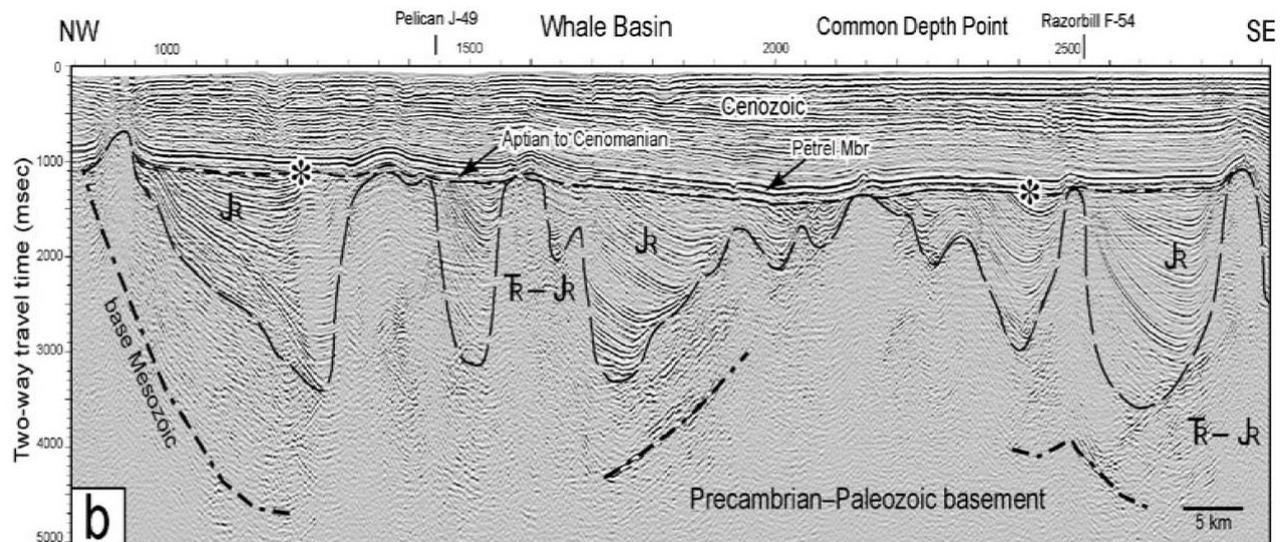


Figure 12. Seismic section in the Whale Basin, from Hiscott et al. (2008). See location in Fig. 1.

Across the Atlantic, on the conjugate European Iberian margin, deposition in the Lusitanian Basin resulting from the rapidly fault-controlled differential subsidence resulted in the dramatic thickness variations of the middle Oxfordian-early Berriasian strata which were succeeded by the deposition of the uniform Lower and Upper Cretaceous succession (Wilson et al., 1989; Rasmussen et al., 1998) (Figs 1, 11). During the Tithonian to Barremian time, a regional angular unconformity developed in the Lusitanian Basin, characterized by tilted half-grabens below the surface and by a marked lithologic change with conglomerates immediately above the surface (Rasmussen et al., 1998; Alves et al., 2002). The Great Interior Basin underwent a principal rifting episode during the Valanginian (Murillas et al., 1990). During earliest Cretaceous time, thermal uplift between Newfoundland and Iberia caused deep truncation of Jurassic rocks in the Whale Basin and Horseshoe Basin, uplift of the Lusitanian Basin, and uplift and eastward tilt of Iberia.

In general, the tectonic history and stratigraphic fill of the basins between Newfoundland and Iberia during the latest Jurassic-earliest Cretaceous show a number of common features (Figs 1, 11). The Whale Basin and Lusitanian Basin experienced regional uplift and erosion during the Tithonian to Barremian, while at the same time, the Jeanne d'Arc Basin, Flemish Pass Basin and Great Interior Basin underwent rifting, producing a conformable or slightly unconformable Jurassic-Cretaceous contact. The Jurassic strata in the Whale Basin and Lusitanian Basin were rotated and tilted associated with salt pillow development during the Late Jurassic-Early Cretaceous (Balkwill and Legall, 1989; Rasmussen et al., 1998; Alves et al., 2002), and no intense inverted structures, such

as tight folds and reverse faults, have been found in these basins (Fig. 12). This suggests that the area between Newfoundland and Iberia was under an extensional environment while at the same time the southern part of the region (Whale Basin and Lusitanian Basin) underwent regional uplift and erosion during extensional tectonics in the Tithonian to Barremian. Ziegler (1989) suggested that thermal doming was the main mechanism controlling the formation of the earliest Cretaceous regional unconformity between Newfoundland and Iberia. Considering the southwards intensification of the uplift, it is tentatively suggested here that the regional unconformity might have been caused by the thermal uplift related to the extension of the Tagus Abyssal Plain during the Late Jurassic-Early Cretaceous before the separation of the Newfoundland and Iberia (Ziegler, 1989; Pinheiro et al., 1992) (Fig. 1).

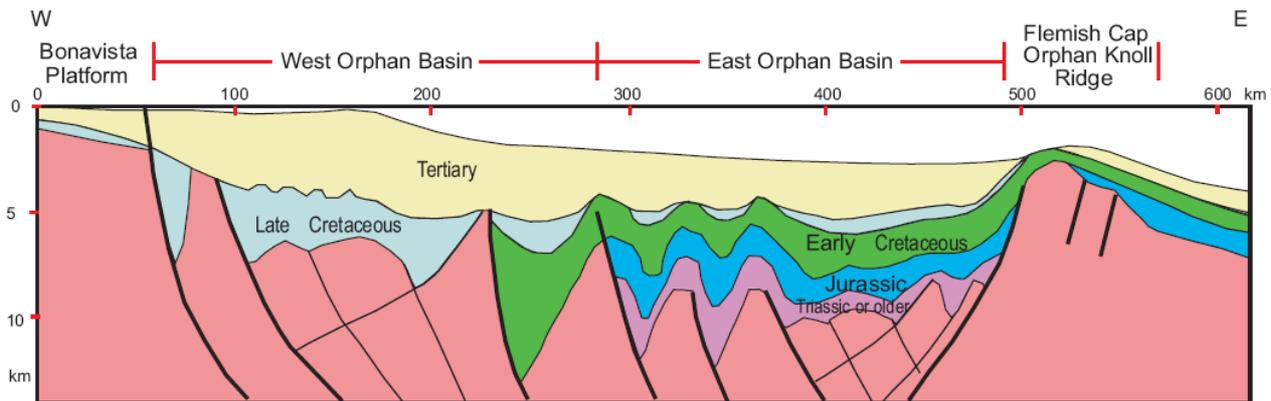


Figure 13. Schematic geological cross-section of the Orphan Basin from the Flemish Cap to the Bonavista platform, from Sibuet et al. (2007).

5. Discussion

The timing of major rifting in the Rockall Basin has been a controversial issue mainly due to lack of borehole data in the region. Palaeogeographic mapping (Ziegler, 1989; Shannon, 1991; Naylor and Shannon, 2005) and plate reconstructions (Srivastava and Verhoef, 1992) suggest that the Rockall Basin is likely to have had a significant early Mesozoic history. Three sedimentary packages have been defined in the Rockall Basin on the basis of wide-angle seismic interpretation. These were tentatively interpreted as an early Tertiary to Recent postrift megasequence, a Cretaceous to early Tertiary postrift megasequence, and a Jurassic and older synrift megasequence (Shannon, et al., 1994; O'Reilly et al., 1995) (Fig. 14). Shannon et al. (1999) suggested that rifting took place in the Rockall Basin in Triassic, Late Jurassic and Early Cretaceous times, and that the Late Jurassic rifting was the most significant event (Fig. 1). However, a single rift phase in the early Cretaceous was also put forward (Joppen and White, 1990; Musgrove and Mitchener, 1996; England and Hobbs, 1997). Lundin and Doré (1997) and Doré et al. (1999) suggested that the Rockall Basin is an Early Cretaceous rift basin and the rotation of the least principal stress direction from E-W in the Late Jurassic to NW-SE in the Early Cretaceous is one of the most fundamental events in the evolution of the northeast Atlantic margin.

The results of the present project, indicating significant uplift along the margin, provide supporting evidence for major Jurassic extension of the Rockall Basin. The results are also used to produce a new, albeit generalised, reconstruction of continental plates during the Late Jurassic, based on the plate reconstruction study of Sibuet et al. (2007), on the basin evolution of the East Orphan Basin (Smee et al., 2003; Enachescu, 2006) and on the comparisons between the conjugate margins.

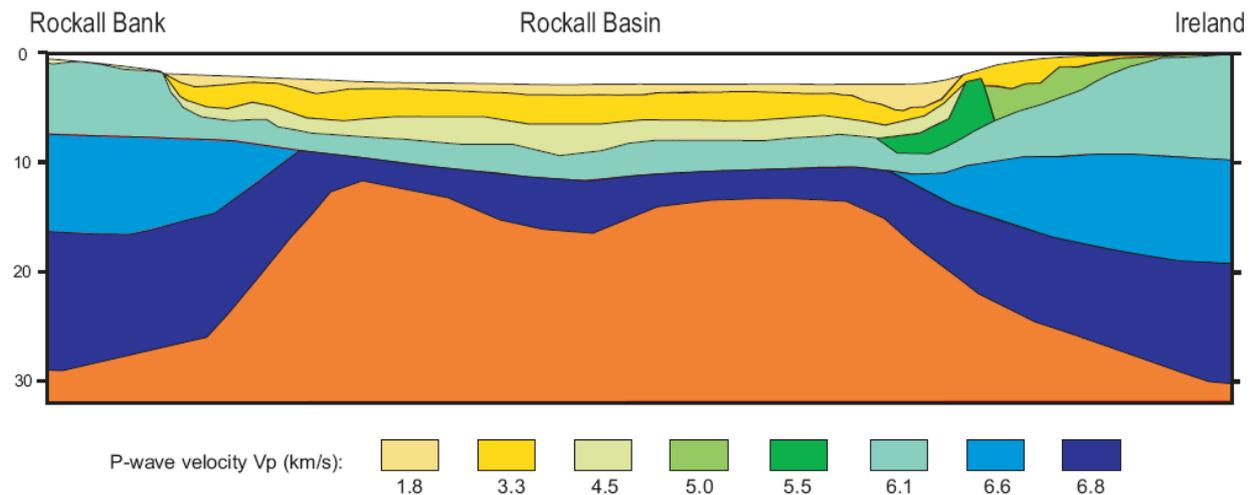


Figure 14. Models derived for the crustal and upper mantle structure across the Rockall Basin (modified from O'Reilly et al., 1996 and Readman et al., 2005).

Sibuet et al. (2007) proposed that between Late Jurassic and Early Aptian (156-118Ma) time, mainly in the Early Cretaceous, Flemish Cap moved 200-300 km SE with respect to North America (Fig. 15). Therefore, during the Late Jurassic, before the migration of the Flemish Cap, the Porcupine Bank, Orphan Knoll and Flemish Cap were located closely each other, and the East Orphan Basin was the southwestward extension of the Rockall Basin (Fig. 16). Due to the relatively thick syn-rift Jurassic sediments in the East Orphan Basin (Smee et al., 2003; Enachescu, 2006) (Fig. 13), it is suggested here that its northeastern counterpart, the Rockall Basin, should also have a thick syn-rift Jurassic sequence, as previously suggested by Shannon et al. (1994) and O'Reilly et al. (1995). We suggest that during the Late Jurassic the Rockall Basin, East Orphan Basin, Flemish Pass Basin, Jeanne d'Arc Basin and Whale Basin formed a southwest-trending rift belt (Fig. 16).

Regional geodynamic changes at the Jurassic-Cretaceous boundary resulted in fundamental regional changes. The distribution and orientation of Jurassic and Cretaceous rifting differed markedly through the European North and Central Atlantic region. As a consequence of the cessation in the Tethys region the north-south Jurassic rift system was transected and overprinted by a set of large NE-SW oriented Early Cretaceous rifts that accumulated very thick, generally marine strata as described by Naylor and Shannon (2011). East-west extension in Late Jurassic time change to NW-SE extension in Early to mid-Cretaceous time in response to major plate movements including the rifting and eventual northward propagation of seafloor spreading in the Labrador Sea between Labrador and Greenland. Some of the older Jurassic structures, orthogonal to the Jurassic extensional direction, were consequently oblique to the Cretaceous regional extension direction, thereby facilitating transpressional uplift and deformation.

During the latest Jurassic-Early Cretaceous, a major transfer zone may have existed the Northeast Atlantic area and the area between Newfoundland and Iberia, with differences experienced in structural evolution and stratigraphic fill (Ziegler, 1989) (Fig. 16) between the two regions. As mentioned Section 4 above, the area between Newfoundland and Iberia was still in an extensional environment during the latest Jurassic-earliest Cretaceous. However, continued crustal extension and rifting in the Rockall Basin resulted in regional uplift and compressional/transpressional folding along the NE Atlantic margin. The crust beneath the Rockall Basin experienced a differential stretching, with the stretching factor β of 8-10 in the upper and middle crustal zones

and 2-3 in the lower crust (Shannon et al., 1994; Hauser et al., 1995; O'Reilly et al., 1995, 1996) (Fig. 14). The more intense extension in the upper and middle crustal zones was balanced through greater lower crustal extension in other parts of the Northwest European plate, such as beneath the Celtic Sea basins (e.g. O'Reilly et al., 1991). The basinal response to this may account for some of the differences in the Lower Cretaceous depositional setting between the areas, and may have also served to focus deformation resulting from Iberian crustal rotation in Late Jurassic to Early Cretaceous time. Regional uplift and folding occurred in basins along the Rockall Basin (Erris, Fursa, Macdara, North Bróna, South Bróna, and Conall basins) (Fig. 2), and basins not very far from the Rockall Basin (Slyne and Porcupine basins). In addition, NW-SE trending transfer zones in the NE Atlantic margin (Kimbell et al., 2005), such as the Anton Dohrn Lineament (Fig. 2), may have acted to balance the extra extension of the upper and middle crust beneath the Rockall Basin, as well as serving to focus transpressional stresses resulting in inversion.

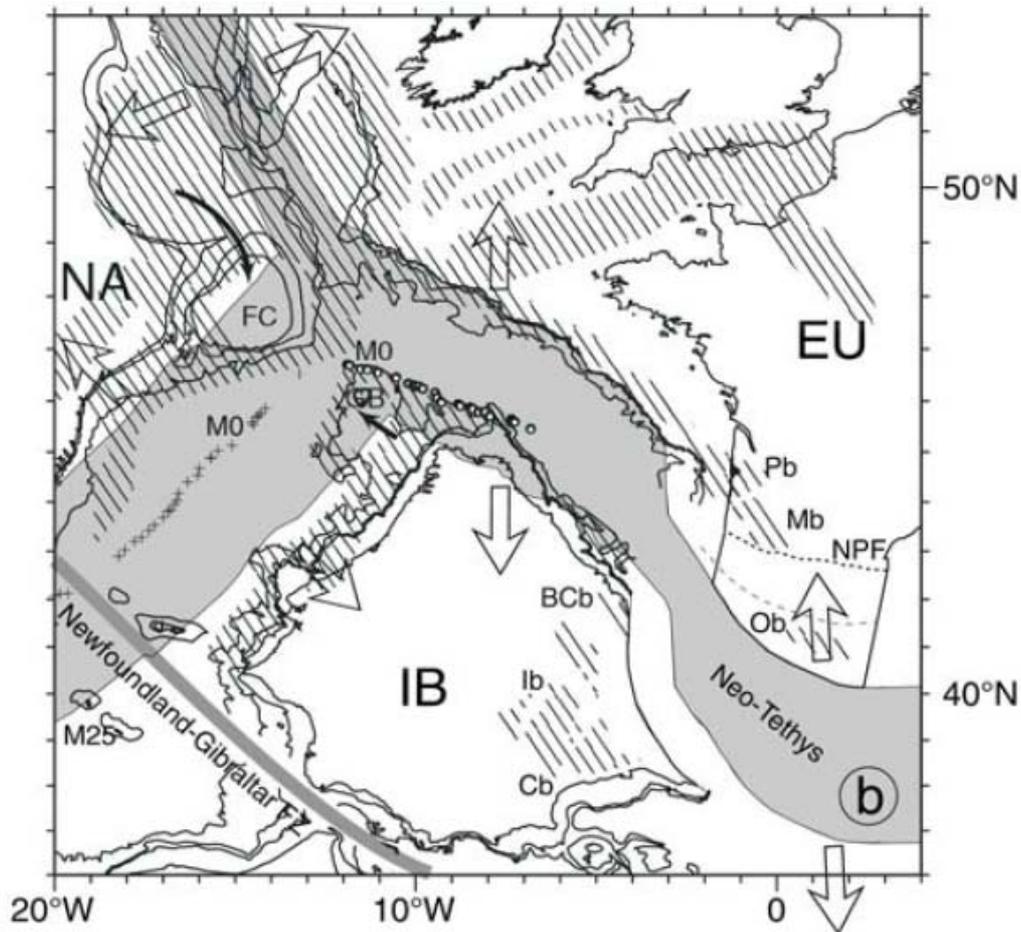


Figure 15. The calculated amount of extension between M25 and M0 (Late Jurassic–Early Aptian) is shown in grey on the M0 reconstruction, using parameters from Srivastava & Verhoef (1992) for chron M25 and from Srivastava et al. (2000) for chron M0 (Sibuet et al., 2007). Hachured lines show continental shelf basins and continental margins where extension occurred during that period. Small black arrows indicate rotation of Galicia Bank and Flemish Cap during this period. BCb, Basque–Cantabrian basins; Cb, Catalan basins; Ib, Iberian Basins; Mb, Mauleon Arzacq basins; NPF, North Pyrenean Fault; Ob, Organya Basin; Pb, Parentis Basin.

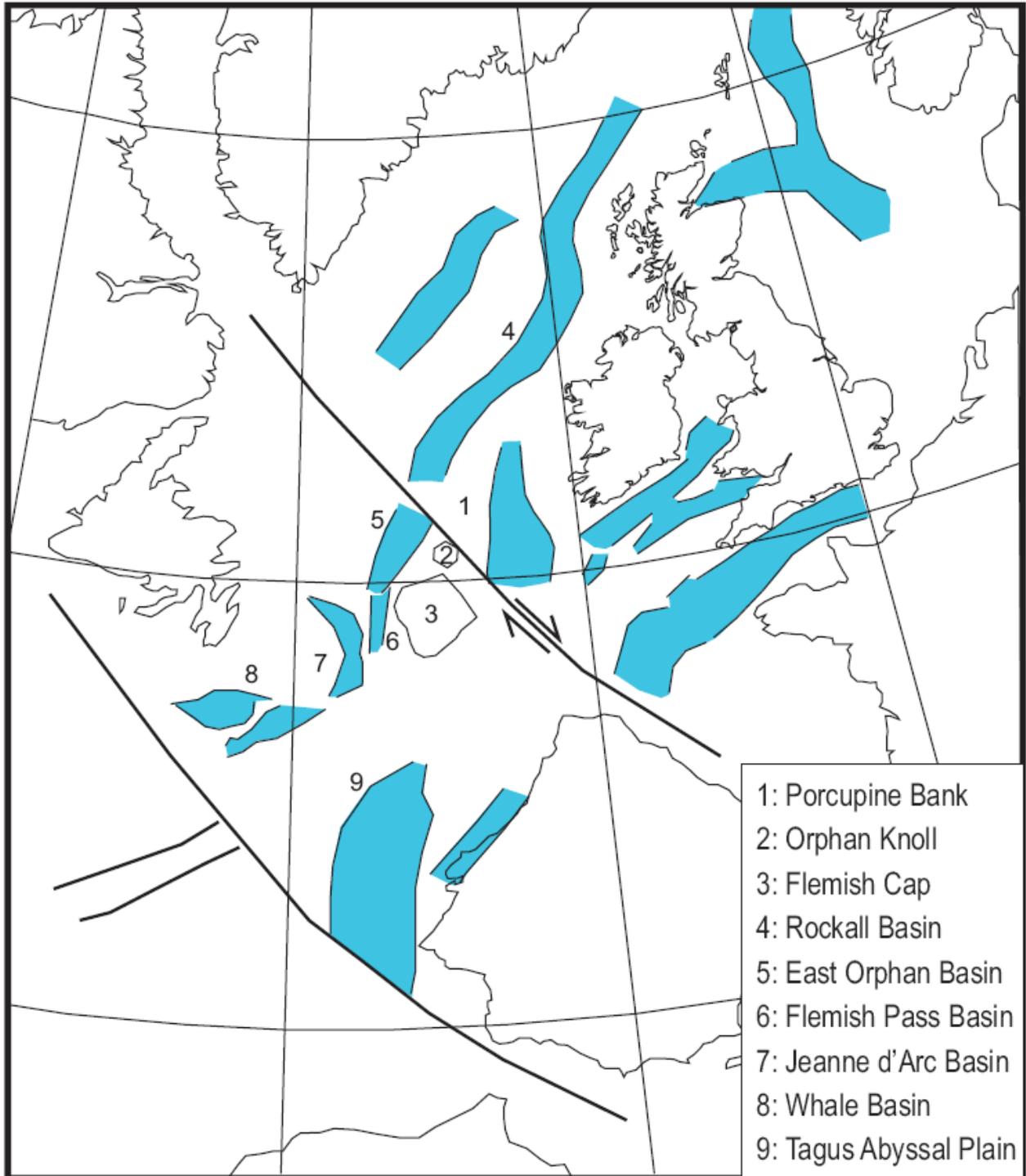


Figure 16. Reconstruction of continental plates, showing the location of North Atlantic borderland rift basins in the Late Jurassic (modified from Sinclair et al., 1994).

6. Conclusions

1. The Base Cretaceous unconformity (sometimes several unconformities) marks an event of regional magnitude, especially throughout the North Atlantic margin basins and the more inboard basins east of the margin. It can be followed along the Rockall Basin margin, as well as the Slyne and Erris basins, together with the Porcupine Basin and the Goban-Celtic Sea margin. It is present, but sometimes less pronounced, in the east Canadian Atlantic margin basins. The uppermost Jurassic to lowermost Cretaceous unconformity generally has an irregular profile, often with considerable relief. However, the shape of the unconformity is likely to reflect the interplay of several effects, including primary topography, compressional/transpressional tectonics, sediment compaction and loading, and later Cretaceous/Cenozoic thermal subsidence.
2. Significant inversion and erosion is documented and interpreted for the Erris, Slyne and other small basins along the Rockall Basin, as well as locally within the Porcupine Basin. Flank uplift, magnified by compressional/transpressional deformation caused by the changing extensional directions between late Jurassic and early Cretaceous times resulted in the formation of a series of anticlinal and synclinal structures trending parallel to the Rockall margins. Their formation was also facilitated by presence of somewhat thinned (and weaker) continental crust in the basinal areas containing Permo-Triassic and Jurassic rift sediments buttressed between the thicker crust of the Erris Ridge, Porcupine High and Irish Mainland Platform. Inversion and erosion is also documented in the Celtic Sea region during the same period of time. However, this appears somewhat different in nature to the Atlantic margin region, and the transition in tectonic styles is seen in the Goban-Fastnet-North Celtic Sea region. This inversion is interpreted as the response to rotation and the onset of seafloor spreading in the Iberian region. In addition, the response to differential crustal extension is likely to have played a role in inversion history.
3. Along the Atlantic margin, the earliest Cretaceous strata encountered in wells are typically of marine origin, with little evidence of subaerial exposure. This is in contrast to the Fastnet and North Celtic Sea region where the early Cretaceous strata above the Base Cretaceous unconformity are typically of fluvial (Wealden) facies. This may point to a submarine origin for the unconformity through much of the Atlantic margin region. The interpreted earliest Cretaceous strata through much of the region has a mounded and onlapping character, suggestive of ponded turbidites. This opens the possibility for the development of stratigraphic and combination traps at Lower Cretaceous level within the Atlantic margin basins.
4. During the Tithonian to Barremian, the basins on the conjugate Newfoundland and Iberia margins were in an extensional setting. In particular, the Whale and Lusitanian basins underwent a regional uplift and erosion possibly due to the thermal uplift related to the crustal extension of the Tagus Abyssal Plain.
5. Based on the interpretation that the Flemish Cap moved 200-300 km SE with respect to North America mainly in the Early Cretaceous, it is suggested the Porcupine Bank, Orphan Knoll and Flemish Cap were located closely each other during the Late Jurassic, and the Rockall Basin, East Orphan Basin, Flemish Pass Basin, Jeanne d'Arc Basin and Whale Basin formed a southwest-trending rift belt.

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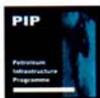
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Appendix 1.

Conference Abstracts

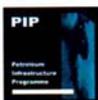


Regional Tectonostratigraphy: the Irish Mesozoic Basins and Their Comparison with Atlantic Canada Counterparts

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The results of a regional review of Late Jurassic to Early Cretaceous basin configurations in the North Atlantic region are presented. These show that the Atlantic Margin basins west of Ireland (Porcupine, Rockall and Slyne-Erris) lay in close proximity to the offshore Newfoundland basins (East Orphan, Flemish Pass and Jeanne d'Arc). In particular, during the Late Jurassic, the Porcupine Bank, Orphan Knoll and Flemish Cap were located closely each other and the East Orphan basin with thick Jurassic succession was the southward extension of the Rockall Basin. Some regional comparisons of Late Jurassic to Early Cretaceous lithofacies illustrate interesting trends. The Base Cretaceous Unconformity is of regional importance in virtually all the Irish basins, as well as many others along both sides of the Atlantic margin. Based on a comparison between the Irish basins, North Sea Rift, and basins between Newfoundland and Iberia, insights are provided on the nature, control and mechanisms of formation of the Late Jurassic to Early Jurassic transition along the North Atlantic margin. This study suggests that during the Jurassic-Cretaceous transitional period, the more intense extension in the upper and middle crust beneath the Rockall Basin was balanced through brittle/ductile transition zones and a series of NW-SE trending transfer zones, resulting in compressional and transpressional folding and uplift along the NE Atlantic margin. In addition, thermal doming appears to have played a major role in the formation of the Cretaceous regional unconformity between Newfoundland and Iberia.



Evolution of the northern Porcupine Basin during the Late Jurassic-Early Cretaceous

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A data base of 15 key wells and approximately 4,000 km of seismic reflection data were examined in the northern Porcupine Basin. During the Late Jurassic (possibly the Oxfordian and Kimmeridgian stages), the basin experienced extension and syn-sedimentation. A series of NNE-trending compressional-driven structural highs and lows developed during the latest Jurassic (Tithonian stage). During the earliest Cretaceous, with exception of synclinal depocentres, extensive areas in the northern Porcupine Basin experienced uplift and became erosional areas. Evidence from the study suggests that compression, uplift and erosion played an important role in the shaping of the depositional and structural architecture of the basin. It is suggested that the differential stretching of the crust beneath the Rockall Basin during the latest Jurassic caused southeast-directed compression and transpression to the northern Porcupine Basin, which modified the original geometry of the Late Jurassic rift basin and gave rise to flexure and folding.