



PORCUPINE STUDIES GROUP

TECTONIC EVOLUTION OF THE PORCUPINE BASIN

PSG Project P00/8

FINAL REPORT

**M.G.NORTON
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EXECUTIVE SUMMARY

In this project, the tectonic development of the Porcupine Basin has been investigated using predominantly 2D seismic reflection data and released well data, although 3D seismic data and potential field data have also been considered.

The precise location and orientation of Caledonian structures within the Porcupine Basin remain uncertain but correlation with Caledonian fault-bounded terranes in Ireland and Newfoundland suggests that a dominant WSW-ENE orientation is likely. The presence of tectonic slices within the basement would be expected to have a major effect on subsequent rift geometries.

The effects of Variscan thrusting and Mesozoic extensional faulting have made it difficult to determine either Carboniferous basin geometries or the tectonic controls responsible for the formation. Southward thickening of the Carboniferous sequence on the northern edge of the Clare Basin on both margins of the Porcupine Basin suggests that the basin was originally elongated WSW-ENE. This is consistent with basin development related to oblique dextral reactivation of Caledonian structures observed in Newfoundland, Ireland and Scotland. Evidence for significant Variscan thrusting has been found in the northwestern part of Quad 45. Up to 45 km of shortening has been estimated.

The presence of a Permo-Triassic sequence is only clear in the North Porcupine Basin. From regional inference and the observed thickness and seismic character of some of the pre-rift sequences beneath the main Mid to Upper Jurassic syn-rift, rocks of this age are thought to be present over most of the rest of the Porcupine Basin. Many of the large basin-bounding faults were probably active at this time.

The main phase of extension occurred during the Mid to Late Jurassic. Earlier rift faults were reactivated and many new ones were formed. The extension accelerated towards the end of the Jurassic, culminating in a final deformation pulse which generated significant rift topography on some of the larger faults and may be responsible for the latest Jurassic to earliest Cretaceous hiatus observed in well data throughout the basin.

Deposition during the earliest part of the Cretaceous was controlled by the inherited rift topography, compaction of the Jurassic syn-rift sequence and post-rift thermal subsidence. The Porcupine Median Volcanic Ridge was initiated during the same period forming one of a set of interpreted extrusive complexes associated with the rift triple junction at the southern end of the Rockall Basin. Relative uplift of both the Porcupine High and Basin at this time was followed by a regional basal Aptian unconformity and a period of subsidence. These observations are explained as a result of the development of a transient plume at the triple junction.

The Late Cretaceous and Palaeocene periods formed a continuation of the post-rift subsidence in the main part of the Porcupine Basin. In the North Porcupine Basin, the southern bounding fault was active during these times with evidence of oblique slip reactivation. There is local evidence of minor inversion during the Late Cretaceous. In the Late Palaeocene, there was another episode of transient uplift accompanied by the intrusion of numerous small hypabyssal intrusions.

Towards the end of the Eocene, many of the main Mid to Late Jurassic rift faults were reactivated, with this minor extensional episode ending during the Oligocene. The Canice and Cillian Basins interpreted to have an exclusively Tertiary fill may have formed at this time.

The history described above is very similar to that interpreted for the Rockall Basin confirming that these two deepwater basins formed in response to the same regional tectonic events, particularly the near constant displacement vector of Canada with respect to NW Europe from the Early Triassic through to the end of the Barremian.

The nature of the deep crustal structure beneath the Porcupine Basin was investigated using estimates of the strain due to upper crustal faulting and modelled lower crustal stretching from potential field modelling carried out as part of PSG project P/004 (Readman and O'Reilly 2002). Estimates from interpreted faulting consistently give lower degrees of stretching than those from other methods. However, a combination of either un-imaged or unresolved faulting and the presence of an earlier (if much smaller) rift phase may be sufficient to reconcile these differences.

Two models have been produced to explain the gravity high associated with the Porcupine Arch. The model that explains this as the result of intrusions into already thinned crust is preferred to the model that uses a single intrusive body replacing the whole thickness of the crust. There are problems with the crustal densities used in the preferred model and further modelling would be necessary to achieve an acceptable result. WARR data recently acquired along this profile should help to resolve these conflicts in interpretation.

Although the dataset available is limited in nature and not fully quantitative, it is consistent with a continuous southward increase in the amount of extension within the Porcupine Basin, in agreement with the earlier work of Tate et al. (1993). This variation of crustal attenuation implies a clockwise rotation of the Porcupine High with respect to Ireland of ca. 10°.

The rift geometry of the Porcupine Basin, which developed during the main Mid to Late Jurassic extensional event, shows a degree of segmentation consistent with that seen in other Mesozoic rift basins. The Lower Cretaceous isochron for the basin has helped to identify several distinct sub-basins of which only three have been named. The observed segmentation appears to be controlled by transfer zones of dominantly WSW-ENE orientation. In most cases, they do not cross the whole basin and are not discrete fault zones. The existence of an earlier (possibly Caledonian) basement fabric is thought to have facilitated along-strike changes in fault location and polarity.

The geometry and origin of the main (named) intrabasinal structures have been reviewed. The North Porcupine Basin is controlled by the fault that bounds the northern side of Finnian's Spur, a possible reactivated Caledonian structure. It has a movement history distinct from the rest of the Porcupine Basin with possible activity in the Carboniferous, Permo-Triassic, Mid to Late Jurassic, Late Cretaceous and Palaeocene.

The Ruadan High and Moling Sub-basin form two closely related structures on the eastern flank of the basin. The Ruadan High varies along its length from a tilted fault block crest to being a collapsed crest of a rollover, depending on the fault throw along

its western margin. The Moling Sub-Basin is the main Late Jurassic to Early Cretaceous depocentre along the eastern margin and has a half-graben geometry. Both of these structures are offset along the position of a major step in the basin-bounding fault zone. There is no evidence of a fault along the position of this apparent offset.

The strong reflector defining the Porcupine Arch is interpreted to be a modified Top Basement event with the underlying crust intruded by igneous material forming a northward continuation of the Porcupine Median Volcanic Ridge (PMVR). The PMVR itself appears to be formed by the coalescence of up to ten separate vents. The degree of compaction over the ridge is very variable but generally supports an interpretation of the Ridge as being mainly volcanoclastic in nature. At its southern end, the PMVR changes in strike from SSE to ESE trending. This coincides with a similar change in the orientation of the Late Jurassic rift faults suggesting that such faults have acted as conduits for the magma.

The Fionn High is a horst-like feature possibly formed as a conjugate divergent overlapping transfer zone between two rift segments of opposing polarity. The fault blocks to the west of the horst indicate a high degree of crustal stretching. A similar degree of attenuation is seen right across the floor of the southern part of the basin.

The uncertainty associated with the existence of the Clare Lineament is highlighted by the range of orientations and locations given for the structure in published papers.

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Some of the results reported here are based on work carried out for Phillips Petroleum and their partners in blocks in the Irish Rockall, Agip and TotalFinaElf. I am grateful for their permission to make use of those results in a wider context. Phillips Petroleum and Marathon also allowed access to the 3D dataset in the area around Block 35/30 and gave permission for reproduction of some examples. Chevron (UK) and their partners allowed me to view their 3D dataset over Blocks 34/19,20 and 35/16 and I would like to thank Lucy Williams for making this possible.

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1. INTRODUCTION

This project was carried out under Contract No. 06.08.2000 with PIPCO RSG Ltd. for the Porcupine Studies Group (PSG) as part of the Petroleum Infrastructure Programme (PIP).

This report describes the tectonic development of the Porcupine Basin which is one of the largest of Ireland's offshore basins (Figure 1.1) with a long history of hydrocarbon exploration. It forms one of a series of major basins (including the Rockall and Faeroe-Shetland Basins) along the Atlantic Margin that have a strong expression in present day bathymetry (Figure 1.2) and are thought to be floored by attenuated continental crust.

The names of geological and bathymetric features in the area of the Porcupine Basin referred to in this report are taken from Naylor et al. (2002) and are shown in Figure 1.3, which is their Enclosure 1.

This report does not intend to be a fully comprehensive review of the existing published data and interpretations on the Porcupine Basin. Most of the interpretation reported here was carried out for this project independently of previous interpretations, whether published or unpublished. Reference in the text has generally been made only to the most recent publications particularly where they review earlier work.

1.1 Aims

Before the contract was awarded, a list of questions was agreed with members of the PSG as a basis for the scope of the P00/8 project. These are included as Appendix 1. Although all of the questions posed have been addressed to at least a limited extent, effort was concentrated on the following aims:

- To consider the effects of Caledonian and Variscan structures on the development of the Mesozoic rift

- To identify the main rift ages and to look at the variation in extension directions and fault block polarity with time
- To provide a model for the Early Cretaceous development of the Porcupine Basin and surrounding areas – extension, magmatism or uplift?
- To identify the extent and origin of Late Cretaceous to Tertiary extension and inversion
- To compare the tectonic development of the Porcupine Basin with the Rockall Basin
- To incorporate the results of other PSG projects, particularly P00/1 Structural Nomenclature, P00/4 Potential Field Modelling and P00/3 Deep Seismice

The tectonic development of the Porcupine Basin is presented in Section 2. Evidence relating to the deeper structure of the crust underlying the basin is considered in Section 3. Aspects of the overall basin geometry and the development of individual structural elements are discussed in Section 4.

1.2 Methods

1.2.1 Fault Interpretation

A first pass fault interpretation was carried out on all the available 2D seismic data. At this stage, the faults were uncorrelated. A preliminary Top Pre-Rift event was then interpreted and the faults were reviewed and correlated wherever possible. In order to be correlated faults had to have significant displacements and to be interpreted clearly on several seismic lines.

The correlated faults were viewed using the perspective view in Seisworks to look for evidence of further segmentation of the faults. These displays were also used to provide a map of the faults at the base of the Cretaceous interval.

1.2.2 Creation of Depth Sections

The time horizons for each profile were converted to depth using a mixture of constant velocity and midpoint depth relationships. This methodology is described in detail in Appendix 2. The resultant depth horizons were redisplayed in Landmark to check for any problems due to missing horizons. They were then exported to GEOSEC a 2D section restoration package. The raw depth horizons were filtered and modified to make them into a complete depth section. Where the geometry of the depth horizons appeared inconsistent, the original time interpretation was checked. In some cases, modifications were made in depth and converted back to time using approximate interval velocities in GEOSEC to allow direct comparison with the original data. Faults were added by joining the hanging wall and footwall cut-offs of the various horizons. Uncertainties in linkage were resolved by comparison with the original time interpretation.

1.3 Database

1.3.1 Seismic Data

Figure 1.4 shows the 2D seismic dataset used in this study. This represents most of the data held by Phillips Petroleum and was close to being a dataset common to all the companies in the PSG, according to checks carried out before the start of the project. Much of the data are either released speculative data or proprietary data. Most of the other lines, particularly the SPB97 lines used in this and P00/1, were approved for use as part of this study.

1.3.2 Potential Field Data

Use was made of the maps of gravity and magnetic data provided in the report by PGW Europe Ltd (2001). The results of potential field modelling along 2D profiles by ARK (2001) and Readman and O'Reilly (2002) were also reviewed as part of this study.

Readman and O'Reilly (2002) was not available in its final version when this report was finalised. The figures from this report were available in draft form only at the time of writing; any views expressed here regarding these results must be regarded as provisional and the authors' final report should be referred to.

1.3.3 Well Data

Phillips Petroleum provided access to all released wells and limited information from the pre-Cretaceous part of the 35/30-1 well. Information was generally taken from the original composite logs although some horizon tops used were based on later revisions by Phillips Petroleum.

2. TECTONIC HISTORY

This section describes the tectonic history of the Porcupine Basin within its regional context, particularly in comparison with the Irish Rockall Basin with which it has many similarities. Both basins currently have clear bathymetric expressions (Figure 1.2) compared to others, such as the Slyne and Celtic Sea Basins, which have none. The scale of post-rift subsidence that the current water depths represent in both cases is a result of major crustal attenuation during Mesozoic rifting. The deep crustal structure of the Rockall Basin is better understood than that of the Porcupine Basin due to the large number of WARR (wide-angle reflection and refraction) profiles recorded across it (e.g. Shannon et al. 1995). This has enabled the likely deep structure of the Porcupine Basin to be predicted to some extent (see Section 3).

2.1 Caledonian Framework

Figure 2.1 shows the main Caledonian tectonic elements thought to underlie the Porcupine Basin. The Caledonides of Ireland, Scotland and northern England consist of a set of elongate crustal blocks bounded by long-lived fault zones. The location and orientation of these structures becomes increasingly uncertain as they are extrapolated to the southwest, although the presence of similar tectonically-bounded slices in Newfoundland which lies to the southwest of Ireland on a pre-rift configuration (Figure 2.2) support the continuation of a similar structural style. Most of the tectonic boundaries shown are likely to be non-vertical. The faults interpreted as strands of the Great Glen Fault are, however, expected to be near vertical.

The Iapetus Suture may mark a major change in crustal composition, which may in part be responsible for changes in the rift geometry between the northern and southern parts of the basin. It is also possible that tectonically-bound slices of higher than average density, e.g. ophiolites, might be present within the crust causing anomalous gravity responses.

2.2 Carboniferous Basin Development

By comparison with the Carboniferous basins of Newfoundland, Ireland and Scotland, it is expected that the Carboniferous basins within the area of the Porcupine Basin were originally elongated NE-SW and were associated with dextral transtensional reactivation of major Caledonian structures (Coward 1993).

Due to the amount of Mesozoic extension and the dearth of seismic data over the Porcupine High and Irish Mainland Platform, there is little information on which to test this hypothesis. The interpretation of the Clare Basin published by Croker (1995) based on gravity data and a few seismic lines is consistent with the proposed geometry. Figure 2.3 shows the seismic character of the Carboniferous sequence on the western side of the Porcupine Basin.

Carboniferous rocks may well be present beneath the basins along the margin of the Irish Rockall but there is no direct evidence to support this.

2.3 Variscan Orogeny

The southern part of the Irish Mainland shows the effects of a major phase of Late Carboniferous contraction associated with the Variscan Orogeny. A number of locations have been published for the 'Variscan Front' south of Ireland, representing the limit of large scale thrusting. Significant deformation, however, is seen to the north of the even the most northerly of these (Cooper et al. 1986, Ford et al. 1992).

Possible Variscan age thrust structures have been identified on seismic lines from Blocks 36/26 and 45/1 in this study. Figure 2.4 shows a 2D seismic line on which there appear to be repetitions of interpreted Westphalian coals due to northward directed thrusts. If the interpretation is correct, there is a minimum 43 km of shortening shown on this section according to a preliminary restoration. Figure 2.5 is a map of interpreted axes of fault bend and fault propagation anticlines from both 2D and 3D datasets. The orientations of the axes are consistent with the expected direction of shortening.

There are no data available on the Porcupine High that would help to constrain any possible continuation of this zone on the western flank of the basin. The zone would be expected to pass to the south of the Irish Rockall.

2.4 Permo-Triassic Extension

Significant thicknesses of Permo-Triassic rocks have only been proven in the North Porcupine Basin; by the 26/21-1 and 26/22-1A wells. This could be regarded as a continuation of the Slyne Basin, which itself contains a thick Permo-Triassic fill. In the area to the south of the North Porcupine Basin, a series of wells show Middle Jurassic unconformably overlying Carboniferous. Although this might in part be due to later erosion on relative highs, it is thought that this was an area of non-deposition during the Permian to Early Jurassic. This is interpreted to result from footwall uplift of Finnian's Spur as a result of extensional movement on its northern flank.

Further to the south the pre-Upper Jurassic sequence thickens and it is presumed that part of this thickening is caused by the reappearance of a Permian to Lower Jurassic interval (Figure 2.6, 2.7). The 34/15-1 and 34/19-1 wells encountered upper Middle to Upper Jurassic in contact with Lower Permian. In both cases, from the seismic data, this contact appears to be faulted (Figures 2.8, 2.9) allowing for some thickness of Triassic to Lower Jurassic. The 35/19-1 well, which found salt apparently interleaved with Late Jurassic mudstones, probably indicates the presence of Upper Triassic to Lower Jurassic evaporites although the exact circumstances are not clear. The 35/15-1 and 36/16-1 wells were both drilled into the footwall of the main basin bounding fault and encountered Carboniferous below Cretaceous. Other wells penetrated no deeper than the upper part of the Middle Jurassic and provide no extra constraint on the presence of rocks of Permo-Triassic age.

As with other areas affected by significant Late Jurassic extension it is difficult to directly demonstrate Permo-Triassic age extensional faulting. Generally there is little evidence of strong divergence of reflectors. However, the fault along the northern margin of Finnian's Spur shows strong evidence of activity, and most of the main basin-bounding faults introduce considerable thicknesses of interpreted Permo-Triassic not present on the surrounding platform areas.

In the Irish Rockall Basin thick sequences are present which predate the Late Jurassic syn-rift package (Figure 2.10). In the Pádraig and Macdara basins (see Figure 1.3 for location) the fault geometry is consistent with the presence of salt within the pre-rift sequence (Figures 2.11 - 2.13). The Conall Basin on the western margin of the Rockall contains a sequence that is consistent with presence of relatively thick Permo-Trias (Figure 2.14) from the seismic velocities deduced from the RAPIDS 33 profile (Mackenzie et al. 2001).

Lower Jurassic sediments are only known from the North Porcupine Basin but their presence is implied wherever there is a thick pre-rift sequence as above. There is no evidence of active rifting during this period and the sequence is generally regarded as post-rift in type.

Figure 2.15 shows the interpreted geometry of the Triassic basins after restoration of Jurassic extension using the beta factors shown in Figure 1.1.

2.5 Middle/Late Jurassic Extension

The main period of rifting in the Porcupine Basin was initiated during the Middle Jurassic and continued until the end of the Late Jurassic (as originally proposed by Croker and Shannon 1987). In some parts of the basin, sequences of this age appear to form a continuous syn-rift package. Elsewhere, there appear to be changes in geometry during this period but there is no consistency that suggests the rifting took place in distinct episodes.

From the age of the preserved sequence, the onset of rifting occurred in the Bajocian. No evidence has been found in this study to support the hypothesis of an 'onset warp' phase of sag without active faulting (Williams et al. 1999). Figure 2.16 shows a seismic line through the 43/13-1 well that indicates active extension on the controlling faults throughout the history of this particular sub-basin. In some areas there is evidence of changes in fault location and polarity, which mean that the Middle Jurassic locally has a pre-rift type geometry compared to the Upper Jurassic. In other

parts of the basin such changes occur between different parts of the Upper Jurassic sequence.

Figure 2.17 shows a line from the 3D dataset over Block 35/30. A combination of excellent data quality and an eight second record length allow an unusually clear view of the structure. Near the base of the section there is a major unconformity showing clear truncation. The underlying sequence can be traced up-dip through a major relay ramp (Figure 2.18) and tied approximately to the 36/16-1 well which indicates this to be Carboniferous. The deep unconformity is therefore interpreted as post –Variscan with a Permian to Lower Jurassic sequence lying above it. The overlying syn-rift package is confirmed as Middle to Upper Jurassic by the 35/30-1 well.

Figure 2.19 shows the Mid to Late Jurassic rift faults superimposed on the Triassic basin geometry. The later rift is located almost entirely within the earlier rift indicating a history of progressive localisation of strain within the crust with time.

2.6 Early Cretaceous Post-rift, Volcanism and Uplift

In the Porcupine Basin the Lower Cretaceous has an early post-rift geometry (Figure 2.20). There is no evidence of active faulting at this time and most faults terminate at the base of the Cretaceous. Those that extend to shallower levels generally have Late Eocene movement on them. A few of the major faults do show significant displacement at the base of the Cretaceous but this is likely to represent the effects of the final phase of Late Jurassic rifting which generated accommodation space too quickly to be completely filled by syn-rift sediments. This is a common feature of large extensional faults throughout the Central Graben, Fisher Bank Basin, Witch Ground Graben and Viking Graben.

The Porcupine Median Volcanic Ridge (PMVR) was clearly active through the early part of this period and may have continued to be active as late as the Aptian. The interpretation of this structure as volcanic in origin was originally proposed by Tate and Dobson (1988) and linked to the occurrence of volcanic material within Lower Cretaceous sediments from Hauterivian to Aptian in age in the 35/8-1 and (more

contentiously) in the 26/21-1 and 35/13-1 wells. Section 4.6 considers the geometry and origin of the ridge in detail.

In the southern part of the Irish Rockall Basin the Barra Volcanic Ridge System has been interpreted to be of Early Cretaceous age (Scrutton and Bentley 1988). A further ridge has also been identified in the Rockall Basin, just to the west of the South Bróna Basin (Norton 2000). Figure 2.21 shows a seismic line through this feature, which is characterised by a fan of strong reflectors thinning away from a high, very reminiscent of the PMVR (Figure 2.22). The age of the seismic reflectors is more uncertain than in the Porcupine, but a similar age is consistent with the information available. These suspected volcanics match in age with the drilled volcanics of the Labrador Shelf (DeSilva 1999).

Apart from the PMVR the most important feature within the Lower Cretaceous of the Porcupine Basin is the Base Aptian unconformity. This highly irregular erosion surface cuts down through previously deposited Lower Cretaceous sediments and locally into the underlying Jurassic (Figure 2.23). In some cases up to 500 ms (> 1 km) of erosional topography is developed, strongly indicating that this is a submarine erosional surface within the basinal area. There is also a regional unconformity associated with the base of the Cretaceous sequence with the uppermost part of the Volgian and the lower part of the Ryazanian missing in all wells drilled in the Porcupine Basin.

On the eastern margin of the Irish Rockall Basin recent drilling as part of the RSG (PIP Conference 2001) has shown that there is a major unconformity between a thin Aptian to Upper Cretaceous sequence and an eroded Upper Jurassic syn-rift fill (Figure 2.24). There is some uncertainty as to the age of the oldest sediments above the unconformity but a similar age to the unconformity on the other side of the Porcupine High seems reasonable. The unconformity on the Porcupine High is planar and is interpreted to be sub-aerial in type.

Two major unconformities have been recognised in the area of the Wessex Basin, the Western Approaches and Cornubian Platform (McMahon and Turner 1998). These lie at the base of the upper Ryazanian and the Apto-Albian respectively matching exactly

in age with those seen in the Porcupine Basin. McMahon and Turner (1998) interpret the earlier erosional event to be the larger and propose a thermal uplift mechanism.

From the combined evidence of uplift and volcanism during the early part of the Lower Cretaceous in the Porcupine Basin and surrounding areas it is proposed that a transient mantle plume was developed, centred at the southern end of the Rockall Basin (Figure 2.25). The location of the proposed plume would have been controlled by the rift triple junction. The size of the area of uplift is similar to that proposed for the Early Jurassic dome in the northern North Sea (Underhill and Partington, 1993).

Jones et al. (2001) found evidence for 200 – 700 m of uplift in the Porcupine Basin during the Early Cretaceous followed by up to 500 m of subsidence. They suggest that this cycle may be caused by anomalously hot mantle.

The shape of the basal Apto-Albian unconformity indicates that a bathymetry was developed similar to that at present, with deep water to the southwest. This suggests that the newly formed oceanic crust had already reached abyssal depths.

2.7 Late Cretaceous Extension and Inversion

Most of the faulting which affects the Chalk Group in the Porcupine Basin is of Late Eocene age (Section 2.9). In the North Porcupine Basin, however, there was active extensional faulting during Late Cretaceous deposition. Figure 2.26 is a depth profile across the North Porcupine Basin passing through the 26/27-1b and 26/22-1a wells. The northern bounding fault to Finnian's Spur (Figure 1.3) was active, shown both by the thick Chalk Group in the hanging wall and the complete lack of Upper Cretaceous on the footwall. For further discussion see Section 4.2.

Late Cretaceous extensional faulting is interpreted from the northern UK Rockall and has been described from the seismic line GSR96-116 across the northern Irish Rockall (Norton, 2000).

An Upper Cretaceous Isochron (Figure 2.27) picks out the thickening in the North Porcupine Basin and the related thinning over Finnian's Spur. The most significant depocentre within the main part of the Porcupine Basin at this time lies along the basin axis in Quad 35. It is not clear why this interval does not continue to thicken to the south in keeping with the increase in Lower Cretaceous in the same direction. This would be expected if the main control on depositional thickness was accommodation space created by a combination of thermal sag and compaction. Re-examination of the Base Chalk pick suggests that it could be deeper in the southern part of the basin. This possibility cannot be ruled out but it is unlikely that this would produce a comparable pattern to that shown by the Lower Cretaceous.

There is locally evidence of minor inversion during Late Cretaceous deposition within the main part of the Porcupine Basin (Figure 2.28). This appears to be part of the reason that the depocentre described above does not extend farther south.

2.8 Palaeocene Magmatism, Uplift, Inversion and Extension

Much of the Porcupine Basin is affected by sporadically developed hypabyssal igneous intrusions of presumed Late Palaeocene age. They are rarely so numerous or so large that they affect seismic imaging in the manner that they do in most of the Rockall Basin, although they are responsible for making interpretation beneath the base of the Chalk Group difficult in northeastern Quad 35. In some cases intrusions near the palaeo-land surface formed as laccoliths (e.g. Figure 4.6)

Interpretation of the well data suggests a general reduction in water depth towards the end of the Palaeocene in the Porcupine Basin. Late Palaeocene to Early Eocene uplift of hundreds of metres has been described from a large area including the whole of the Rockall and Porcupine Basins. This uplift is thought to be caused by the thermal effects of the Iceland plume (White and Lovell 1997, Jones et al. 2001).

The northern part of the Irish Rockall Basin was affected by Late Palaeocene to Early Eocene inversion (Figure 2.29). This is interpreted to result from enhanced ridge push forces developed immediately after break-up along the elevated spreading centre between Greenland and Hatton-Rockall.

In the North Porcupine Basin there is local evidence of thickening of the Palaeocene across the fault that bounds the north side of Finnian's Spur (Figure 2.30).

Figure 2.31 summarises the regional tectonic affects caused by the Iceland hotspot and the breakthrough of the North Atlantic northwest of the Hatton and Edoras Banks.

2.9 Late Eocene Extension

Many of the faults that define the edges of the Middle/Late Jurassic rift were reactivated during the Late Eocene to earliest Oligocene. Figure 2.32 shows an example from the controlling fault to the Moling Sub-basin. It is inferred that in the initial stage of reactivation a new fault developed above the top of the Chalk Group, displaced into the footwall of the older fault. The new fault segment then appears to have linked through to the existing fault along the base of the Chalk. Continued movement on this fault gave rise to the observed crestal collapse graben. The high dip angle of the new extensional fault segments led to the suspicion that their reactivation had a significant strike-slip element. By using the extra control available from the 3D dataset, it is possible to show that all of the fault elements within the Tertiary strike parallel to the underlying fault, rather than forming the en-echelon arrays that would be expected for oblique slip.

No faulting of this age has been described from the Rockall Basin. Several basins on the Porcupine High (the Cillian, Canice and Bríd Basins) contain fault-bounded Tertiary. Both the age of the sequences and that of the faulting are poorly known but may be related to the Late Eocene faults described above. Badley (2002) describes Late Tertiary movement on faults in Connemara and South Mayo which may be related to the faulting observed in the Porcupine Basin.

West-east extension in the Porcupine Basin during the Late Eocene does not have an obvious cause in terms of regional tectonics, although it might be related to the near north-south compression apparently responsible for the inversion of the Foinaven Sub-basin, at the southern end of the Faeroe-Shetland Basin, and the Wyville-Thomson Ridge (Boldreel and Andersen 1993). The possibility that the observed

faulting is a result of compaction over the edge of the Moling Sub-basin is discounted as the activity on these faults is restricted to a short time-range. If compaction was responsible it would be expected that the faulting would be active throughout the Late Cretaceous and Tertiary, dying out upwards gradually rather than abruptly.

2.10 Post Eocene Development

In the Oligocene the basin was affected by a phase of erosion similar in both scale and type to that which occurred at the beginning of the Aptian (Figure 2.23). The Eocene sequence records a change from deltaic to marginal marine in the Lower Eocene to open marine at the top. Some large scale base level change is implied, possibly caused by accelerating subsidence following collapse of the uplift due to the Iceland plume. This process may also be the cause of the onset of deep water circulation in the Rockall Basin, somewhat earlier, towards the end of the Eocene (Stoker et al. 2001).

Figure 2.33 presents a comparison of the topography of the current seabed with the unconformities at the base of the Oligocene and the Aptian. They all show a similar pattern suggesting that at each period the basin had the shape of an embayment with sediment transport from the Celtic Shelf down to the Porcupine Abyssal Plain.

2.11 Comparison between the tectonic development of the Porcupine and Irish Rockall basins

Figure 2.34 is a comparison between the tectonic development of the Porcupine and Irish Rockall Basins. The histories of the two areas are very similar with only minor differences during the Tertiary (see McDonnell and Shannon, 2001 for a more detailed comparison of the Tertiary stratigraphic evolution of the two basins). This is in contrast to the views of several workers who recognised a westward migration of the active extensional basins with time (e.g. Doré et al. 1999).

The geometry of the basin-controlling faults in both the Porcupine and Irish Rockall Basins are consistent with the almost constant WNW movement of northeastern Canada with respect to northwest Europe (Knott et al. 1993, Figure 2.35) from the Early Triassic through to the end of the Barremian.

The development of the Rockall Basin according to Knott et al. (1993) was quite different to that presented here, due to their assumption that the Rockall-Hatton crustal block was attached to Greenland until the end of the Palaeocene. Their model predicted over 200 km of highly oblique displacement along the axis of the Rockall Basin during the Jurassic to Early Cretaceous with orthogonal opening confined to the Aptian-Santonian period.

Evidence for Mesozoic rifting has been found offshore southeast Greenland (Larsen et al. 1999) and on the Hatton Bank (Ken Hitchen, personal communication) and the assumption that Rockall-Hatton formed part of the Greenland plate is no longer considered valid.

3. DEEP CRUSTAL STRUCTURE

This section considers the structure of the crust underlying the Porcupine Basin. Information from recent relatively deep seismic surveys (e.g. the SPB97 survey – processed to 9 seconds two-way time) on the geometry of post, syn and pre-rift sedimentary packages and related faulting has been compared with the results of deep seismic reflection / WARR data and the modelling of potential field data.

Results of modelling along the various transects are considered from north to south.

3.1 Forms of data and types of modelling used

3.1.1 Deep seismic reflection and WARR data

It was hoped that new WARR data, commissioned by the PSG, would be available, at least in early processed form before the end of the present study. For various logistical reasons the data were not acquired last summer (2001). The data were acquired this year and it is hoped that they will eventually help to reduce the uncertainties on the nature and degree of crustal stretching beneath the Porcupine Basin.

The existing deep seismic and WARR data were reviewed as part of Project P00/3a (Dardis et al. 2000) and it was felt that little useful information could be derived, in addition to that already published, even if the data were to be reprocessed. The AMP –N and –L profiles were an exception but these data were acquired for an industry consortium and remain confidential.

An interpretation of the COOLE dataset was published by Makris et al. (1988). Crustal thicknesses are interpreted to decrease from 23 km in the east (inclusive of sediment) to 10 km at the continent-ocean boundary across the mouth of the Seabight where it runs into the Porcupine Abyssal Plain. These values are similar to those obtained along the RAPIDS profile along the axis of the southern part of the Irish Rockall Basin (Shannon et al. 1995) and are therefore consistent with a crustal stretching of $\beta \approx 5$.

3.1.2 Potential Field Data

2D gravity and magnetic modelling have been carried out on profiles across the Porcupine Basin as part of the P00/4 project. Readman and O'Reilly (2002) have produced gravity models along three transects, seismic lines PW93-304, SPB97-103 and PSB97-35A. ARK (2001) generated both gravity and magnetic models along SPB97-103.

3.1.3 Structural Modelling

The degree of upper crustal faulting was examined along three west-east profiles across the Porcupine Basin using structural restoration techniques as part of this study. The profiles modelled were PW93-304, SPB97-103 and SPB97-113 (see Figure 3.1 for locations).

3.2 **PW93-304**

Figure 3.1 shows this seismic line with an interpretation carried out for this project. The free-air gravity model along this profile is shown in Figure 3.2. Readman and O'Reilly (2002) interpret a dipping high density body within the upper part of the crust in the centre of the basin. Their model gives a stretch factor of $\beta \approx 2$ taken from the total crustal thickness. The high density body might either represent intrusion of basic igneous material as suggested for SPB97-103 or a tectonic slice of higher density material which originally formed part of the crust prior to rifting (see also Section 2.1).

Figure 3.3 is the depth section taken from the interpretation shown in Figure 3.1. On the eastern flank of the basin, a Carboniferous sequence is shown, based on the 36/16-1 well. Elsewhere in the basin the pre-rift is shown as undifferentiated but may contain a significant Carboniferous section. The base of the pre-rift represents the deepest sub-parallel reflector that can reasonably be considered as real. Variability in data quality has, therefore, led to inconsistencies between the Top Basement pick in adjacent fault blocks.

From a line-length restoration at the level of Top Pre-Rift (i.e. base of Middle-Upper Jurassic) at total stretch of $\beta = 1.46$ has been estimated. The total extension is calculated as 26.7 km.

Assuming that the discrepancy between the stretch estimated from the gravity model and that for the imaged faulting is due to an earlier rift, this would imply a stretch of $\beta = 1.37$ for the Permian to Early Jurassic rifting. This is thought to be a considerable overestimate and at least some of the ‘missing’ extension is likely to be due to a combination of poor imaging and sub seismic resolution faulting.

3.3 SPB97-103

This seismic line (Figure 3.4, showing the interpretation carried out for this study) was modelled by both ARK Geophysics (ARK 2001) and DIAS (Readman and O’Reilly 2002). Figures 3.5 - 3.7 show the final models. There are major differences between the two models, which reflect the non-unique nature of the technique. Readman and O’Reilly (2002) have chosen to model the anomalous body which gives rise to the gravity high as a discrete body replacing the whole thickness of the continental crust. This is similar to an interpretation of the central part of the section as a basic intrusion (essentially the same as oceanic crust) or possibly serpentinitised peridotite. ARK (2001) have instead modelled the gravity high by introducing bodies of higher density crust (equivalent to ordinary crust intruded by basic igneous material) coupled with some lateral variations in crustal density.

If the body proposed by Readman and O’Reilly (2002) is an igneous intrusion related to the Porcupine Median Volcanic Ridge, and therefore of Early Cretaceous age, it is hard to explain how the necessary crustal extension was effected during a post-rift period. It is also difficult to understand how the extreme ‘necking’ of the crust was achieved with relatively minor extension in the overlying syn-rift.

The general model of thinned crust modified by the intrusion of significant volumes of basic igneous material, the lateral equivalent of that extruded to form the PMVR to the south, is considered here to be the most likely interpretation. However, the ARK

model does use unrealistically low densities for the middle and lower crust and would need substantial revision to provide an acceptable model.

Figure 3.8 is the depth section constructed using the interpretation shown in Figure 3.4.

A line-length balance at the level of Top Pre-Rift gives a stretch for the whole section of $\beta = 1.37$. The total amount of extension is calculated as 27.0 km.

It is expected that the new WARR line currently being acquired will greatly reduce the uncertainties regarding crustal structure over this part of the basin.

3.4 SPB97-113

Figure 3.9 is the interpreted seismic line. No potential field modelling was carried out on this profile as part of the PSG programme. Needham et al. (1999) published a modelled profile along this seismic line indicating a heavily thinned crust (~5 km) with a central intrusive body beneath the PMVR although no densities are shown and the crust is not subdivided.

Baxter et al. (2001) have reported the results of structural modelling on a profile which runs sub-parallel to and ca. 20 km to the south of SPB97-113. They used the combined reverse and forward modelling techniques described by Roberts et al. (1993) and Kusznir et al. (1995). As with most studies of this type around the Atlantic Margin there is a large discrepancy between the modelled stretch and that observed from upper crustal faulting. Baxter et al. (2001) explain this by extending the age of the main rifting event well into the Early Cretaceous although this suggestion is not supported by this study (see Section 2.6).

Figure 3.10 is the depth profile constructed from the interpretation shown in Figure 3.9. The estimated stretch at Top Basement level for the whole basin along this profile is $\beta = 1.41$ and the total extension is calculated as 40.2 km. Figure 3.10 also shows that the estimated stretch for the inner part of the rift is $\beta = 1.65$.

3.5 PSB97-35a

This profile comes from the southern part of the Porcupine Basin, at the point where the axis changes from approximately north-south to WSW-ENE trending. The seismic line was not one that was available in the dataset used for this project. It is however close to seismic line SPB97-129 (Figure 3.11) over the northwestern half of the profile.

Readman and O'Reilly (2002) modelled this profile as a fairly symmetrically thinned crust (Figure 3.12). The overall thinning of the central part of the basin gives a stretch in the range of $\beta = 4$ to 5. Johnson et al. (2001) modelled lines SPB97-129 and 144 which cross the basin close to PSB97-35A at least on its western margin. Their modelled profile gives similar results with an estimated stretch in the range $\beta = 4.0$ to 4.5. From the observed faulting a stretch of $\beta = 2.8$ has been estimated as part of this study along the seismic lines used by Johnson et al. (2001). As with other profiles this discrepancy can be explained as a combination of unresolved faulting and an earlier rifting event.

3.6 Discussion

Although the dataset available is limited in nature and not fully quantitative, it is consistent with a continuous southward increase in the amount of extension within the Porcupine Basin in agreement with the earlier work of Tate et al. (1993). This variation of crustal attenuation implies a clockwise rotation of the Porcupine High with respect to Ireland. The possibility of a rift triple junction towards the southern end of the Porcupine Basin (see Section 4.1) might suggest that the maximum crustal thinning is actually at this point. Water depth, which is generally the best proxy for crustal thickness (in an inverse fashion) in the area of the Atlantic Margin, would alternatively suggest that the amount of thinning increases continuously up to the edge of the Porcupine Abyssal Plain as originally proposed by Makris et al. (1988). The shape of the basal Apto-Albian unconformity (Figure 2.33) implies the existence of a bathymetric gradient along the axis of the basin through to the edge of the abyssal plain. This itself implies a continuous increase in crustal thinning in the same

direction. An increase in thinning is also supported by an increase in the thickness of the Lower Cretaceous post-rift sequence (Figure 3.13). Some uncertainty remains, however, due to the lack of data coverage over the southwestern part of the basin.

In both the Porcupine and Irish Rockall Basins it has been suggested that discrepancies in the amount of stretching estimated for upper crust, lower crust and lithospheric mantle could be explained by depth-dependent stretching. On passive margins such discrepancies can be explained by varying strain gradients within the three layers. Davis and Kusznir (2001) have proposed such a model to explain not only the difficulties in reconciling subsidence history with observed faulting but also the presence of serpentinised peridotites at seabed on sediment starved passive margins. The space problem associated with the different gradients is avoided as there is an overall area balance in the section (Figure 3.14).

In a basin which is floored by a thinned but continuous layer of continental crust any differences have to be balanced laterally. Any lack of strain in a layer within the basin must be made up with higher strains outside the basin which will have their own thermal and mechanical effects.

Naylor et al. (2002) refer to greater stretching in the upper to mid crustal layer compared to the lower crust and lithospheric mantle in both the Rockall and Porcupine Basins. It is proposed that this is accommodated by shearing along a detachment along the top of the lower crust. This excess stretching must be balanced elsewhere by areas of anomalous stretching in the lower layers of the lithosphere. Such areas would be characterised by a thin unfaulted syn-rift sequence followed by a post-rift of similar geometry and extent (Figure 3.15). The other implication of such a model is that there would be a deficit in the post-rift subsidence within the original basin. This is actually the reverse of what is observed, as estimates of stretching from subsidence routinely suggest much greater β values than those estimated from upper crustal deformation (e.g. Baxter et al. 2001).

4. PORCUPINE BASIN MESOZOIC RIFT GEOMETRY

This section considers the variation in the Mesozoic rift geometry along the length of the basin. It also examines the geometry and origins of some of the structures identified in the Structural nomenclature report (Naylor et al. 2002).

4.1 Overall Geometry

Figure 4.1 is a map of the position of the main Middle /Late Jurassic rift faults at Base Cretaceous and shows the distribution of Upper Jurassic and Lower Cretaceous depocentres. On this basis the Porcupine Basin can be divided into several structurally-defined sub-areas. To the south of Finnian's Spur the western and eastern margins are described separately.

The North Porcupine Basin is distinct in terms of both geometry and history and is discussed below.

On the western margin, to the south of Finnian's Spur, the structure is dominated by northeast trending faults dipping to the northwest (Figure 4.2). Locally there appear to be east-dipping listric faults detaching at a shallow level. The lack of a Permo-Triassic section in this area with the potential for the development of evaporites, means that the faults are probably detaching on Westphalian coals.

In most of Quads 34 and 43 the western margin is characterised by north to north-northeast trending faults throwing down to the east. This part of the margin can be further subdivided as shown in Figure 4.1. The central portion, which is only properly imaged on SPB97-103, shows a marginal fault with a relatively small displacement (Figure 3.4 and 3.8). A major half-graben is developed in the segments to both the north and south of this part of the basin, although the lack of coverage to the west on the available data makes it impossible to determine the geometry of the marginal fault. The lack of an obvious half-graben on line SPB97-103 suggests that it crosses the margin close to a major transfer that offsets the basin margin significantly.

To the south of the 43/13-1 well the orientation of the margin changes and this is matched by a change in the strike of the main basin bounding fault to northeast trending. The details of this part of the margin have not been determined due to the lack of commonly held data. The two ridges identified by Naylor et al. (2002) as part of the system of volcanic ridges are here interpreted as tilted fault blocks. They share this northeasterly trend.

On the eastern margin, the area just to the south of Finnian's Spur is poorly imaged and the structure remains unclear. It appears however to be a very large half-graben containing potentially a full Permo-Triassic to Upper Jurassic sequence as an unbroken syn-rift fill similar to that seen in the Slyne Basin. Attempts to map a top of Pre-Rift from this area produced a pick that further south matched the Top Carboniferous unconformity (Figure 2.17).

Further south the margin consists of north-trending extensional faults that dip to the west. As described below in Sections 4.3 and 4 this area is divided into two parts by a large offset in the position of the marginal fault. The offset is not caused by the presence of any significant transfer structure. Figure 2.18 is a section down the relay ramp produced at the offset in the marginal fault and there is no evidence of a high-angle cross-cutting structure.

In the southern half of Quad 45 the polarity of the extensional faults change and the basin has a ramp type margin (Figure 4.3).

South of about UTM 5700000N (approx. 50deg 20mins N) the orientation of the extensional faults changes on both margins. This coincides with an abrupt broadening of the basin. It is possible that this represents a triple junction in the rift as this would accommodate the apparent changes in extension direction.

The connection between this area, the mouth of the basin (the Lugh High of Naylor et al. 2002) and the Goban area has not been investigated due to the lack of seismic data.

The segmentation of the Porcupine Basin appears to be controlled by WSW-ENE trending lineaments (Figure 4.1). In most cases they do not cross the whole basin and

are not discrete fault zones. They suggest that an earlier (possibly Caledonian) fabric in the underlying basement has had an important control on the development of the rift but not by direct reactivation of the structures (except for the fault that bounds the North Porcupine Basin). It is proposed that the pre-existing crustal fabric facilitated changes in the position and polarity of the extensional faults formed during the propagation of the rift.

4.2 North Porcupine Basin

The history of this basin is quite distinct from that of the Porcupine Basin as a whole. Subsidence within this basin is controlled by the fault that forms the northern boundary to Finnian's Spur. This fault has a WSW-ENE trend, possibly reactivating a Caledonian structure, at a high angle to the rest of the Porcupine Basin, which probably explains its different movement history.

The basin may have been active during the Carboniferous as suggested by Figure 2.22. It was undoubtedly active during the Permo-Triassic, Middle/Late Jurassic, Late Cretaceous and Palaeocene extensional episodes. This structure was not reactivated during the Late Eocene.

The geometry of the fault zone bounding Finnian's Spur is complex, with large changes over small distances. Figure 4.4 shows a section parallel to that seen in Figure 2.30, 10 km to the northeast. The rapid change in geometry is consistent with oblique slip movement, particularly during the Late Cretaceous and Palaeocene periods.

The link between this basin and the Slyne Basin is unclear due to the paucity of data and its generally poor quality.

4.3 The Ruadan High

This structure was defined by Naylor et al. (2002) and consists of a relative structural high dividing the Moling Sub-basin to the east from the main part of the Porcupine Basin to the west.

It is considered here to be in part the crest of a tilted fault block and in part the collapsed crest of a rollover. The exact geometry of the high depends on the geometry of the faults controlling the Moling Sub-basin and the size of the west-dipping fault bounding its western side. Both Sub-basin and High are divided into a southern and northern part due to a large offset of the basin margin. Immediately to the north of this offset the Ruadan High appears as a broad feature (Figure 4.5) with some internal faulting.

In the southern part the western bounding fault is quite large with a significant footwall uplift. This geometry is seen on line SPB97-103 (Figures 3.4 and 3.8) and Figure 4.5. Further to the north the geometry becomes more complex with the formation of a collapse graben at or near the crest of the Ruadan High (Figure 2.7). In the northern part the faults to the west have much smaller throws and the High appears more like a collapsed rollover (Figures 3.1 and 3.3).

The presence of a collapsed rollover within the Ruadan High along large parts of its length suggests that the fault zone bounding the Moling Sub-basin to the east has an irregular geometry, which resulted in the formation of a fault bend fold. The cause of this irregularity is unknown but may be related to the presence of Variscan thrust structures as described in section 2.3.

4.4 The Moling Sub-basin

This sub basin forms the main Middle/Late Jurassic depocentre on the eastern side of the Porcupine Basin (Naylor et al. 2002). It shows varying degrees of complexity from a single half-graben to as many as three subordinate half-grabens. To the south its extent is controlled by the extent of the major down-to-the-west extensional fault

system that forms the basin margin. The northern end of the sub-basin is poorly defined due to the generally low seismic data quality.

As with the related Ruadan High (see above) the Sub-basin can be divided into two parts across a major offset in the basin margin. The northern Moling Sub-basin is shown on Figures 2.7, 2.20, 3.1, and 3.3; the southern Sub-basin is shown on Figures 2.17, 3.4, 3.8, and 4.6.

4.5 The Porcupine Arch

This structure was named by Naylor et al. (2002) and consists of a strong seismic reflector with a broad anticlinal geometry. This is best seen on line SPB97-103 (Figure 3.4). This has been interpreted (Reston et al. 2001) as representing the S-reflector as seen on the Galician margin (Reston et al. 1995), a contact with serpentinised upper mantle. There is some evidence of extensional faults flattening as they approach the reflector but elsewhere it appears to be offset by high-angle faults. There are similarities to the structure of the Gjallar Ridge on the Norwegian margin where a strong convex-up mid-crustal reflector is recognised (Lundin and Doré 1997), with an associated gravity high attributed to underplating (Skogseid et al. 1992). Johnson et al. (2001) have named the seismic event the 'n' - reflector and interpret it to represent the top of the crystalline crust although they suggest that it may form the so-called 'brittle-ductile' transition, (actually a downwards change from localised simple shear along fault zones to more distributed pure shear within the lower crust).

In this study the reflector was initially picked as Near Top Basement. Figure 4.7 shows part of line SPB97-103 in which the event is picked partly as a stratigraphic event (Near Top Basement) and partly as a fault. A possible continuation of the reflector as Near Top Basement in the hanging wall of the interpreted fault is indicated. Unfortunately the SPB97-103 line is the only commonly-held seismic line with a sufficient record length to show the event clearly.

The results of potential field modelling require some form of relatively high density body within the crust beneath the centre of the basin, underlying the arch. As discussed in Section 3.2 the preferred model does not include a large discrete intrusive

body but suggests instead thinned crust containing a large proportion of intruded material. The igneous material probably represents an intrusive northward continuation of the extrusive PMVR.

Based on the data available to date, the Porcupine Arch is interpreted to be an intrabasinal high with a relatively thin pre-rift cover overlying thinned and intruded basement.

4.6 The Porcupine Median Volcanic Ridge (PMVR)

The origin of this feature has already been discussed in both Sections 2 and 3. The geometry of the ridge varies along its length. Figures 4.8 to 4.11 show variations from north to south along the ridge.

Near its northern end, the ridge is NNW-trending, relatively narrow (ca. 4 km at its base) with a conical shape and a clear compactional effect in the overlying Cretaceous sequence (Figure 4.8). In its centre, it becomes higher with an apparently erosional top and a much broader base (ca. 20 km across) (Figure 4.9). The compactional effect of the ridge generally reduces in the central part and locally internal faulting is seen. On some lines there appear to be smaller cones on the flanks of the main ridge (Figure 4.10). At its southern end, the ridge becomes WNW-trending and again becomes narrow with a conical shape and clear compactional effects (Figure 4.11). The variation in the degree of observed compaction over the flanks of the PMVR suggests that most of this feature consists of volcanoclastic rocks with only subordinate lavas.

Figure 4.12 is a contoured time map of the top of the PMVR. It shows that the ridge is probably built up from at least ten separate vents that coalesced with time. The change in strike of the ridge occurs close to a change in strike and polarity of the main Late Jurassic rift faults. This observation is consistent with the position of the PMVR being controlled by Late Jurassic faults acting as magma conduits.

This study does not support the suggestion that the PMVR effectively continues as the Fionn High (see below), the most southerly part of the ridge has an almost west-east trend.

Reston et al. (2001) have proposed an alternative explanation for the ridge as an extrusive serpentinite complex. In their model, water penetrating down in to the uppermost mantle as a result of crustal thinning in the Late Jurassic caused large-scale serpentinisation. The volume change caused during the hydration of the peridotite that led to a diapiric extrusion of the serpentinite to the surface.

The serpentinite model does not explain the presence of low-angle reflectors beneath the PMVR over much of its length. It is also hard to equate this explanation with the reflector geometries observed within the PMVR itself which are entirely consistent with a volcanic edifice containing a mixture of predominant tuffs with subordinate lavas. The model of the PMVR proposed by Tate and Dobson (1988) is considered here to be supported by all the available data.

4.7 The Fionn High

This high has been described by Naylor et al. (2002) as a complex faulted or thrust high paralleling the bathymetric trend of the eastern margin of the Porcupine Seabight. As stated above the Fionn High is not considered continuous with the PMVR.

Figure 4.13 shows a 2D seismic section through the Fionn High. It appears on this and other lines to be a horst-like feature with tilted fault blocks of opposing polarity throwing down to either side. This structure may represent a conjugate divergent overlapping transfer zone (Morley et al. 1990) between two rift segments of opposite polarity.

In Figure 4.14 the Fionn High marks the edge of a set of highly rotated fault blocks throwing down to the west, which may have formed slightly later (or possibly continued to move later) than the less rotated fault blocks of opposite polarity to the east. This is considered a structure typical of highly attenuated crust and the result of large displacement extensional faulting.

4.8 Structure of the Basin Floor

It has been stated by Naylor et al. (2002) that the central part of the Porcupine Basin is “structurally simple with the base of Cretaceous at a depth of 6 sec. TWT in the basin centre, and narrows northwards until the zones of tilted fault blocks on each flank merge together in the north of the basin”. Part of the apparent simplification is due to the generally poor imaging beneath the base of the Cretaceous sequence particularly in the southern part of the basin where the Base Cretaceous reflector lies at greater than 7 seconds in the basin centre. However, some seismic lines across the southern part of the basin do appear to show highly rotated fault blocks. Figures 3.11 and 4.14 together cover almost the full width of the basin centre. The interpreted fault blocks are consistent with a high degree of crustal attenuation (estimated $\beta \approx 2.8$) and are similar to those seen in the main part of the southern Irish Rockall Basin (Figure 4.15).

4.9 The Clare Lineament

This structure has been interpreted on the basis of gravity data to cross the Porcupine Basin in the zone where there is an overall change in basin structure as shown by free-air gravity maps. This has then been extended onto the adjoining Porcupine High and Celtic Platform in a variety of positions and orientations (Figure 4.16). Tate (1992) extended the structure, originally mapped by Dingle et al. (1982) as a Mesozoic precursor to the Charlie-Gibbs Fracture Zone, across the Porcupine Basin in a WNW-ESE orientation. His version of the lineament passed through the southern end of the PMVR and through the offset of the basin’s eastern margin just south of the Túr Igneous Centre.

The Geological Society Special Publication No. 188 contains two papers which figure the Clare Lineament, Johnson et al. (2001) and McGrane et al. (2001). They coincide at the western edge of the area but diverge increasingly to the east with Johnson et al. (2001) curving their version around the southern end of the gravity high and ending up in line with the Killarney-Mallow Fault, one of the candidates for the so-called Variscan Front. McGrane et al. (2001) take their lineament with only a slight curve

across the southern Porcupine Basin passing across its eastern margin just north of the Tóim High. Naylor et al. (2002) include a gravity lineament on the final version of their structural elements map. It is unnamed but assumed to represent a further interpretation of the Clare Lineament.

The lineaments according to Johnson et al. (2001) and Naylor et al. (2002) could represent structures predating the main Mid/Late Jurassic rifting event as the former is nearly parallel to the extension vector within the basin and the latter would be rendered near linear after restoration of the crustal thinning. The structure shown by McGrane et al. (2001) could only post-date the rifting because its orientation is unaffected as it crosses the margins of the Porcupine Basin.

I do not believe that there is a strong case for interpreting a continuous structure on the basis of the available data, apart from within the Porcupine Basin.

5. CONCLUSIONS

- 1) The main phase of rifting in both the Porcupine Basin and the Irish Rockall Basin occurred in the Late Jurassic following the lines of existing Permo-Triassic basins.
- 2) Evidence for significant crustal shortening during the Variscan Orogeny has been found on the eastern margin of the Porcupine Basin in the area of blocks 36/26 and 45/1.
- 3) The southern part of the Irish Rockall and the Porcupine Basins were affected by uplift and volcanism during the Early Cretaceous related to a transient mantle plume.
- 4) The Porcupine Basin is strongly segmented with sub-basins developed generally of ca. 50 km strike extent. The boundaries between sub-basins appear to be controlled by WSW-ENE features of possible Caledonian trend, although they do not in general appear to be throughgoing fault zones.
- 5) The gravity high associated with the Porcupine Arch probably relates to a relatively high proportion of intrusive basic igneous material emplaced during the Early Cretaceous within previously thinned crust. This is likely to be the northward continuation of the Porcupine Median Volcanic Ridge, but formed in an area where the magma did not reach the surface.
- 6) The amount of crustal stretching is interpreted to increase continuously from $\beta < 2$ at the northern end of the Porcupine Basin up to approximately $\beta = 6$ at the continent-ocean boundary to the southwest. This implies a significant clockwise rotation of the Porcupine High during the main Late Jurassic rifting event.
- 7) The North Porcupine Basin has a distinct history from the rest of the basin having been active during the Carboniferous, Permo-Triassic, Middle/Late Jurassic, Late Cretaceous and Palaeocene periods. The basin is controlled by

the fault on the north side of Finnian's Spur, which is interpreted to be a reactivated earlier, possibly Caledonian, structure.

- 8) Many of the extensional faults which define the inner part of the Porcupine Basin show significant offset at Base Cretaceous level. The clearly post-rift geometry of the immediately overlying Lower Cretaceous sequence implies that this late movement was either latest Jurassic or earliest Cretaceous in age, approximately coeval with the regional unconformity at this level.

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APPENDIX 1

QUESTIONS ABOUT THE PORCUPINE BASIN THAT THE STUDY MIGHT ADDRESS

- 1) What was the pre-Carboniferous structural framework?
- 2) What was the form of the Carboniferous basins?
- 3) What is the nature of the Devonian to Carboniferous transition?
- 4) Where does the 'Variscan Front' pass through the Porcupine Basin, and what form does it take?
- 5) What is the relationship between the Slyne Basin and the Porcupine Basin?
- 6) How different is the 'North Porcupine Basin' to the rest?
- 7) How much Lower Jurassic is there (or was there)?
- 8) What are the main rift ages?
- 9) What was the extension direction during each rift episode?
- 10) How does the rift polarity vary through the basin, and did this change with time?

- 11) What effect did Early Cretaceous magmatism have?
- 12) How do the answers to 6 and 7 fit with the Plate Tectonic model for the area?
- 13) Is there evidence of any phases of inversion?
- 14) What effect did the Iceland Plume have?
- 15) Can we quantify the amount of excess subsidence during the Tertiary?

APPENDIX 2 DEPTH CONVERSION METHODOLOGY

For the Tertiary section use was made of relationships of the form $V_i = V_0 + kz$ between interval velocity and mid-point depth below seabed previously derived by Phillips Petroleum from well data. Well data covering the three Cretaceous intervals, the Chalk Group, the Apto-Albian and the Ryazanian-Barremian, were analysed as part of this study. Figures A2.1 to A2.3 are plots of midpoint depth versus interval velocity for these intervals. In all cases there is a reasonably good fit to a linear relationship and the derived V_0 and k values are shown. In order that the interval velocities of the Cretaceous should not reach unrealistic values the Chalk Group were clipped at 5500 m/s and the other two intervals were clipped at 4500 m/s. Well control on velocities in the pre-Cretaceous section is poor and it was decided to use a constant 4500 m/s for the Triassic to Jurassic.

The velocity - depth relationships were reworked into velocity – time where each equation is solved from knowledge of the depth to the top of the interval calculated previously. e.g.

$$V_{i2} = 2 (k_2 \times Z_1 + V_{02}) / (2 - k_2 \times C_2)$$

where V_{i2} is the interval velocity of the second layer, k_2 is the gradient taken from the velocity versus midpoint depth plot for the second layer, Z_1 is the depth of the top of the layer (in this case the depth to seabed), V_{02} is the intercept at zero depth and C_2 is the time thickness (isochron) for the interval.

A copy of the depth conversion script that was run using Phillips Petroleum's proprietary software horizoncalc is shown below.

HORIZONS

t01 = h1 = seabed

t02 = h4 = Oligocene Unconformity

t03 = h345 = Top Chalk

t04 = h392 = Base Chalk

t05 = h335 = Aptian-Albian Unconformity

t06 = h28 = Base Cretaceous

t07 = h569 = Top Pre-rift

t08 = h575 = Generic deeper event

d0n = depth of nth horizon

c0n = isochron between nth and (n-1)th horizon

d0n = isopach between nth and (n-1)th horizon

D0n = output depth horizon

VELOCITY FUNCTIONS

Seawater constant $V_1 = 1485$ m/s

Seabed to Oligocene Unconformity $V_1 = k02 \times d01 + 1704$

Oligocene Unconformity to Top Chalk $V_1 = k03 \times d02 + 2040$

Top Chalk to Base Chalk $V_1 = k04 \times d03 + 2500$

Base Chalk to Aptian-Albian Unconformity $V_1 = k05 \times d04 + 1818$

Aptian-Albian Unconformity to Base Cretaceous $V_1 = k06 \times d05 + 2060$

Pre-Cretaceous constant $V_1 = 4500$ m/s

DEPTH CONVERSION SCRIPT

k01=0.0; k02=0.88; k03=0.51; k04=1.05; k05=0.93; k06=0.54; k07=0.0; k08=0.0;

t01=h1; t02=h4; t03=h345; t04=h392; t05=h335; t06=h28; t07=h569; t08=h575;

c01=t01; c02=t02-t01; c03=t03-t02; c04=t04-t03; c05=t05-t04; c06=t06-t05; c07=t07-

t06; c08=t08-t07;

c02=eclip(c02,0,8000,0);

c03=eclip(c03,0,8000,0);

c04=eclip(c04,0,8000,0);

c05=eclip(c05,0,8000,0);

c06=eclip(c06,0,8000,0);

c07=eclip(c07,0,8000,0);

c08=eclip(c08,0,8000,0);

v01=1485;

p01=c01*v01/2000;

$D01=p01;$
 $d01=0.0;$
 $v02=2*(k02*d01+1704)/(2-k02*c02/2000);$
 $v02=clip(v02,0,4500);$
 $p02=c02*v02/2000;$
 $d02=d01+p02;$
 $v03=2*(k03*d02+2040)/(2-k03*c03/2000);$
 $v03=clip(v03,0,4500);$
 $p03=c03*v03/2000;$
 $d03=d02+p03;$
 $v04=2*(k04*d03+2500)/(2-k04*c04/2000);$
 $v04=clip(v04,0,5500);$
 $p04=c04*v04/2000;$
 $d04=d03+p04;$
 $v05=2*(k05*d04+1818)/(2-k05*c05/2000);$
 $v05=clip(v05,0,4500);$
 $p05=c05*v05/2000;$
 $d05=d04+p05;$
 $v06=2*(k06*d05+2060)/(2-k06*c06/2000);$
 $v06=clip(v06,0,4500);$
 $p06=c06*v06/2000;$
 $d06=d05+p06;$
 $v07=4500;$
 $p07=c07*v07/2000;$
 $d07=d06+p07;$
 $v08=4500;$
 $p08=c08*v08/2000;$
 $d08=d07+p08;$
 $D02=d02+D01;$
 $D03=d03+D01;$
 $D04=d04+D01;$
 $D05=d05+D01;$
 $D06=d06+D01;$
 $D07=d07+D01;$

$D08=d08+D01;$

N.B. Clips and eclips prevent the thicknesses and velocities taking on unrealistic values