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The Erris Ridge: a major geological feature in the NW Irish Offshore Basins

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Abstract: The Erris Ridge is a narrow structural high that separates the Erris and Rockall Troughs. It has a composite internal character and its orientation is thought to be controlled by a pre-Caledonian structural fabric which was frequently reactivated during Caledonian to Cenozoic time. In the north it is fault-bounded and probably contains rocks of Palaeozoic and older age. It formed a positive topographic feature which was progressively onlapped during Permo-Triassic to Cretaceous times. Fault reactivation occurred along its western boundary in Tertiary times and it was submerged by approximately latest Miocene times. Further south the Ridge is more complex. The Palaeozoic and older core is flanked to the SE by interpreted Permo-Triassic to Lower Jurassic strata which constitute a fault-controlled, uplifted, remnant of a half-graben basin. This composite structure was probably inverted during Late Jurassic times and remained as a topographic feature until Cretaceous times. It was progressively onlapped during Cretaceous and Tertiary times, with a minor phase of fault reactivation during the Early Tertiary. The Ridge acted as a rigid block which facilitated the focusing of several phases of crustal extension in the Erris Trough and in the Rockall Trough.

Keywords: Rockall Trough, rifting, crust, extension, passive margins.

A number of sedimentary basins lie along the flank of the broad NW European passive margin in the North Atlantic. They developed in response to multi-phase rifting which represented early attempts at continental separation in Late Palaeozoic and Mesozoic times (Shannon 1991*a*). A rift–drift transition in Cretaceous times (Shannon *et al.* 1995*a*) reflects the onset of sea-floor spreading in the North Atlantic. Oceanic crustal development occurred along the Iberian spreading axis in Early Cretaceous times with later spreading along a NNE–SSW axis west of Ireland in Late Cretaceous and Tertiary times (Knott *et al.* 1993). The basins of the Atlantic Margin extend from offshore mid-Norway to west of Ireland and include the Møre, Faeroe–Shetland, West Shetland, Donegal, Erris, Slyne and Porcupine Basins (Fig. 1). These structurally linked basins can be divided into a set of narrow early Mesozoic (Permo-Triassic to Middle Jurassic) inboard (landward) basins and a band of large outboard (oceanward) basins that have a longer history (including thick Cretaceous and Tertiary sediments). The inboard basins such as the West Shetland, Minches, Sea of Hebrides, Slyne, Erris and Donegal Basins, are typically asymmetrical, half-graben, basins (Fig. 1). They are separated from the outboard basins such as the Faeroe–Shetland and Rockall Basins by a number of pronounced elongate ridge and platform features such as the Rona, Erris and Slyne Ridges and the Outer Hebrides Platform. This paper analyses the composite development of one such extensive feature, the Erris Ridge, and speculates upon its structural significance on the flank of the North Atlantic passive margin.

Regional structural setting

The Late Palaeozoic–Cenozoic basins west of Ireland form a complex set of tectonically-linked sedimentary depocentres. In the south of the region the Porcupine Basin, containing in excess of 10 km of Mesozoic and Tertiary strata in places, is separated from the Rockall Trough, containing up to 6 km of sediment (Shannon *et al.* 1994, 1995*b*; Hauser *et al.* 1995) by the Porcupine Bank and the Porcupine Ridge. These comprise a broad, shallow crystalline basement bank (Fig. 1). The Porcupine Basin broadens southwards in response to increasing crustal extension (Tate 1993; Tate *et al.* 1993). Further northwards the N–S orientation of the Porcupine Basin gives way to a NE–SW (Caledonian) structural orientation exhibited by the narrow Slyne–Erris–Donegal Basins (the NW Offshore Basins), which generally contain up to 3 km of strata, although inversion may have locally removed up to 1.2 km of sediment (Scotchman & Thomas 1995). These basins are separated from the Rockall Trough by an intermittent structural high. The Slyne Ridge is an extension of the Porcupine Bank and separates the Slyne Trough from the Rockall Trough. The Erris Trough is separated from the Slyne Trough by a major strike-slip zone (Trueblood & Morton 1991; Trueblood 1992). The Erris Ridge (Fig. 1), to the north of this zone, separates the Erris Trough from the Rockall Trough. Further along strike to the NE the basins west of Scotland show a similar pattern of narrow basins (e.g. Hebrides and West Shetlands) separated from the larger Faeroe–Shetland and Rockall Basins by a set of intermittent structural ridges such as the Sula–Sgeir High and the Rona Ridge (Booth *et al.* 1993). Drilling and seismic data indicate that the inboard basins typically comprise several kilometres of Permo-Triassic to Middle Jurassic strata with an attenuated to absent Late Jurassic to Tertiary succession (Naylor & Shannon 1982; Stoker *et al.* 1993). The succession in the larger outboard basins is more poorly constrained but these appear to have a thicker Cretaceous and Tertiary succession (Shannon *et al.* 1993; Mudge & Rashid 1987).

The Erris Ridge coincides with a major regional change in crustal thickness. The unstretched crust beneath Ireland is 30 km thick (Lowe & Jacob 1989). Wide-angle seismic reflection data (Shannon *et al.* 1994, 1995*b*; O'Reilly *et al.* 1995*a*, *b*) indicate a pre-rift basement crustal thickness of 20 km beneath the Erris Trough, while the pre-rift crust has a thickness of 5–8 km beneath the central part of the Rockall Trough. The

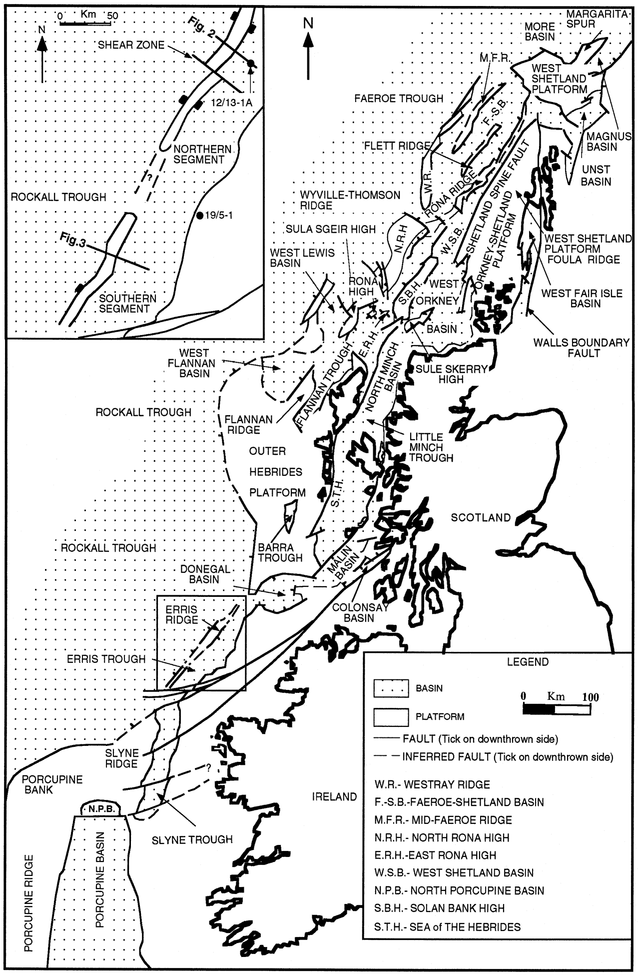

Fig. 1. Location of the Erris Ridge in the regional context of basins and ridges in the Atlantic borderlands. Insert map shows the location of Figs 2 and 3.

transition from the very thin crust of the Rockall Trough, where the whole crustal stretching factor is in the range 4–6, to the thicker crust of the Erris Trough with a whole crustal stretching factor of less than 2, coincides with the Erris Ridge. This coincidence points to an inherited basement structural control on the focusing of crustal extension in the region.

Geological and geophysical control

Only six wells have been drilled in the area (two in 1996) and consequently the geological control is poor. Drilling in the Slyne Trough (Trueblood 1992; Scotchman & Thomas 1995) encountered a Lower to Upper Jurassic succession comparable to that of the Hebrides Basins (Trueblood & Morton 1991). The released wells indicate a Carboniferous to lowermost Jurassic succession with locally thick Lower Cretaceous submarine fan and Tertiary marine strata (Murphy & Croker 1992). These wells have been used as control points tied into the seismic data base. The seismic lines used have a dip spacing of approximately 7.5 km and strike lines are 12.25 km apart. They form part of two non-exclusive surveys, almost 3000 km in extent, shot by PGS Nopec in 1991 and 1993. No wells have been drilled in the Irish sector of the Rockall Trough and correlations between the Erris Basin and the Rockall Trough, on opposite sides of the Erris Ridge at pre-Tertiary level, are speculative. DSDP well 610 in the south of the Rockall Trough provides some geological and seismic control on the Upper Tertiary succession (Masson & Kidd 1986). Regionally extensive seismic horizons on expanding spread profiles (Joppen & White 1990) and seismic reflection data (Shannon *et al.* 1993) in the Rockall Trough have been correlated with, and extrapolated from, the DSDP data.

Erris Ridge

The Erris Ridge can be mapped as a relatively narrow (typically 5–7 km) elongate, intermittent feature, for approximately 150 km. A NW–SE zone of poor data quality midway along the Ridge (Fig. 1) coincides with a minor lateral offset and is interpreted as a sinistral transverse shear zone similar in trend to comparable features interpreted in the West Shetlands region by Rumph *et al.* (1993). Further south a narrow zone, with poor seismic control, has been indicated as a gap in the Ridge (Naylor & Shannon 1982) and this separates the Erris Ridge into a northern and a southern segment. These have different internal seismic character and are described separately.

Northern segment

In the north the Erris Ridge is bounded along the NW side by a major NW-dipping normal fault of Miocene and older age, while a series of smaller SE-dipping normal faults of Permo-Triassic to Cretaceous age locally bound the SE flank of the Ridge (Fig. 2). The upper part of the fault-bounded Ridge in this region locally contains some coherent reflectors while the core is typically devoid of reflectors. The Ridge is onlapped progressively by Permo-Triassic, Lower Jurassic, Cretaceous and Lower Tertiary sediments (Fig. 2) and is therefore assumed to be older than these strata (i.e. Permo-Triassic). The age constraint on the onlapping strata is provided by the 12/13-1A well (Fig. 2). The Permo-Triassic succession is preserved in a series of fault blocks to the east of the Ridge. It comprises a package of SE-dipping coherent reflectors which are unconformably overlain by a thin Lower Jurassic succession. Lower Cretaceous (Ryazanian–Albian) submarine fan sandstones and shales progressively onlap and thin northwestwards onto the Erris Ridge. Despite the absence of Jurassic strata of post-Hettangian age the Lower Cretaceous strata rest with only a slight unconformity upon the Lower Jurassic succession. The Cretaceous strata have a broad synclinal geometry on the SE flank of the Ridge, with the general NW dip flattening out westwards of the limits of the Permo-Triassic fault blocks. Uppermost Cretaceous strata onlap the SE crest of the Ridge, although in places a Late Tertiary erosion surface cuts down to the crest of the Ridge and obscures the contact between the Upper Cretaceous and the underlying Ridge. The Lower Tertiary succession in the Erris Trough is characterized by a downlapping unit of westward-prograding strata. Unfortunately, the dating of the Tertiary succession in the 12/13-1A well is poor thereby preventing its accurate subdivision.

The geological control on the onlapping strata is poor to the west of the Erris Ridge in the northern region. The pronounced reflector at the top of a high-amplitude sequence is correlated on seismic character with the Green Reflector of Masson & Kidd (1986) and with the base of the RT3 succession of Shannon *et al.* (1993) and a latest Early Miocene age is suggested. A downlapping sequence of high-amplitude events immediately above this event thickens towards the NW faulted boundary of the Ridge (Fig. 2) and is interpreted as a latest

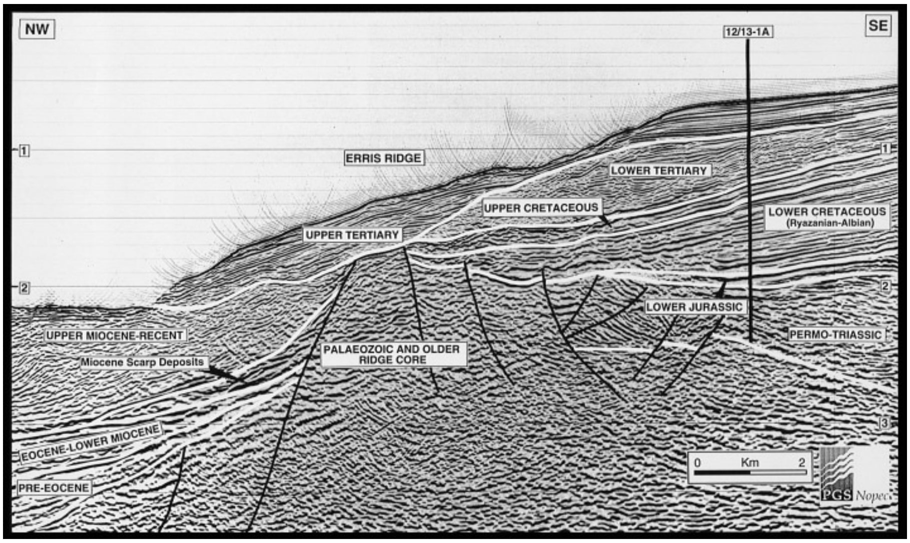

Fig. 2. Seismic profile across the northern segment of the Erris Ridge (location shown on Fig. 1). The position of the 12/13-1A well is indicated. The Ridge, probably composed of Palaeozoic and older rocks, was submerged by latest Cretaceous times. See text for full discussion. Vertical scale is in seconds (two-way-travel time).

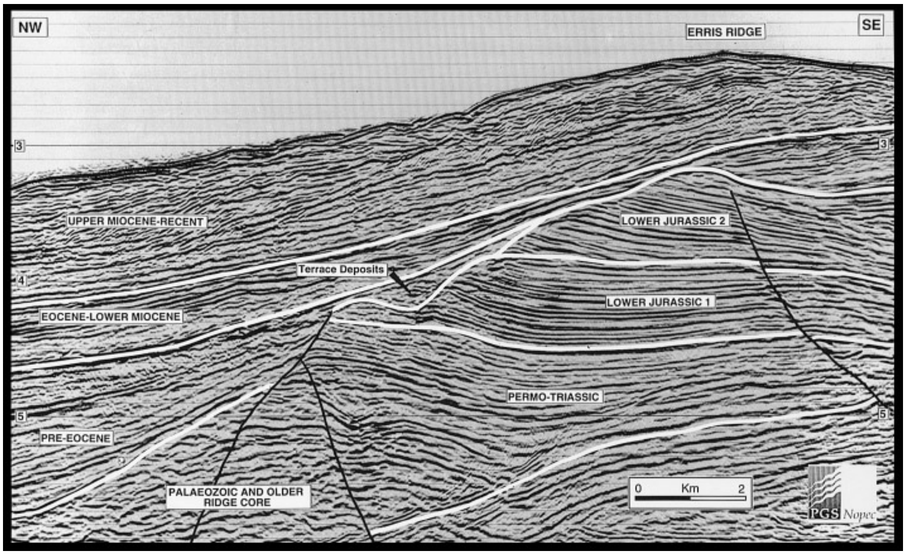

Fig. 3. Seismic profile across the southern segment of the Erris Ridge (location shown on Fig. 1). The Ridge comprises a basement core with annealed Permo-Triassic and Lower Jurassic and was submerged by latest Early Miocene times. See text for full discussion. Vertical scale is in seconds (two-way-travel time).

Early to Late Miocene scarp. The overlying succession consists of a NW-prograding series of discontinuous, medium- to low-amplitude reflectors. Close to the Erris Ridge the pre-Upper Miocene succession is subdivided into two seismic sequences. The upper one thins towards the ridge margin and is interpreted, on the basis of regional correlations (Masson & Kidd 1986; Joppen & White 1990; Shannon *et al.* 1993), as being of Eocene to Early Miocene age. The underlying sequence onlaps a number of fault dip slopes and is probably of Cretaceous to Early Tertiary age. Occasional examples are seen of downlapping wedge-shaped seismic packages resting upon the fault terraces. They are onlapped by the Eocene–Miocene sequence but their age relationships with the Cretaceous–Early Tertiary sequence is uncertain and they could be either coeval or older. They point towards the presence of a fault topography in pre-Eocene times.

Southern segment

The southern segment of the Erris Ridge, like that further north, comprises a pronounced ridge feature that separates the sedimentary depocentres of the Erris Trough to the east from the Rockall Trough to the west, and onto which younger sediments onlap in both directions. However, the seismic character of the Erris Ridge is significantly different in the south of the region where it is characterized by the presence of a number of seismic sequences with distinct internal reflection configurations. Three sequences with distinctly different seismic character occur within the ridge complex (Fig. 3), while a seismically transparent core can sometimes be identified. The uppermost sequence displays a wedge-shaped, southeastward thinning, internal geometry with high-amplitude, continuous reflectors dipping at a progressively shallower angle towards the SE. It downlaps onto the underlying sequence which consists of high-amplitude, parallel, continuous reflectors. These dip towards the SE on the NW flank and have a shallow NW dip on the SE flank of the Ridge. The underlying, conformable, sequence contains relatively high-amplitude, discontinuous reflectors. Some internal thickness variations occur and these are associated with open folds within the succession. This is underlain by a core, located at the NW edge of the Ridge complex, which contains few coherent internal reflectors. Its contact with the overlying sequences is unclear but it appears likely that it is faulted.

Dating of the sequences in the southern segment of the Erris Ridge is poorly constrained, with no wells drilled on, or in the immediate vicinity of, the Ridge. The nearest well is 19/5-1, on the eastern side of the Erris Trough. This encountered a thin Tertiary, Jurassic and Permo-Triassic section overlying a thick Carboniferous succession (Tate & Dobson 1989*b*). Extrapolation of the seismic packages westwards from the well suggests that the Ridge is likely to be of pre-Cretaceous age. The core has a similar seismic character to the Erris Ridge in the northern segment and also to the Palaeozoic succession drilled in 19/5-1. The overlying sequence is interpreted as Permo-Triassic as it can be mapped, with moderate confidence, northwestwards across the basin from the 19/5-1 well. The internal thickness variations and folds are interpreted as the results of halokinesis. The sequence is also similar in its internal reflector configuration to the Permo-Triassic sequence lying on the SE flank of the Erris Ridge in the northern segment. The two overlying sequences are more difficult to date with confidence due to the incomplete Jurassic section, and the absence of Cretaceous strata, in the 19/5-1 well. The older of the sequences, when mapped southeastwards, appears to coincide with the Lower Jurassic succession in the well. Its seismic character is also very similar to the thin Lower Jurassic sequence seen on seismic profiles through the 12/13-1A well further north (Fig. 2), and to the Lower Jurassic strata seen in many other Irish offshore basins (e.g. Shannon 1991*b*, fig. 7.7). The uppermost seismic sequence in the Erris Ridge is also interpreted as being of Lower Jurassic age and is likely to consist of a succession of marine limestones, marls, shales and occasional sandstones. This is based largely upon the similarity of the seismic character to the underlying sequence and to the Lower Jurassic in other nearby basins. While a Middle to Upper Jurassic age cannot be ruled out, the general non-marine nature of these strata in adjacent basins would be expected to produce a more discontinuous and variable amplitude seismic signature. Mapping southwards from the control well (12/13-1A) indicates that the Lower Cretaceous succession onlaps the SE part of the Ridge and suggests a pre-Cretaceous age for the southern segment of the Erris Ridge. While this would suggest a considerable thickness (probably in excess of 2 km) of Lower Jurassic strata in the region, comparable thicknesses have been indicated in other Irish basins, notably the Celtic Sea (Shannon 1991*b*) and the Kish Bank Basin (Broughan *et al.* 1989).

On the SE side of the Ridge in the south the onlapping succession is interpreted as Upper Jurassic to Cretaceous. This is based upon extrapolation downdip from the 19/5-1 well and on mapping from the 12/13-1A well further NE along strike. On the NW side the strata can be correlated to the Tertiary succession along strike to the NE with reasonable confidence. The interpreted latest Early Miocene reflector extends across the crest of the Ridge and indicates submergence of the Ridge by this time. The underlying Eocene to Early Miocene sequence onlaps the Ridge slope with the first sediments to overtop the Ridge lying immediately below the latest Early Miocene reflector (Fig. 3). The pre-Eocene succession progressively onlaps the Ridge and dips to the NW. A number of small, wedge-shaped packages of parallel sub-horizontal reflectors occur on the NW flank of the Ridge and lie unconformably on the interpreted Lower Jurassic succession within the Ridge (Fig. 3). They are draped by younger strata which in turn are onlapped by the interpreted Eocene reflector. They are interpreted as preserved erosional terraces of pre-Eocene (possible Middle–Upper Jurassic) age and are discussed further below.

Discussion and conclusions

The northern segment of the Erris Ridge is interpreted as being composed of Palaeozoic and older rocks. This is partly constrained by the age of the onlapping Permo-Triassic to Cretaceous strata encountered in the 12/13-1A well (Fig. 2). The occasional coherent reflectors seen within the upper part of the Ridge in the northern area are suggestive of a sedimentary or metasedimentary nature and a Late Palaeozoic age seems likely while the central core may comprise older basement. The 19/5-1 well encountered a thick Carboniferous succession (Tate & Dobson 1989*a*; Murphy & Croker 1992) and the available seismic data can be broadly traced from the well to the Erris Ridge, although the seismic data quality in the region of the well is such that it is impossible to map individual important reflectors (e.g. Base Dinantian, Intra-Namurian) with any confidence towards the Erris Ridge. The SE margin of the Ridge forms the western boundary of the Permo-Triassic rift basin and the rather chaotic nature of the Permo-Triassic close to the boundary is thought to be due to fault-induced halokinesis. Jurassic strata are thin but there is no direct evidence to indicate the post-Hettangian Jurassic history in the northern segment. However, there is no clear evidence from sonic logs to indicate any significant erosion at the Jurassic–Cretaceous boundary, which is close to conformable on Fig. 3. This suggests that this part of the Ridge and basin system was inactive during late Early through Late Jurassic times, although subsidence may have occurred further east in the Erris Trough. The westward decrease in dip of the pre-Tertiary onlapping strata, and the angular relationship with the overlying Lower Tertiary succession which lacks the decrease in dip, is interpreted as being due to footwall uplift associated with end-Cretaceous to earliest Tertiary faulting along the NW edge of the Ridge. The wedge-shaped downlapping unit (Fig. 2) immediately above the latest Early Miocene reflector points to the western margin of the Ridge being a pronounced scarp feature during Late Miocene times. Further modelling work is required to resolve if this represents a residual scarp from the end Cretaceous faulting or was the product of a later period of reactivation. A number of tectonic pulses and regressive episodes have been identified in the Late Cretaceous and Tertiary of the basins along the Atlantic Margin (Boldreel & Andersen 1993; Booth *et al.* 1993; Shannon *et al.* 1993) and these are interpreted as the interplay between crustal stresses due to changes in directions and rates of sea-floor spreading and the effects of the Iceland hot spot.

The southern segment of the Erris Ridge has a significantly different character. The deep ridge core is equated with the main ridge further north and is interpreted as a Palaeozoic and older series of rocks. However, as described above, the overlying stratified successions are interpreted as being of Permo-Triassic to Early Jurassic age. They are thought to represent an inverted basin which annealed against the eastern margin of the deep ridge core and acted as a positive feature in late Mesozoic and Early Tertiary times.

The thickness variations and downlapping nature of the uppermost sequence (Lower Jurassic 2) is interpreted as syn-sedimentary growth within the hanging wall of a SE-dipping fault system located at the SE margin of the interpreted ridge core. Hangingwall subsidence resulting from such a fault would result in a general NW dip within the sedimentary succession and not the SE dip which is seen. The geometry of the observed SE dip, steepening towards the NW margin of the Ridge, can be modelled as footwall uplift on a younger

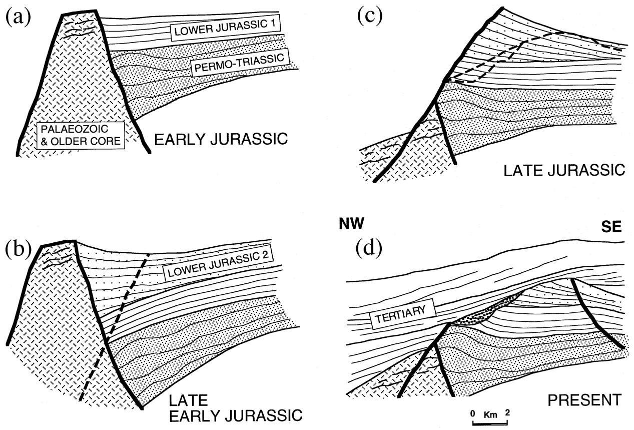

Fig. 4. Schematic diagram illustrating the development of the southern segment of the Erris Ridge (see Fig. 3). (**a**) Permo-Triassic rift strata overlain by Lower Jurassic thermal subsidence deposits which abut against an early Erris Ridge core composed of Palaeozoic and older basement. (**b**) Growth faulting on SE-dipping fault in latest Early Jurassic times. Dotted line indicates location of Late Jurassic NW-dipping fault. (**c**) Late Jurassic NW-dipping faulting resulting in footwall uplift towards the fault. Interpreted basement (relatively unclear on seismics) in hangingwall results from transpressional and/or strike slip movement on fault. Dotted lines indicate the limits of later erosion and the location of preserved terrace, scarp and footwall wastage deposits. (**d**) Line drawing interpretation of Fig. 3, showing the present morphology of the Ridge, onlapped by Tertiary strata.

(post-Lower Jurassic 2) fault. The slight NW dip observed in the Lower Jurassic 1 sequence towards the SE margin of the Ridge reflects footwall uplift on a smaller SE dipping fault. Figure 4 illustrates the suggested development of the southern segment of the Ridge.

The NW slope of the Ridge is likely to have been significantly modified by footwall erosion and mass wastage in post-Early Jurassic times. Evidence for this is preserved in the occasional terrace deposits shown on Fig. 3. These predate the onlapping interpreted Eocene–Lower Miocene strata and their angular relationship, albeit slight, with the underlying strata points to a post-Early Jurassic age. The SE margin of the terraces are steep but there is no evidence of faulting cutting the underlying Lower Jurassic strata. The sub-horizontal reflectors are interpreted as the product of terrace erosion associated with a sealevel stillstand following the major phase of faulting described above. These are overlain by a veneer of NW-dipping reflectors which are interpreted as the products of subsequent footwall wastage and scree collapse. These, in turn, are onlapped by the interpreted Eocene succession. While the available data do not allow the precise dating of the terrace succession, it is speculated that they may be of Late Jurassic age and may correspond in age to the rift deposits in the nearby Porcupine Basin (Shannon *et al.* 1995*a*). A minor phase of fault movement on the NW flank in pre-Eocene times appears to mark the last phase of major tectonic movement on the southern segment of the Ridge, although it appears to have remained as a topographic feature until Eocene times. This is in contrast to the northern segments which underwent probable Miocene fault reactivation.

The composition and development of the Erris Ridge and its environs provide an insight into the evolution of the flank area of the Atlantic passive margin. It is similar in orientation and structural setting to a number of elongate ridges, such as the Rona Ridge, in the West Shetlands region which separate the smaller inboard from the larger outboard basins. The variations in internal structure and external morphology point to the composite nature of the Erris Ridge. Its spine is suggested to be a Palaeozoic-covered deep-seated feature which controlled the location and development of Mesozoic and Cenozoic basin margins. It may represent a pre-Caledonian intraforeland thrust, parallel to, and along strike from, the Outer Isles Thrust (Lailey *et al.* 1989) which was suggested by Hitchen & Ritchie (1993) to have possibly formed the core of the Rona Ridge. Because of their deep structural root such structures were probably periodically reactivated during the development of the region and acted as rigid footwall blocks against which later sediments were sometimes annealed and incorporated into the ridge structure, as in the southern segment of the Erris Ridge. This ridge is thought to have served as the western footwall of the Erris Trough and the eastern footwall of the Rockall Trough with the Rona Ridge playing a comparable role separating the West Shetland and Faeroe–Shetland Basins. Similar ridges, albeit broader than the Erris and Rona Ridges, have been recorded on the flanks of passive margins in other areas where they also separate narrow landward basins from more extensive seaward basins. Examples include the Gamba and Lambarene Horsts offshore Gabon (Brink 1974).

The sediments which onlap and drape the Erris Ridge show a generally consistent onlapping pattern illustrative of a relative sealevel rise. The downlapping and prograding unit (Miocene scarp deposits) on the NW flank of the Erris Ridge in the northern segment reflects an interruption to this pattern with renewed faulting and footwall uplift on this segment of the Ridge. The general NW dip of the strata into the Rockall Trough is thought to be due to thermal subsidence following extensive rifting in the central part of the basin.

Overall the Erris Ridge, which is part of an extensive ridge system separating a band of narrow, typically early Mesozoic, basins from a band of larger and basins with a more prolonged history, lies along the shelf edge and coincides with the western boundary of major crustal thinning on the flank of the North Atlantic passive margin. Its location is probably ultimately controlled by inherited basement structural fabrics and it has acted as a barrier to crustal extension which was focused initially to the east during early Mesozoic times and later to the west in the Rockall Trough.

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