Marine Geology 229 (2006) 113 – 132

MARINE GEOLOGY
INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS

www.elsevier.com/locate/margeo

Mid- to Late Cenozoic canyon development on the eastern margin of the Rockall Trough, offshore Ireland

Gavin M. Elliott [a,*], Patrick M. Shannon [a], Peter D.W. Haughton [a], Daniel Praeg [a,1], Brian O'Reilly [b]

[a] *UCD School of Geological Sciences, University College Dublin, Belfield, Dublin 4, Ireland*
[b] *Dublin Institute for Advanced Studies, 5 Merrion Square, Dublin 2, Ireland*

Received 6 July 2005; received in revised form 17 March 2006; accepted 20 March 2006

Abstract

The sediment-undersupplied eastern margin of the Rockall Trough, west of Ireland, is incised by numerous canyons and slope failure features. Swath multibeam bathymetry has been integrated with 2D seismic profiles to constrain the Neogene evolution of the slope and its canyons. The morphology varies along the margin, with canyon heads located at mid-slope depths in the south but extending onto the shelf in the north. West of Porcupine Bank, slope gullies connect with a distributative channel system on the trough floor, while north of Porcupine Bank the basin floor is flat and featureless. Draped fault-blocks and deep structures exerted an important influence on slope gradients, canyon extent and geometry. A 'bottom driven' upslope–retrogressive slope failure mechanism is inferred for canyon formation. They were initiated by failure localisation following widespread slope rotation and instability linked to differential subsidence that produced a latest Eocene–early Oligocene (C30) regional unconformity. In the NE Rockall, where the greatest density of canyons occurs, a large mass failure wedge directly overlies the C30 surface and the seabed canyons have incised the upper part of the wedge. Axial profile data indicate that canyons in the NE Rockall Trough formed in Mid-Cenozoic times but were locally reutilised as sediment conduits during Plio-Pleistocene slope progradation.

© 2006 Elsevier B.V. All rights reserved.

Keywords: Rockall Trough; canyons; slope failure; Cenozoic; undersupplied

1. Introduction

Sediment-oversupplied slopes and continental margins continue to receive much attention in the literature (e.g. Gulf of Mexico: Weimer, 1990; Galloway et al., 1991; Nile River delta: Samuel et al., 2003; Rhone delta: Droz et al., 2001; Bonnel et al., 2005). These slopes are characterised by seaward progradation, often associated with major deltas linked to canyon systems that acted as conduits for sediment delivered to deep-water, particularly during sea level lowstands. Less attention has been given to sediment-undersupplied slopes. Undersupplied slope successions are typically relatively thin, lack evidence for major progradation and have an overall morphology that reflects primarily the underlying structural configuration. In addition, they can contain relatively old near-surface features. In this paper the

---

[*] Corresponding author. Present address: National Oceanography Centre, Southampton, European Way, Southampton, SO14 3ZH, UK. Tel.: +44 2380 594683; fax: +44 2380 596554.
E-mail address: gme@noc.soton.ac.uk (G.M. Elliott).

[1] Present address: Istituto Nazionale di Oceanografia e Geofisica Sperimentale (OGS), Trieste, Italy.

0025-3227/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.margeo.2006.03.008

evolution of the eastern margin of the Rockall Trough, a slope remote from sources of terrigenous input during much of the Mid- and Late Cenozoic, is investigated. Paradoxically, despite the limited sediment supply, numerous large canyons and erosional features traverse the slope.

The main aims of this study are to (1) document the slope morphology and underlying stratigraphy using seabed and subsurface acoustic data; (2) assess the history of canyon incision in the area, and (3) relate the canyon development to the Cenozoic tectono-stratigraphic evolution of the margin.

2. Regional setting

The Rockall Trough is a NE–SW trending, deep-water bathymetric feature on the northeast Atlantic continental margin, west of Ireland (Fig. 1). It is part of a regional complex of deep-water basins and intervening structural highs that resulted from crustal extension that accompanied opening of the North Atlantic Ocean (Doré et al., 1999). Water depths range from 200–500 m at the shelf-slope break, to >4000 m on the Porcupine Abyssal Plain in the south. The axis of the trough coincides with an underlying sedimentary basin, the Rockall Basin, which contains up to 6 km of Palaeozoic to recent deposits (Naylor et al., 1999; Morewood et al., 2004). The margins of the Rockall Trough are narrow and steep, with gradients typically 3–7° along the eastern margin, although locally exceeding 20°. Despite being an intracratonic feature, the flanks of the Rockall Trough approximate the shelf-slope morphology of simple ocean–continent margins.

A regional Cenozoic stratigraphic framework, based on unconformity-bound regional stratigraphic units, has been established for the Rockall and Porcupine basins (Stoker et al., 2001; McDonnell and Shannon, 2001). Three major erosional unconformities; C30 (late Eocene–early Oligocene), C20 (mid-Miocene) and C10 (early Pliocene), are identified within the Mid- to Late Cenozoic succession. They reflect regional changes in the patterns of sediment supply and oceanographic circulation, linked to plate reorganisations, and have been related to km-scale differential vertical (epeirogenic) tectonic movements (Stoker et al., 2005). The C30 unconformity is associated with large-scale differential subsidence and deepening of the Rockall Trough in latest Eocene times. This resulted in a westward rotation of the slope and was accompanied by the onset of bottom current activity that initiated major sediment drift accumulations on the trough floor (Wold, 1994; Howe et al., 1994; Stoker, 1998).

The Rockall Trough is an important oceanographic gateway in the North Atlantic circulation system with a complex stratified water column defined by water masses with different salinities and oxygen contents (Lonsdale and Hollister, 1979). The dominant modern bottom current circulation system involves northward flow along the eastern margin of the trough with a return flow south along the western margin. The distribution of contourite deposits suggests this pattern has persisted since the Pliocene (Stoker, 1997). This anti-clockwise circulation pattern has been important in the shaping of the margin through contour current sedimentation and erosion on the basin floor and margins (Unnithan et al., 2001).

Seabed features, consistent with mass failure, have been reported along the margins of the Rockall Trough since the 1970s. Clarke et al. (1970) suggested that gravitational sliding produced a prism of sediment found along the base of slope west of the Porcupine Bank. Surface morphology was examined using seismic reflection profiles by Roberts (1972, 1975), Flood et al. (1979) and Faugeres et al. (1981) and revealed a large region of slope failure on the eastern flank of the Rockall Bank. Sidescan sonar data have revealed the presence of numerous canyons along the eastern margin of the Rockall Trough (Kenyon, 1987; Unnithan et al., 2001; Shannon et al., 2001). Despite these studies, little is known about the timing and history of canyon formation.

3. Data and methods

This study integrated seabed imagery (multibeam bathymetry and sidescan sonar) with subsurface data (seismic reflection and 3.5 kHz echosounder profiles) from slopes on the eastern margin of the trough. This methodology has allowed both modern slope morphology and patterns of slope development through time to be constrained.

During the last six years, an extensive, predominantly multibeam swath bathymetric, survey of deep water Irish territorial waters, including the Rockall Trough and its flanks, has been carried out on behalf of the Geological Survey of Ireland. The dataset was gridded at 450 m grid spacing for examination of the overall morphology along the margin. The data were used to obtain bathymetric profiles along both the canyon axes and intercanyon slopes to help characterise their morphology along the eastern margin. Six canyons were selected for detailed study using a higher resolution 250 m grid.

Bathymetric data were complemented with TOBI sidescan sonar data obtained in 1998 on behalf of the

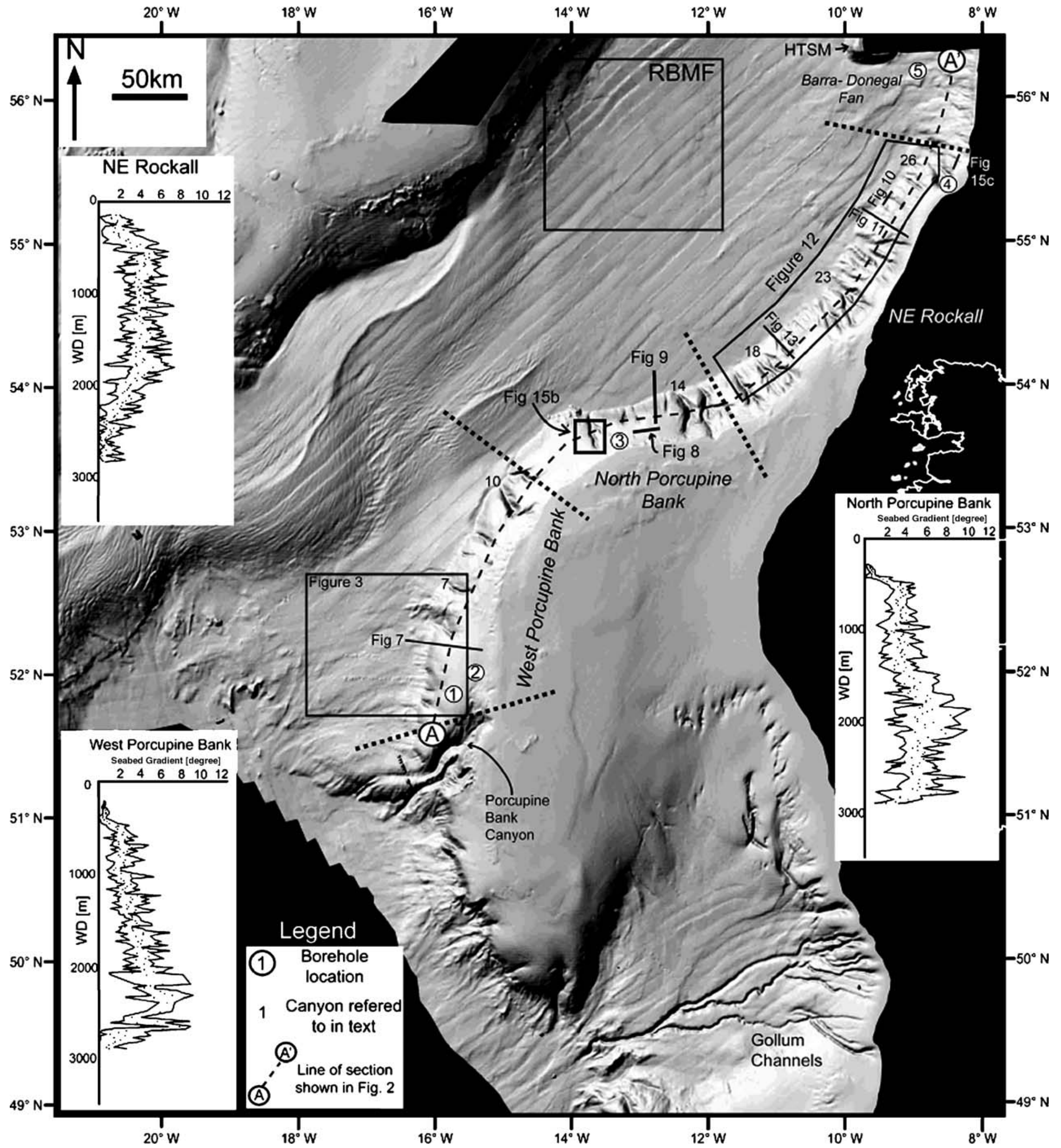

Fig. 1. Shaded relief bathymetric map of study area (bathymetry courtesy GSI), highlighting the highly incised eastern margin of the Rockall Trough and the canyon-free western margin. The parallel stripes on the basin floor are acquisition acoustic artefacts. Gradient analysis plots of seabed gradient against water depth for West Porcupine Bank, North Porcupine and N.E. Rockall. HTSM = Hebrides Terrace Seamount are shown as insets. RBMF = Rockall Bank Mass Flow. Boreholes and exploration wells: 1 = 83/24-sb01/-sb02, 2 = 83/20-sb01, 3 = 16/28-sb01, 4 = 12/13-1A and 5 = 5/22-1.

Rockall Studies Group (RSG). This survey did not cover the entire slope, being focused mainly upon the mid- to upper slope sections (see Shannon et al., 2001 for further details). Sidescan sonar data provides sediment textural and morphological information about the seabed and images subtle seabed features that the multibeam bathymetry cannot resolve (e.g. current lineations). The TOBI images are particularly powerful when draped on the bathymetric data (Mienert and Weaver, 2003).

In order to constrain evolution of the slope, various subsurface data, particularly shallow 3.5 kHz echosounder data acquired as part of the 1998 TOBI survey, were examined. Approximately 28,000 km of 2D exploration seismic profiles were also reviewed, with the densest coverage along the NE Rockall region. Further south along the Porcupine Bank the data density is limited for the lower slope and basin floor.

Lithological and age constrains on the seismic datasets are provided by a small number of hydrocarbon exploration wells (Fig. 1), complimented by four RSG stratigraphic boreholes tied to high-resolution site survey seismic profiles (Haughton et al., 2005).

4. Slope morphology

To facilitate analysis, the studied eastern slopes of the Rockall Trough were subdivided into four morphologically distinct zones: West Porcupine Bank, North Porcupine Bank, NE Rockall and Barra–Donegal Fan (Fig. 1). Each has different slope profiles, canyon densities and base-of-slope relationships. The surface morphology of each zone is described below, before the stratigraphic evidence for the slope development is assessed. The southern limit of the study area is the large Porcupine Bank Canyon system (Fig. 1), comprising three confluent axial channels, each with an axial length of ~60 km. The canyon complex is up to 800 m deep and strikes approximately NE–SW, oblique to the west-facing western flank of the Porcupine Bank. It was described by Unnithan et al. (2001) and is therefore not considered in any further detail here. The northern limit of the study area is the Hebrides Terrace Seamount (Fig. 1).

4.1. Surface morphology

4.1.1. West Porcupine Bank

The shelf-slope break west of the Porcupine Bank varies from c. 500 m in the south to c. 400 m in the north (Fig. 2), and base of slope shallows northwards from c. 2900 to c. 2600 m. The width of the slope ranges 30–45 km, with seabed gradients commonly 3–7°. The upper slope has low gradients (3–4°) with a change in the mid-slope to steeper gradients (4–7°) to produce a distally-steepening slope profile.

Canyons in this area are restricted to the steeper lower and mid-slope areas and do not breach the shelf-edge. The axial length of the canyons ranges 15–20 km with an incision density of c. 4 per 100 km. Headwall water depths decrease from south to north (c. 1600 to almost 700 m (Fig. 2). Canyons generally have a single axis and are orientated perpendicular to the west-facing slope. They are separated by steep (>5°) intercanyon slopes with a fluted appearance on the steeper lower slope due to numerous parallel linear channels or gullies up to 100 m deep. A series of erosional basin floor channels extend away from the base of slope and converge towards the Porcupine Abyssal Plain to the SW. Significantly, these channels are not linked updip to the canyon features but instead connect to intervening slope gullies. The steeper lower slope gradients rotate rapidly into the low gradient (<2°), westward-dipping basin floor. On the shallower part of the slope, two morphologically-distinct domains are distinguished: (1) a large southern region of smooth slope devoid of slope failure features and flanked along its upper limit by apparently fresh failure scarps and (2) an area of slope to the north that has numerous failure scarps surrounding canyon heads that extend further upslope (Fig. 3).

The canyon axes have convex-upward profiles with steeper (6–8°) upper sections and gentler (4–6°) lower sections (Fig. 4a–b). Sidewall and headwall gradients average ~10° and reach a maximum of ~20°. Typically, the southern canyon walls are steeper than the northern sidewalls (Fig. 5a–b). Tributaries, where developed, occur on the shallower northern canyon margins (Fig. 6). Canyon planforms vary from broadly straight with a sinuous axis to those with a gentle curvature (Fig. 6). They are mostly 1–4 km wide and 100–300 m deep (Fig. 5e). Canyons 7 and 10 are unusual, having incised up to 750 m into the slope although not connecting updip with the shelf break.

4.1.2. North Porcupine Bank

The shelf-slope break along the North Porcupine Bank is at c. 300–250 m. The base of slope occurs c. 2800 m and exhibits an abrupt change from the slope to a flat basin floor in contrast to the progressive shallowing seen west of the Porcupine Bank. The distally-steepening main slope profile observed further south is still apparent but is less pronounced. The width of the slope varies c. 25–40 km and gradients range 3–7°.

The North Porcupine Bank slope section is characterised by a number of large distributative canyons, some of which extend to the shelf-edge. The canyon lengths range from 20 to over 40 km (Fig. 2). Canyons may be confined to the slope (headwall WD range ~1500 m) or extend to the shelf edge (headwall WD c. 300–250 m). The density of the canyons is greater than

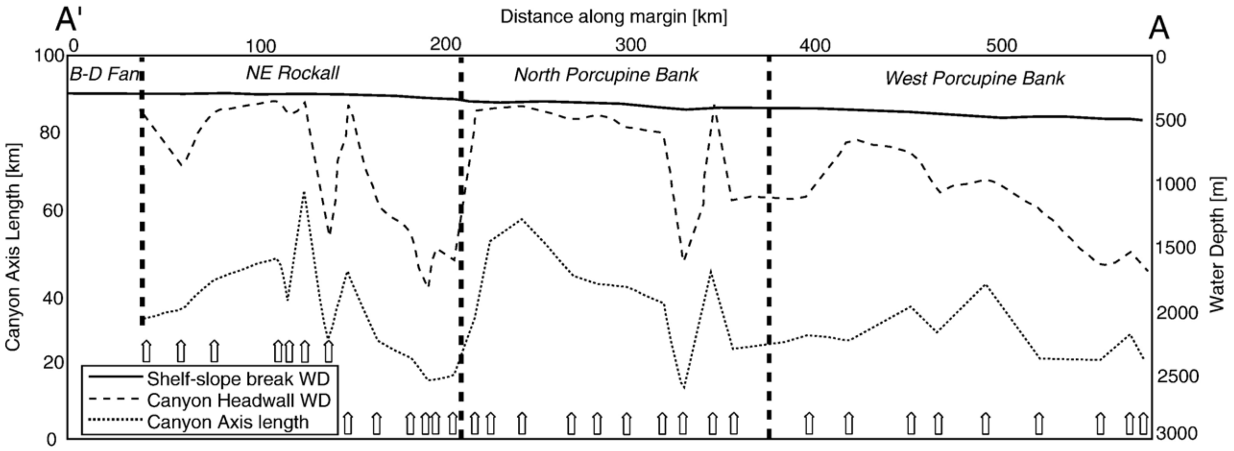

Fig. 2. Plot showing varying shelf break along the margin (500 m in south, 200 m in north). The canyon headwall position moves from a mid-slope position in the south to a predominantly shelf-edge breaching position in the north. Arrows indicate location of seabed canyon. See Fig. 1 for location of section A–A′.

seen further south (6/100 km) although the distribution in not uniform with large regions of non-incised slope separating more densely incised slope sections. The slope between the canyons is smooth and shows very little evidence of recent slope failure or channelling, even where slope angles exceed 5°. There is evidence that alongslope current activity is high, with sediment moats and lineations associated with large carbonate mounds found on the upper slope (Fig. 2 of O'Reilly et al., 2003).

In planform, most canyons are perpendicular to the regional slope. The upper reaches of some canyons have a 'cauliform' geometry with numerous branches and tributaries coalescing into a single large axial channel. On the lower slope, the canyon axes rotate to the west and pass onto a basin floor that is almost flat and devoid of any surface features such as channels or submarine fans. The canyon axial profiles in this region show a broadly concave-up profile with lower axial gradients (4–6°) than seen further south, but similar in shape to

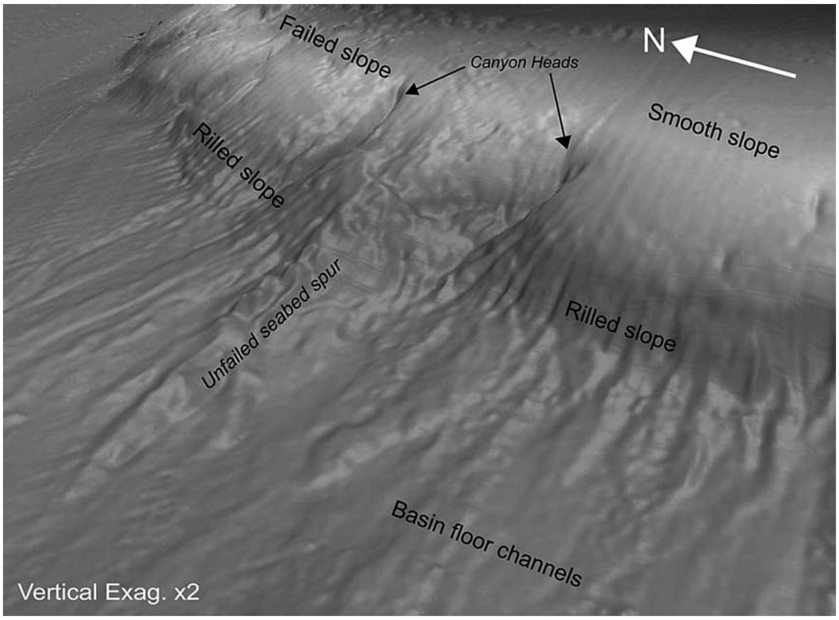

Fig. 3. Digital Elevation Model image of the base-of-slope in the southern part of the study area. The rilled base of slope can be seen to be 'feeding' out into the basin floor channel system that leads to the Porcupine Abyssal Plain.

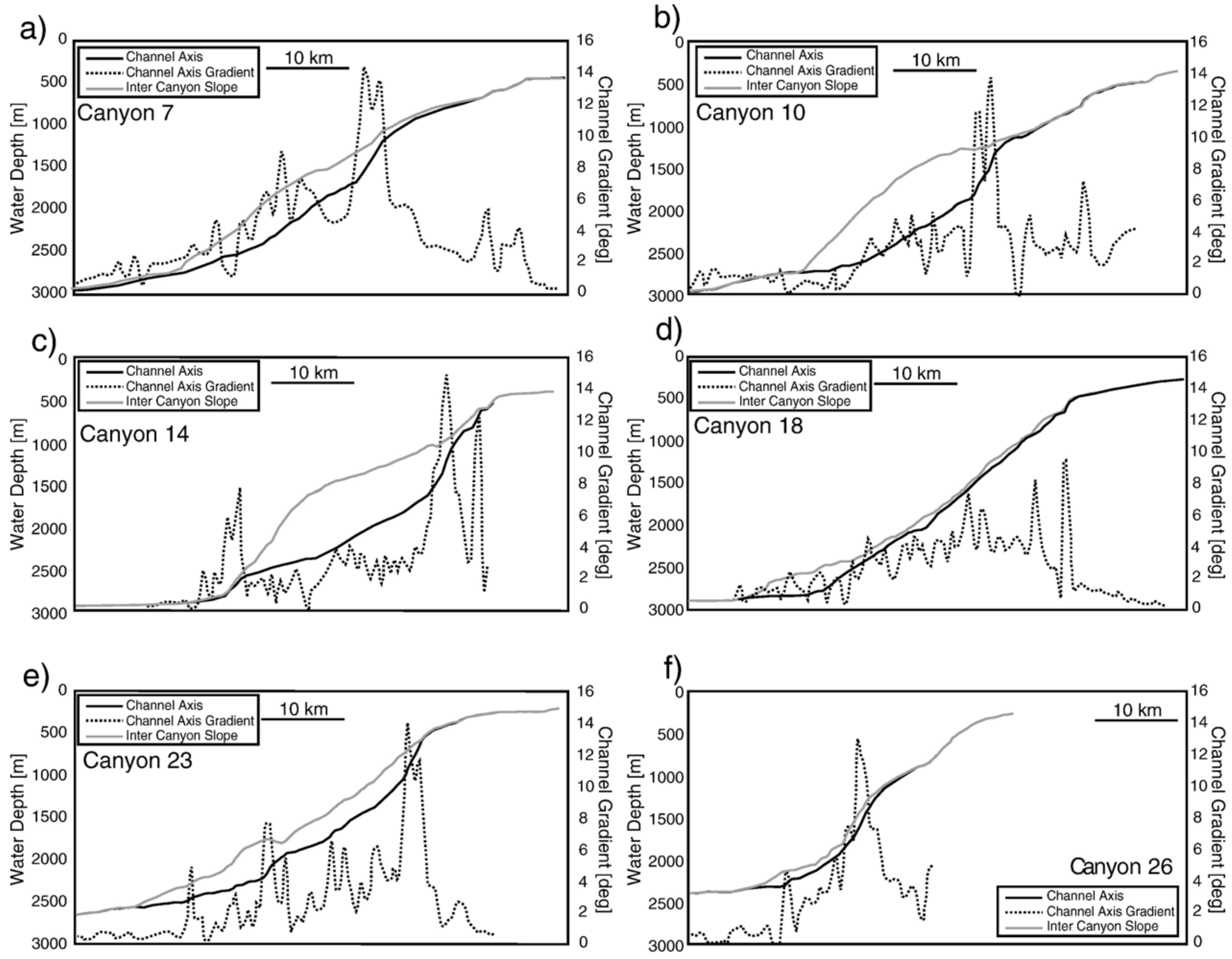

Fig. 4. a–f: Axial distance–depth profiles for the canyon axes, intercanyon slope and also channel axial gradient. Canyons 7, 10 and 26 are slope confined while canyons 14, 18 and 23 breach the shelf-edge. Axial profiles show a broadly concave-up profile in both canyon types. Basement influence can be seen clearly in (f) limiting the upslope extension of the canyon.

the flanking intercanyon slopes (Fig. 4c–d). Axial profiles show a sharp inflection point at the base of slope due to the extension of the near horizontal basin floor into the lower part of the canyons to onlap the canyon floor. Sidewall gradients are similar to those further south with an average of ~10° and maximum of up to 20°, but the cross-canyon asymmetry seen to the south is not observed (Fig. 5d). Width/depth ratios on this part of the margin are higher than those further south due to increased canyon width (up to 8 km), particularly in the headwall regions.

4.1.3. N.E. Rockall

The shelf-slope break along the NE Rockall sector is shallower than elsewhere, ranging from c. 250 to 200 m (Fig. 2). The base of slope continues to shallow progressively northwards from c. 2800 to c. 2100 m and the lower slope grades onto the basin floor. The width (25–60 km) remains similar to that further south, but the gradient is reduced (3–5°) and the profile has changed to a broadly convex-up profile, a more common characteristic of other margins around the world (O'Grady et al., 2000).

The NE Rockall slope has the highest density (c. 10/100 km) of canyon incisions along the margin with few areas of un-incised slope. Canyons length range from 15 to over 60 km, and are both slope-confined and more commonly shelf-edge breaching. Failure on non-canyonised slopes is rare but does occur in some locations producing headwall scarps up to 18 km long and 100 m high. No seafloor lineations or sediment waves are imaged on sidescan sonar data and carbonate mounds are notably absent, despite being common elsewhere along the margin on the upper slopes (O'Reilly et al., 2003).

Canyons on the NE Rockall slope have a broadly cauliform morphology with axial channels converging

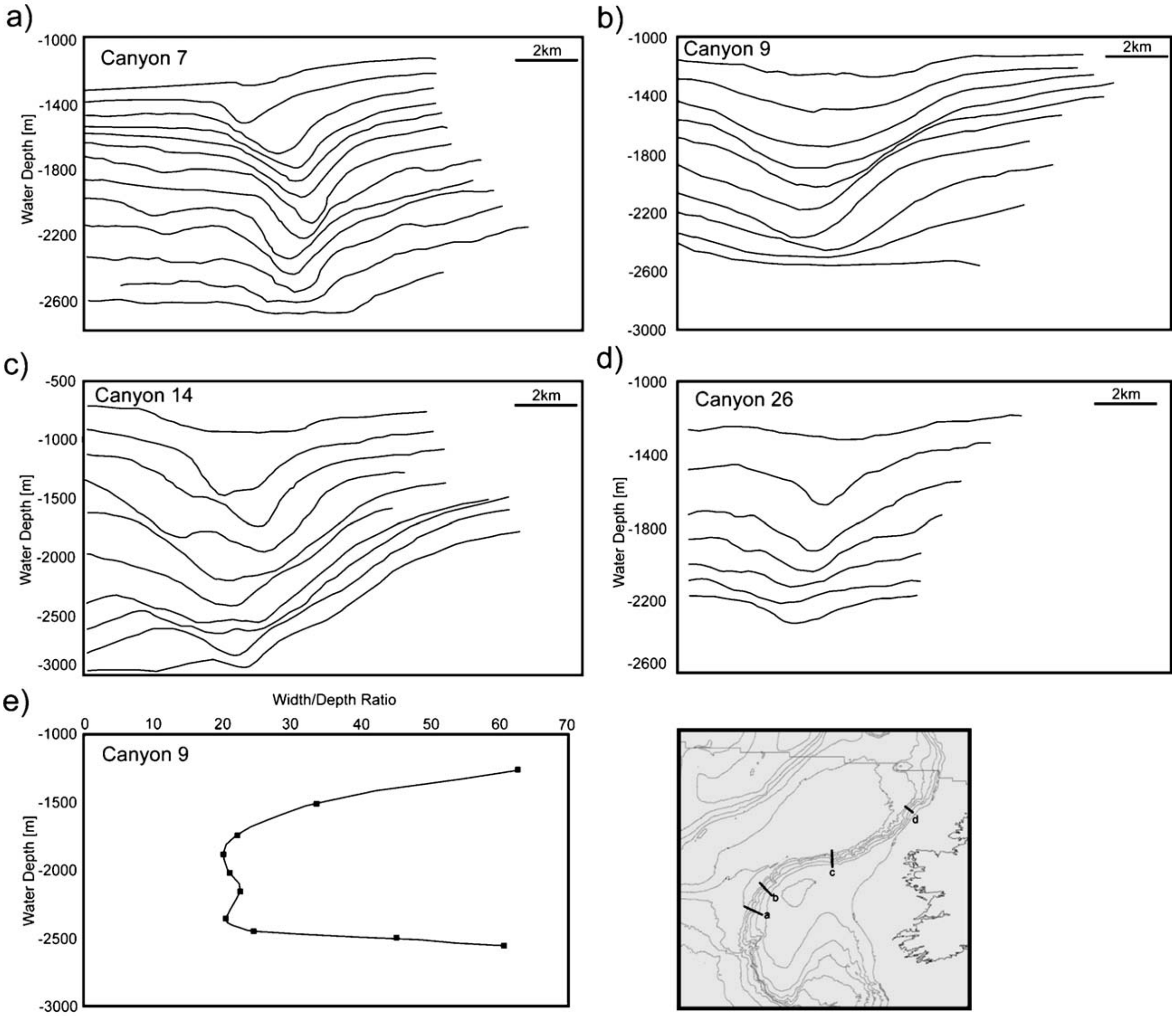

Fig. 5. a–e: (a–d) Cross-sectional distance–depth profiles across four canyons showing a change from broad 'U' shaped to 'V' shaped profiles. (e) Width–depth ratio plotted against depth for Canyon 9, highlighting the general pattern of large *W*/*D* in headwall and mouths decreasing into the body.

downslope to form a single, broad U-shaped channel. Canyons 18 and 23, which breach the shelf edge, have a gentle convex-up profile that broadly reflects the shape of the exterior slope (Fig. 4e–f). The lower reaches of the canyons merge with the basin floor implying backfilling rather than channel incision onto the basin floor. The canyon sidewalls have gradients of 10° to 13°, and width/depth ratios greater than 100 in the lower reaches of the canyon, reflecting the broad, shallow nature of the canyon mouths.

4.1.4. Barra–Donegal Fan slope

The slope spanning the UK/Ireland median line has no canyons. The shelf-edge is at c. 200 m and the base of slope is subtle with a gradient changes from 2° to >0.5° at c. 2000 m. The slope width increases from c. 30 km in the south to greater than 65 km adjacent to the median line. The seabed gradient (1–2°) is less than that seen elsewhere, with a maximum gradient at the shelf-edge.

The slope exhibits no slope escarpments but it is characterised by high backscatter returns on sidescan sonar, reflecting the presence of large (100 m deep) irregular scours producing an undulose seafloor. The upper slope is characterised by numerous shallow slope gullies that open onto the slope and lose their definition with a planform similar to the 'bottleneck slides' of Prior and Coleman (1979). This region also

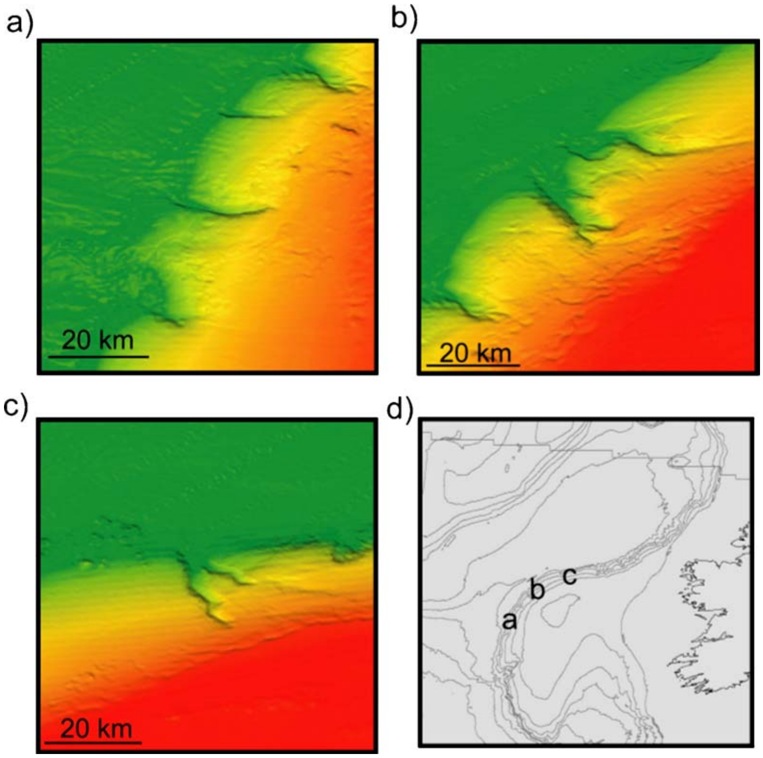

Fig. 6. (a) Image map of Canyon 7 highlighting its curved plan-form relative to the regional slope. (b) Canyon 10 showing a higher number of tributaries on the NE flank compared to the SW. (c) Sinuosity demonstrated by Canyon 12.

lacks carbonate mounds and indications of alongslope current activity.

5. Mid- to Late Cenozoic slope stratigraphy

Seismic stratigraphic relationships (McDonnell and Shannon, 2001; Stoker et al., 2001, 2005) were used to correlate the Cenozoic basin floor succession (up to 2 km thick) with the condensed section (<500 m thick) on the slope. Lithofacies and age control was provided by borehole and well data tied to reflection profiles. This analysis allowed the timing and style of slope development to be constrained, with implications for the initiation, growth and activity of the canyons.

5.1. West Porcupine Bank

Stratigraphic control along the West Porcupine Bank is limited to two boreholes described by Haughton et al. (2005). Three unconformity-bound Cenozoic packages were identified from these boreholes and shallow high-resolution seismic profiles: 1) lower to middle Eocene pelagic micrites, 2) Miocene bioturbated silty clays and 3) Plio-Pleistocene sandy clays. The late Eocene–early Oligocene C30 unconformity surface can be traced along the slope on seismic profiles, based on a tie to the 83/20-sb01 borehole, where it separates the Miocene from underlying Cretaceous. Regional correlation reveals that the slope is heavily eroded. Canyon incision truncates most major stratigraphic surfaces and the base of the canyons locally cut down into the Mesozoic strata (Fig. 7). The canyon axes are devoid of sediment infill, with only minor disrupted packages along the sidewalls. The seismic data show that the mid-slope canyon heads are primary features and are not the result of infilling of the upper parts of canyons that originally extending further upslope. The regions of smooth slope have a thin Cenozoic succession and exhibit truncation of seismic reflections at the seabed. Commonly regions of acoustic basement are imaged at the seabed and these are correlated with regions of high backscatter return on sidescan sonar.

The lower slope and base of slope is steep with an internally disrupted, mounded package found on the lower slopes but not on the basin floor. The base of this package is irregular and it is difficult to trace any regional stratigraphic surfaces through it. The canyons incise this package. The base of the slope and basin floor succession shows parallel, continuous reflections in which the regional stratigraphic unconformities surfaces

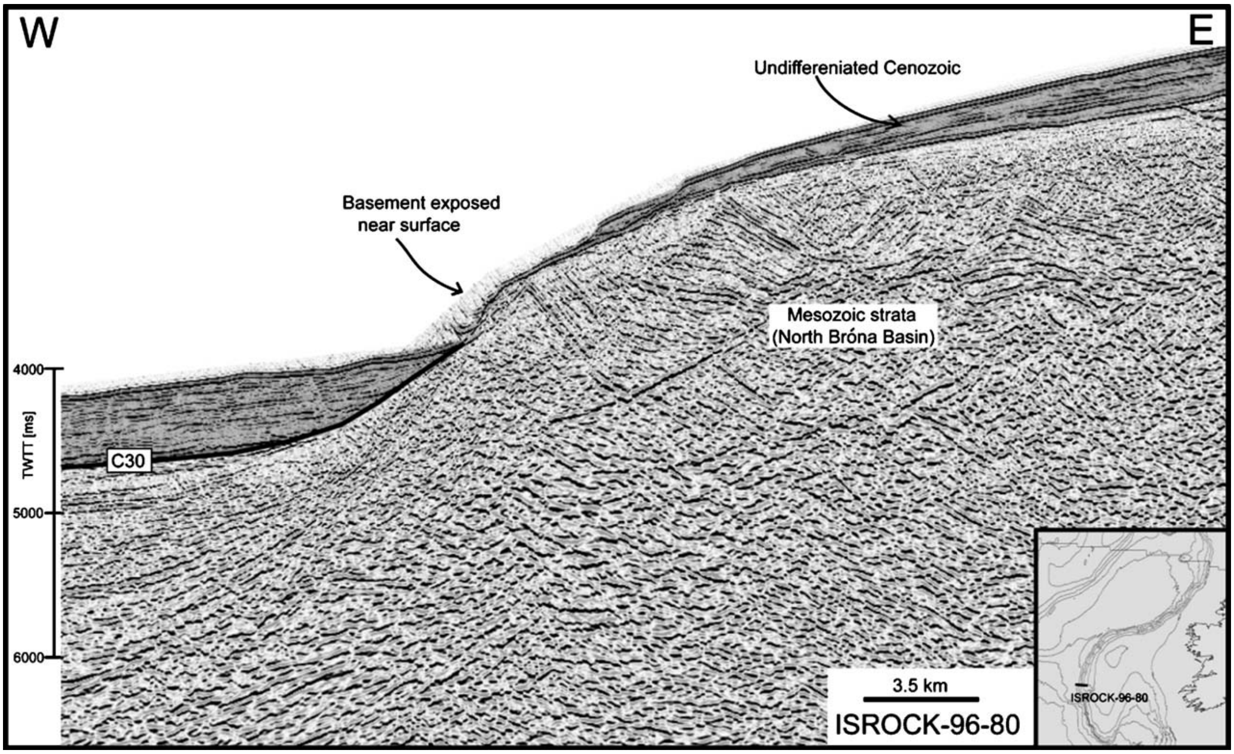

Fig. 7. 2D seismic profile from the West Porcupine Bank showing the controlling presence of Mesozoic basins and basement blocks upon the Cenozoic to present day slope morphology.

can be traced. The basinal package onlaps the base of slope, in particular the C30 unconformity surface, with no lobes or packages indicative of submarine fans.

5.2. North Porcupine Bank

Stratigraphic age control in this area is provided by borehole 16/28-sb01, described by Haughton et al. (2005) (Fig. 1). This borehole sampled the thin slope section and consists of Early–Mid-Eocene calcareous mudstones and sandstones (130 m thick) overlain by a veneer (c. 14 m) of Plio-Pleistocene sandy gravel. These Cenozoic strata overlie thin Cretaceous calcareous sandstone and a basalt in which the borehole terminated. The semi-coherent reflections associated with the Eocene succession exhibit internal disruption on high-resolution seismic profiles. The prominent C30 regional unconformity is absent in the borehole, although an unconformity is recognised on seismic profiles updip from the borehole. This surface truncates the Eocene package correlated to the borehole and therefore probably corresponds to C30.

Canyons incise into the Mesozoic succession and in some cases into acoustic basement. Internally the canyons show no internal fill, although some small internally disrupted packages are imaged along the sidewalls. Two infilled canyons (Fig. 8) are imaged on seismic profiles updip of the slope-confined canyons in a region of smooth unfailed seabed. These buried canyons are c. 300 ms TWTT deep and truncate reflections within the Eocene succession. The slope in this area is devoid of failure features. The C10 unconformity surface is very hard to recognise in this area but the carbonate mounds in the region have been shown to be rooted on an unconformity, suggested to be C10 (Van Weering et al., 2003).

The base of slope succession is similar to that further south with the basinal strata comprising parallel to wedge-shaped, coherent reflections punctuated by the regional unconformities. The C30 surface is onlapped by younger strata with an externally mounded geometry. The C10 unconformity is uneven, reflecting the top to the mounded strata, and is onlapped by parallel, post-C10 strata (Fig. 9). A base of slope wedge is recognised in the north of the area and is more pronounced along the NE Rockall margin.

5.3. NE Rockall

The Cenozoic chronostratigraphy of the NE Rockall slope is not well constrained because well 12/13-

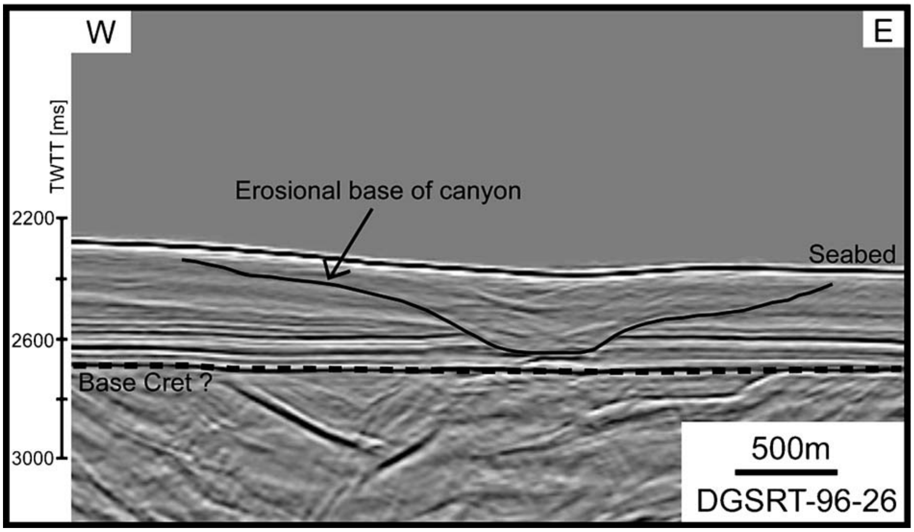

Fig. 8. Small buried canyon imaged on 2D seismic reflection line showing incision into Paleogene and Cretaceous strata. Significant seabed erosion has taken place with no Neogene strata remaining on the slope along much of the North Porcupine Bank.

1A, drilled in the Erris Basin to the east, recovered only a lower Cenozoic succession. Well 5/22-1, located on the Barra–Donegal Fan, records most of the Cenozoic succession and provides a good C30 pick that can be traced south along the NE Rockall slope.

The C30 and C10 surfaces can be traced widely through the base of slope and slope. There is no

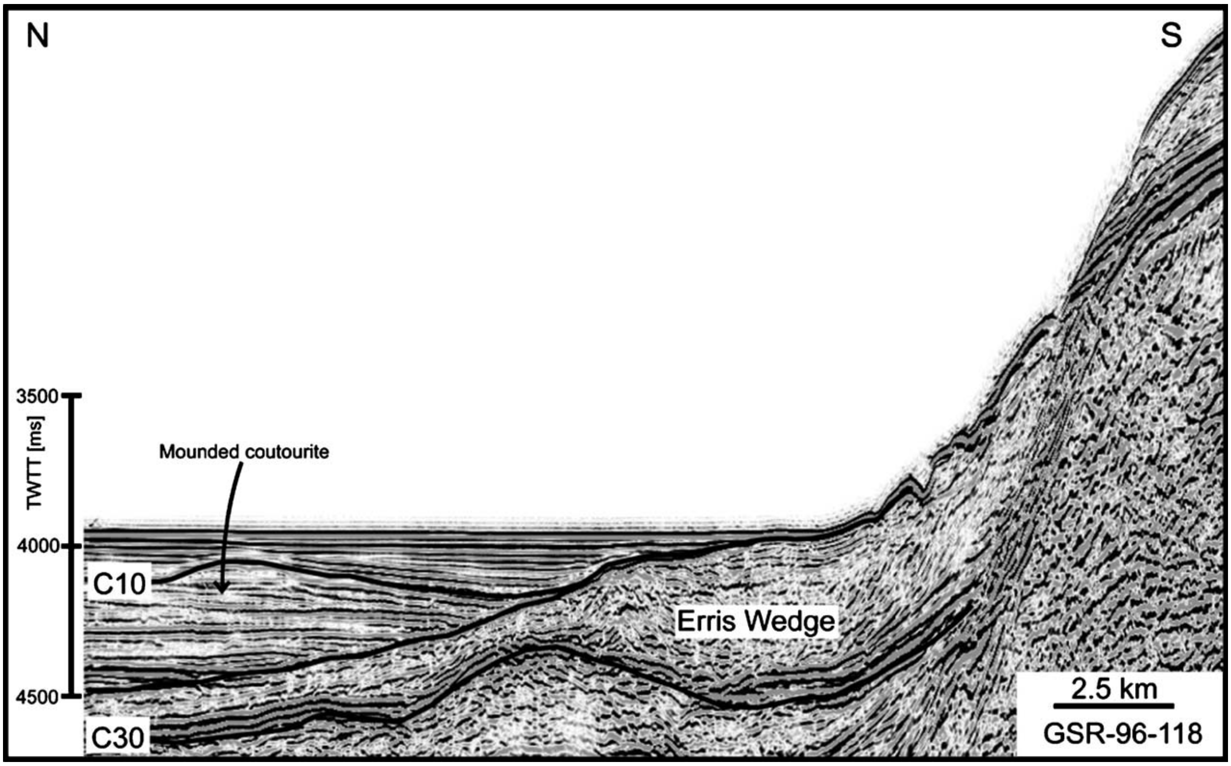

Fig. 9. Seismic reflection profile from the base of North Porcupine Bank. The C10 surface is erosional and is controlled by contouritic mounding producing an infilled and onlapped moat. This profile marks the southern edge of the Erris Fan, which becomes more prominent along the NE Rockall.

evidence of buried canyons but surficial ones incise the C30 to C10 succession. These are not infilled, although some are draped by continuous parallel reflections. The lower parts of the canyon axes are partially infilled and the C10 surface can be traced from the intercanyon slope into the fill (Fig. 10).

A large base of slope wedge overlies the C30 unconformity and dominates the lower slope and base of slope succession (Fig. 11). This basinward-thinning package, the Erris Wedge, can be traced from the North Porcupine Bank to the southern limit of the Barra–Donegal Fan. It varies little in thickness along strike with a maximum thickness c. 500 m. The upper surface of the Erris Wedge has been incised by canyons, resulting in local thinning of the wedge (Fig. 12). Internally the Erris Wedge shows two distinct seismic facies with a lower package of disrupted, non-continuous reflections grading into an upper package of sub-parallel, continuous reflections. The upper surface of the wedge is onlapped by basinal strata, generally along a single prominent surface, although multiple onlap surfaces are locally recorded along the upper surface of the wedge (Fig. 13). The post-Erris Wedge succession is composed of parallel, continuous reflections that onlap the wedge, with a thin lobe of seismically opaque material thinning onto the basin floor at the surface.

5.4. Barra–Donegal Fan

Three wells and a dense grid of seismic profiles elucidate the thick Cenozoic succession of the slope and basin floor in this region. The Barra–Donegal Fan consists of clinoforms that downlap the C10 surface and prograde the shelf-slope break by c. 10 km. The sub-C10 strata consist of a series of wavy, parallel, continuous reflections that onlap the C30 surface. There is no evidence of buried canyons or of significant slope failure in the strata between C10 and C30. The Erris Wedge pinches out at the southern limit of the Barra–Donegal Fan.

Large lobes imaged on the seafloor in this region are resolved on seismic data and have an opaque internal seismic character and abrupt terminus. The mid- to upper slope is composed of a mounded seismic facies with little internal structure, limited to the uppermost

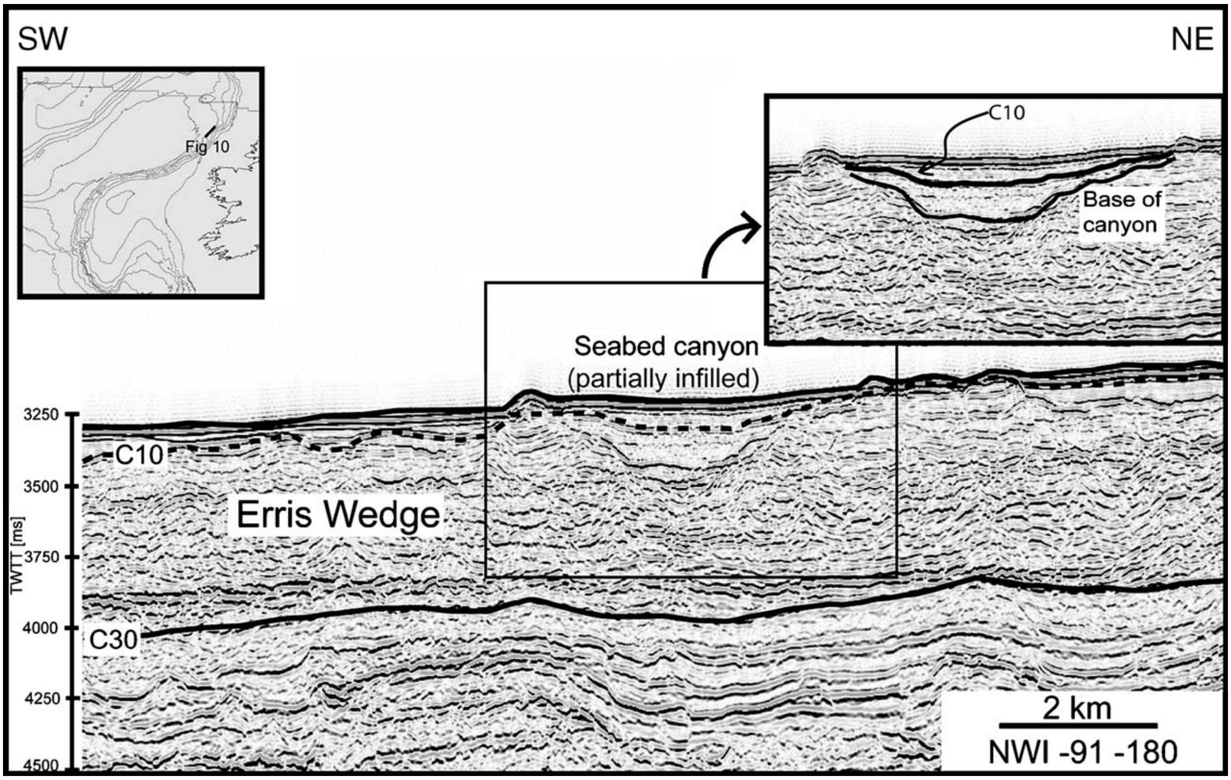

Fig. 10. 2D seismic reflection profile from the NE Rockall showing a partially infilled canyon with the regional C10 unconformity traced within the canyon fill. The canyon incises the failed wedge material, shown in Fig. 9, which does not truncate the C30 surface.

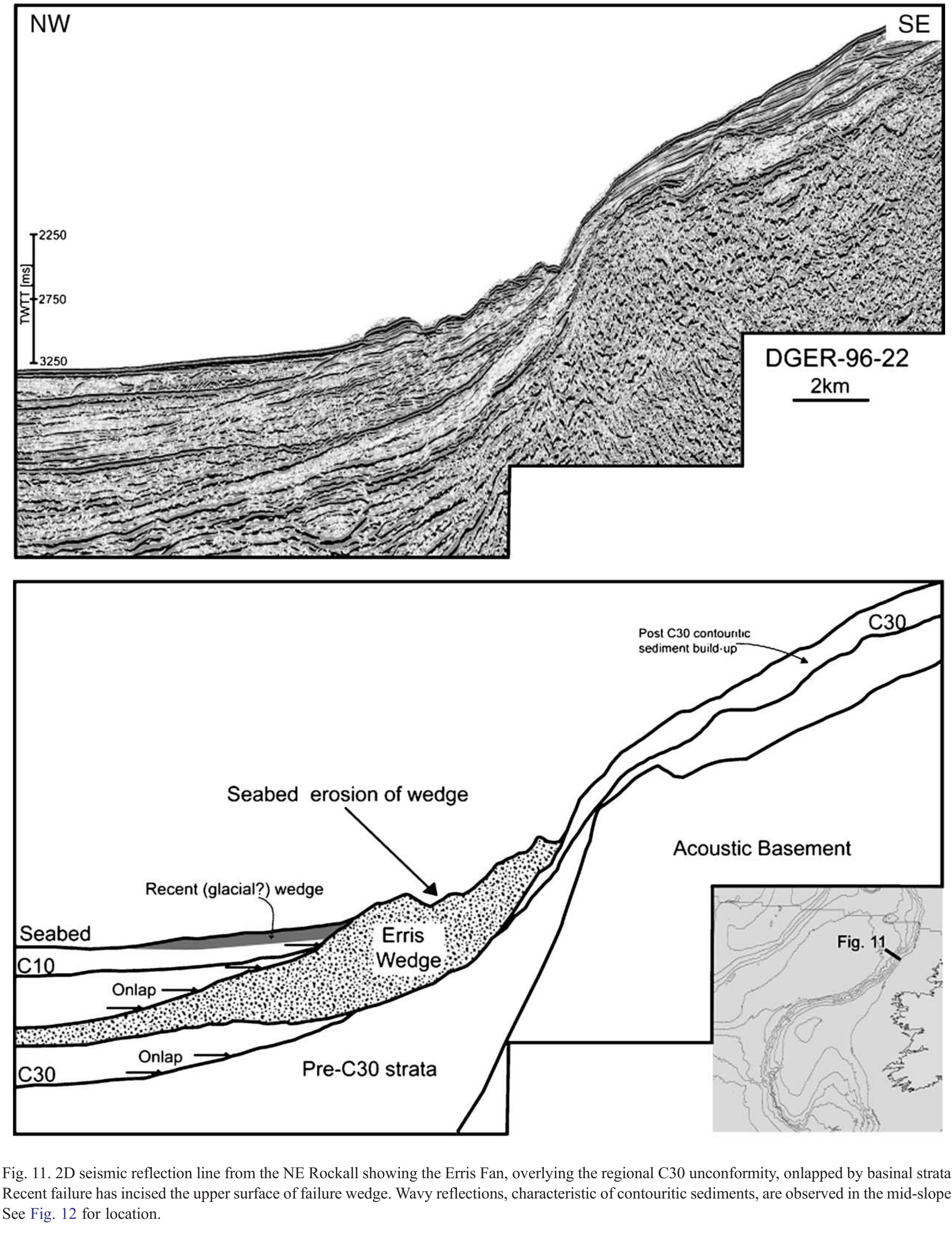

Fig. 11. 2D seismic reflection line from the NE Rockall showing the Erris Fan, overlying the regional C30 unconformity, onlapped by basinal strata. Recent failure has incised the upper surface of failure wedge. Wavy reflections, characteristic of contouritic sediments, are observed in the mid-slope. See Fig. 12 for location.

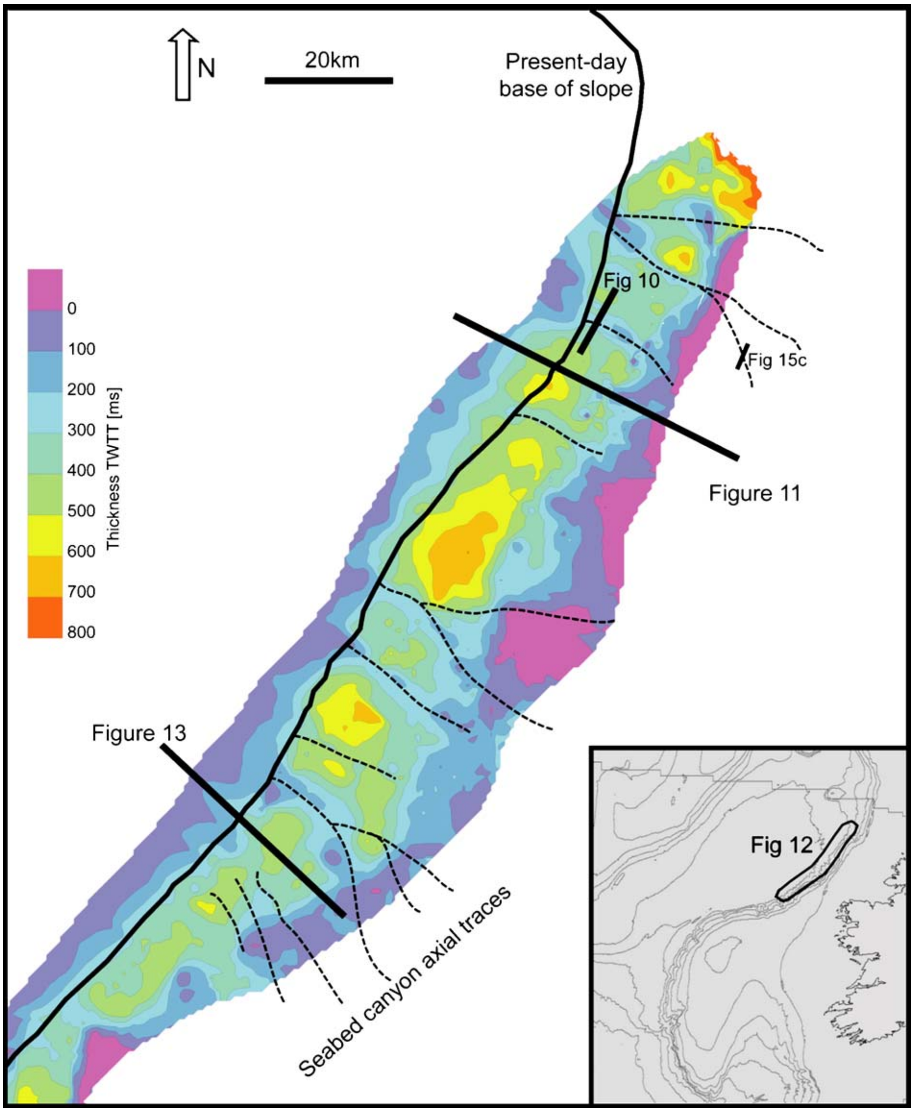

Fig. 12. Isopach map of Erris Fan showing the present day base of slope and canyon axes. The latter incise the wedge and terminate at the base of slope yet show buried extensions into the basin suggesting that outboard submarine fans may exist.

part of the seismic profiles above the C10 unconformity surface.

6. Interpretation

The Mid- to Late Cenozoic evolution of the eastern margin of the Rockall Trough and establishment of the modern slope varied from south to north (Fig. 14). Along the West Porcupine Bank, much of the Cenozoic stratigraphy has been removed by slope failure and canyon incision to leave a thin slope succession that drapes the Mesozoic perched basins along the flanks of the margin. Canyons restricted to the lower to mid-slope with a smooth to locally rugose upper slope characterise this part of the margin. The potential for up-dip sediment supply from the east to nourish flows that could have eroded the canyons is limited due to the presence of the Porcupine Basin to the east. This basin would have sequestered most sediment derived from the Irish mainland.

Glacial drawdown of sea level was insufficient to bring the shoreline onto the bank top, as the West Porcupine Bank is too deep (c. 500 m) to have been impacted by the 100 m sea level fall envisaged for glacial periods (Chappell and Shackleton, 1986). Proximal sediment supply via slope failure is therefore the most likely explanation for slope incision. Pratson et al. (1994), Pratson and Coakley (1996) suggested that

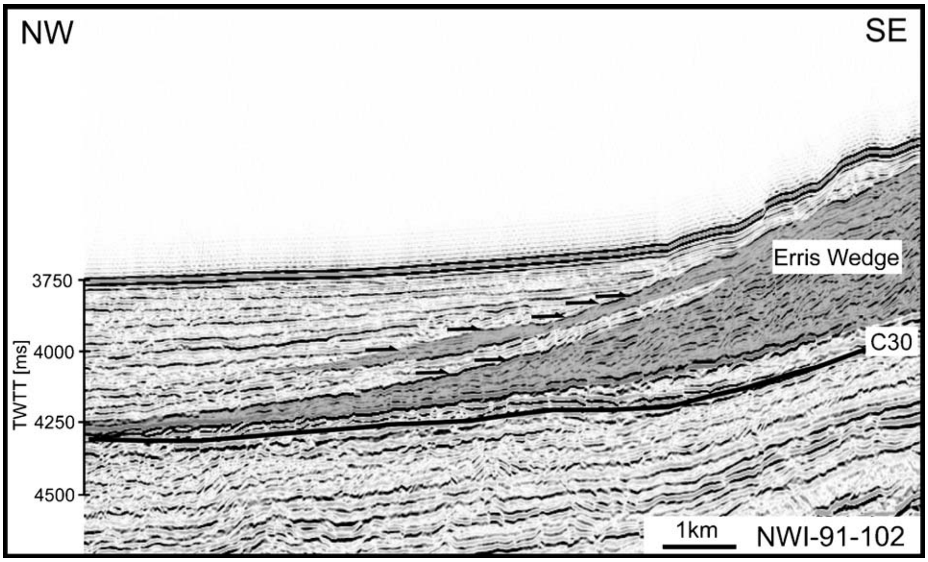

Fig. 13. 2D seismic profile of the Erris Fan with multiple onlap surfaces, interpreted as multiphase failures. See Fig. 12 for location.

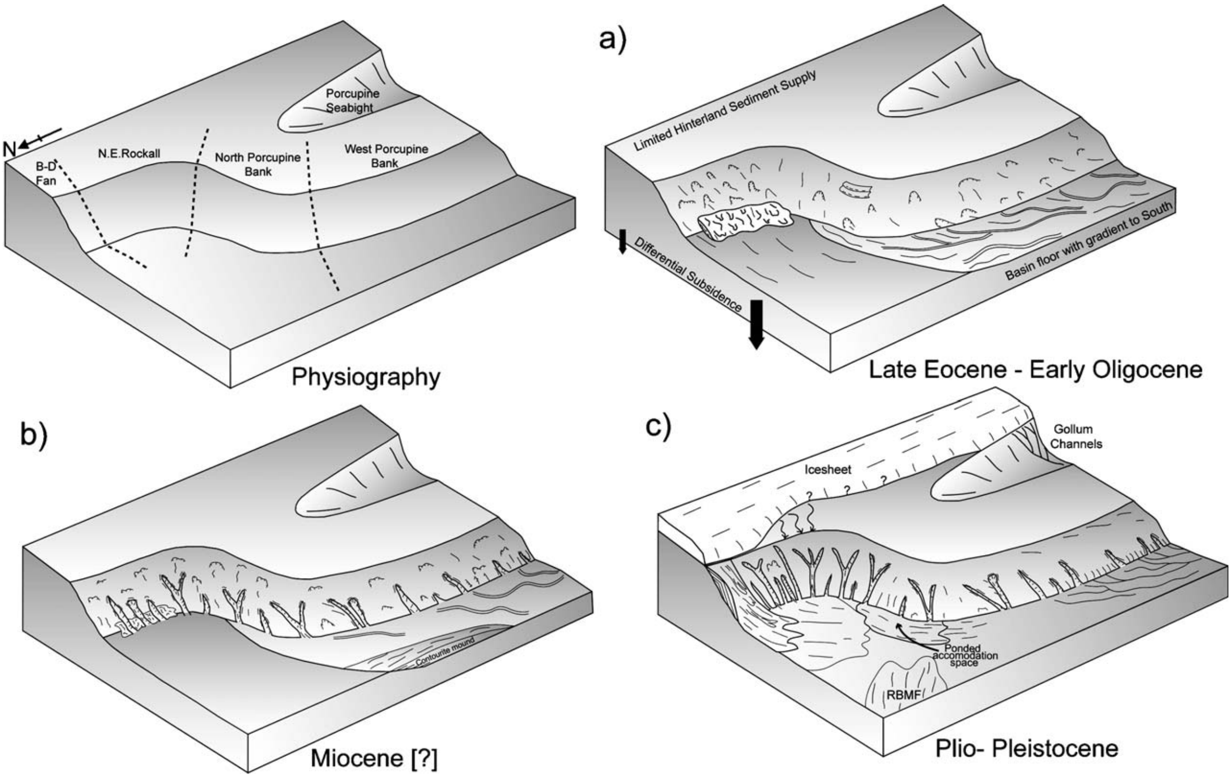

Fig. 14. Slope evolution model for the Mid- to Late Cenozoic of the western margin of the Rockall Trough. (a) Latest Eocene–Early Oligocene differential subsidence produced a regional slope, the C30 unconformity, promoted large-scale slope failure and initiated bottom current activity. The basin floor in south has a gradient towards the south promoting southward drainage. (b) Failure continued and localized to form canyons via retrogressive failure undermining of the upper slope. Flow evolution promoted the production of turbidity flows causing incision of failure wedge. Contouritic mounding infilled the basin floor producing significant topography. (c) Canyons retrogress to the shelf edge. Plio-Pleistocene tilting of the margin promoted shelf edge sediment supply, which utilised the canyons already available, backfilling those in the NE Rockall. Canyons along the NPB are infilled at the base of slope by contouritic sediments to give a flat basin floor.

slope failure and the passage of turbidity currents could promote canyon incision by triggering the formation of slope channels on the lower slopes (Fig. 14a). The formation of slope channels could lead to channelling of any further flow and initiate retrogressive headward failure and promote the growth of canyons. The headwall and sidewall gradients of the west Porcupine Bank examples are in excess of 10° and sharp slope failure scarps imply that the canyons have undergone sidewall and headwall failure. These failure processes are also supported by the presence of disrupted packages of sediment imaged on seismic profiles along the sidewalls of many of the canyons. The inferred upslope extension of the canyons, and the presence of a distally-steepening slope, are controlled by the presence of the perched basins and footwall highs beneath the trough margin (Fig. 7). As the slope is sediment-undersupplied, the condensed Cenozoic slope drape has not eliminated the original structural morphology of the slope.

Recent work (Øvrebø et al., 2006) suggested that the channels on the lower slopes of the West Porcupine Bank may be due to downslope sand transport triggered by contour currents. Occasional increases in the amount of alongslope sand transport can lead to an increase in the density of the nepheloid layer. This density increase at the mid-slope gradient change can trigger sandy density currents that erode the lower slope to produce the channels. Additionally, the STRATAGEM Partners (2003) suggested that the Porcupine Bank was a site of Plio-Pleistocene localised uplift and that this movement may have promoted slope failure.

Further north on the North Porcupine Bank slope segment, the canyon density increases and several canyons breach the shelf slope break while the occurrence of slope failure decreases. A supply of shelf sediment to the slope is possible as some canyons breach the shelf-edge, the shelf break is in close proximity of the Irish mainland, and there is no intervening inboard basin. However, the extension of the near horizontal post-C10 basin floor succession into the canyon mouths, and the way it onlaps the base of slope, suggest that the slope has been inactive since at least the Early Pliocene. Although there are failure scarps on the sidewalls of some of the canyons, evidence for intercanyon slope failure is rare (Fig. 15a–b). The sedimentary infill of the C10 topography at the base of slope apparently was not derived from the adjacent slope as the post-C10 package onlaps the C10 surface, and there are no indications of plunge pools, sours or sediment lobes emanating from the base of slope. The ultimate source of this fill is either distal flows from the Plio-Pleistocene Barra–Donegal Fan system to the northeast or even the mass failure complex on the flank of the Rockall Bank.

A possible scenario is that slope canyons originally connected with a SW axial drainage system on the trough floor (explaining the westward rotation of some canyons) but this was extensively modified by deep contour current activity prior to C10, producing the mounded C10 surface (Fig. 14a–c). Contouritic mounding may have disrupted subsequent axial trough drainage, providing ponded accumulation for the outflow from large gravity flow failures on the trough flanks.

On the mid- to upper slope, in the regions unaffected by canyon incision, large tracts of slope are devoid of slope failure scarps. High-resolution seismic profiles image detachments offsetting the Eocene succession indicative of gravitational sliding (Fig. 10a, Haughton et al., 2005). Two infilled canyon axes are imaged within the Eocene succession (Fig. 8) and, although they are not linked to the slope confined canyons downdip, it is possible that canyons such as these may have acted as foci for failure and the generation of the later large canyons during the Eocene. The lack of any significant proven Oligocene and Miocene strata along the North Porcupine Bank highlights the amount of erosion that has taken place. This erosion likely occurred post Mid-Eocene according to correlation with the failure encountered within the 16/28 borehole.

The highest density of canyon incision along the eastern trough margins is seen on the NE Rockall slope segment where the shelf break is closest to the Irish and UK mainland. The Erris Wedge overlying the C30 unconformity has an internally-disrupted seismic facies characteristic of a mass transport complex (Fig. 11). The upward-transition to a more organised reflector package represents the change from widespread, large volume, slope failure to turbidity currents derived from upslope failures. Unfocused failure evolved to apron development but gave way to focused supply and canyonisation. The consistent lateral thickness suggests that this wedge is a linear sourced apron. The wedge was incised by the canyons, suggesting that the canyons are younger than this Oligocene wedge. The lower parts of the canyon axes are buried beneath the basinal strata and extend beyond the dataset. Partial infilling of the lower part of the canyons can explain the axial profile shape (gentle concave-up) and this must have occurred during the late Miocene to Plio-Pleistocene, as the C10 unconformity can be traced through the lower canyon fill. This evidence provides an upper age limit to the formation of the canyons and indicates shelf supply was directed down the canyons to the basin floor (Fig. 15c). The large

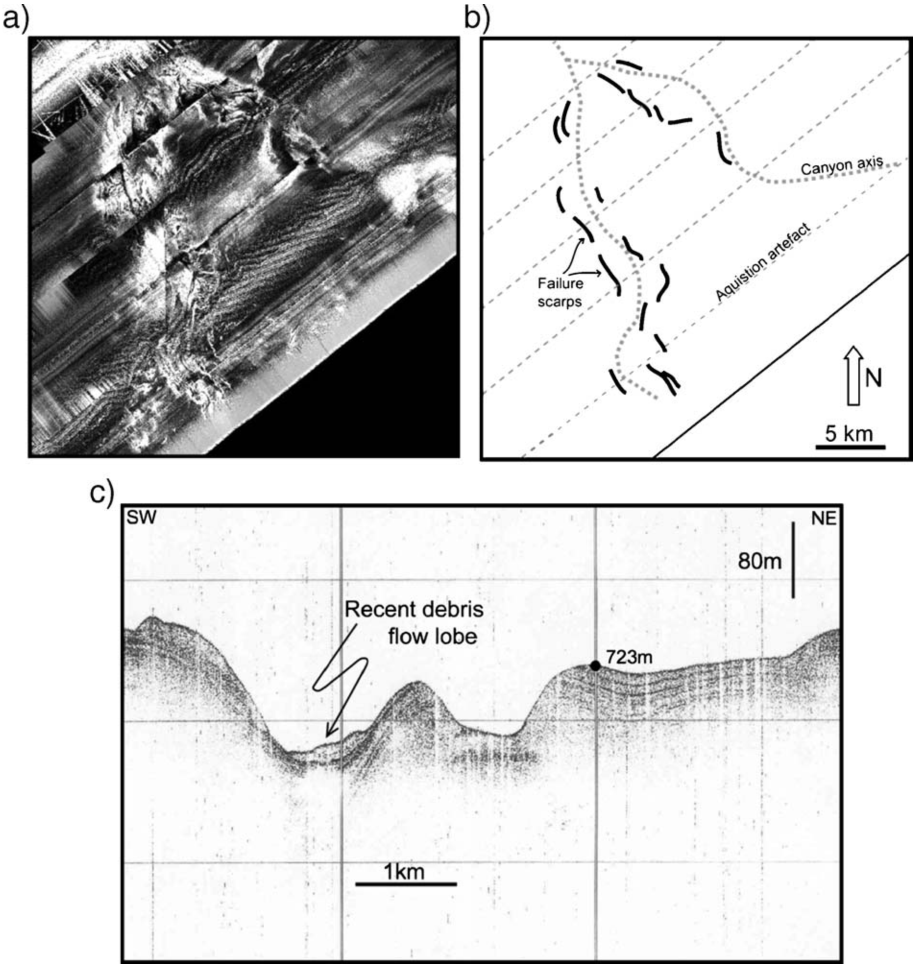

Fig. 15. (a–b) TOBI sidescan sonar image and interpretation from the North Porcupine Bank showing the canyon axis flanked by failure scarps indicative of sidewall collapse. (c) 3.5 kHz echosounder profile over the headwall region of a canyon with a debris flow lobe imaged in the axis, age is unknown but it may have originated due to sidewall collapse (see Fig. 1, 12 for location).

Plio-Pleistocene Barra–Donegal Fan, at the northern end of the slope strike transect, represents the southernmost part of a system of seaward-prograding shelf-slope wedges recognised along the NW European margin. These were initiated at the same time as the C10 unconformity, onto which the wedges downlap (Stoker et al., 2005). It is possible that the canyons had retrogressed upslope to breach the shelf-edge by the Pliocene and acted to bypass a component of the fluvial, and later glacial, sediment associated with the prograding wedge. Reutilisation of canyons may have modified their shape and explain the concave-up axial profiles. The last glacial maximum icesheet limit is thought to have been close to the present day shelf edge in this area and could have provided sediment to the canyons also and contributed to the infill of their lower parts. Cronin et al. (2005) presented gravity core evidence from the mouth of one of the canyons showing that glacial sands are present in water depths of c. 1500 m from an ice front that presumably retreated away from the slope break promoting canyon infilling.

7. Discussion

Large-scale slope failure and canyon initiation occurred on the Rockall margin in post-Late Eocene times immediately following the formation of the C30 unconformity surface. Despite being an undersupplied slope system from the Late Eocene, a variable pre-C30 sedimentary supply regime may have influenced the response of the slope to Late Eocene slope rotation. Moore and Shannon (1992) and subsequent workers recorded a series of Eocene deltaic sequences and submarine fans within the Porcupine Basin suggesting that this basin sequestered sediment delivered from the Irish mainland to the east. It is therefore likely that the

Erris Wedge consists of reworked sediment that was originally deposited through Eocene progradation of the margin.

An alternative interpretation is that the basin floor had a southern slope leading to the Porcupine Abyssal Plain. This regional slope may have fed any failure products towards the abyssal plain thus explaining the lack of large base of slope wedges as the basin floor was a conduit for sediment flow to the south. The increase in the amount of tributaries along the northern sidewalls would suggest sediment movement to the south due to a regional basinfloor dip. The buildup of contouritic sediment onlapping the C30 surface and the base of slope represents the aggradation of basin floor infilling the topography with mounded and sheet contourites. This mounded topography may be represented by the morphology of the C10 surface along the North Porcupine Bank, which was infilled by the distal limits of the Barra–Donegal Fan and also later slope failures along the Rockall Bank.

Basement and older syn-rift architecture is important in undersupplied slopes as there is only a thin drape of sediment overlying rotated fault blocks and the morphology is strongly influenced, over a long period of time, by underlying structure. This is evident along the eastern margin of the Rockall Trough where the upslope extension of some of the canyons has been limited by the presence of erosionally-resistant basement blocks close to the surface (Fig. 4f). Lallemand and Sibuet (1986) reported that canyons are commonly oriented along tectonic fabrics such as faults. This is not the case along the eastern margin of the Rockall, where the canyons are, on the whole, oriented normal to the slope in a region of few obvious NW–SE orientated faults and where the major fault systems are dominantly slope parallel (Naylor et al., 1999).

McGrane et al. (2001) and Kimbell et al. (2005) interpreted large (>500 km long) NW–SE deep-seated lineaments from gravity and magnetic measurements across much of the NE Atlantic margin. Two of these (the Anton Dohrn and the South Hatton lineaments) are of particular interest. The Erris Wedge and the highest frequency of canyon incision occurs between these two crustal lineaments. The difference in canyon incision might be explained by a difference in the Late Cenozoic subsidence, controlled by these deep crustal lineaments, within the basin.

The architecture and evolutionary model of canyon development along the eastern margin of the Rockall Basin has significance for understanding basin margin development in a global context. A universal characteristic of slope failures and canyon systems on basin margins is that they are controlled by a combination of steep slopes and sediment supply. The architecture of such systems reflects an interplay between subsidence and sedimentation. Sediment-rich margins, such as the eastern USA continental slope, are typified by clinoform progradation creating relatively steep slopes (albeit typically shallower than the Rockall Margin). These are cut by mass failure complexes and have a heavily canyon-incised slope. The failure complexes mainly occur on the mid- to lower slopes and their location is controlled by the steepness of clinoform foresets (McHugh et al., 2002). In contrast to those on the Rockall margin, the canyons are not confined to the margin below the shelf-slope break but cut the entire slope, are commonly linked to fluvial and glaciofluvial systems on the shelf (O’Leary, 1996) and act as major slope bypass conduits.

The Nova Scotia margin is also characterized by canyon incision and tabular slope failures, similar in broad appearance to those on the Rockall margin. Mosher et al. (2004) described canyon systems, deeply incised and with retrogressive headwalls cutting slopes of typically 2–4°. In common with the Rockall margin (Øvrebø et al., 2006) periods of sediment failure appear to correspond with glacial advances. However, in contrast, the Neogene (and especially the Plio-Pleistocene) succession on the Scotian margin is thicker, the slopes are shallower (probably due to a higher Plio-Pleistocene glacial sediment flux) and the canyons generally reach the shelf-slope break. Mosher et al. (2004) attributed the failures to glacially-related triggers, with other possible causes including earthquakes, salt tectonics and fluid escape. While these factors could have played a role in triggering sediment failure on the Rockall margin, unlike the Scotian margin, the main initial canyon formation is pre-glacial.

The slopes and margins associated with major deltas such as the Gulf of Mexico (Galloway et al., 1991), the Nile River delta (Samuel et al., 2003) and the Rhone delta (Bonnel et al., 2005) show similar characteristics, with the delta linked directly to the canyon systems which act as conduits for sediment delivered to deep-water basin floor fans. The Celtic Sea/Bay of Biscay margin (Droz et al., 2001; Zaragosi et al. 2001) has a broadly similar passive margin setting to the Rockall Trough and is also heavily incised by multiple canyon systems. In this passive margin setting, like that of the Rockall Trough, the basin margin slopes are produced by crustal thinning and associated lithospheric thermal plume patterns (Praeg et al., 2005) rather than by sediment progradation. They are also typically old and inherited from earlier rift or basement geometries, with only modification from the post-rift sedimentation. Unlike the Rockall Trough, where there is limited supply of shelf-derived sediment due to its distal setting, the canyon systems in the Celtic/Biscay margin are supplied by large shelf drainage systems and bypass the slope through extensive incision to feed large deep-water basin floor fans. Characteristic differences therefore occur between basin margins where there is a high sedimentation rate fed by a copious supply of shelf-derived sediments and those, typified by the Rockall Trough margin, which are sediment-undersupplied or sediment-starved and where the sediment supply is limited to slope reworking.

8. Conclusions

1. New bathymetric evidence from the eastern margin of the Rockall Trough show that numerous canyons incise its steep (3–7°) slopes. The canyons in the north of the study area have no extension onto the basin floor, whereas in the south a channel system is seen extending across the modern trough floor. These channels cannot be tied back to the main canyons. Instead the channel network seems to issue from erosional lower slope gullies between the canyons.
2. Canyons are classified into those that breach the shelf edge and those that do not. The position of the headwall on the slope is controlled by the presence of local basement highs close to the surface that limited upslope propagation of the incisions.
3. The initiation of widespread slope failure is thought to have occurred from the latest Eocene and closely postdates the regional C30 unconformity. Rapid deepening of the basin at this time lead to the formation of the slope and triggered mass failure that localised and evolved into canyon incision.
4. The canyons cut the C30 unconformity but are cut by the C10 unconformity. They likely formed in latest Eocene to Oligocene times and are clearly pre-Pliocene in age.
5. Alongslope contour currents are important in shaping the lower slopes of the West Porcupine where extensive rilling and a basin floor channel system may have resulted from the spilling-off of sediment-laden currents promoting erosion.
6. Present day canyon activity is limited to occasional sidewall collapse but during the Plio-Pleistocene the canyons in the NE Rockall were active sediment conduits for shelf derived sediment feeding onto the Barra–Donegal Fan
7. A retrogressive 'bottom driven' model for the formation of the canyons along the eastern Rockall Trough is proposed. This can explain the presence of canyons restricted to a mid-slope position. The Rockall canyons are therefore inferred to be relatively old features that persist due to the under-supplied nature of the margin.

Acknowledgements

The Geological Survey of Ireland is thanked for access to the Irish National Seabed Survey Zone 3 swath bathymetry data. The seismic reflection and well data were provided by the Petroleum Affairs Division of the Department of Communications, Marine and Natural Resources. The Rockall Studies Group of the Irish Petroleum Infrastructure Program is thanked for the provision of the TOBI and 3.5 kHz data on Fig. 15. GE is supported by an Enterprise Ireland Scholarship. The paper benefited from the comments and suggestions of the referees.

References

Bonnel, C., Dennielou, B., Droz, L., Mulder, T., Berne, S., 2005. Architecture and depositional pattern of the Rhone Neofan and recent gravity activity in the Gulf of Lions (western Mediterranean). Mar. Pet. Geol. 22 (6–7), 827–843.

Chappell, J., Shackleton, N.J., 1986. Oxygen isotopes and sea level. Nature 324, 137–140.

Clarke, R.H., Bailey, R.J., Taylor Smith, D., 1970. Seismic reflection profiles of the continental margin west of Ireland. Geology of the Eastern Atlantic Continental Margin IGS Report 70/14. HMSO, pp. 67–76.

Cronin, B.T., Akhmetzhanov, A.M., Mazzini, A., Akhmanov, G., Ivanov, M., Kenyon, N.H., 2005. Morphology, evolution and fill: implications for sand and mud distribution in filling deep-water canyons and slope channel complexes. Sediment. Geol. 179 (1–2), 71–97.

Doré, A.G., Lundin, E.R., Jensen, L.N., Birkeland, Ø., Eliassen, P. E., Fichler, C., 1999. Principal tectonic events in the evolution of the northwest European Atlantic margin. In: Fleet, A.J., Boldy, S.A.R. (Eds.), Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference. Geol. Soc, London, pp. 41–61.

Droz, L., Kergoat, R., Cochonat, P., Berne, S., 2001. Recent sedimentary events in the western Gulf of Lions (western Mediterranean). Mar. Geol. 176 (1–4), 23–37.

Faugeres, J.-C., Gonthier, E., Grousset, F., Poutiers, J., 1981. The Feni Drift: the importance and meaning of slump deposits on the eastern slope of the Rockall Bank. Mar. Geol. 40, 49–57.

Flood, R.D., Hollister, C.D., Lonsdale, P., 1979. Disruption of the Feni Sediment drift by debris flows from Rockall Bank. Mar. Geol. 32, 311–334.

Galloway, W.E., Dingus, W.F., Paige, R.E., 1991. Seismic and depositional facies of Paleocene–Eocene Wilcox Group Submarine canyon fills, Northwest Gulf Coast, USA. In: Link, M.H., Weimer, P. (Eds.), Seismic Facies and Sedimentary Processes of Submarine Fans and Turbidite Systems. Springer-Verlag, New York, pp. 247–271.

Haughton, P.D.W., Praeg, D., Shannon, P.M., Harrington, G., Higgs, K., Amy, L., Tyrrell, S., Morrissey, T., 2005. First results from shallow stratigraphic boreholes on the eastern flank of the Rockall Basin, offshore western Ireland. In: Doré, A.G., Vining, B.A. (Eds.), Petroleum Geology: North-West Europe and Global Perspectives. Geol. Soc., London, pp. 1077–1094.

Howe, J.A., Stoker, M.S., Stow, D.A.V., 1994. Late Cenozoic sediment drift complex, Northern Rockall Trough, North Atlantic. Paleoceanography 9 (6), 989–999.

Kenyon, N.H., 1987. Mass wasting features on the continental slope of northwest Europe. Mar. Geol. 74, 57–77.

Kimbell, G.S., Ritchie, J.D., Johnson, H., Gatliff, R.W., 2005. Controls on the structure and evolution of the NE Atlantic margin revealed by regional potential field imaging and 3D modeling. In: Doré, A.G., Vining, B.A. (Eds.), Petroleum Geology: North-West Europe and Global Perspectives. Geol. Soc., London, pp. 933–946.

Lallemand, S., Sibuet, J.-C., 1986. Tectonic implications of canyon directions over the northeast Atlantic continental margin. Tectonics 5, 1125–1143.

Lonsdale, P., Hollister, C.D., 1979. A near-bottom traverse of Rockall Trough: hydrographic and geologic inferences. Oceanol. Acta 2, 91–104.

McDonnell, A., Shannon, P.M., 2001. Comparative Tertiary stratigraphic evolution of the Porcupine and Rockall Trough. In: Shannon, P.M., Haughton, P.D.W., Corcoran, D.V. (Eds.), The Petroleum Exploration of Ireland's Offshore Basins. Geol. Soc., London, Spec. Publ., pp. 323–344.

McGrane, K., Readman, P.W., O'Reilly, B.M., 2001. Interpretation of transverse gravity lineaments in the Rockall Basin. In: Shannon, P. M., Haughton, P.D.W., Corcoran, D.V. (Eds.), The Petroleum Exploration of Ireland's Offshore Basins. Geol. Soc., London, Spec. Publ., pp. 393–399.

McHugh, C.M.G., Damuth, J.E., Mountain, G.S., 2002. Cenozoic mass-transport facies and their correlation with relative sea-level change, New Jersey continental margin. Mar. Geol. 184, 295–334.

Mienert, J., Weaver, P.P.E., 2003. European Margin Sediment Dynamics: Side-Scan Sonar and Seismic Images. Springer-Verlag, Berlin, p. 309.

Moore, J.G., Shannon, P.M., 1992. Paleocene–Eocene deltaic sedimentation, Porcupine Basin, offshore Ireland and a sequence stratigraphic approach. First Break 10, 461–469.

Morewood, N.C., Shannon, P.M., Mackenzie, G.D., 2004. Seismic stratigraphy of the southern Rockall Basin: a comparison between wide-angle seismic and normal incidence reflection data. Mar. Pet. Geol. 21, 1149–1163.

Mosher, D.C., Piper, D.J.W., Campbell, D.C., Jenner, K.A., 2004. Near-surface geology and sediment-failure geohazards of the central Scotian Shelf. AAPG Bull. 88, 703–723.

Naylor, D., Shannon, P.M., Murphy, N.J., 1999. Irish Rockall Basin region — a standard structural nomenclature system. Petroleum Affairs Division, Special Publication, 1/99.

O'Grady, D.B., Syvitski, J.P.M., Pratson, L.F., Sarg, J.F., 2000. Categorising the morphologic variability of silliclastic passive continental margins. Geology 28, 207–210.

O'Leary, D.W., 1996. The timing and spatial relations of submarine canyon erosion and mass movement on the New England continental slope and rise. In: Gardiner, J.V., Field, M.E., Twichell, D.C. (Eds.), Geology of the Seafloor: View from GLORIA. Cambridge Univ. Press, Cambridge.

O'Reilly, B.M., Readman, P.W., Shannon, P.M., Jacob, A.W.B., 2003. A model for the development of a carbonate mound population in the Rockall trough based on deep-towed sidescan sonar data. Mar. Geol. 198, 55–66.

Øvrebø, L.K., Haughton, P.D.W., Shannon, P.M., 2006. A record of fluctuating bottom currents on the slopes west of the Porcupine Bank, offshore Ireland — implications for Late Quaternary climate forcing. Mar. Geol. 225, 279–309.

Praeg, D., Stoker, M.S., Shannon, P.M., Ceramicola, S., Hjelstuen, B. O., Laberg, J.S., Mathieson, A., 2005. Episodic Cenozoic tectonism and the development of the NW European 'passive' continental margin. Mar. Pet. Geol. 22, 1007–1043.

Pratson, L.F., Coakley, B.J., 1996. A model for the headward erosion of submarine canyons induced by downslope-eroding sediment flows. Geol. Soc. Amer. Bull. 108, 225–234.

Pratson, L.F., Ryan, W.B.F., Mountain, G.S., Twichell, D.C., 1994. Submarine canyon initiation by downslope-eroding sediment flows: evidence in Late Cenozoic strata on the New Jersey continental slope. Bull. Geol. Soc. Am. 106, 395–412.

Prior, D.B., Coleman, J.M., 1979. Submarine landslides — geometry and nomenclature. Z. Geomorphol. N.F. 23, 415–426.

Roberts, D.G., 1972. Slumping on the eastern margin of the Rockall Bank, North Atlantic Ocean. Mar. Geol. 13, 225–237.

Roberts, D.G., 1975. Marine geology of the Rockall Plateau and Trough. Philos. Trans. R. Soc. Lond. Ser. A: Math. Phys. Sci. 278, 447–509.

Samuel, A., Kneller, B., Raslan, S., Sharp, A., Parsons, C., 2003. Prolific deep marine slope channels of the Nile Delta, Egypt. Bull. Am. Assoc. Pet. Geol. 87, 541–560.

Shannon, P.M., O'Reilly, B.M., Readman, P.W., Jacob, A.W.B., Kenyon, N.H., 2001. Slope failure features on the margins of the Rockall Trough. In: Shannon, P.M., Haughton, P.D.W., Corcoran, D.V. (Eds.), The Petroleum Exploration of Irelands Offshore Basins. Geol. Soc., London, Spec. Publ., pp. 455–464.

Stoker, M.S., 1997. Mid- to Late Cenozoic sedimentation on the continental margin off NW Britain. J. Geol. Soc. Lond. 154, 509–515.

Stoker, M.S., 1998. Sediment drift development on the continental margin off NW Britain. In: Stoker, M.S., Evans, D., Cramp, A. (Eds.), Geological Processes on Continental Margins: Sedimentation, Mass-wasting and Stability. Geol. Soc., London, Spec. Publ., pp. 229–254.

Stoker, M.S., Van Weering, T.C.E., Svaerdborg, T., 2001. A Mid- to Late Cenozoic tectonostratigraphic framework for the Rockall Trough. In: Shannon, P.M., Haughton, P.D.W., Corcoran, D.V. (Eds.), The Petroleum Exploration of Ireland's Offshore Basins. Geol. Soc., London, Spec. Publ., pp. 411–438.

Stoker, M.S., Praeg, D., Shannon, P.M., Hjelstuen, B.O., Laberg, J.S., Nielson, T., van Weering, T.C.E., Sejrup, H.P., Evans, D., 2005. Neogene evolution of the Atlantic continental margin of NW Europe (Lofoten Islands to SW Ireland): anything but passive. In: Doré, A.G., Vining, B.A. (Eds.), Petroleum Geology: North-West Europe and Global Perspectives. Geol. Soc., London, pp. 1057–1076.

STRATAGEM Partners, 2003. Stoker, M.S. (Compiler). Neogene evolution of the glaciated European Margin. A product of the EC-supported STRATAGEM Project. World Wide Web Address: http://www.stratagem-europe.org.

Unnithan, V., Shannon, P.M., McGrane, K., Readman, P.W., Jacob, A. W.B., Keary, R., Kenyon, N.H., 2001. Slope instability and sediment redistribution in the Rockall Trough: constraints from GLORIA. In: Shannon, P.M., Haughton, P.D.W., Corcoran, D.V. (Eds.), The Petroleum Exploration of Ireland's Offshore Basins. Geol. Soc., London, Spec. Publ., pp. 439–454.

Van Weering, T.C.E., De Haas, H., Akhmetzhanov, A.M., Kenyon, N. H., 2003. Giant carbonate mounds along the Porcupine and SW Rockall Trough margins. In: Mienert, J., Weaver, P.P.E. (Eds.), European Margin Sediment Dynamics. Springer, Berlin, pp. 211–216.

Weimer, P., 1990. Sequence stratigraphy, facies geometries, and depositional history of the Mississippi Fan, Gulf of Mexico. Bull. Am. Assoc. Pet. Geol. 74, 425–453.

Wold, C.N., 1994. Cenozoic sediment accumulation on drifts in the northern North Atlantic. Paleoceanography 9 (6), 917–941.

Zaragosi, S., Le Suave, R., Bourillet, J.F., Auffret, G.A., Faugeres, J. C., Pujol, C., Garlan, T., 2001. The deep-sea Armorican depositional system (Bay of Biscay), a multiple source, ramp model. Geo Mar. Lett. 20 (4), 219–232.