Temporal and spatial variations in Late Quaternary slope sedimentation along the undersupplied margins of the Rockall Trough, offshore west Ireland

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A total of 63 gravity cores, together with high-resolution bathymetry data and sidescan sonar imagery, were studied along both eastern and western margins of the Rockall Trough, offshore west Ireland. The datasets are used to establish the response of the slopes to high-frequency glacial forcing and they help constrain the shallow stratigraphy left on undersupplied current-swept slopes. During full glacial conditions, multiple episodes of mass wasting took place against a backdrop of weak bottom current activity and ice-rafting. During interstadials and interglacials, the eastern trough margin was characterised by more stable slopes and strong bottom currents resulting in periods of erosion and winnowing and the deposition of sandy biogenic (interglacial) and mixed clastic-biogenic (interstadial) contourites. On the western margin, the currents remained weak resulting in mud-prone deposits. Spatial variations in current flow reflect variations in slope gradient and the impact of local topographic highs or depressions that deflected and enhanced or forced deceleration of the currents, explaining the distribution of sands and muds.

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Introduction

The Rockall Trough is the bathymetric expression of the undersupplied Rockall Basin on the Atlantic margin west of Ireland. The trough is flanked by the Rockall Bank to the west and the Porcupine Bank and the Erris High to the east (Fig. 1). The trough floor deepens gradually from 1200 m in the NE to 4500 m in the SW, and contains a large contourite drift, the Feni Drift, plastering the western margin, together with localised clastic fans (the Barra / Donegal Fan) on the northeast trough floor (Fig. 1). The latter reflect local clastic input as a consequence of the Plio-Pleistocene advance of an ice margin to the shelf break (Stoker 1995). In the northwest Rockall Trough, an extensive area of slope remobilisation extends from the slope out onto the trough floor (the Rockall Bank Mass Flow, Fig. 1; Flood et al. 1979; Unnithan et al. 2001). Otherwise the trough floor is relatively featureless lacking large clastic fans or extensive glacigenic aprons that characterise the Northeast Atlantic margin elsewhere (e.g. Weaver et al. 2000).

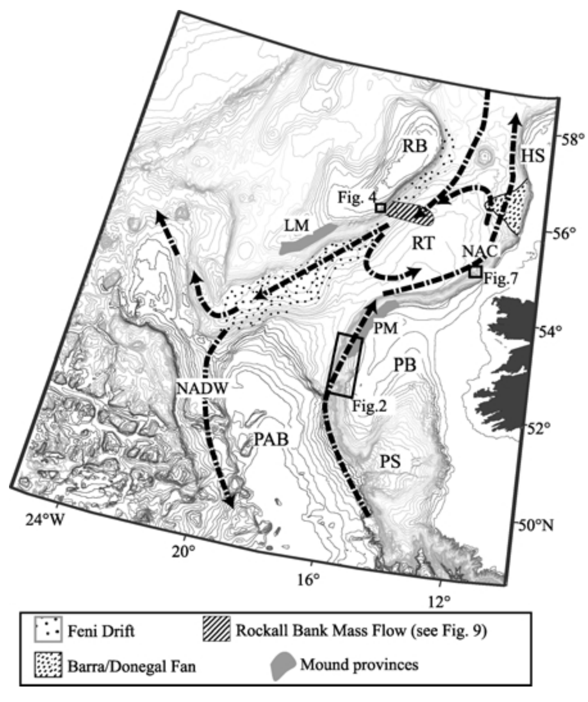

Fig. 1. Map showing the main morphological elements in the Rockall Trough and the general oceanographic circulation. Abbreviations: RT = Rockall Trough; PB = Porcupine Bank; PAB = Porcupine Abyssal Plain; RB = Rockall Bank; HS = Hebrides Shelf; EH = Erris High; NADW = North Atlantic Deep Water; NAC = North Atlantic Current; LM = Logachev Mound province; and PM = Pelagia Mound Province.

The margins of the trough are draped by a thin Cretaceous and Cenozoic succession, typically no more than a couple of hundred metres thick. In the absence of thick sediment wedges, the large-scale morphology of the marginal slopes is primarily a function of their structural development (Haughton et al. 2005).

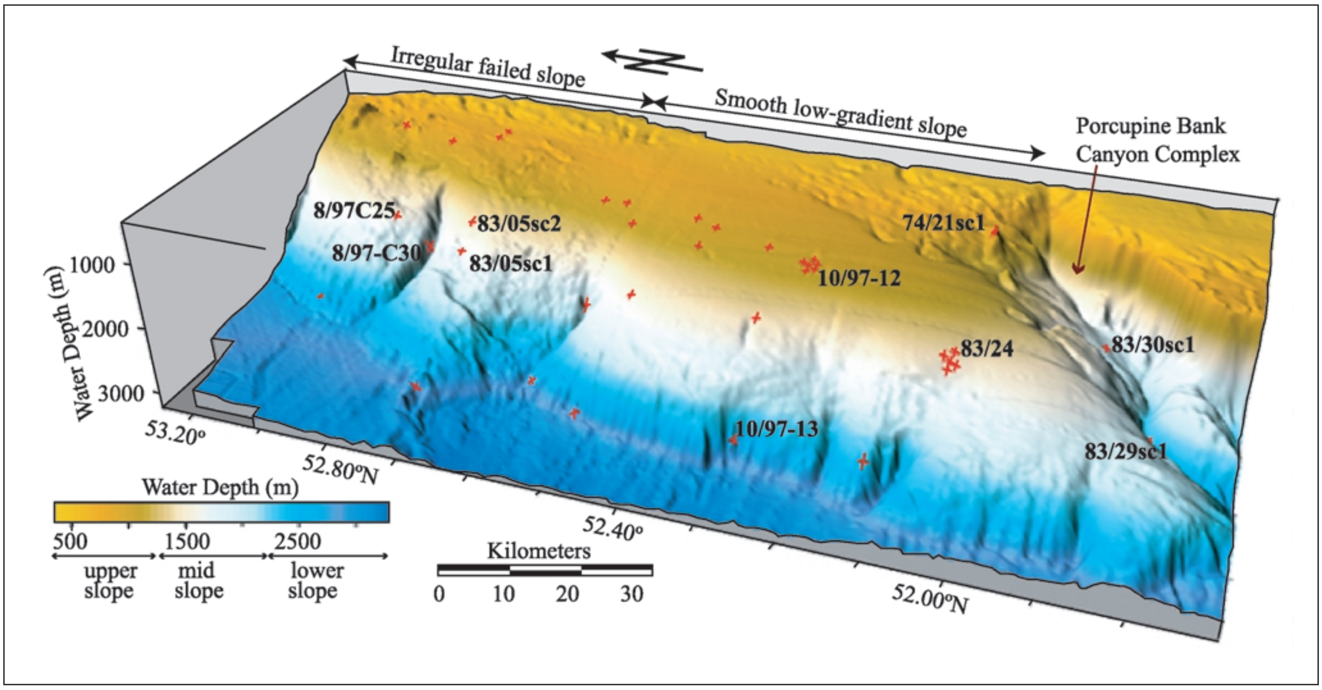

Fig. 2. 3D bathymetric representation of slopes flanking west Porcupine Bank at the southeast entrance to the Rockall Trough (see Fig. 1) with labelled cores shown in Figs. 3, 6 and 8. The figure shows the location of the smooth slope, the irregular slope and the Porcupine Bank canyon complex. See text for further discussion. The bathymetry data are courtesy of the Geological Survey of Ireland (GSI).

The better-known and cored eastern margin is underlain by perched Jurassic tilted fault blocks and footwall highs that are unconformably overlain by thin Cretaceous and Palaeogene sediments (Haughton et al. 2005). The present-day deep basin developed during a phase of Late Eocene-Oligocene differential subsidence that rotated both the earlier fault blocks and the Cretaceous-Palaeogene to create the extant slope (e.g. Stoker et al. 2002). Whereas the overall slope is broadly a function of this tilting, a convex-up shape locally represents draping of basement highs associated with the original Jurassic footwalls; these steepened regions are sites of major post-tilting sliding. Seismic profiles demonstrate the association of the onset of contourite deposition with tilting and deepening, and vigorous bottom currents have been an important element of slope evolution from the Oligocene to the present (Stoker et al. 2002). The position of the trough means that it is an important gateway for waters moving northwards from low latitudes (e.g. North Atlantic Current, NAC), and southbound outflow from the Norwegian Sea (North Atlantic Deep water, NADW; Fig. 1). This was critical during Pleistocene to Holocene glacial-interglacial cycles, as the thermohaline circulation is strongly coupled to climatic fluctuations (e.g. Keigwin et al. 1994; Oppo & Fairbanks 1990).

The morphology of the Rockall seabed is well known from regional side-scan surveys (TOBI, Shannon et al. 2001; GLORIA, Unnithan et al. 2001), and more recently from high-resolution bathymetry surveying. A range of marginal slope styles is evident, ranging from areas of low-gradient, smooth and undisturbed slopes, to those populated with carbonate mounds, to slopes moderately and heavily remoulded by gravity failures or cut by prominent canyons. In this study, key examples of the different slope styles are examined, using recently acquired dense arrays of gravity cores in combination with seabed imagery. The aim is to explore the interplay between downslope gravitational processes and along-slope current reworking straddling glacial-interglacial and interstadial-stadial cycles at different points along the trough margins. The datasets help constrain the lithology and shallow stratigraphy left on undersupplied current-swept slopes, and represent an alternative to the more common descriptions of oversupplied slope wedges.

Morphology

The margins of the trough are narrow (10 - 40 km) with steep slopes (Unnithan et al. 2001). The eastern trough margin has gradients of 1 to 10° and locally more than 20°, e.g. near the Erris High (Fig. 1). Shallower gradients of 4° or less occur along the western margin of the Rockall Trough (Unnithan et al. 2001). The shelf break is identified as a sharp increase in slope gradient occurring at water depths of 300 to 600 m. Based on bathymetry data and TOBI imagery, four styles of slope and base-of-slope morphology have been identified: i) smooth low-gradient slopes; ii) areas of irregular slope with fields of carbonate mounds and other seabed highs; iii) irregular failed slopes; and iv) an extensive area of mass-flow deposition extending off the lower slope onto the basin floor.

Areas of smooth low-gradient slopes

Regions of relatively smooth slope have been recorded on the Feni Drift plastering the western trough margin, where Unnithan et al. (2001) identified areas of low backscatter on GLORIA imagery at mid-slope levels (1000 to 2000 m). This is a region with a continuous mud-prone stratigraphy, recording little difference in current strength from interglacial to glacial periods (e.g. Kidd & Hill 1986; van Weering & de Rijk 1991). Along the eastern trough margin, a TOBI study by O'Reilly et al. (2001) identified a region of low backscatter with only rare slope failures between 52° and 52°40'N on the western flanks of the Porcupine Bank (Fig. 2), just north of the Porcupine Bank Canyon Complex.

Gravity coring and sedimentology

The smooth slope on the west Porcupine Bank has been a focus of the present study and high-resolution bathymetry shows that the upper to mid slope gradients are 1° to 3°, whereas it steepens distally to 3° - 9°. A total of 27 gravity cores arranged in three slope-parallel transects reveal a coherent stratigraphy traceable across an area of at least 1500 km2. This set of cores has been described in more detail by Øvrebø et al. (in press) and is therefore only briefly reviewed here.

The cored shallow stratigraphy comprises three main packages, numbered I to III down core (Fig. 3). Package III is made up of pale-coloured biogenic oozes (lithofacies P; Table 1) alternating with units of brown siliciclastic mud (lithofacies IH; Table 1). Lithofacies P commonly displays reverse grading and bioturbation with sharp tops and gradational to sharp bases. The muds of lithofacies IH are poorly sorted with abundant ice-rafted debris (IRD).

Package II is a siliciclastic mud-prone interval comprising lithofacies IH with two erosive-based, graded sand-mud couplets (lithofacies C-1 and IH; Table 1; Fig. 3). The erosive bases and sand beds can be traced for at least 70 km across the slope. Another prominent erosion surface separates packages II and I containing lithofacies C-2 (Table 1), a calcareous, moderately sorted, upward-fining sand to mud deposit.

Dating

Oxygen isotope profiling of a Porcupine Bank core was compared to other North Atlantic cores (e.g. ODP core

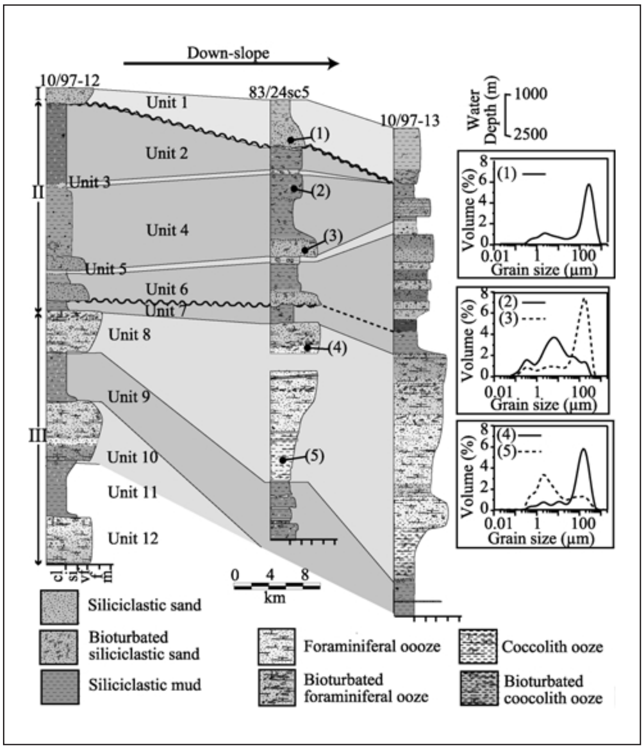

Fig. 3. Downslope stratigraphic correlation between three of the cores targeting the Porcupine Bank slopes (see Fig. 1 for location). Notice that most of the units can be traced across the slope, picking out two significant erosive surfaces at the base of the units 6 and 1, respectively. These units have been grouped into three broader stratigraphic packages numbered I to III as indicated on the left-hand side of the diagram. The figure also shows the grain size distribution for the sample points in brackets.

982, Venz et al. 1999). This correlation combined with ^{14}C AMS dating established that package I is equivalent to Marine Isotope Stage (MIS) 1, i.e. the Holocene, whereas package II spans MIS 2 to 4, the last glacial, with the sand-mud couplets falling within MIS 3. Below this, package III is interpreted as an alternation between interglacials and glacials, i.e. MIS 13 to 5. For further discussion of the chronology of the Porcupine Bank cores, see Øvrebø et al. (in press).

Interpretation

The composition, moderate sorting, reverse grading and bioturbation, indicate that lithofacies P is a biogenic contourite of interglacial origin. The onset of past glacials is remarkably abrupt and revealed by a rapid switch in sediment supply from pelagic carbonate to siliciclastic mud with IRD (lithofacies IH), with a fall in current strength to account for the poor sorting, suggesting a muddy contourite interpretation for lithofacies IH. Package III is thus characterised by muddy contourites deposited from weak bottom currents during the previous glaciations alternating with interglacial periods characterised by increased

Table 1. Characteristics of lithofacies identified on the margins of the Rockall Trough.

	Colour (Munsell colour chart representations)	Sedimentary structures and lithology	Grain-size distribution	Contacts	Carbonate content	IRD (Lithics > 150 µm)	Setting	Depositional mechanism
Lithofacies IH	Moderate yellowish brown (10YR5/4)	Occasional graded sandy mud	Poorly sorted mud	Gradational to sharp top and bas	10-20%	Abundant	Smooth slope and canyon	Ice rafting + hemipelagic settling from weak bottom currents
Lithofacies P	Greyish orange to pale orange (10YR7/4 and-8/2)	Reverse- and normal-graded sand and mud Bioturbated	Mud – poor sorting Sand – moderate sorting, dominance of fine/medium sand	Gradational to sharp	65-70%	Rare	Smooth slope	Bottom current winnowing and deposition
Lithofacies C1 and C-2	Pale yellowish brown (10YR6/2)	*C-1:* Occasionally bedded muddy sand *C-2:* Normal graded muddy sand to mud	*C1:* Moderate sorting, dominance of fine sand *C2:* Mud – poor to moderate sorting. Sand – moderate sorting, dominance of fine sand	Sharp to erosive base Bioturbated top	*C-1:* 30-50% *C-2:* 50-60%	Rare to common	*C-1:* Smooth slope *C-2:* All areas	Bottom current winnowing + deposition
Lithofacies D	Moderate to dark yellowish brown (10YR5/4 and 4/2)	Intercalated mud and sand beds. Mud and sand clasts	N/A	Internal sharp and deformed contacts	~35 %	Common	Mounded slope	Debris flows
Lithofacies S	Moderate yellowish brown and pale orange (10YR5/4 and 8/2)	Carbonate and siliciclastic beds with floating sand and mud clasts	N/A	Internal, sharp and deformed internal contacts	Variable (10-70%)	Rare to common	Region of slab failures	Slumping
Lithofacies T-1	Light olive grey (5Y 5/1)	Structureless	Moderate to good sorting, dominance of fine/medium sand	Sharp / erosive base Gradational top	–	Common	Canyon	Mass flows, possibly turbidity currents
Lithofacies T-2	Olive to light olive grey (5Y 3/2 and 5/2)	Horizontal and cross-lamination	Moderate to good sorting, dominance of fine/medium sand	Sharp top and base	37-41%	Rare	Rockall Bank mass flow	Turbidity current
Lithofacies H-1	Dark yellowish brown (10YR 4/2)	Laminated and well-consolidated mud	Poorly sorted mud	Sharp to gradational top Base not cored	10-15%	Rare	Region of slump scarp	Hemipelagic settling
Lithofacies H-2	Pale Yellowish brown (10YR 6/2)	Bioturbated mud	Poorly sorted mud	Bioturbated base	37-61%	Rare	Rockall Bank mass flow	Hemipelagic settling
Lithofacies H-3	Dark Yellowish brown (10YR 5/2 - 4/2)	Structureless mud with occasional lenses of laminated mud	Poorly sorted mud	Bioturbated top Sharp base	21-34%	Rare	Rockall Bank mass flow	Hemipelagic settling interrupted by muddy turbidity currents
Lithofacies H-4 and H-5	*H-4:* light olive grey (5Y5/2) *H-5:* olive grey (5Y5/1)	Heavily bioturbated and well consolidated mud	Poorly sorted mud	Sharp top Sharp, angular contact separating H-4 and H-5	*H-4:* 34% *H-5:* 25%	Rare	Rockall Bank mass flow	Hemipelagic settling interrupted by gravity sliding

bottom-current activity and deposition of biogenic contourites. The last glaciation (package II) is represented by muddy contourites (lithofacies IH) interrupted by two sand-mud couplets. The extensive erosional surface at the base of the first couplet is attributed to waxing bottom currents during MIS 3, followed by waning to produce the muddier cap to the couplet. A second couplet suggests that the pattern was repeated. A bottom-current origin for the couplets is consistent with the moderately sorted texture and the geometry of lithofacies C-1, which stretches for >70 km parallel to the slope. During late glacial times the deposition of muddy contourites (IH) was resumed. Deglaciation was accompanied by another phase of strong currents leading to erosion and subsequent deposition of lithofacies C-2 (package I).

Uneven mounded slopes

Carbonate build-ups and other mounds of uncertain origin (volcanic or emergent fault block highs) have been identified at the seabed or in the shallow subsurface along several parts of the margin of the Rockall Trough (e.g. Croker & O'Loughlin 1998). Clusters of carbonate mounds have been recorded along both margins at water depths of 500 to 1200 m (e.g. the Pelagia mounds on the northwest flank of the Porcupine Bank and the Logachev mounds on the southeast Rockall Bank; Fig. 1). In addition unpublished work on TOBI side-scan sonar imagery has identified a prominent high-backscatter feature interpreted as a major rock outcrop on the western margin of the trough at a water depth of 1200 m (55°50' to 56°10'N; O'Reilly et al. 2001). High-resolution bathymetry data show the latter as a string of seabed highs in this area. High-resolution bathymetry data as well as previous shallow seismic studies (Haughton et al. 2005) show that the mounds and highs are associated with deep fringing moats (Fig. 4) resulting from current scour operating parallel to the slope.

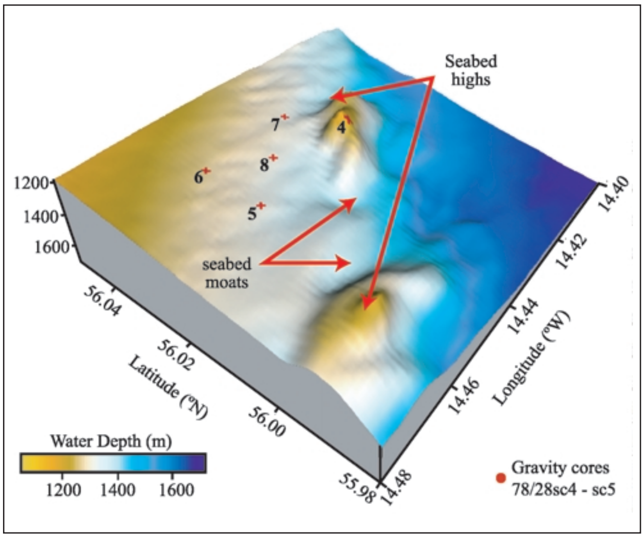

Fig. 4. 3D bathymetric representation of seabed highs (see Fig. 1 for location) showing the location of five gravity cores (see Fig. 5) and extensive moating in the vicinity of the mounds. The bathymetry data are courtesy of the Geological Survey of Ireland (GSI).

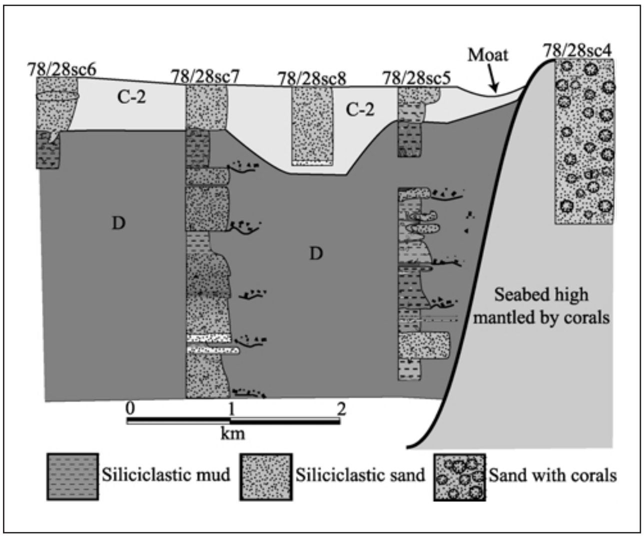

Fig. 5. Correlation of cores targeting an area of seabed highs. The cored stratigraphy shows lithofacies C-1 (interpreted as contourites) overlying an interval comprising lithofacies D (interpreted as debrites) onlapping the topographic high. The interpretation of a seabed moat adjacent to the high is from bathymetry data (see Fig. 4).

Gravity coring and sedimentology

Gravity coring in the area of the Pelagia mound province at water depths of 800 - 1000 m on the west Porcupine Bank, and on and around a seabed high on the margin of the Rockall High, show the highs/mounds are in both cases sites of active coral growth. Coring between the highs shows that these intermound depressions are characterised by deposits dominated by poorly-sorted, sharp-based sand and mud beds (lithofacies D; Table 1) lacking sedimentary structures but with abundant floating mud and sand clasts. Grain counting reveals that the deposits mainly contain cold-water foraminifera (e.g. *N. pachyderma* sinistral), lithic clasts interpreted as ice-rafted debris, and a variable content of bivalve fragments. Lithofacies D is capped by sharp-based moderately-sorted sands of Lithofacies C-2 with low *N. pachyderma* sinistral content and a minor IRD component (Fig. 5). The facies are described in more detail in Øvrebø (2005).

Interpretation

The poor sorting and disorganised nature of lithofacies D suggest debris-flow activity is common in the vicinity of highs and mounds. The composition of the debrites (high IRD and N. pachyderma sinistral) and the position beneath lithofacies C-2 drapes (= Holocene) suggest that these debris flows reflect instability during glacial times. The clastic composition of lithofacies D and lack of coral debris further suggest that the debris flows were not sourced from the mounds themselves but instead from failures upslope of the mounds. During glacial times these mounds acted as local obstacles damming the debris flows. The debrites are capped by lithofacies C-2, which is interpreted as a bottom-current reworked sand on account of the sharp base, moderate sorting and mottled appearance. The mounds have deflected these bottom currents forcing local accelerations, increased turbulence and scouring resulting in the formation of seabed moats.

Irregular failed slope

Seabed imaging shows that this is the most common slope morphology flanking the Rockall Trough, and a wide range of slope failures have been recognised including slab failures, slump scarps and canyons (e.g. Shannon et al. 2001; Unnithan et al. 2001).

Region of slab failures on the Porcupine Bank

Directly north of the area of smooth slope on the west Porcupine Bank, a region of irregular seabed (52°40' -53°00'N) at water depths of 1000 to 2000 m has been identified (Fig. 2) and is an area of high backscatter on TOBI imagery and rugose topography on the high-resolution bathymetry survey. The overall slope gradient in the area is modest at 1° - 3°. O'Reilly et al. (2001) described this as an area from which tabular slabs of slope sediment have been removed forming terraces or scarps which have gradients of up to 10°. These slabs may have disintegrated and transformed to form debris flows or turbidity currents as they moved further downslope (O'Reilly et al. 2001). Gravity coring in this area has recovered chaotic deposits (lithofacies S; Table 1) comprising remobilised carbonate and siliciclastic beds with floating sand and mud clasts and internal sharp and occasionally deformed contacts (Fig. 6) that are described in more detail in Øvrebø (2005). The top of lithofacies S is commonly associated with thin bands (<1 cm) of well-sorted coarse sand. Sharp-based, well-sorted, mottled sands of lithofacies C-2 (described earlier on the smooth slope; Table 1) overlie lithofacies S.

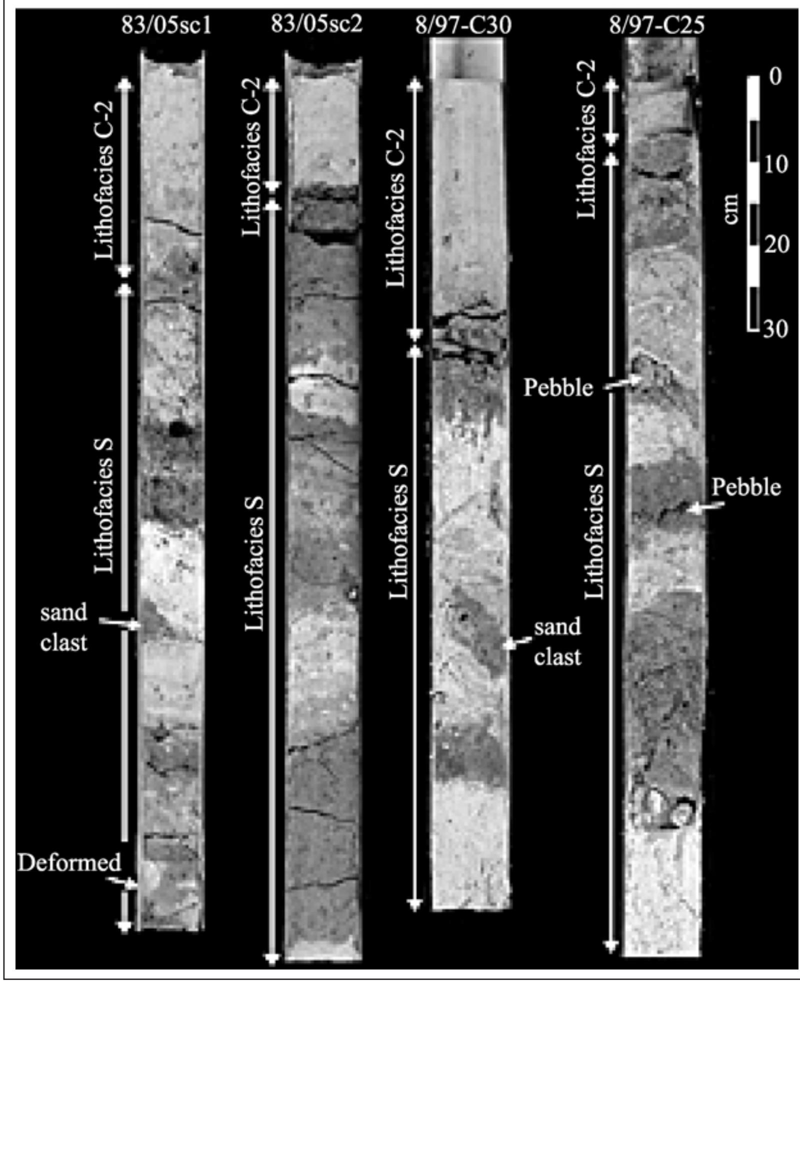

Fig. 6. Core photographs of lithofacies S overlain by lithofacies C-2. The lithofacies was identified in four of the cores. The cores revealed a chaotic and abrupt alternation of carbonate-rich beds and clastic-rich beds. Also note the sharp and occasionally inclined internal contacts.

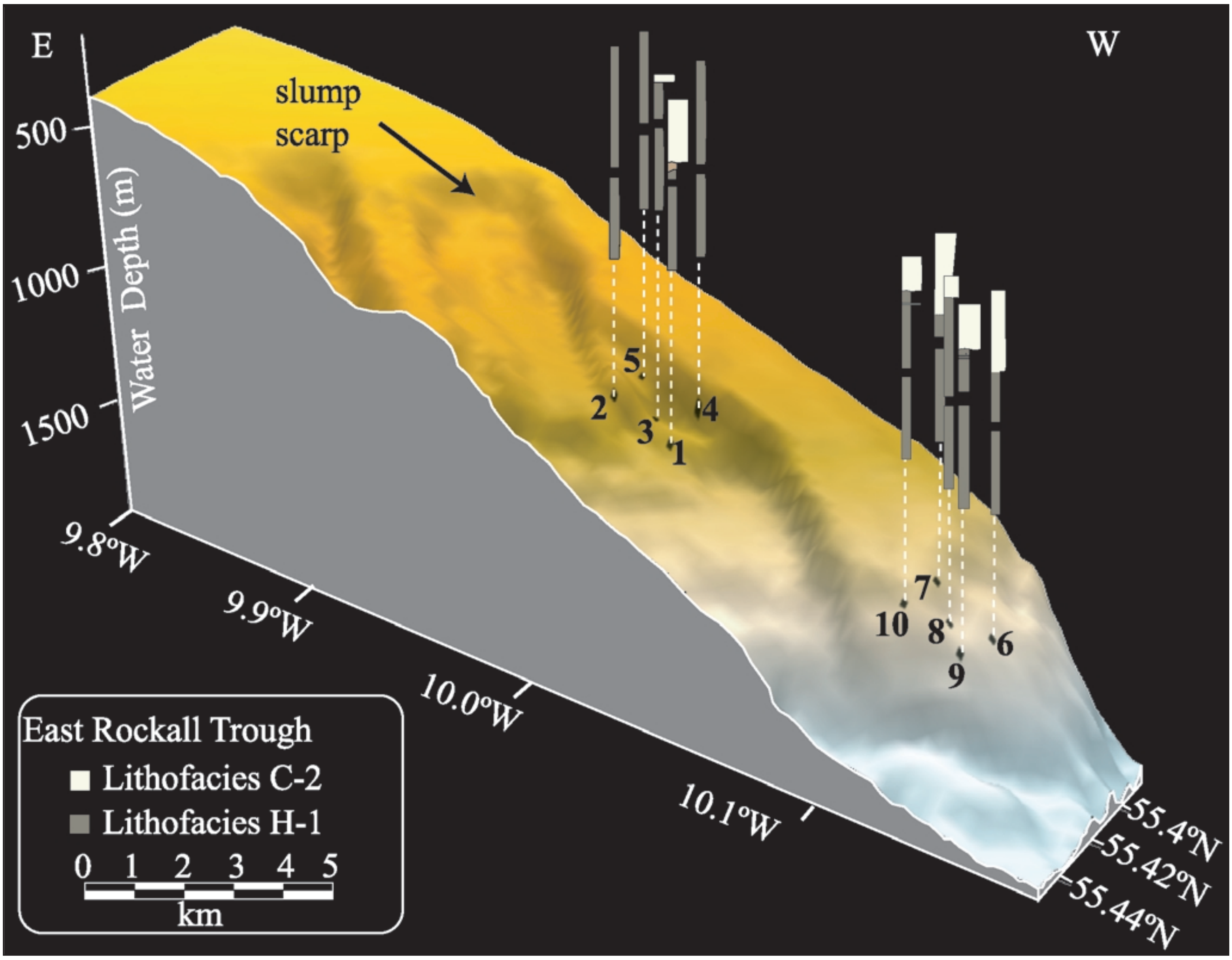

Fig. 7. Detailed 3D bathymetric representation of the region of large slump scarps on the flanks of the Erris High together with simplified core logs of the gravity cores recovered in the area. The bathymetry data are courtesy of Geological Survey of Ireland.

Interpretation

Lithofacies S is interpreted as the result of one or more episodes of slumping (internal contacts are hard to discern) on the basis of its chaotic structures and deformed contacts. The top of these slumps have later been winnowed by strong bottom currents as indicated by the thin bands of coarse sands. The bottom-current activity continued during the Holocene, depositing the sorted sands of lithofacies C-2. A sandy contourite interpretation of this sand is consistent with the good sorting, the mottled appearance and the sharp base. The recent operation of strong currents is also supported by TOBI imagery on which abundant current lineations are apparent on this part of the slope.

Region of large slump scarps on the flanks of the Erris High

Further north on the eastern margin of the trough, extensive cross-cutting slump scarps are present on the slopes at 56˚25'N. These occur at mid-slope levels (900 to 1400 m) and are up to 2 km wide with headwall scarps up to 125 m high with slopes of up to 20˚ (Fig. 7). The overall mid-slope gradient is 1˚ to 5˚, but at ~1400 m an arcuate-shaped scarp marks a pronounced increase in gradient to 8˚ - 15˚. Gravity coring downslope of the slump scars reveals a simple stratigraphy (H-1 and C-2) comprising only one to two lithofacies (Fig. 7). These are described in more detail in Øvrebø (2005). Lithofacies H-1 is present in all the cores as a non-bioturbated, well consolidated and poorly sorted, laminated mud. In all but three of the cores, it is overlain by lithofacies C-2, an ungraded sand with an erosive base, except in core 11/20sc7 where the sand is reversely graded with a gradational base.

Dating

AMS C14 dating on planktonic foraminifera from lithofacies C-2 reveal ages of 1.7 and 7.5 ka (calibrated to calendar ages using CALIB 4.3; Stuiver et al. 1998), establishing that C-2 was deposited during the Holocene, implying sedimentation rates of ~10 cm/ky.

The position of lithofacies H-1 (beneath C-2) and sediment composition (e.g. with abundant *N. pachyderma* sinistral) indicates that the muds were most likely deposited during the last or an earlier glacial period.

Interpretation

Lithofacies H-1 is inferred to be the result of hemipelagic settling. The Holocene sands capping this mud have a broadly unimodal grain-size distribution, moderate sorting and a mottled appearance implying that they are bottom-current reworked. This is also consistent with previous work by Armishaw et al. (2000) who interpreted similar deposits on the Barra Fan to the north as contourites. East of the Erris High, in core 11/20sc7, lithofacies C-2 displays reverse grading with a gradational base. A gradual increase in the bottom-current strength may be inferred during deglaciation and onset of the Holocene. In the other 11/20-cores, the sands have an erosive base, suggesting a phase of strongly erosive currents during the Early Holocene, followed by strong but depositional bottom currents in the later part of the Holocene.

The occurrence of dated Holocene sands within the slump scars suggests the main phase of downslope movement took place during glacial conditions. The lack of slump features in the cores (contrast with the Porcupine Bank slumps) is probably because only the head regions of these large failures have been cored, and the displaced material was transported further downslope. The irregular seabed morphology produced by downslope slumping may have interacted with subsequent Holocene bottom currents sweeping along the slope. Thus, the absence of sands in three of the gravity cores in the lee of a major slump-induced step on the sea floor may reflect the control of local topography on deposition.

Canyons

Canyons are the most prominent features of the eastern margin of the Rockall Trough whereas they are absent along the western margin. The most spectacular canyon is the Porcupine Bank Canyon Complex described by Unnithan et al. (2001). It originates at the bank margin at 500 - 700 m water depth and is up to 20 km wide and 1000 m deep with steep walls (~ 30°). Several minor canyons also incise the eastern margin from 52° to 56°N, originating at mid- to lower-slope levels (1500 - 2000 m) and are up to 300 m deep and 7 km in width. Two gravity cores were recovered from the axis of the northern branch of the Porcupine Bank Canyon Complex (Fig. 2; see Øvrebø 2005). These cores reveal slightly bioturbated and structureless muddy deposits (lithofacies IH) interrupted at lower core levels by a series of stacked, well-sorted and sharp-based sand beds (lithofacies T-1; Fig. 8 and Table 1).

Interpretation

The mud is the result of hemipelagic settling possibly from weak bottom currents travelling down the canyon axis. The well-sorted stacked sand beds suggest that the mud deposition has been interrupted by a series of turbidity currents.

Extension of mass-flowage on to basin floor

In the NW Rockall Trough, Flood et al. (1979) used side-scan sonar imagery, echo soundings and core samples to describe a zone of extensive slumping that evolved downslope into a series of debris flows and turbidity currents that partly disrupted the Feni Ridge around 55° to 57°N. They termed this remobilised zone the 'Rockall Bank Mass Flow' (Roberts 1975; Unnithan et al. 2001). The slumps were thought to have occurred during several phases spanning the last glacial and early post-glacial times. Faugères et al. (1981) suggested that sea-level rises associated with ice melting may have favoured gravity-flow release.

An examination of four new gravity cores along a traverse across the Rockall Bank Mass Flow (Fig. 9) revealed dominantly muddy deposits, which on the basis of sediment composition and the degree of consolidation can be divided into six units, numbered 1 to 6 downcore comprising lithofacies H-2 to H-5 and T-2 (Fig. 10 and Table 1; see Øvrebø 2005). The top unit 1 (lithofacies H-2) is a structureless and mottled, carbonate-rich mud (40 - 60 %) with a gradational base and dominated by warm-foraminifera species (e.g. *N. pachyderma* dextral).

Below unit 1, a poorly consolidated mud unit (unit 2; lithofacies H-3) is present with a bioturbated top. In the two deepest cores, thin laminated mud bands interrupt unit 2 (Fig. 10). In core 08/02sc1, unit 2 sits sharply on top of unit 4 that comprises lithofacies H-1 (described above). In the two most basinward cores (08/09sc1 and 09/07sc1), unit 2 sits sharply on top of 25 to 35 cm thick sand beds (lithofacies T-2; unit 3). Lithofacies T-2 is a well-sorted, cross-laminated and sharp-based sand. In core 09/07sc1 unit 3 sharply overlies unit 4 (lithofacies H-2) whereas in core 08/09sc1 unit 3 lies sharply on top of a well-consolidated and bioturbated mud (lithofacies H-4; unit 5) with a cold-water foraminifera fauna (i.e. *N. pachyderma* sinistral). Unit 5 is separated from the underlying unit 6 (lithofacies H-5) by a clay-smeared, inclined contact. Compositionally, lithofacies H-4 is similar to lithofacies H-5, as they both have low carbonate content (35 % for H-4 and 25 % for H-5) and a diverse, but low foraminifera content (970 - 2100 grains/g) with cold-water species (e.g. N. pachyderma

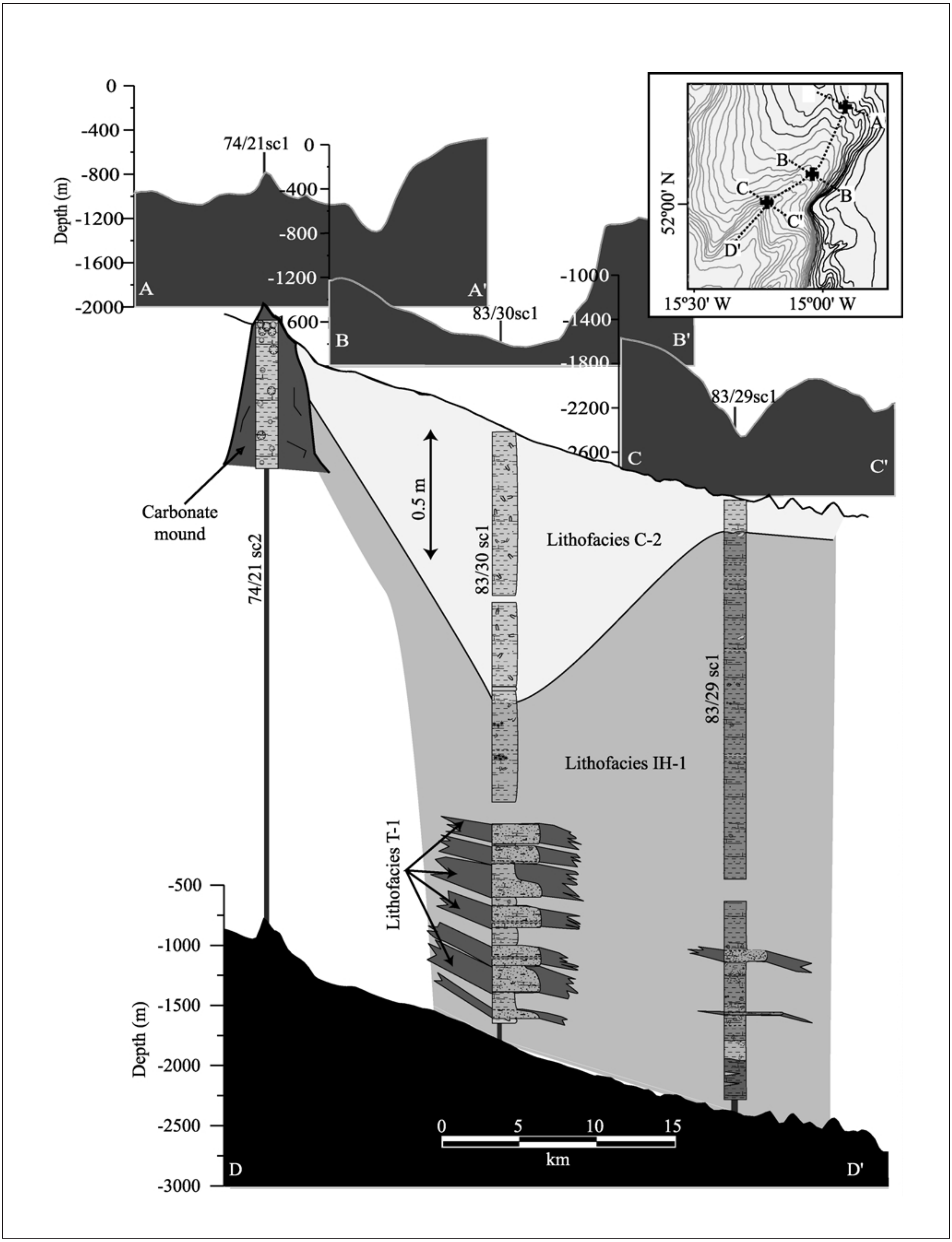

Fig. 8. Correlation of the three cores targeting the Porcupine Bank Canyon complex. The upper three bathymetric profiles show cross-sections perpendicular to the canyon-axis at the coring sites, whilst the lower shows a cross-section parallel to the canyon axis (see inset map for location of profiles).

sinistral) dominant. However, the lithofacies differ from each other in colour and ichnofabric, as H-4 is light olive grey mud with yellowish grey coloured burrows, whereas the underlying H-5 is an olive grey mud with dark olive grey coloured burrows.

Dating

Based on limited radiometric ^{14}C work (calibrated to calendar ages using CALIB 4.3; Stuiver et al. 1998), the sediment composition and the sequence of the lithofacies within the cores, it is possible to partly constrain the timing of the depositional events along the mass-flow traverse. The sediment composition and near-seabed position of unit 1 places it to the Holocene. The underlying unit 2 belongs to the last glacial as indicated by the abundant *N. pachyderma* sinistral content and the ^{14}C dating which places it to the late glacial (< 20 ka). The sand beds of unit 3 are most likely of glacial origin on the basis of their core position and sediment composition (abundant *N. pachyderma* sinistral and IRD), which is confirmed by absolute dating. In core 08/09sc1 unit 5, beneath the sand, is beyond the resolution of the ^{14}C method (> 45 ky), whereas unit 2, directly above the sand, is dated to 10.2 ky, suggesting that sand of unit 3 is associated with a lengthy hiatus at this coring location. In core 09/07sc1 the dating shows unit 3 to post-date 21.7 ky. Dating of the top of unit 4 (~21.7 ky) revealed this unit to be of glacial age postdating the deposition of unit 5 in core

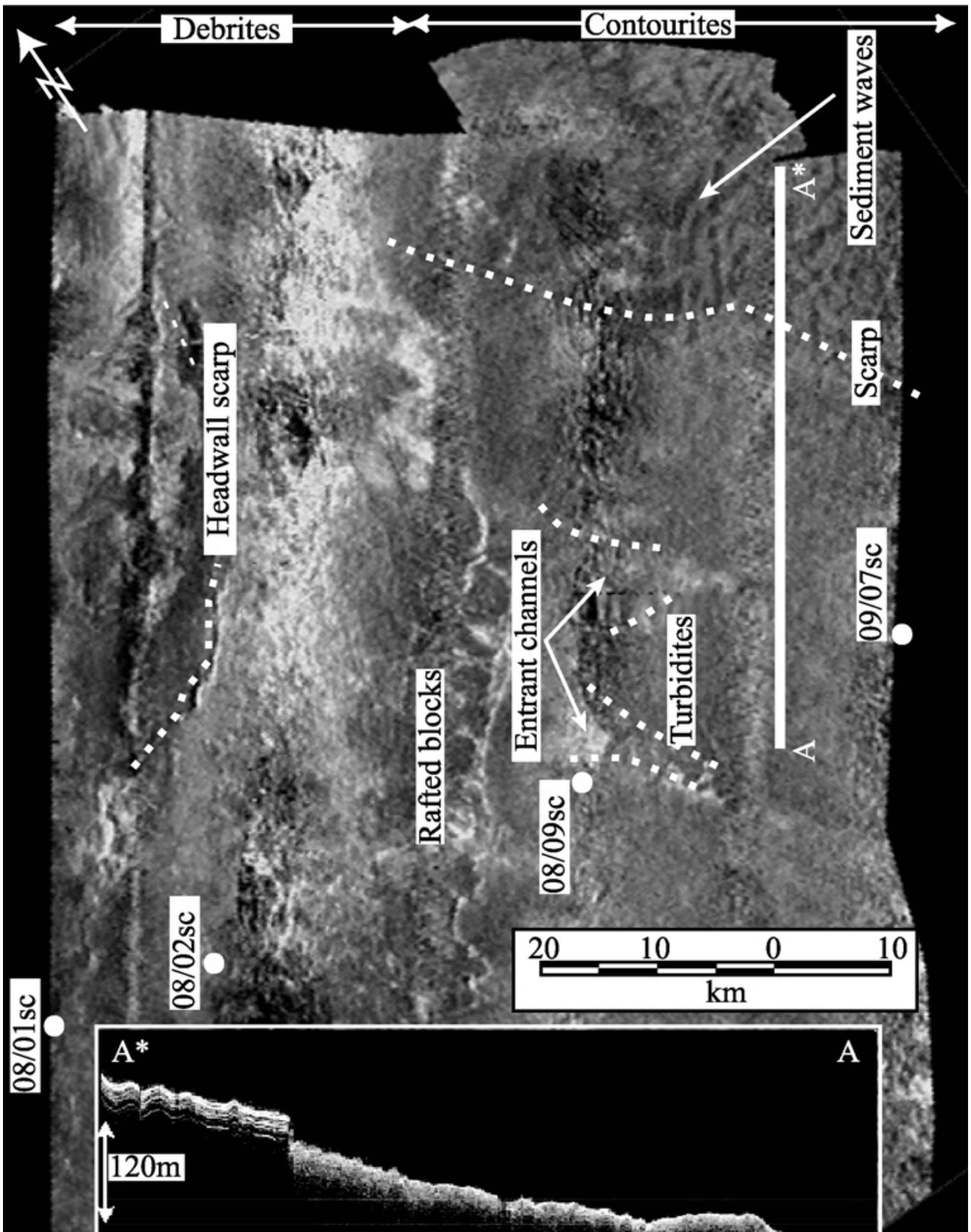

Fig. 9. GLORIA sidescan sonar imagery covering the study area (modified slightly from Unnithan et al. 2001) together with an echosounder profile (A – A). The locations of the gravity cores logged as part of the present project are also shown.*

08/09sc1. Unit 5, together with unit 6, are beyond the resolution of 14C dating, but the faunal composition (e.g. abundant N. pachyderma sinistral) suggests a glacial origin for these units.

Interpretation

Lithofacies H-2 to H-5 have features (ungraded, structureless and commonly bioturbated) that can be ascribed to hemipelagic settling. The remoteness of continental sources and the thickness of the mud deposits, with estimated sedimentation rates of 10 cm/ky, indicate the presence of weak currents supplying the muds to the basin floor. This is consistent with the results of van Weering & de Rijk (1991) who recognised similar mud deposition at base of slope (c. 40 km south of study area) and attributed this to a relatively low-energy bottom-current regime.

The hemipelagites and muddy contourites were disrupted by gravity sliding that created horizontal and inclined slip surfaces, which occur in the cores in the form of extremely sharp contacts separating facies with different sediment composition and ichnofabrics (e.g. between units 2 and 4 in core 08/02sc1 and between units 5 and 6 in core 08/09sc1; Fig. 10) . The time constraints suggest sliding occurred mostly during the last glaciation. The gravity sliding may have caused exhumation of older sediments explaining the well-consolidated nature of units 4 and 5.

In both the outermost cores (08/09sc1 and 09/07sc1; Fig. 10), unit 3 is characterised by a sand bed that is well-sorted with a sharp basal contact, well-developed lamination and lacking the bioturbation that is common in many of the deep-water sands cored in the Rockall area. The sands are interpreted as turbidites. Their position deep in the trough is consistent with flow transformation, with the slope failures on the canyon-free slope releasing sandy turbidity currents, at least locally. Examination of the sand fraction reveals that the turbidity currents reworked pre-existing cold-water, most likely glacial deposits.

The deposition of late glacial unit 2 was interrupted by several smaller remobilisation events, as evidenced by 1 cm thick bands of laminated mud that was slightly more consolidated than the surrounding clay of unit 2 (Fig. 10). These muds can be interpreted as muddy turbidites. At the end of the last glaciation and the Holocene (unit 1) no evidence of sliding was recorded, and the deposition was dominated by hemipelagic settling.

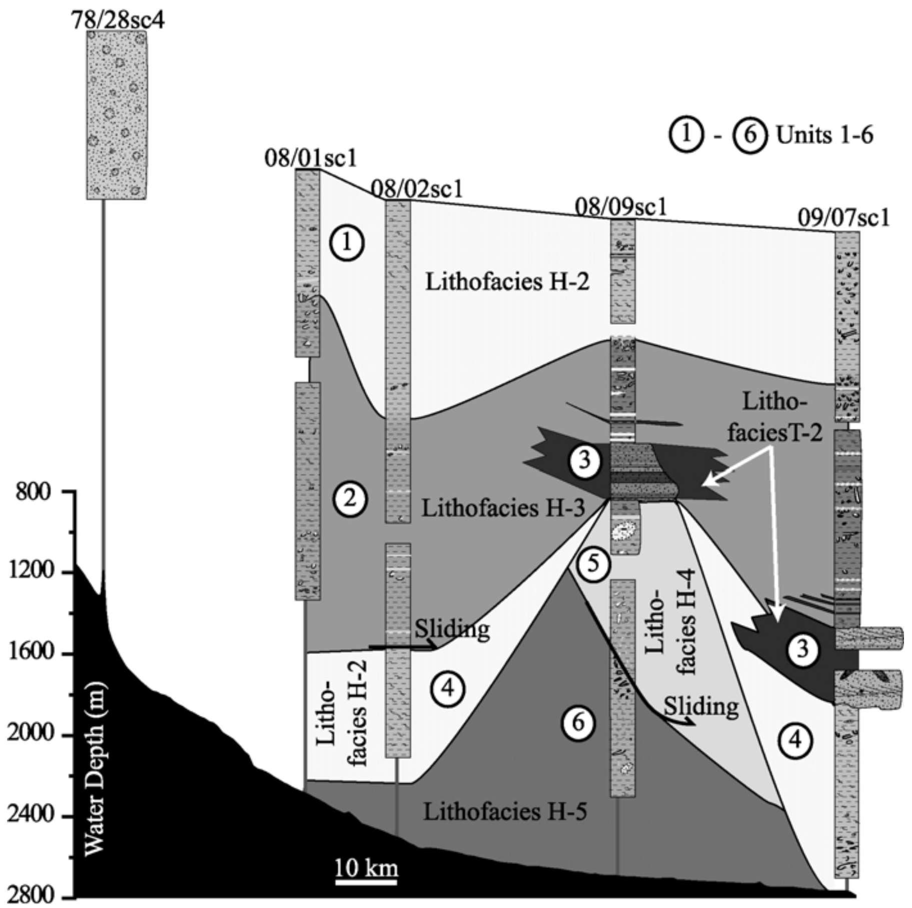

Fig. 10. Stratigraphic correlation across part of the Rockall Bank Mass Flow showing units 1 to 6.

Synthesis

The gravity cores establish a strong link between seafloor morphology and the cored near-seabed stratigraphy. Long-distance (10's of km) stratigraphic correlations were only possible in areas of smooth and gentle slopes. In areas of high backscatter and irregular slope morphology, slumping and sliding is evident in the cores and the slope succession cannot be correlated at km scale.

Seabed scarps and mass-flow deposits were found in a wide-range of settings: (i) debris-flows occurred in the vicinity of seabed highs and associated with canyons heads with slope gradients ranging from 1° to 15° in water-depths of 700 - 2000 m; (ii) slumping at mid-slope levels (1000 - 2000 m water depths) with slope gradients of 1° to 3°; (iii) turbidites were recovered at 1800 to 2300 m in the Porcupine Bank canyon complex where the gradient of the axis is 3 to 10º but with canyon walls of up to 30°; (iv) sandy and muddy turbidite beds were also recorded on the shallow dipping basin floor (<0.5°) in the NW Rockall Trough at c. 2700 m water depth and up to 90 km from the base of marginal slopes of the Rockall Bank; and (v) seabed scarps and associated sliding were also recorded on the basin floor (< 0.5°) in the area of the Rockall Bank Mass Flow. The wide range of failure types and associated deposits, occurring both in slope and basin-floor settings, indicate that slope stability is largely unrelated to slope gradient. However, the highest frequency of slope failures is in areas where bottom currents are eroding or winnowing the seabed, that is along the entire eastern margin and on the north Feni Drift (north of 55°30'N). This suggests that bottom currents have an important role in controlling the location of slope failures, whereas the controls on timing and the exact location of the sliding are less certain. Evans *et al.* (in press) suggested that the timing and location of the sliding is determined by a combination of several factors including tectonics, sedimentation rates, glacially induced tectonic movements, postglacial rebound, gas hydrates and pore-pressure changes. Of these, sedimentation rates can only exert a minor control, as the Rockall Trough is an undersupplied basin. Henriet et al. (2001) suggested that gas hydrates could explain at least some of the slope failures in the Porcupine Basin. To fully evaluate whether the glacially induced factors are important in the Rockall Trough, a better control on the extent of the glaciations within the Rockall Trough is needed. Locally, overturning of icebergs has been suggested as a trigger mechanism on the Hebrides Slope (Howe 1995). This may also have occurred on other parts of the margin, as iceberg ploughmarks have been recorded on the eastern trough margin by Belderson et al. (1973) and on the Porcupine Bank (unpublished work, Xavier Monteys, Geological Survey of Ireland, pers. comm.).

The sliding and slumping created an irregular seabed topography with canyons, slump and failure scarps, superimposed on regional gradient changes relating to the draped structure on these undersupplied slopes. The slope morphology influenced the behaviour of bottom currents sweeping the marginal slopes, particularly during interstadial and interglacial periods when bottom currents were enhanced. The contourites preserved on the low-gradient west Porcupine Bank slope reflect the large-scale morphology of this part of the margin. The prominent canyon complex to the south may cause northward-directed contour currents to experience a significant loss in momentum due to partial deflection of the current and turbulence shedding due to the rough seabed morphology and interactions with deeper water masses in the canyon (Martin White, National University of Ireland, Galway, pers. comm.). This favours deposition in the area immediately to the north of it, explaining the accumulation of an intact, yet condensed, contourite drape here. A general thinning of the latter succession occurs northward into a section of failed slope and carbonate mounds, suggesting either the currents became progressively more sediment depleted or they picked up in strength as they regained their lost momentum. Upon reaching the northern limit of the intact contourite drape, the currents were strong enough to cause lineations at the seabed and to excavate scours around the carbonate mounds. Current enhancement in the vicinity of seabed highs and mounds can account for the presence of sharp-based sandy contourites and moating near the seabed high on the west margin. The seabed topography may also locally focus and enhance the current flow, as is the case on the Erris High where the seabed is characterised by large slump scarps.

On a regional scale the seabed topography was also an important control on the spatial distribution of contourites. Along the eastern trough margin, several intervals of sandy contourites were deposited during past interglacials and interstadials (e.g. Porcupine Bank) and during the Holocene (e.g. Porcupine Bank and the Erris Ridge) with prominent erosion surfaces recorded within MIS 3 (e.g. Porcupine Bank) and in the Early Holocene (e.g. Porcupine Bank and the Erris Ridge). Previous studies have also recorded sandy or silty contourites from interstadials (distal Barra Fan; Knutz et al. 2002) and Early Holocene erosion, followed by the deposition of sandy contourites (e.g. Barra Fan; Armishaw et al. 1998; Howe 1996). On the western margin, the stratigraphy is rather different as it is mostly mud-prone with no obvious erosion surfaces (e.g. Kidd & Hill 1986; van Weering & de Rijk 1991). An exception is the mounded slope area (see Fig. 4) on the western trough margin where sharp-based sandy contourites were recovered. Mud is also less common to the northeast of the Rockall Bank, where Howe et al. (2001) recorded gravel lags. These stratigraphic con-

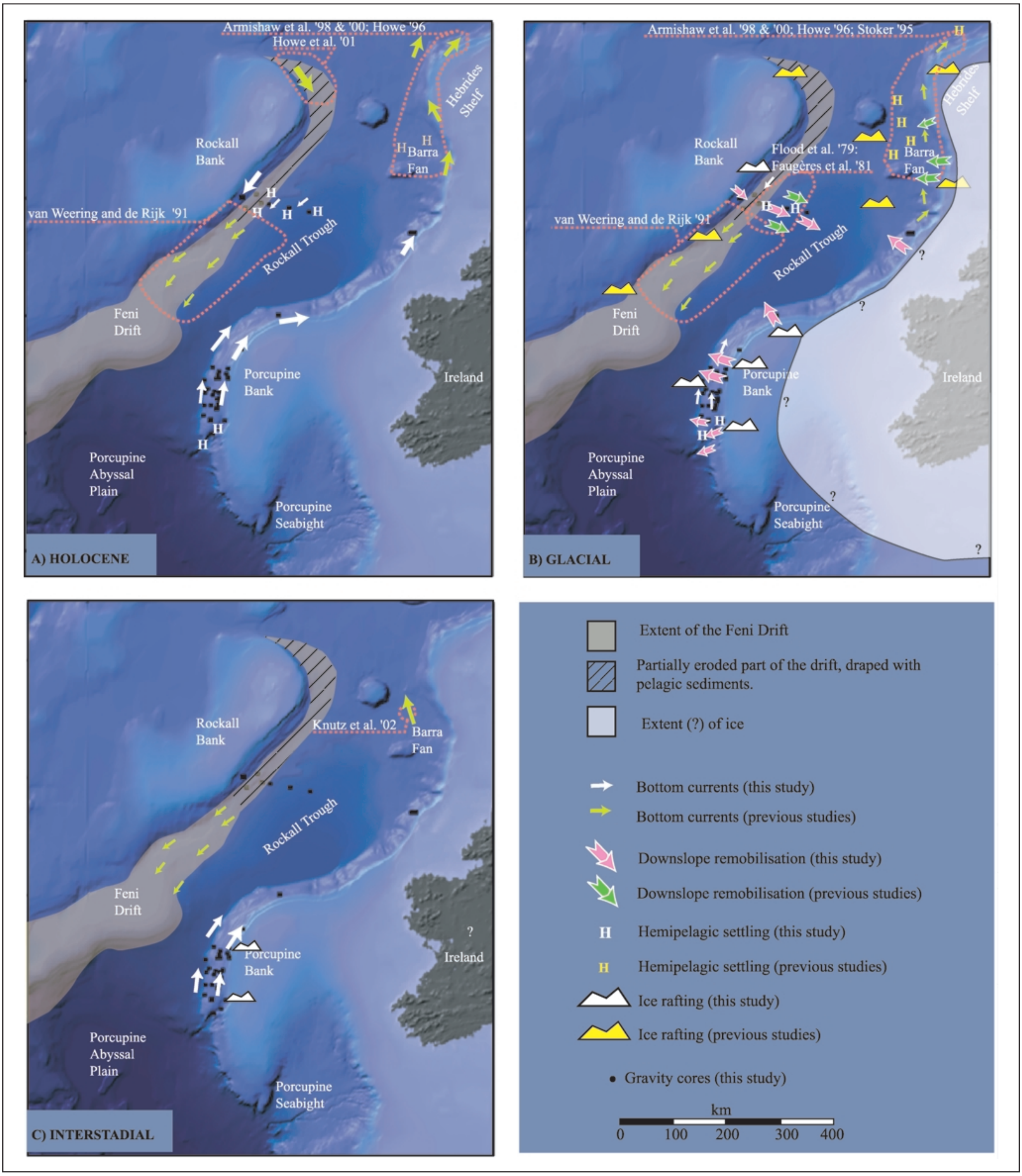

Fig. 11. Reconstruction of depositional processes active along the margins of the Rockall Trough during the Holocene (A), glacial (B) and interstadial times (C) integrating the results of the present work and previous studies (see text for references). The width of the arrows indicates the relative strength of the bottom currents. Previous study areas, referred to in the text, are outlined by dashed lines.

trasts between the two margins cannot be explained by the oceanographic circulation alone, as modern current measurements, albeit limited, do not suggest large variations in velocity across the trough. On the Porcupine Bank, north-moving flows have maximum velocities ranging from 29 cm/s (~2500 m) to 37 cm/s (~500 m; Dickson & McCave 1986); on the Hebrides Shelf maximum velocities are 15 - 25 cm/s at water depths of 500 m - 1100 m (Howe & Humphery 1995); and on the Feni Drift maximum current velocities reach 37 - 39 cm/s at water depths of 3000 - 4000 m (Dickson & Kidd 1986). The margin morphology may, however, explain the depositional differences across the trough, as the eastern margin is steeper (6° up to 22°) and more frequently incised by canyons and slope failures than the smoother western margin (1° - 4°; e.g. Unnithan et al. 2001). On the eastern margin, the northward-flowing currents thus impinge on a narrower area of the slope than the southward-flowing currents do on the western margin. This combined with the irregular topography of the eastern margin could explain why winnowing/erosion and deposition of sands are more common along the eastern margins than on the western margin.

Depositional evolution

The gravity cores establish important vertical variations in the stratigraphy of the slopes, with sandy contourites deposited during interglacials and interstadials and muddy contourites, ice-rafting and/or mass-flow deposits recovered for colder periods. The following discussion will compare and contrast the deposits recognised at each of the sites along the margin, starting with the Holocene, then considering the colder stages of the last glacial (MIS 2 - 5d) and finishing with a discussion of the depositional response to interstadial warming identified within MIS 3 (see Fig. 11).

Holocene

Bottom currents are the main Holocene depositional process within the Rockall Trough (Fig. 11), with a widespread Early Holocene erosion event affecting large parts of the eastern Rockall Trough. Except for brief cooling periods (e.g. the 8.2 ka cooling event; Alley et al. 1997), the Holocene was characterised by a warm climate, and the early part of the Holocene (8 to 5 ka) has been described as the warmest period over the last 13,400 yrs (Koç et al. 1993). This period may be linked to slightly stronger thermohaline circulation than at present day explaining the widespread erosion. The Late Holocene (c.5 ka to the present) has been characterised by a gradual cooling (Koç et al. 1993), and the more depositional bottom currents and graded deposits from this period may reflect this slow cooling, on account of a slight decrease in the thermohaline circulation as shown by computer modelling undertaken by Crucifix et al. (2002). An Early Holocene warming and subsequent cooling is in agreement with Holocene $d^{14}C$ profiles from deep-water corals (Stuiver et al. 1998), which show higher $d^{14}C$ for the first half of the Holocene.

Last glacial

Along the eastern margin, downslope mass-wasting was the most important slope-shaping process combined with weak bottom currents controlling the distribution of mud (Fig. 11). The evidence for glacial bottom currents is sparse along the eastern margin (Fig. 11), with weak currents recorded on the Porcupine Bank (this study) and on the Hebrides Slope (e.g. Knutz et al. 2002; Masson et al. 2002). Along the western margins weak bottom currents were recorded on the basin floor at 56°N, showing little variation in intensity from glacial to Holocene, which is in agreement with studies of the Feni Drift south of the mass-flow area by van Weering & de Rijk (1991).

Previous studies suggest that the pattern of glacial current circulation was different to that of today, as variations in the position and strength of NADW have occurred on glacial-interglacial time scales during the Pleistocene (e.g. Flower et al. 2000; Gröger et al. 2003; Venz et al. 1999). During the last glacial the production of NADW has fluctuated on a millennium scale, and three modes of circulation can be recognised: a stadial mode; a Heinrich mode; and an interstadial mode (e.g. Rahmstorf 2002). During the stadial mode, NADW formation was less vigorous and occurred at a lower latitude than today and the interstadial mode (e.g. Rahmstorf 2002; Sarnthein et al. 1994). A reduced thermohaline circulation could explain the deposition of mud on both margins of the Rockall Trough.

Interstadials

Enhanced bottom currents related to interstadial warming during MIS 3 were recorded on the slopes west of Porcupine Bank (Fig. 11), represented by two sharp- to erosive-based sand-mud couplets. As for the Holocene, the strong interstadial currents may also have been affected by the seabed topography, explaining the presence of the couplets directly north of the Porcupine Bank Canyon Complex. The distal Barra Fan is the only other place within the Rockall Trough that enhanced bottom-current activity has been recorded during interstadials in the form of calcareous silty to muddy contourites (Knutz et al. 2002). On the western margin, van Weering and de Rijk (1991) argued for persistent low-energy, bottom-current conditions throughout the last 125 ky.

During MIS 3, an interstadial mode of circulation operated in the North Atlantic with vigorous NADW formation in the Nordic seas (e.g. Duplessy et al. 1988; Kissel et al. 1999; Sarnthein et al. 1994). Based on stable isotope and Cd/Ca data, Boyle and Rosener (1990) reported rapid fluctuations coupled with changes in the formation of NADW during MIS 3. Kissel et al. (1999) argued that the variable stadial-interstadial deep-water circulation within MIS 3 was due to a modulation of strength of the deep-water production rather than an on-off switch in the NADW production (see also Boyle 1995). A rapidly changing deep-water circulation affecting the North Atlantic and the Rockall Trough could explain the deposition of the two sand-mud couplets representing two successive episodes of waning bottom currents on the Porcupine Bank.

The conditions during the MIS 3 interstadials were similar to the Holocene (Bond et al. 1999) with bottom-current flow directed northward along the eastern margin. This is supported by palaeoceanographic and sedimentary studies (e.g. Kissel et al. 1999; Knutz et al. 2002; Rahmstorf 2002) and by the presence of contourites directly north of the Porcupine Bank Canyon Complex, as the latter would have dampened the northward current flow favouring deposition. This northward flow transports warm water northwards to the Nordic Seas where NADW is produced, and which have important implications for the global climate (see e.g. Bond et al. 1999; Clark et al. 2002; Keigwin et al. 1994; Rahmstorf 2002).

Conclusions

The detailed gravity core studies reported here, when combined with results from previous studies of the Rockall Trough, show that the nature of Late Quaternary slope sedimentation has varied with both time and space. Slope deposits on the eastern margin of the trough have proved to be the most sensitive to variations in the current circulation on both glacial/interglacial and stadial/interstadial time scales, with sandy contourites and extensive erosive surfaces during warm periods and muddy deposits with variable ice-rafted debris during cold periods. This is in contrast to the western margin, where a mud-prone stratigraphy records no significant changes in the current circulation during the late Quaternary. Local and regional bathymetric controls were superimposed upon the temporal variations in the current activity, with canyons, slope-gradient variations and seabed highs serving both to deflect the path of the bottom currents as well as to locally reduce or enhance the current strength. The effect of local topography was observed on both margins of the trough, and was most evident during times of strong currents, that is interstadials (during MIS 3) and interglacials (e.g. the Holocene). Locally, glacial downslope remobilisation has disrupted the slope stratigraphy and in places overprinted the depositional signatures of bottom current activity (e.g. in the mounded slope region).

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