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Continental margin sedimentation, with special reference to the north-east Atlantic margin

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ABSTRACT

The north-east Atlantic continental margin displays a wide range of sediment transport systems with both along-slope and down-slope processes. Off most of the north-west African margin, south of 26°N, upwelling produces elevated accumulation rates, although there is little fluvial input. This area is subject to infrequent but large-scale mass movements, giving rise to debris flows and turbidity currents. The turbidity currents traverse the slope and deposit thick layers on the abyssal plains, while debris flows deposit on the continental slope and rise. From the Atlas Mountains northwards to 56°N, the margin is less prone to mass movements, but is cut by a large number of canyons, which also funnel turbidity currents to the abyssal plains. The presence of a lithospheric plate boundary off SW Iberia is believed to have led to high rates of sediment transport to the deep sea. Even larger quantities of coarse sediments have fed the canyons and abyssal plains in the Bay of Biscay as a result of drainage from melting icecaps. Bottom currents have built sediment waves off the African and Iberian margins, and created erosional furrows south of the Canaries. The Mediterranean outflow is a particularly strong bottom current near the Straits of Gibraltar, depositing sand waves and mud waves in the Gulf of Cadiz. North of 56°N, the margin is heavily influenced by glacial and glaciomarine processes active during glacial times, which built glacial trough-mouth fans, such as the North Sea Fan, and left iceberg scour marks on the upper slope and shelf. Over a long period, especially during interglacials, this part of the margin has been greatly affected by along-slope currents, with less effect by turbidity currents than on the lower latitude margins. Large-scale mass movements are again a prominent feature, particularly off Norway and the Faeroes. Some of these mass movements have occurred during the Holocene, although high glacial sedimentation rates may have contributed to the instability.

Keywords: Continental margin, sediments, slope processes, debris flow, turbidity current, bottom current

INTRODUCTION

In this paper, we describe the sedimentary processes, and map the major sedimentary features, on the north-east Atlantic continental margin from north-west Africa to northern Norway (Fig. 1). This region includes areas of passive margin with low sediment input, areas with high glacial sedimentation, areas incised by canyons, areas of fan sedimentation, areas with low gradient continental slopes, and areas with steep continental slopes.

Continental margins are important areas for investigation, since they form a 'new frontier' for exploitation by the hydrocarbons industry, and increasing numbers of telecommunication cables are laid across them. Nevertheless, many of the sedimentary processes displayed here remain poorly understood. Major advances in our knowledge of continental margins have followed the development and deployment of long-range side-scan sonars, such as GLORIA, which can image large areas in relatively short time intervals. Further advances have been achieved following the development of much higher-resolution deep-towed side-scan, and of swath bathymetry. There has been some ocean drilling of passive continental margins by Deep Sea Drilling Project (DSDP) and the Ocean Drilling Program (ODP), especially of modern fans (Legs 96, 116, 155), sediment drifts (e.g. Legs 94, 172, 181), and abyssal plains (Legs 149, 157). Down-slope processes have not been specifically targetted except in Legs 150 and 174 A, both on the New Jersey margin, where a down-slope transect of cores was drilled.

In this paper, we have limited our discussion to sedimentary processes operating from the shelf edge to the abyssal plain, so including the continental slope, continental rise and abyssal plain. In all cases, it is important to include the sediments of the abyssal plains as part of the continental margin, because the plains are formed by sediments derived from the margin. Within this area, the dominant sedimentary processes are along-slope sediment transport, which builds sediment drifts and waves, and down-slope processes involving mass wasting (sediment slides, debris flows and turbidity currents). In addition, canyons can be incised into the slope, in some cases cutting across the shelf, and large submarine fans may be built off major points of sediment supply. The scale of some of the processes can be very large; for example, the Storegga slide off Norway has an estimated volume of 5700 km^3 (Bugge *et al.*, 1988), while a single turbidite in the Madeira Abyssal Plain has a volume in excess of 300 km^3 (Weaver *et al.*, 1992, 1995).

MAIN SEDIMENTARY PROCESSES

Submarine slides and debris flows

Sediment instability resulting in submarine slides and debris flows is very common on some continental margins, and single events are frequently very large (of the order of hundreds of square kilometres). Should failure occur, then the ocean floor offers unimpeded slopes and flat-floored basins hundreds of kilometres in length, allowing flow over enormous distances. Slides are defined as the downward and outward movement of slope-forming materials, wherein shear failure occurs along one or several surfaces (see Hampton *et al.*, 1996, for a thorough review). Many submarine slides disintegrate down-slope into debris flows which are described as the movement of granular solids, sometimes mixed with minor amounts of entrained water on a low slope. The typical end product is a mass of displaced blocks of sediment or rock embedded in a more highly disrupted matrix. Debris avalanches are used here to describe submarine slides where little or no water entrainment occurs, and the resulting run-out distances are less. High-latitude slopes commonly consist of stacked debris flows (Vorren *et al.*, 1998). Such flows have been studied in the field and experimentally (e.g. Mohrig *et al.*, 1999), and are believed to flow on a lubricating layer of water between the flow and the underlying material—a process referred to as hydroplaning.

Turbidity currents

Turbidity currents occur on a variety of scales, and are a common feature of many continental margins. The largest turbidity currents form deposits in the deep ocean, and are termed megaturbidites; they are often linked to mass movements occurring higher up the slope. These currents transport tens to hundreds of cubic kilometres of sediment, and appear to be able to travel immense distances over extremely low-gradient slopes. They dump their sediment load only when they become ponded on the flat abyssal plains at the base of the slope. Individual mud-dominated turbidites commonly form layers up to a few metres in thickness over the whole abyssal plain (Pilkey, 1987; Rothwell *et al.*, 1992).

On the continental slope and rise, turbidity currents are usually funnelled down-slope by canyons and channels. Canyons are generally V-shaped in profile and are often eroded into bedrock. In plan view, they display tributary canyon systems with a number of orders of tributary, including steep, gullied slopes. They may originate offshore of a sediment point source, such as a river, and generally occur on, or just seaward of the shelf-break. Canyons commonly pass down-slope into channels, which are shallower than canyons, more U-shaped in profile, and may have depositional elements such as levees and aggradational floors. Deep-water channels occur in a variety of forms, from deep, narrow erosive channels, to broad, shallow distributary channels. Meandering channels tend to occur on fans with gentle gradients and a

dominantly fine-grained sediment supply (e.g. Clark *et al.*, 1992). Both canyon and channel floors can have bedforms such as gravel and sand waves and erosional scours.

Turbidity currents generally deposit the majority of their load on turbidite fans. The rivers running into the north-east Atlantic are relatively small and the resultant fans are usually built near the foot of the slope, beyond the canyon mouths.

Bottom currents

Bottom currents often play a major role in continental margin sedimentation. They can erode, mould, transport and redistribute sediments supplied to the slope and rise by down-slope flows and vertical settling. Bottom current features include erosional furrows and moats, and depositional bedforms, such as contourite drifts and sediment waves.

Contourite drifts are the primary deposits of bottom currents, and are widespread throughout the World Ocean. Contourite drifts occur on a variety of scales, from small patch drifts (<100 km^2) to giant elongate drifts (>100 000 km^2). Controls on contourite accumulation include the following: (1) active geostrophic circulation—this varies through time, for example, bottom currents are generally more active during interglacials, so contourite deposition is increased during these periods; (2) sea-floor topography—this can influence bottom current flow velocity, leading to sediment erosion or deposition in certain areas; (3) sediment supply—many contourite deposits actually derive the majority of their sediment from turbidite systems, because turbidity currents are one of the main mechanisms for sediment to be transported to the slope, rise and basins; (4) nepheloid layer turbidity—this also affects the ability of bottom currents to deposit or erode sediment (Faugeres *et al.*, 1993).

PROCESS INTERACTION ON THE NORTH-EAST ATLANTIC MARGIN

The nonglaciated margin south of 26°N (mass-wasting processes dominant)

Down-slope processes

The passive continental margin off north-west Africa, between 15°N and 26°N, is dominated by mass-wasting processes (submarine slides, debris flows and megaturbidites) (Fig. 2c). This is because of a number of factors, including low terrigenous input and local upwelling. This part of the margin receives very little fluvial sediment, particularly the margin off the western Sahara. However, a number of upwelling cells (Sarnthein *et al.*, 1982) give rise to high accumulation rates along the upper slope and shelf edge. The megaturbidites derived from this margin and deposited on the Madeira Abyssal Plain are distinguished by their high organic contents (0·5–2%; Rothwell *et al.*, 1992), suggesting that it is the sediments resulting from the upwelling which are unstable, presumably as a result of slope oversteepening.

The upper parts of submarine slides often show spectacular detail when imaged with high-resolution side-scan sonar (Fig. 3), or swath bathymetry. The Saharan Slide off west Africa (Simm & Kidd, 1984; Masson *et al.*, 1992) included about 600 km^3 of sediment, which was transported up to 700 km down-slope, across gradients ranging from 1·5° to 0·1°. Although not strictly part of the continental margin, the Canary Islands are also subject to large-scale mass wasting. The head and sidewalls of the El Golfo debris avalanche in the Canary Islands extend from about 3000 m below sea-level to almost 1000 m above sea-level, forming a distinct arcuate cliff in the side of the island of El Hierro. This debris avalanche contains 150–180 km^3 of rock and debris which extends some 60 km down-slope, to a water depth of about 3500–4000 m (Masson, 1996). Some of the blocks in the debris avalanche are 1 km across.

In contrast to the margin to the south and to the north, well-developed turbidite fans are not present on the north-west African margin. This is because of the lack of major sediment point sources and because terrigenous input overall is limited and intermittent (Wynn *et al.*, 2000a). The limited input means that turbidity currents on the margin are infrequent, but on a large scale. They flow along linear turbidity current pathways that transport material up to 1200 km offshore to the deep abyssal plains. In addition, many parts of the margin have complex seafloor topography, which further inhibits fan development. Sandy lobes may occur at the terminations of channels on the proximal margins of abyssal plains. For example, although the fill of the Madeira Abyssal Plain is dominated by a thick sequence of ponded turbidite muds (Fig. 4), a sandy lobe has developed on the eastern margin of the plain near the termination of the Madeira Distributary Channel System (MDCS).

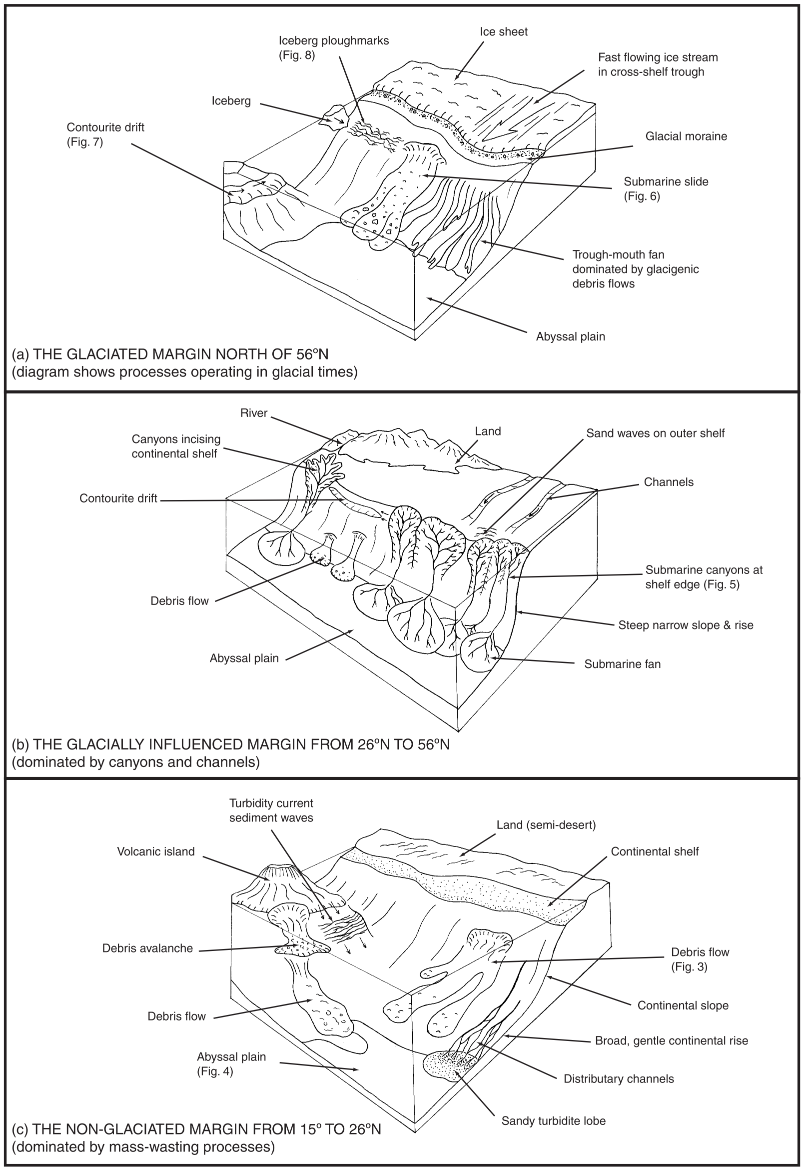

Fig. 2. Schematic diagrams, showing the idealized sedimentary features on (a) the glaciated margin north of 56°N, (b) the margin from 26°N to 56°N (dominated by canyons and channels, and (c) the margin from 15°N to 26°N (dominated by mass-wasting processes).

The MDCS is the best-developed distributary channel network on the north-west African margin and is some 500 km long. It extends from the western edge of the intraslope Agadir Basin to the eastern edge of the Madeira Abyssal Plain, and occurs on gradients of 0·3° to 0·05°. The shallower (<20 m deep), braided channels within the system occur on slopes of about 0·07°, whereas the narrower, more incised (up to 50 m deep) channels occur on slightly steeper slopes of about 0·3°. Unlike most distributary channels, levees are not developed in the MDCS, because there is no significant turbidity current overspill. This is because the sandy bedload is wholly confined within the channel, and the fine-grained suspension cloud travels as an unchannelized sheet flow across the rise (Masson, 1994). It is likely that other well-developed distributary channel systems supply material to the Cape Verde Basin (Jacobi & Hayes, 1992) and the southern margin of the Madeira Abyssal Plain; however, data for these areas are lacking.

A major canyon system occurs on the western Saharan margin at 26°N (von Rad & Wissmann, 1982). Twenty-five closely spaced canyons occur at a water depth of 1000–3000 m. They have an average spacing of just 10 km, and are different from most other canyons on the north-east Atlantic margin, in that they do not generally reach back to the shelf edge, and rarely extend down-slope beyond the slope–rise boundary. There is currently no fluvial input on this part

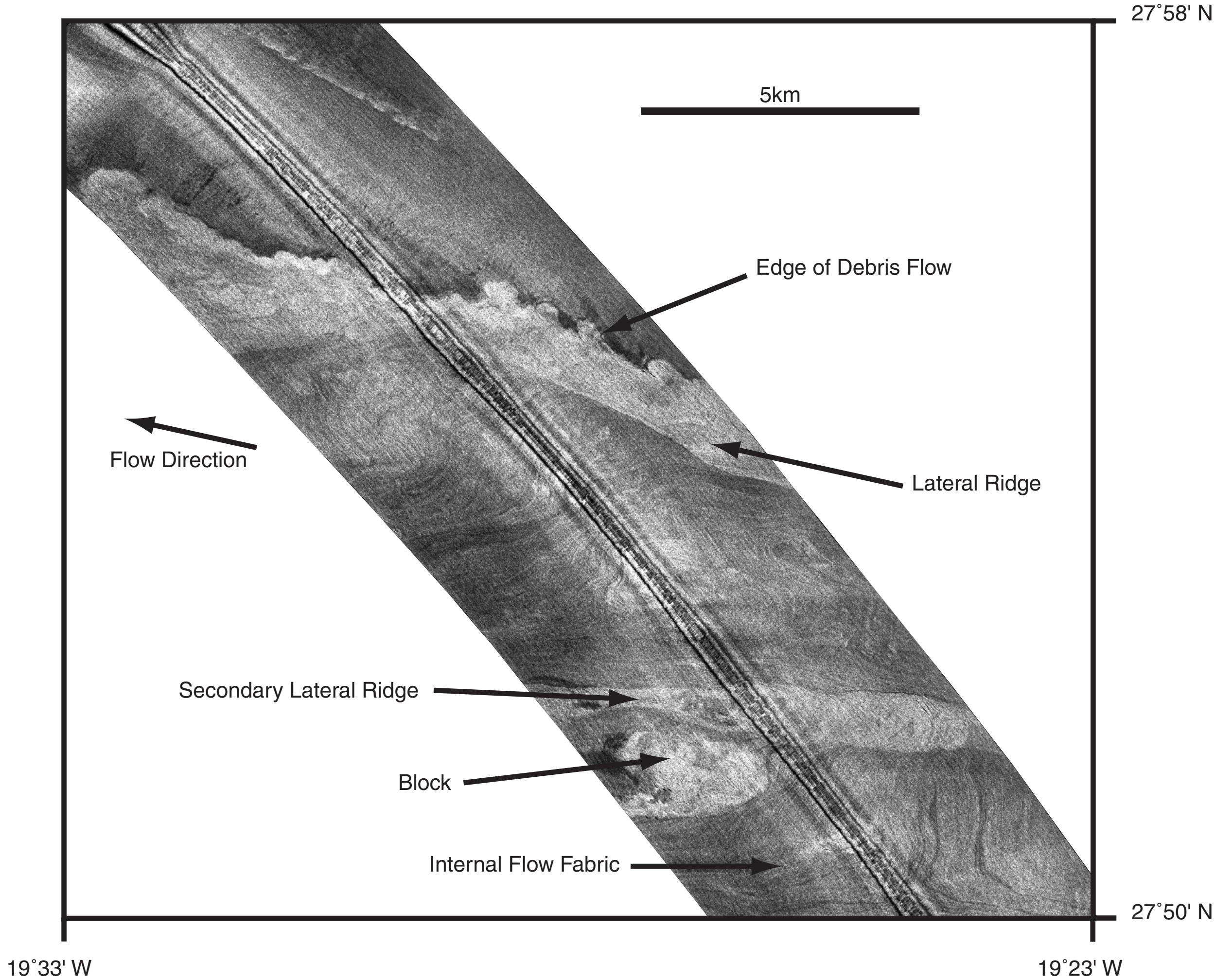

Fig. 3. TOBI (30 kHz deeptowed, side-scan sonar) image, showing the edge of the Saharan debris flow, west of the relatively starved north-west African margin. High levels of backscatter are shown as light tones. For location, see Fig. 1.

of the margin, and most aeolian input onto the shelf is swept southwards by strong currents (Sarnthein *et al.*, 1982). Therefore, the canyons are believed to have formed during previous lowstands of sea-level, when there was increased terrigenous input (von Rad & Wissmann, 1982). The close spacing of the canyons appears to be controlled by the steeper slope angles in this area. The north-west African continental slope generally has a slope angle of 0·5°–2° but, in the area of the canyon system, the slope angle is increased to 3°, leading to closely spaced canyon incision (von Rad & Wissmann, 1982). This highlights how subtle changes in seafloor gradients can have a dramatic control on slope processes. A similar example of control on canyon formation by slope gradient is found in the Porcupine Seabight (Kenyon, 1987).

Recent investigations on the lower slope and rise north-west of the Canary Islands have revealed that fields of sediment waves on open slopes may be generated by unconfined turbidity currents (Wynn *et al.*, 2000b). Sediment waves can also be generated by bottom currents, but a number of criteria can be used to distinguish the two types.

These criteria are as follows. (1) Turbidity current waves typically show a regular downslope decrease in dimensions, and bottom current waves are generally more irregular. (2) Turbidity current wave crestlines are aligned parallel to the slope, and are often sinuous and bifurcating. Bottom current waves on slopes are generally developed at an angle to the slope and are more uniform. (3) Core studies of different wave types typically reveal evidence of turbidity current deposition *or* bottom current deposition.

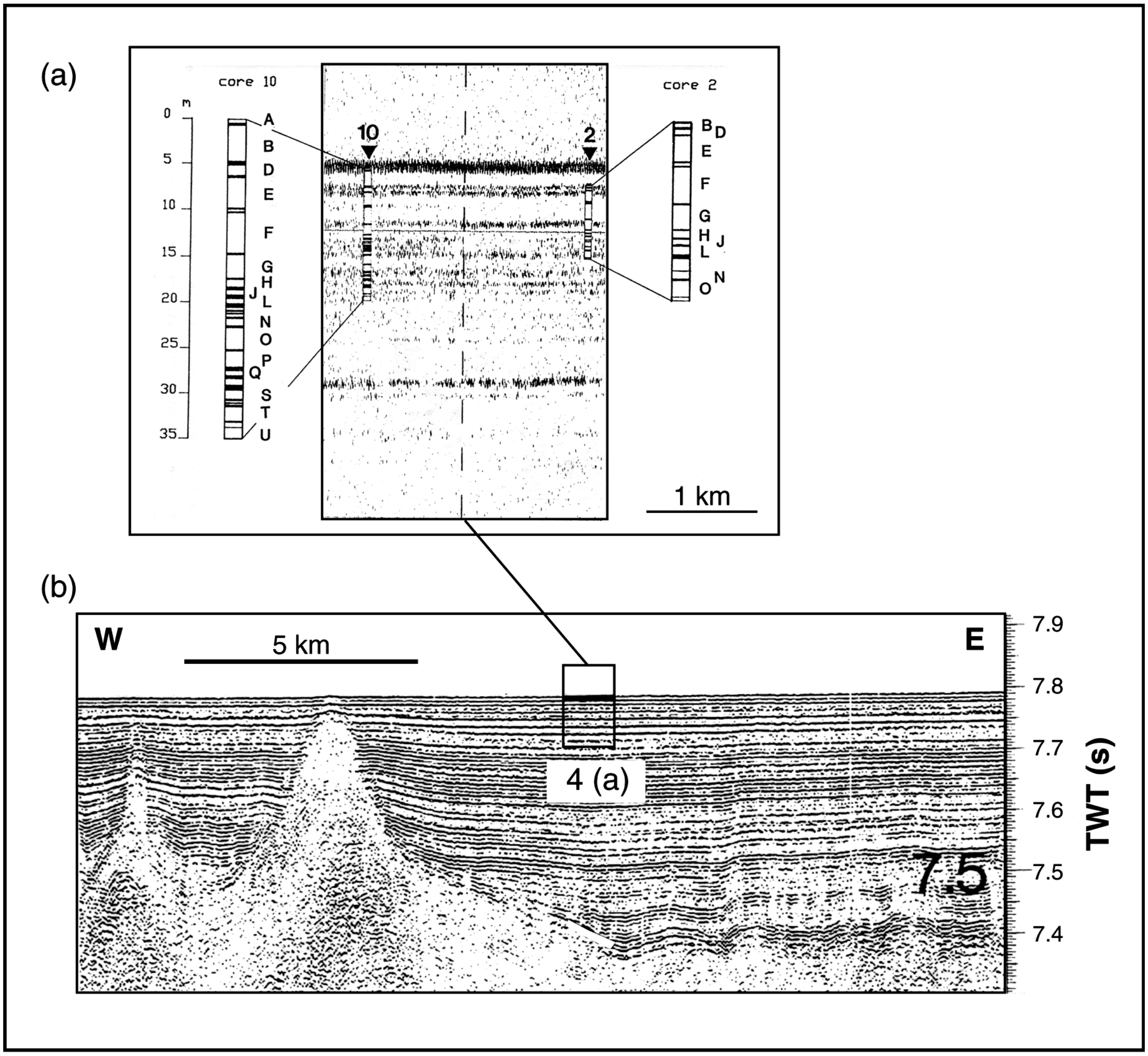

Fig. 4. (a) 3·5 kHz profile across a section of the Madeira Abyssal Plain (31°N, 25°W), with two cores showing how the megaturbidite sequence can be roughly correlated with seismic reflectors. The lettering scheme on the two cores represents individual megaturbidites as defined by Weaver *et al.* (1992). (b) Airgun seismic profile of ponded megaturbidites from the Madeira Abyssal Plain. Boxed area represents the high-resolution profile shown in (a). For location, see Fig. 1.

(4) Bottom current sediment waves only form beneath bottom currents of 9–50 cm s^{-1} (e.g. Flood, 1988). They do not occur in areas with weak or absent bottom currents (although the bottom current regime in the past must be taken into account). (5) A thorough examination of the oceanography, seafloor topography, and sedimentary regime in the area of a wave field will often give conclusive evidence of its origin. Wave heights of turbidity current sediment waves around the Canary Islands are up to 70 m, and wavelengths are up to 2·4 km. The waves are aligned roughly parallel to the slope and migrate upslope. Cores taken through the waves show a sequence of interbedded turbidites and pelagic/hemipelagic sediments. Overall, the dimensions, morphology and mode of formation of the waves are very similar to those described for sediment waves on channel-levee backslopes (e.g. Nakajima *et al.*, 1998). Sediment waves in turbidity current channels have also been described from the flanks of the western and northern Canary Islands (Wynn *et al.*, 2000b). These waves are smaller and coarser-grained than those formed

by unconfined flows. They have wave heights up to 6 m and wavelengths up to 1·2 km.

Along-slope processes

Antarctic bottom water (AABW) is responsible for forming erosional furrows and sediment waves on the continental rise off north-west Africa (Jacobi & Hayes, 1984, 1992). In the area of the Saharan Seamounts, AABW is funnelled between the seamounts and strengthened by tidal currents, leading to the formation of erosional furrows.

The glacially influenced margin from 26°N to 56°N (canyon and channel processes dominant)

Down-slope processes

This margin has a series of large submarine canyons and little or no evidence of submarine slides (Fig. 2b). North-east of the Canary Islands is an area of canyoned margin beginning with the Agadir Canyon. These canyons funnel sediment derived from the Atlas Mountains across a continental slope which is considerably narrower than that to the south. The turbidity currents deliver sediments directly to the Seine Abyssal Plain (Davies *et al.*, 1997) and the Agadir Basin. The Agadir Basin is an intraslope basin from which sediment flows now spill over and flow down-slope to the Madeira Abyssal Plain (Masson, 1994; Wynn *et al.*, 2000a).

TOBI deep-towed side-scan sonar surveys at the mouth of the Agadir and Lisbon Canyons have revealed extensive zones of erosional scours and bedforms associated with the transition zone between canyon mouth and depositional lobe. These transition zones are commonly developed at the mouths of submarine canyons and channels (see Normark & Piper, 1991, for a review), and are created by the increased turbulence and erosive power of turbidity currents undergoing flow expansion. The flow expansion may be linked to a hydraulic jump (Komar, 1971) in areas where there is a significant break-of-slope at the canyon/channel mouth. At the mouth of the Agadir and Lisbon Canyons, individual erosional scours up to 21 m deep and 500 m wide have been imaged. In addition, fields of chevron-shaped scours, erosional scarps and sediment waves have all been imaged in this zone. The Agadir Canyon system feeds infrequent (one every 30 000 years), large-volume (up to 250 km^3) turbidity currents to the Agadir Basin (Weaver *et al.*, 1992). These turbidity currents spread out and flow as sheet flows across the basin floor, which is topographically constrained by volcanic islands and seamounts. Many of the flows continue westwards to the Madeira Abyssal Plain but, in doing so, they often deposit much of their sandy bedload in the Agadir Basin as a sheet sand (Ercilla *et al.*, 1998).

The margin from Iberia to the southern Rockall Trough is dominated by canyons which are often deeply incised. The canyons on the eastern side of the Rockall Trough are, as yet, poorly mapped but are known to exist even on the Porcupine Bank margin, which is relatively isolated from areas of fluvial input (Roberts, 1975). It has been noted before (e.g. Emery & Uchupi, 1984) that this concentration of canyons is near the southern limits of the Quaternary ice cover, and coarse sediment carried by meltwater may have fed them. Canyons were most active during lowstands of sea-level, because more material was transported to the canyon head at these times. Many canyons are largely inactive during interglacials, and can become partly infilled with pelagic and hemipelagic sediments. However, infrequent events, such as earthquakes, may trigger large turbidity currents at any time. For example, the 1755 Lisbon earthquake triggered a massive turbidity current that is believed to have travelled along the Setubal Canyon and out onto the Tagus Abyssal Plain (Thomson & Weaver, 1994). Location, morphology and spacing of canyons is controlled by a combination of sediment supply, slope angle, seafloor topography and structure (e.g. faults). On the west Portuguese margin, the canyons are dominantly controlled by the positions of river mouths which would have been closer to the canyon heads during lowstands of sea-level. Several canyons on this margin (e.g. Setubal Canyon) even cut back to the inner shelf, and feed directly from the lower reaches of major river valleys. The west Portuguese continental margin is steep and narrow, and the turbidity currents have built large abyssal plains at the foot of the slope (Milkert & Weaver, 1996; Lebreiro *et al.*, 1997). On the extensively canyoned north Biscay margin, the canyons are fed by cross-shelf glacial drainage channels, and by tidal shelf sand transport (Kenyon *et al.*, 1978; Reynaud *et al.*, 1999). The canyons are restricted to areas of steeper gradients with an angle of 4°–9°. Many of the canyons are aligned

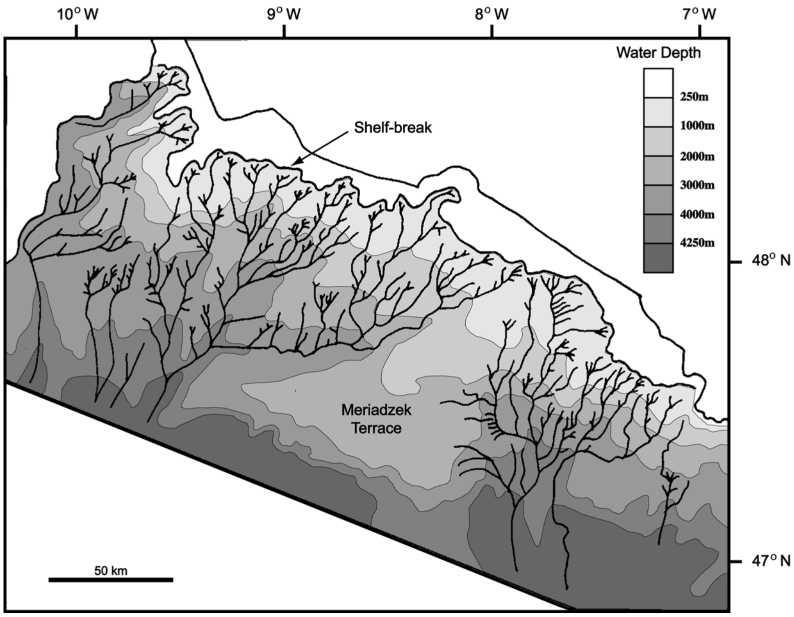

Fig. 5. Line diagram based on swath bathymetry, showing the detailed and complex morphology of canyons on the continental slope bordering the Celtic Sea Shelf (Biscay margin). Modified from Bourillet and Loubrieu (1995). For location, see Fig. 1.

oblique to the slope, and their morphology is clearly related to underlying basement topography and faulting (Kenyon *et al.*, 1978; Lallemand & Sibuet, 1986).

Most canyons in the study area have gullied walls and a number of minor tributary canyons feeding sediment from the continental shelf (Fig. 5). They merge down-slope into one major canyon before terminating directly onto a basin floor. Small distributary channels are known in a few cases to have developed beyond the canyon mouths, e.g. on the Celtic Fan (Droz *et al.*, 1999), and beyond the Gollum Canyon system in the Porcupine Seabight. The Gollum Canyon system has canyons up to 280 m deep and 1·5 km wide that develop down-slope into a dendritic pattern of slightly sinuous channels running across the floor of the Seabight (Kenyon *et al.*, 1978). Levees are absent from this channel system, probably for the same reasons as for the MDCS. Beyond the Seabight, distributary channels are only up to 40 m deep. The largest abyssal plains are found on this sector of the margin as demonstrated in Fig. 1 (which is an equal area projection). This is presumably because of higher turbidity current activity in this area, as a result of increased glaciomarine sediment supply at the edge of the Quaternary ice sheet.

Along-slope processes

The Mediterranean outflow water (MOW) is responsible for the creation of a wide range of bottom current features on the south and west Iberian margin (Kenyon & Belderson, 1973; Nelson *et al.*, 1999). Immediately west of the Straits of Gibraltar, the MOW flows at up to 250 cm s^{-1}, and erosional scours and sand ribbons cover the seafloor. Further west, the current velocity decreases to 40–75 cm s^{-1} and sand waves are developed. A progressive decrease in velocity to around 20 cm s^{-1} leads to the development of mud waves up to 40 m high. Further west, on the south and west Portuguese margin, the MOW is responsible for shaping the seafloor sediments into a series of contourite drifts down to depths of about 1500 m. These drifts are generally small and isolated, for example, the Faro Drift on the southern Portuguese margin is about 50 km long and 10–25 km wide (Faugeres *et al.*, 1985).

The glaciated margin north of 56°N (glacial and along-slope processes dominant)

Down-slope processes

There is a marked change in shelf and slope morphology where the Quaternary icecaps were in proximity to the margin (Fig. 2a). The shelves as far south as 56°N (west of Scotland) are crossed by troughs that were cut near to the shelf edge by fast-flowing ice streams, and the maximum southerly extent of icesheets during the glaciations was to southern Ireland. South of 56°N, the slope is dominated by canyons, probably formed by erosive turbidity currents fed by a plentiful

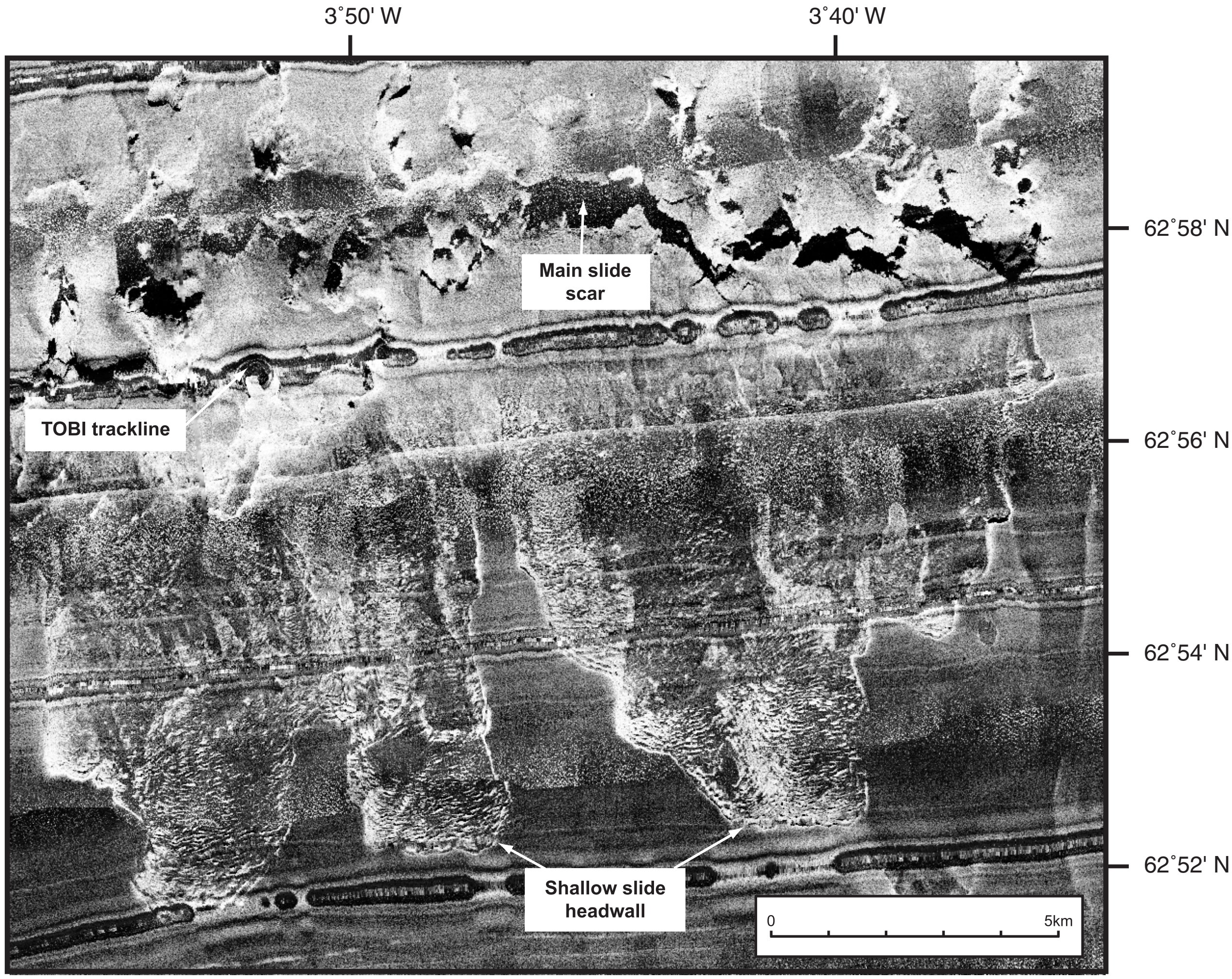

Fig. 6. TOBI side-scan sonar mosaic, showing an area of mass movements north of the Faeroe Islands. Shallow slides occur upslope of a major slide scar (seen as black shadows), representing a deeper failure. Down-slope is to the north. High levels of backscatter are shown as light tones. Modified from van Weering *et al.* (1998b). For location, see Fig. 1.

supply of coarse sediment. North of 56°N, there are few large canyons. The reasons for this are not established. Possibly, the glacial meltwater that must have carried large amounts of material across the shelf was largely diverted into the cross-shelf troughs and fed to the slope at these few point sources, causing sliding rather than turbidity currents and canyon cutting. It has also been suggested that the strong currents along the upper slope have prevented canyon formation, as is the case on the north-western Atlantic margin to the south of Cape Hatteras (Kenyon, 1987).

The geometry and processes of sedimentation along the margin in the Norwegian Sea have been reviewed by Vorren *et al.* (1998), and similar processes act along the margin west of Scotland. At the mouth of the cross-shelf troughs, there are usually trough-mouth fans, accumulations of sediment on the slope, which have a characteristic internal geometry very different from typical low-latitude turbidite fans. Of the two main small-scale geometries, the most common are stacks of glacial debris flows: long, narrow tongues of a fairly consistent size and composition that extend down-slope. Less frequent are classic debris flows which are usually much more extensive and varied in thickness (King *et al.*, 1996; Baltzer *et al.*, 1998).

Modelling of the flows within ice sheets by Dowdeswell and Siegert (1999) shows the predicted pattern of ice flux to the shelf edge along the Eurasian margin. Sediment flux transported by the icestreams has also been modelled and agrees well with the known distribution and size of trough mouth fans. The southernmost glacial

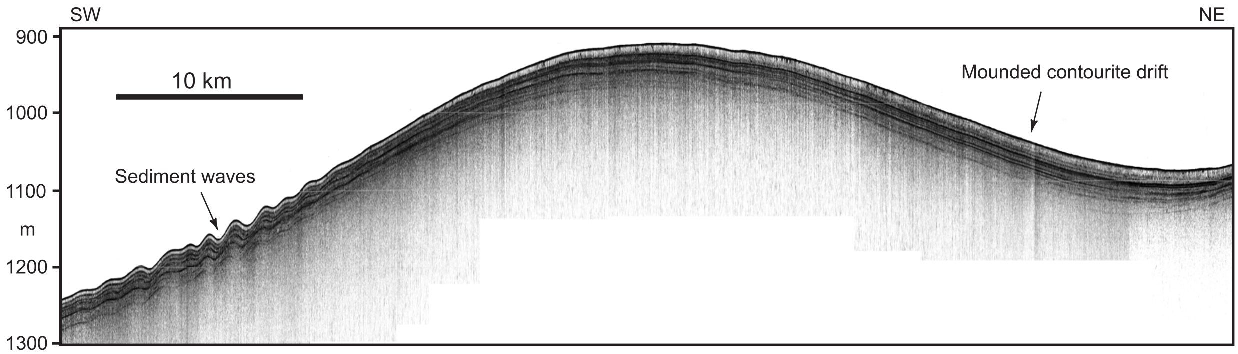

Fig. 7. 3·5 kHz profile, showing sediment waves on the flank of a sediment drift in the north-east Rockall Trough (59°45′N, 07°40′W). For location, see Fig. 1.

fan is the Barra Fan. The presence of extensive turbidite deposition at the foot of the Barra Fan (Roberts, 1975; Faugeres *et al.*, 1981) and the network of tributary gullies at the top of the fan (Armishaw *et al.*, 1998) are unusual glacial fan features, so this is possibly a transitional example of a glacial fan. A further example of a glacial fan west of Scotland is the Sula Sgeir Fan (Baltzer *et al.*, 1998). West of the Shetland Islands, there are no well-developed cross-shelf troughs and no major depocentres. The extensive areas of both classic and glacial debris flows form what could be called a slope apron.

The two major areas of glacial drainage result in the enormous North Sea Fan (King *et al.*, 1996) and the Bear Island Fan (Dowdeswell *et al.*, 1997; Vorren *et al.*, 1998). Both consist mainly of large numbers of stacked glacial debris flows. The Bear Island Fan is comparable in size with the largest low-latitude turbidite fans, such as the Mississippi Fan, which consists mainly of large numbers of stacked channel-levee complexes. Both the largest fans are modified by major slides. The slides either bound the fans, such as the Storegga and North Faeroes Slides (Fig. 6) on the northern and southern margins of the North Sea Fan (van Weering *et al.*, 1998a,b), or are on top of them, such as the Bjornoyrenna Slide (Laberg & Vorren, 1993) on top of the Bear Island Fan. The best-studied slide is the Storegga Slide (Bugge *et al.*, 1987, 1988; Evans *et al.*, 1996). This is a site of repeated failure. Less well-studied slides include that east of Rockall Bank (Roberts, 1972; Flood *et al.*, 1979), the Traenadjupet Slide (e.g. Dowdeswell *et al.*, 1996) and the Andoya Slide (Laberg *et al.*, 1999). It seems likely that seismic investigations will reveal a complex history of repeated failure for most of these slides. It has been suggested that these slides could be caused by detachment of slabs of sediment charged with solid gas hydrate, released as the seawater warms up (Bugge *et al.*, 1988; Mienert *et al.*, 1998). Bottom-simulating reflectors have been detected near the Storegga Slide and modelling predicts that the Norwegian Sea margin should be a likely place for gas hydrate formation (Miles, 1995).

Along-slope processes

Bottom currents have developed an extensive suite of contourite drifts and mud waves in the north-east Rockall Trough area (Fig. 7). In this region, there is a complex circulation of bottom water, and mixing between three or four different water masses may occur. Generally, bottom currents have a greater influence on sedimentation during interglacials, because much of the slope was affected by large-scale mass movements and turbidity currents during glacial periods. North-east of the Faeroe Islands, the Norwegian Sea deep water (NSDW) has formed contourite deposits on the upper slope (van Weering *et al.*, 1998a). Part of the NSDW then flows south through the Faeroe–Shetland Channel as Norwegian Sea overflow water (NSOW), before moving west over the Wyville–Thomson Ridge. It partially mixes with Labrador Sea water (LSW) and AABW to form North Atlantic deep water (NADW), which circulates as an anticlockwise gyre in the Rockall Trough. In this region, a number of contourite drifts have formed, and three distinct types can be recognized (Stoker *et al.*, 1994). These are as follows: distinctly mounded elongate drifts; broad sheet drifts; and isolated patch drifts (including moat-related drifts). Sediment waves occur on the flanks of these drifts, and have wave heights up to 20 m

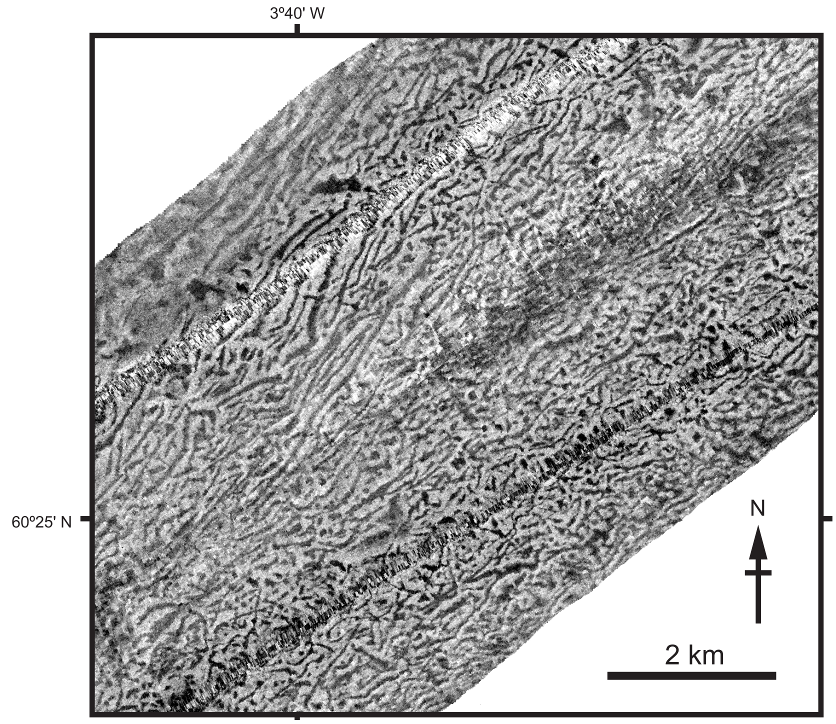

Fig. 8. TOBI side-scan sonar mosaic, showing iceberg plough marks on the upper slope west of Scotland (60°N, 03°W; Masson *et al.*, 1997). The pattern of plough marks changes from criss-crossing to parallel as the slope steepens to the north-west. High levels of backscatter are shown as light tones. For location, see Fig. 1.

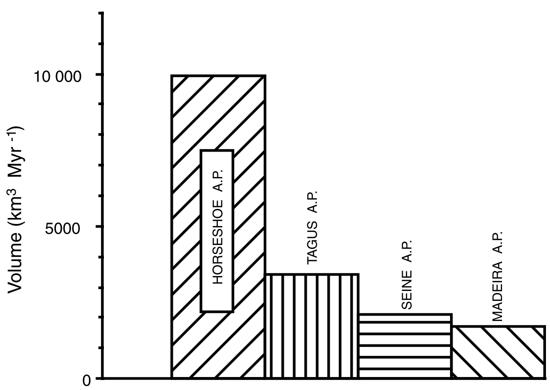

Fig. 9. Graph showing how the volume of turbidites per million years varies on four different abyssal plains. The volume of material contributed to the abyssal plains increases as one goes northwards, because the margin is both more tectonically active and has a greater sediment supply in this area.

and wavelengths up to 2 km (Fig. 6). Further south and west, adjacent to the Rockall Plateau, are the giant Feni and Hatton Drifts (McCave & Tucholke, 1986).

During glacial periods, the currents moved large icebergs around the north-east Atlantic. Where they impinge on the continental slope and outer shelf, they form patterns of iceberg plough marks (Fig. 8; Belderson *et al.*, 1973). They generally occur down to about 700 m, except where buried by later sedimentation. It is usual to find a dense network of criss-crossing iceberg plough marks on the shelf and upper slope, and isolated plough marks running along-slope in deeper water. The southernmost limit of known plough marks is west of Ireland.

Relatively strong currents are found both bounding the drifts and in other areas where topography enhances flow speeds, such as the gateway of NSDW across the Iceland–Faeroe–Scotland Ridge. These can winnow away the finer sediments and prevent deposition. Sandy bedforms and thin sheet sands are found, such as those along the upper slope from Scotland to northern Norway (Kenyon, 1986), and in the Faeroe–Shetland Channel (Masson *et al.*, 1997). The exit from the Faeroe Bank Channel resembles the northern Gulf of Cadiz, in having small drifts bounded by coarse floored channels, some of which appear to be aggradational (Kenyon *et al.*, 1998).

DISCUSSION

Variations in sedimentation pattern along the margin

The map (Fig. 1) and the preceding description show that sedimentary processes vary along the length of the continental margin. There are three primary margin types: nonglaciated, glacially influenced and glaciated. Mass movements are common on the nonglaciated margin south of about 26°N. From here to 56°N, on the glacially influenced margin, there are few mass movements but canyons are common, cutting into a steep continental slope. North of 56°, on the glaciated margin, most of the prominent seafloor features were generated during the last ice age and are now being reshaped by along-slope currents. An exception to this simple model is the submarine sliding which has occurred off Norway during the Holocene (e.g. the Storegga Slide with a date of emplacement of 7100 years; Bondevik *et al.*, 1997), although these features may also be related to climate change, such as via earthquakes associated with isostatic rebound initiating the sliding.

Off north-west Africa (the nonglaciated margin), there is little sediment input from the continent, but high productivity along the upper slope produces accumulation rates of up to 147 m Myr^{-1}, in contrast to mid- and lower slope accumulation rates of 20 m Myr^{-1} (Ruddiman *et al.*, 1988). This leads to oversteepening of the slope and potential instability. Therefore, sediment sequences along the upper part of this margin show a series of hiatuses, each representing tens to hundreds of metres of missing sediment, and with durations of hundreds of thousands of years (Weaver, 1994). Further downslope, the sediment sequence contains a number of debris flow deposits and, at the base of the slope, the abyssal plain fills gradually with a series of megaturbidites. The large sediment slides off Norway operate in a similar fashion but, in this area, there are also substantial deposits derived from ice sheet transport. The rate of accumulation of these ice-derived sediments is very high and they rapidly build large fan-like bodies. At the present day, they are largely inactive and Holocene sedimentation has added only a thin veneer to the surface of the glacial fans.

The glacially influenced margin is characterized by a steep continental slope and relatively large abyssal plains which almost coalesce. Off the Iberian margin, frequent earthquakes are correlated with frequent turbidite deposition, although the frequency of turbidite emplacement seems to have been higher during glacial periods (Lebreiro *et al.*, 1997). Although there is limited information on the canyons and abyssal plains in the Bay of Biscay, the density of canyons is striking. This may be because of the large amounts of sediment which would have been transported across this margin during ice ages, and particularly during ice retreat. There was no ice sheet near the shelf edge in this area during the ice ages, but the inland drainage basins of the UK, France and Iberia would have been much more active in transporting sediment eroded by ice at these times. South of the Atlas Mountains, there would have been no influence of ice and, north of southern Ireland, grounded ice processes would have operated near the shelf edge, especially in front of cross-shelf troughs, producing stacked debris flow deposits. The high sediment inputs and steep, narrow continental slopes have led to most of the deposition being on the abyssal plains, such that these have grown to a very large size. Therefore, to summarize, the large size of these abyssal plains is a result of a combination of (1) high sediment supply from glacial outwash; (2) a narrow, steep slope and rise which leads to sediment bypassing; and (3) the high seismicity of the margin off south-west Iberia triggering frequent turbidity currents (Fig. 9).

One consequence of the differing margin physiographies is the distribution of sand from the numerous turbidity currents. For basins at the base of steep continental slopes, e.g. the Tagus and Horseshoe Basins off Portugal (Lebreiro *et al.*, 1997) and the Bay of Biscay (Droz *et al.*, 1999), turbidity currents have enough velocity to carry large volumes of sand to the abyssal plain. The sand is then dumped across a large area centred around the point of entry. On the Tagus Abyssal Plain, this sandy area forms a very low-relief fan with shallow channels, and covers approximately 20% of the total plain area. At the other extreme, the Madeira Abyssal Plain lies at the base of a very low-angle continental slope (1:300) and, in this case, the ratio of mud to sand is much higher (of the order of just a few per cent of sand). The sand component in these turbidity currents may be deposited in channels and intraslope basins on the continental slope and rise. Sands deposited on the plain are concentrated around distributary channel terminations (Wynn *et al.*, 2000a). This concentration of sand in one part of the plain produces laterally as well as vertically graded sediment units.

Turbidity currents can be generated by hyperpycnal discharge at the mouths of 'dirty' rivers. The flows will follow the basin floor if the plume density is greater than that of the surrounding salty water. Such flows rarely occur off large rivers but they may occur off small rivers with a high suspended-sediment load (Mulder & Syvitski, 1995). Such rivers may have been common on the steep, narrow land surrounding the Iberian Peninsula and, during periods of high glacial meltwater drainage, on the shelf to the north.

It is interesting to note that the spectacular meandering channels that are so common on the west African margin to the south of the study area are absent from the north-west African and west European margin. This is probably because of a combination of gradient and sediment composition. On the north-west African and west European margin, the outer shelf is dominated by coarse-grained sediments, so most canyons and channels are formed by sand-rich turbidity currents.

Long-term history of the margin

The abyssal plain turbidites provide an excellent record of large-scale mass-wasting events in the Canary Basin, because each major event here seems to produce both a debris flow deposited on the continental slope and rise, and a turbidity current that deposits on the abyssal plain. Therefore, drill-holes through the abyssal plain sequence can provide a record of the largest mass-wasting events that have occurred at a variety of locations on the basin margins. In this way ODP Legs 157 (Schmincke *et al.*, 1995) and 149 (Whitmarsh *et al.*, 1996), which drilled the Madeira and Iberia Abyssal Plains, respectively, each provided a history of their basin. In the case of the Iberia Abyssal Plain, the turbidite input and, hence, basin filling began at about 2·4 Ma, coincident with the onset of Northern Hemisphere glaciations (Milkert & Weaver, 1996). In the Madeira Abyssal Plain, turbidite sedimentation began abruptly in the middle Miocene, at a time when ice began to build up rapidly on Antarctica (Weaver *et al.*, 1998). This external climatic change could have caused significant reorganisation of sedimentation along the world's continental margins. It would have initiated a time of lowered sea-level, which may have allowed sediments to be deposited beyond the shelf edge on the upper slope for the first time. In addition, the build up of ice would have led to the production of cold bottom waters in Antarctica, which would, in turn, have caused a reorganization of ocean circulation. This may have led to increased upwelling and associated sedimentation along the West African margin (see Sarnthein *et al.*, 1982). Both these processes would have caused an oversteepening of the upper continental slope, possibly leading to mass wasting and initiation of organic-rich turbidites which reached the abyssal plains.

CONCLUSIONS

A range of sedimentary processes affect the north-east Atlantic continental margin from north-west Africa to northern Norway. Processes vary considerably along the margin, with some areas being dominated by down-slope and others by along-slope transport and deposition. In the more northern areas, there are also significant differences between the processes that operated during glacial periods and those that operate today. The main sectors of the margin and their respective dominant processes are as follows.

1 *The nonglaciated margin south of 26°N.* High rates of upwelling here produce elevated accumulation rates along the upper slope, although there is little fluvial input and canyons are rare. This sediment is subject to mass movements involving dislocation of hundreds to thousands of square kilometres of sediment, on timescales of a few tens of thousands of years. The resultant debris flows are deposited across the continental slope and rise, and large-scale turbidity currents transport hundreds of square kilometres of sediment to the abyssal plains.

2 *The glacially influenced margin from 30°N to 56°N.* In this area, there is more fluvial input and the margin is less prone to large-scale mass movements. A number of canyons funnel turbidity currents down the steep slopes to the extensive abyssal plains. Some canyons, such as the Agadir Canyon, have built high levees. The presence of a lithospheric plate boundary off south-west Iberia is associated with frequent earthquakes and has led to high rates of sediment transport to the deep sea via the canyon systems. In addition, there is a high sediment supply to the shelf edge, because a lot of sediment was transported by glacial outwash during and at the end of glacial periods. The Mediterranean outflow has built a series of sediment drifts in the Gulf of Cadiz and off south-west Portugal, although the along-slope transport is interrupted by a number of large canyons, some of which cut back into river mouths.

3 *The glaciated margin north of 56°N.* Here, the margin is heavily influenced by glaciomarine processes which build fans composed largely of

stacked debris flows. These occur in front of the fast-flowing ice streams that have cut cross-shelf troughs. There are iceberg plough marks on most of the upper slope and outer shelf. During interglacials, this part of the margin has been affected by along-slope currents. Giant submarine slides are again a prominent feature, particularly off Norway and the Faeroe Islands. Some of these slides have occurred during the Holocene, although high glacial sedimentation rates and failure at melting gas hydrate layers may have contributed to the instability.

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