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The Northwest African slope apron: a modern analogue for deep-water systems with complex seafloor topography

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Abstract

The Northwest African slope apron is an interesting modern analogue for deep-water systems with complex seafloor topography. A sediment process map of the Northwest African continental margin illustrates the relative roles of different sedimentary processes acting across the entire margin. Fine-grained pelagic and hemipelagic sedimentation is dominant across a large area of the margin, and is considered to result from 'background' sedimentary processes. Alongslope bottom currents smooth and mould the seafloor sediments, and produce bedforms such as erosional furrows, sediment waves and contourite drifts. Downslope gravity flows (debris avalanches, debris flows and turbidity currents) are infrequent but important events on the margin, and are the dominant processes shaping the morphology of the slope and rise. The overall distribution of sedimentary facies and morphological elements on the Northwest African margin is characteristic of a fine-grained clastic slope apron. However, the presence of numerous volcanic islands and seamounts along the margin leads to a more complex distribution of sedimentary facies than is accounted for by slope apron models. In particular, the distribution and thickness of turbidite sands are controlled by the location of the break-of-slope, which is itself controlled by the pre-existing submarine topography. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Northwest Africa; Slope apron; Turbidity currents

1. Introduction

The Northwest African continental margin has been the focus of intensive research in the last thirty years. Early sediment facies maps, based on 3.5 kHz echo-sounder profiles, were produced for various sections of the margin (Embley, 1976; Embley & Jacobi, 1977; Jacobi, 1976; Jacobi & Hayes, 1982, 1984, 1992) and these have increased our understanding of the interactions between gravity flows, bottom currents and pelagic/hemipelagic sedimentation in continental slope and rise settings.

More recent studies have concentrated on the mapping of turbidity current pathways, debris flows and debris avalanches around the Canary Islands, with increasing use of the GLORIA and TOBI side-scan sonar systems. This work has led to a greater understanding of the sedimentary processes across the margin, such as debris flows (e.g. Gee, Masson, Watts & Allen, 1999; Masson, Huggett & Brunsden, 1993; Masson, van Niel & Weaver, 1997; Weaver, 1995), the character and distribution of turbidity current pathways (Masson, 1994), and the recognition of catastrophic landslides on the flanks of the western Canary Islands (Masson, 1996; Watts & Masson, 1995).

In this study we review the seafloor sedimentary processes of the Northwest African continental margin, and investigate the applicability of slope apron models to this system. Our understanding of the interplay between different sedimentary processes has benefitted from the production of a new sediment distribution and process map (Fig. 1) which covers the entire margin, from the continental shelf to the deep abyssal plains. This paper builds upon previous studies of the area by 1) describing the sedimentary processes operating across the entire Northwest African margin, 2) attempting to classify the Northwest African margin as a fine-grained clastic slope apron, and 3) discussing the controls on sand distribution within the system.

2. Methods

The sediment process map has been compiled by the authors using data collected on a number of research cruises on board the RRS Discovery and the RRS Charles Darwin (e.g. Masson, 1994, 1996; Masson, Kidd, Gar-

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dener, Huggett & Weaver, 1992; Weaver, Rothwell, Ebbing, Gunn & Hunter, 1992; Weaver et al., 1995). Many of the cruises were undertaken as part of the multinational STEAM project (Sediment Transport on Eastern Atlantic Margins). A variety of data collection techniques were employed during these research cruises, and they have been grouped into four main categories:

Bathymetric data for the majority of the study area was collected by 12 kHz-profiling. Some parts of the study area, in particular the flanks of the Canary Islands, have high-resolution bathymetric coverage collected using the Simrad EM12 multibeam echo-sounder. This has been particularly useful in the recognition of debris avalanche scars (e.g. Watts & Masson, 1995).

3.5 kHz-profiles have been collected across a large area of the margin, and are used to image a wide variety of seafloor acoustic facies. These range from turbidity current channels and debris flows, to volcanic seamounts and sediment wave fields. A review of the technique was presented by Damuth (1980), and echo-character definitions for the Northwest African margin are described in Embley (1982), Kidd, Simm and Searle (1985), and Masson et al. (1992). Table 1 summarises the echo-character definitions used in this study.

Swath imaging in the study area has been undertaken using the Geological Long-Range Inclined Asdic (GLORIA) and Towed Ocean Bottom Instrument (TOBI) side-scan sonar systems. GLORIA is a 6.5 kHz long-range side-scan sonar, with a swath width of up to 45 km. It is towed near the surface at speeds of up to 10 knots, allowing large areas of the seafloor to be mapped relatively quickly. A modified version of the GLORIA interpretation scheme given by Kidd et al. (1985) was presented by Masson et al. (1992). GLORIA has primarily been used in the mapping of debris flows and channel systems in the central part of the study area. TOBI is a 30 kHz high-resolution side-scan sonar, with a swath width of about 6 km (Murton, Rouse, Millard & Flewellen, 1992). It is deep-towed, and has primarily been used for detailed mapping of gravity flow deposits. These include the channel systems east of the Madeira Abyssal Plain (Masson, 1994), and the debris flows and debris avalanches around the Canary Islands (Masson et al., 1993; Masson, 1996; Watts & Masson, 1995). The sidescan character definitions used in this study are displayed in Table 1.

Sediment cores have been recovered from many areas of the Northwest African margin. For example, over 160 cores have been taken from the Madeira Abyssal Plain (Rothwell, Pearce & Weaver, 1992). Piston, kasten, gravity and box corers have all been recovered, with the majority of cores being <10 m long. Core data has proved to be useful in confirming earlier interpretations of sediment facies, based purely on acoustic facies. In this study we also summarise the initial results from three cores recovered from the Agadir Basin during RRS Discovery cruise 225, and combine this with other core data to interpret sand distribution across the study area. Core character definitions used in this study are shown in Table 1.

A number of previously published studies have also been used in areas of the map not covered by the STEAM project. The echo-character maps of Jacobi and Hayes (1982, 1992) have been particularly useful for the mapping of submarine landslides, sediment waves, erosional furrows, and canyon and channel systems. In addition, the published maps of the Saharan Debris Flow (Embley, 1976), the Western Saharan Canyon System (von Rad & Wissman, 1982), the bedforms in the Gulf of Cadiz (Kenyon & Belderson, 1973), and the contourite drifts of the Southern Portuguese margin (Stow, Faugeres & Gonthier, 1986) have also been used in this study.

3. Physiology and oceanography of the Northwest African margin

The Northwest African margin is bordered by a flat continental shelf that is generally 40–60 km wide, although maximum shelf widths of >100 km occur off the Western Saharan coast. The shelf-break is at a water-depth of 100–200 m. Beyond the shelf-break, the continental slope has a width of 50–250 km, and displays slope angles of 1–6°. In some areas, e.g. adjacent to the Western Sahara Canyon System, slope angles may reach 40°. The slope passes to the continental rise at water depths of 1500–4000 m, with gradients ranging from about 1° on the lower slope/upper rise, to 0.1° on the lower rise (Masson et al., 1992). The rise is generally 100–1500 km wide, and terminates at a water depth of 4500–5400 m, beyond which lies the flat expanse of the deep abyssal plains. Large sections of the Northwest African slope and rise are punctuated by numerous volcanic islands and seamounts, and are dissected by canyons and channels (Fig. 1). This creates a complex submarine topography, that has greatly influenced the sedimentary processes operating upon this margin.

Deep-water bottom currents off the Northwest African margin include the North Atlantic Deep Water (NADW) and the Antarctic Bottom Water (AABW). The NADW occurs at a water-depth of 2000–3800 m and flows in a southerly direction, the AABW occurs below 3800 m and flows in a north-easterly direction. Bottom currents along the margin are thought to be fairly weak at the present day, with current velocities generally between 1 and 6 cm/s (Lonsdale, 1978, 1982; Sarntheim et al., 1982)

4. Sedimentary processes on the Northwest African margin

Previous overviews of the Northwest African margin have largely concentrated on the description of seafloor features in terms of their echo-character (e.g. Embley,

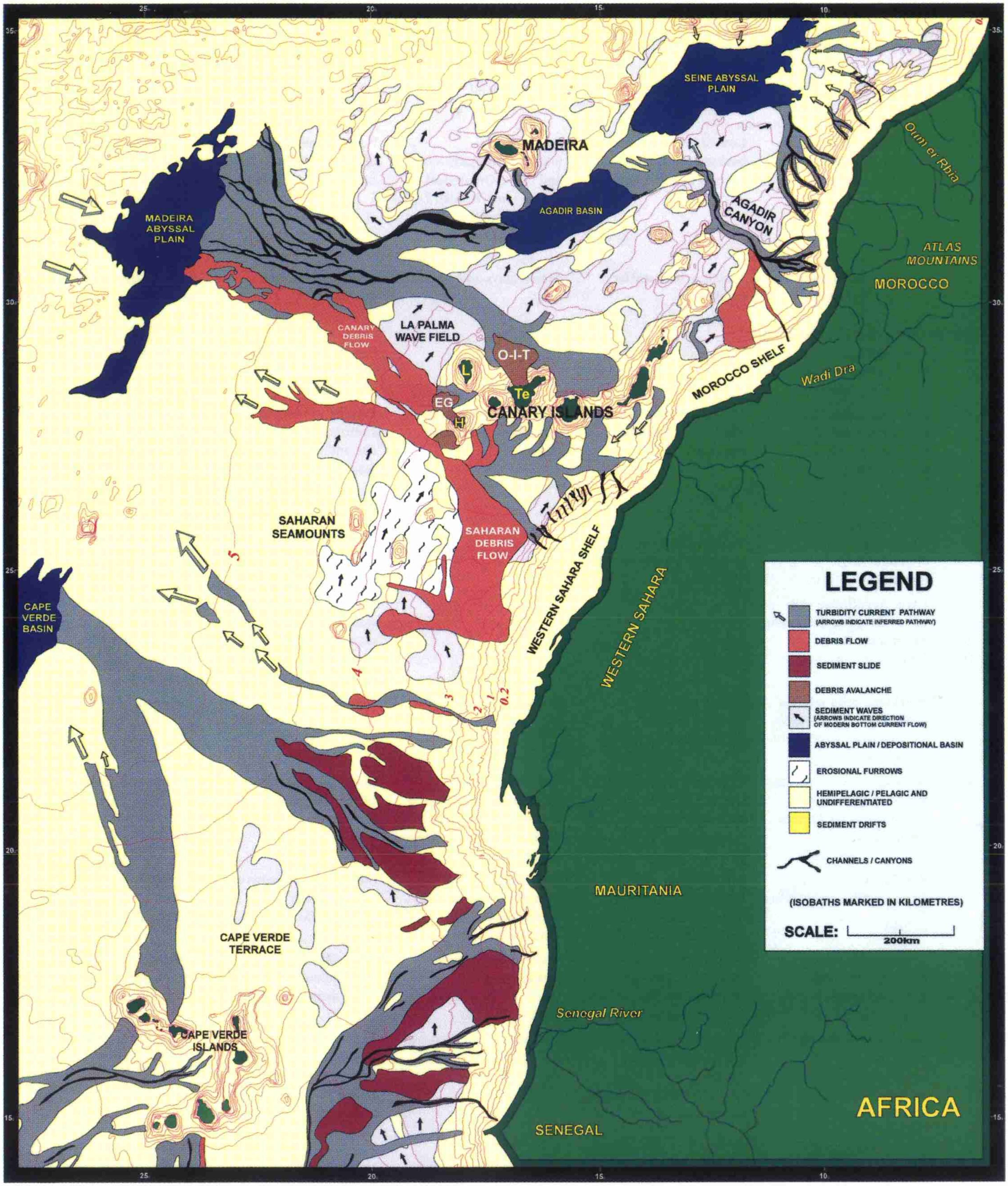

Fig. 1. Sediment process map of the Northwest African margin. This map is largely based on 3.5 kHz-profiles and sidescan sonar images, and shows the complex interplay between pelagic/hemipelagic sedimentation, alongslope bottom currents and downslope gravity flows. Bathymetric contours in kilometres. Abbreviations: *Te*, Tenerife; *L*, La Palma; *H*, El Hierro; *O-I-T*, Oratava-Icod-Tino Debris Avalanche; *EG*, El Golfo Debris Avalanche.

Table 1

Character, location and interpretation of morphological features and sedimentary deposits on the Northwest African margin. Compiled using data from Masson et al. (1992) and Jacobi and Hayes (1992)

No.	Echo-character	Sidescan character	Core character	Location	Interpretation
Pelagic and hemipelagic sedimentation					
1	Continuous, flat, subbottom reflectors, >50 m penetration	Low to intermediate backscatter, featureless or vaguely mottled/lineated	On slope/rise—interbedded marls, oozes and clays, On abyssal plains—interbedded f–g turbidities and marls, oozes and clays	Found across large areas of the continental slope, rise and abyssal plains	Flat-lying pelagic/hemipelagic drape on slope/rise OR f–g turbidities and pelagic/hemipelagic sediments on abyssal plain
2	Irregular, undulating >50 m penetration	Very low backscatter patches	Marls, clays and oozes	Flanks of volcanic seamounts	Pelagic drape on seamounts
Bottom current features and deposits					
3	Very regular, overlapping hyperbolae, tangent to seafloor			Parallel to bathymetric contours, around seamounts	Erosional furrows
4	Regular, undulating, may show marked asymmetry. >50 m penetration	Distinct, regular bands of low to intermediate backscatter	Interbedded fine-grained silts, clays, marls and oozes	Parallel to bathymetric contours, on continental rise and around seamounts	Bottom current sediment waves
Gravity-flow features and deposits					
5	Rough seabed with abundant large hyperbolae	Variable backscatter. Irregular, blocky texture		On, or adjacent to, slopes of volcanic islands	Debris avalanche deposits
6	Large hyperbolae with vertex elevation decreasing downslope. Rare subbottom reflectors			Continental slope/rise, slope and base of seamounts and volcanic islands	Submarine slide deposits. Deposits grade from 'hummocky' near slide-scar and 'blocky' downslope
7	Prolonged echo with no penetration. Small-scale rough seabed with many hyperbolae	High backscatter, strongly lineated perpendicular to slope	Buried slide-scars show hiatus in sequence	Continental slope, slopes of volcanic islands and seamounts	Sediment-slide scars
8	Acoustically transparent, lens-shaped units with prolonged echo. Onlaps other facies	High backscatter lobate sheets, lineated with well-defined boundaries	Variable. Blocky unsorted material in f–g matrix OR deformed but coherent blocks of original sed sequence	Slope/rise and on slopes of volcanic islands and seamounts	Debris-flow deposits
9	Parallel-bedded with 10–30 m irregular penetration	Intermediate backscatter, lineated with variable backscatter lineations	Interbedded f–g turbidities and clays, marls, oozes. Low sand/shale ratio	Slope and rise, generally perpendicular to bathymetric contours	Turbidity current pathways and channel overbank deposits
10	Topographic lows on profiles, often with decreased penetration	Straight or curved narrow lineaments. High backscatter, or high with low central stripe	Interbedded c–g turbidities and clays, marls, oozes. High sand/shale ratio	Slope and rise, generally perpendicular to bathymetric contours	Turbidity current channels
11	Regular, undulating, often with marked asymmetry. Penetration increases downslope, from <10 to 50 m	Distinct, regular bands of low to intermediate backscatter. Spacing between bands decreases downslope	Turbidities, interbedded with marls, clays and oozes	Slopes of volcanic islands and seamounts, levee backslopes, channel floors. Parallel to slope contours	Turbidity current sediment waves
Other features and deposits					
12	Sharp to prolonged echo with no penetration. Large-scale rough seabed with large hyperbolae	Very high backscatter, linear to irregular patches		Seamounts and volcanic island slopes. Canyon walls	Basement rock outcrop

1982; Jacobi & Hayes, 1982, 1992) and sidescan sonar-/core character (Masson et al., 1992). The descriptions of these features have therefore been well documented, and are summarised in Table 1. The present study has built upon this work by producing a map that is process-oriented (Fig. 1), and the following section looks at the nature of these processes, and how they are distributed across the margin.

4.1. Pelagic/hemipelagic sedimentation

Fine-grained pelagic and hemipelagic sediments are widespread throughout the study area, and are considered to result from 'background' sedimentary processes (e.g. settling of dead planktonic organisms and wind-blown terrigenous dust). The sediments commonly occur in association with abyssal hills and seamounts, and across large areas of the continental slope and rise. Pelagic/hemipelagic sediments are also a significant component of the basin-fill on this margin. For example, on the Madeira Abyssal Plain, the sedimentary record for the last 300,000 years has revealed that 600 km^3 of turbiditic sediments have been deposited, together with 60 km^3 of pelagic/hemipelagic sediments (Rothwell et al., 1992).

4.2. Alongslope processes (bottom currents)

The dominant deep-water bottom currents on the Northwest African margin are the south-flowing NADW (2000–3800 m), and the north-flowing AABW (below 3800 m). At the present-day these currents generally flow at velocities of <5 cm/s, although in areas where the current flow is affected by a tidal component this figure may increase to 20 cm/s (Lonsdale 1978, 1982; Sarnthein et al., 1982). These currents are responsible for smoothing the fine-grained seafloor sediments, and also produce a variety of bedforms. These include erosional bedforms such as furrows, and depositional bedforms such as sediment waves.

4.2.1. Erosional furrows

Erosional furrows are best developed in the area of the Saharan Seamounts (Fig. 1), and are thought to have been formed by intensified AABW flow around and between the seamounts. The lack of large turbidity current pathways in the Saharan Seamount region also promotes the formation of furrows as there is relatively low sediment input into this area. The furrows are aligned parallel to the regional bathymetric contours and display negative relief (Lonsdale, 1978, 1982; Jacobi & Hayes, 1992).

4.2.2. Sediment waves

Several fields of sediment waves also occur in the study area, some of which have been formed by AABW and NADW. However, as they are constructional bedforms, they only occur in areas which receive a regular sediment supply. The wave fields on the continental rise south of the Agadir Basin (Fig. 1) occur at a water depth of 3500–4500 m, and are thought to have been formed by northeast-flowing AABW. The waves migrate upslope and display wavelengths up to 1.1 km and wave amplitudes up to 7 m. They are 'downstream' of a major turbidity current pathway, and it seems likely that the waves are maintained by fine-grained sediments derived from this system by 'flow-pirating'. This process involves the redirection of fine-grained turbidity currents by bottom currents, either during or after deposition. However, it should be noted that the relationship between bottom currents, turbidite systems and wave fields can be complex, and that some sediment wave fields in the study area appear to be formed by turbidity currents (see next section).

4.3. Downslope processes (gravity-flows)

Sediment gravity-flows are infrequent but important events on the Northwest African margin. They are the dominant process in shaping the morphology of the margin, as they often overprint pelagic/hemipelagic and bottom current deposits. There are four main types of gravity-flow deposit in the study area (Fig. 2).

4.3.1. Submarine slides

Many slope failures on the Northwest African margin have been described using the general terms '*submarine landslide*' or '*submarine slide*' (e.g. Embley, 1976, 1982; Embley & Jacobi, 1977; Jacobi, 1976; Jacobi & Hayes, 1982, 1992). In particular, these terms have been applied to several large slope failures which appear to be complex events and include elements of slumping, sliding and debris flow.

A number of large submarine slides flank the Cape Verde Terrace (Jacobi & Hayes, 1982, 1992), and occur as part of a major gravity-flow complex, termed the Cape Verde Slide Complex. This has affected an area of 30,000 km^2, with individual slide masses reaching 500 km in length. The submarine slides interfinger with turbidity current pathways in a complex pattern, and in many of the slide zones multiple slide scars and a complicated depositional morphology indicate multiple slide movements (Jacobi, 1976). The submarine slide deposits typically display increasing deformation and evidence for mobilisation downslope, grading from hummocky and blocky material through to smoother debris flow material (Jacobi & Hayes, 1982).

4.3.2. Debris avalanches

Debris avalanches result from catastrophic failure of the steep upper slopes of volcanic islands, producing a blocky deposit on the lower island slopes. The avalanche

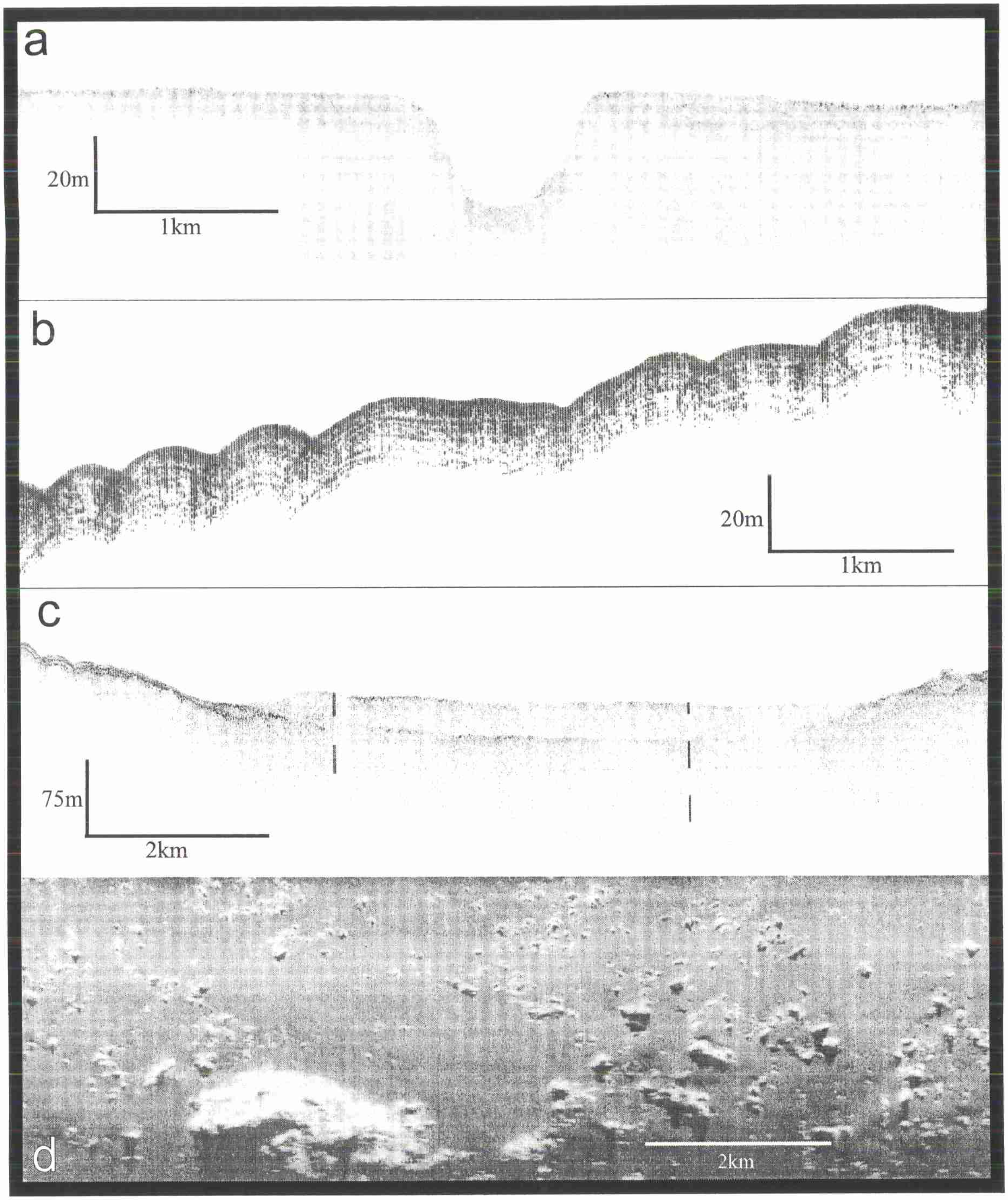

Fig. 2. Gravity-flow deposits in the study area: (a) TOBI 7 kHz-profile across a channel on the lower rise. (b) 3.5 kHz-profile showing turbidity current sediment waves on the flanks of La Palma. (c) 3.5 kHz-profile through a section of the Saharan Debris Flow. The debris flow deposit is the thick acoustically transparent layer lying within the topographic low. (d) TOBI image of a section of the Orotava-Icod-Tino debris avalanche complex north of Tenerife. Note the variation in size of avalanche blocks lying on the surface. Light shades indicate high backscatter, dark shades indicate low backscatter.

headwall may have a subaerial expression (Moore, Clague, Holcomb, Lipman, Normark & Torresan, 1989).

Several debris avalanches have recently been discovered on the submarine flanks of the volcanic Canary Islands (Masson, 1996; Watts & Masson, 1995). The Orotava-Icod-Tino debris avalanche on the north flank of Tenerife has affected an area of 5500 km^2, has a volume of 1000 km^3 and a length of 100 km. It can be traced onshore directly into the Orotava and Icod landslide valleys (Watts & Masson, 1995). Fig. 2d shows individual blocks up to several hundred metres across on the surface of the avalanche deposit.

The El Golfo debris avalanche is also traceable onshore, directly into the El Golfo embayment on the island of Hierro. This avalanche affects an area of 1500 km^2, has a volume of 250–350 km^3, and a length of 40–45 km. The 900 m high scarp that heads the embayment is believed to be the avalanche headwall. Angular blocks up to 1.2 km wide and 200 m high have been imaged on the avalanche deposit surface using TOBI. Downslope, at 3500–4000 m water depth, the debris avalanche merges with the Canary Debris Flow. It seems likely that loading of the slope sediments by the El Golfo debris avalanche triggered the Canary Debris Flow, and also the volcaniclastic 'b' turbidite found on the Madeira Abyssal Plain, as discussed by Masson (1996).

4.3.4. Debris flows

Debris flows are gravity-flows that contain numerous large clasts supported and carried by a finer-grained matrix (Stow, 1985; Varnes, 1978). Debris flow deposits are poorly sorted and internally structureless, and typically have a pebbly mudstone texture. Two very large debris flows, the Canary and Saharan Debris Flows, occur in the centre of the study area, and have been mapped and studied in detail (Masson et al., 1992; Weaver et al., 1995).

The Canary Debris Flow extends all the way across the continental rise to the edge of the Madeira Abyssal Plain. It originated at 4000 m water depth on the western slopes of the Canary Islands, and is 100 km wide near the source, thinning to 60 km wide near its termination, with a thickness of 5–20 m (Weaver et al., 1995). The debris flow has affected an area of 40,000 km^2, has a volume of 400 km^3, and a length of 600 km (Masson et al., 1992). Sediment blocks up to 300 m in diameter have been imaged on its surface.

The Saharan Debris Flow (Fig. 2c) displays two distinct provinces, a source area scar, and a debris flow deposit (Embley, 1976). This debris flow is 20–50 m thick (Embley, 1982; Jacobi & Hayes, 1992) and stops on a steeper slope than the Canary Debris Flow (200 km ESE of the Madeira Abyssal Plain), which suggests that it was a more viscous flow (Masson et al., 1992). It has affected an area of 48,000 km^2, has a volume of 1100 km^3, and a length of 700 km (Jacobi & Hayes, 1992).

4.3.5. Turbidity current pathways and sediment waves

Most turbidity current pathways (TCPs) originate as a series of tributary canyons at the shelf break, before passing downslope into one main feeder canyon or channel. On the continental rise the TCPs open out into a series of distributary channels (Fig. 2a), and the channel levees are very subdued or non-existent. The TCPs finally spread out to form distributary lobes at the edges of the abyssal plains, and this is where the majority of the turbidity current load is deposited.

There are several major TCPs within the study area, through which sediments derived from the continental margins, islands and seamounts are transported downslope to the deep abyssal plains. The Madeira TCP is the largest on this margin and is described in detail in the next section. A number of smaller TCPs have also been mapped in the study area. A series of TCPs transport sediments from the Mauritanian and Senegalese margins to the Cape Verde Basin and Gambian Abyssal Plain (Jacobi & Hayes, 1982, 1992), while in the north of the study area a series of short TCPs pass onto the Seine, Tagus and Horseshoe Abyssal Plains (Davies, van Niel, Kidd & Weaver, 1997; Lebreiro, 1995; Lebreiro, McCave & Weaver, 1997).

Recent work undertaken on two sediment wave fields on the flanks of the western Canary Islands has revealed that they were formed by turbidity currents (Wynn, Masson, Stow & Weaver, 1999). The La Palma wave field covers some 20,000 km^2 of the continental slope and rise, and consists of waves that display amplitudes of <5–70 m, and wavelengths of 0.4–2.4 km (Fig. 2b). This wave field has been formed by unconfined turbidity currents originating on the northern slopes of La Palma. The El Julan wave field lies within a channel on the southwest flank of El Hierro. The sediment waves have an average wavelength of 0.8 km, and an amplitude of about 6 m. This wave field has been formed by channelised turbidity currents.

5. The Madeira turbidity current pathway

The Madeira TCP is the largest in the study area with a total length of 1500 km. It transports sediments derived from the Moroccan margin and the Canary Islands, westwards to the Agadir Basin and the Madeira Abyssal Plain. In this section we summarise previously published data from this pathway and combine it with new data collected during RRS Discovery cruise 225. This has allowed us to investigate the key controls on sand distribution within the system (see Discussion).

The Madeira TCP originates on the northern edge of the Morocco Shelf, as a series of straight tributary canyons at the shelf-break, offshore from the hinterland of the Atlas Mountains. These canyons merge into one major canyon, the Agadir Canyon, on the continental slope. The Agadir Canyon is about 460 km long, 5–15 km wide and 600–1500 m deep. It is slightly meandering (Jacobi & Hayes, 1992), and runs roughly perpendicular to the regional slope, its morphology being largely controlled by the adjacent salt diapirs and volcanic seamounts. Levees are well developed in its lower reaches, before it broadens out on the lower rise at a water depth of 4275 m. A channel system then runs onto the Agadir Basin below 4300 m (Ercilla et al., 1998).

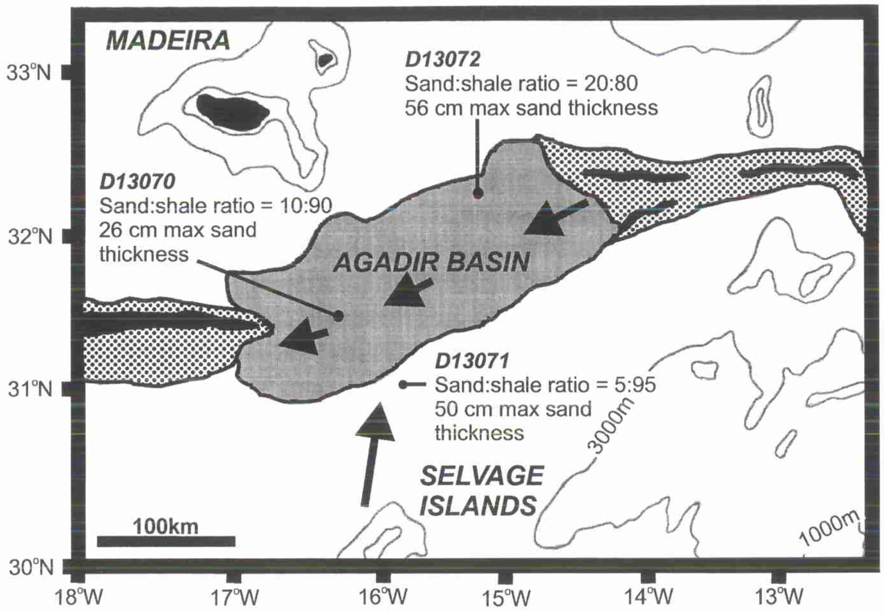

Fig. 3. Turbidite sand distribution in the Agadir Basin. The sand/shale ratio for three cores are shown, together with the maximum sand-bed thickness in each core. Note that the core on the eastern plain, closest to the mouth of the Agadir Canyon, has the highest sand/shale ratio and the thickest sand. Stippled areas are turbidity current pathways. Channels shown in black. Arrows indicate main transport directions for turbidites on the plain.

The Agadir Basin (Fig. 3) is a large intraslope basin lying at a water depth of 4275–4450 m. It has an area of 22,000 km^2 and is almost flat, having a gradient of just 0.02°. Three cores recovered from the basin during RRS Discovery cruise 225 contain a sequence of turbidite sands, silts and muds, interbedded with pelagic/hemipelagic marls, oozes and clays (Fig. 3). The results of an initial investigation of these cores are summarised as follows: Core D13072 is 8 m long and was recovered from the north-east edge of the basin. It contains nine turbidites with a sand/shale ratio of 20:80, and a maximum sand-bed thickness of 56 cm. Core D13070 is 10 m long and was recovered from the western basin floor. It contains nine turbidites with a sand/shale ratio of 10:90, and a maximum sand-bed thickness of 26 cm. Core D13071 is 12 m long and was taken through a sediment wave field on the lower rise, 100 m above the basin floor. This core contains 15 turbidites with a sand/shale ratio of 5:95, and a maximum sand-bed thickness of 50 cm. The provenance of these turbidites has yet to be determined. Sand/shale ratios are therefore highest in the proximal basin-fill, and are lower in the distal basin-fill and on the slopes to the south of the basin

Some turbidity currents are able to travel the length of the Agadir Basin, and enter the broad distributary channel system on the continental rise east of the Madeira Abyssal Plain (Masson, 1994). This pathway consists of two distributary channel systems running adjacent to one another. The northern channel system is sourced at the western edge of the Agadir Basin and runs west and north-west before terminating as a large depositional lobe on the north-east margin of the Madeira Abyssal Plain. The southern channel system originates on the island slopes north-west of the Canary Islands, and runs west-north-west before terminating as a depositional lobe on the eastern margin of the Madeira Abyssal Plain (MAP). Most of the channels within the pathway are < 20 m deep and 5 km wide (Fig. 2a), although they may reach a depth of 50 m and a width of several km's (Masson et al., 1992). The sinuosity of the channels is low and levees are rarely developed (Masson, 1994). Core data from these channels is sparse, but results seem to suggest that channels in the northern system contain turbidites mostly derived from the Moroccan margin (via the Agadir Basin), and that the volcaniclastic turbidites in the southern channel system are derived from the Canary Islands. Overall, there appears to be increased sand deposition within the channels, as opposed to the interchannel areas (Masson, 1994). However, it should be noted that large turbidity currents (e.g. the 'b' turbidite of Masson (1994)) can flush out much of the sediment from within the channels on their passage downslope. At the present-day the channels therefore appear to be part of a bypassing system, and are dominantly acting as sediment conduits for turbidity currents travelling downslope to the Madeira Abyssal Plain.

The Madeira Abyssal Plain (MAP) is the largest abyssal plain in the study area, covering an area of 68,000 km^2 (Rothwell et al., 1992). It is extremely flat, with a slope of less than 0.01°, and a surface relief varying by less than 10 m (Searle, 1987). Cores recovered from the plain have revealed that the ratio of turbiditic to pelagic sediments is approximately 10:1, with the sedimentary record over the last 300,000 years revealing that 600 km^3 of turbidites,

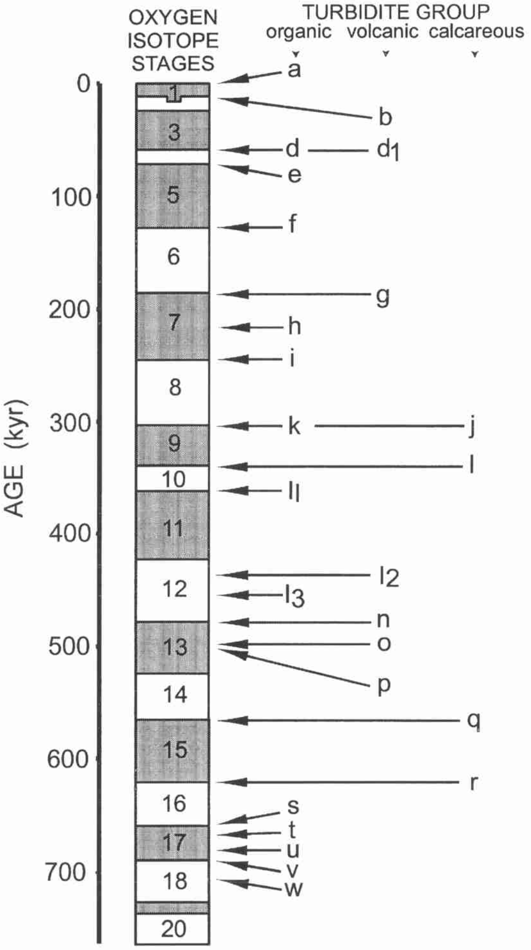

Fig. 4. Schematic diagram showing the age of turbidite emplacement on the Madeira Abyssal Plain, in relation to the oxygen isotope timescale (from Weaver et al., 1992). Three distinct subgroups of turbidites can be recognised, derived from the Northwest African margin (organic), the volcanic islands (volcanic), and the seamounts to the west of the plain (calcareous).

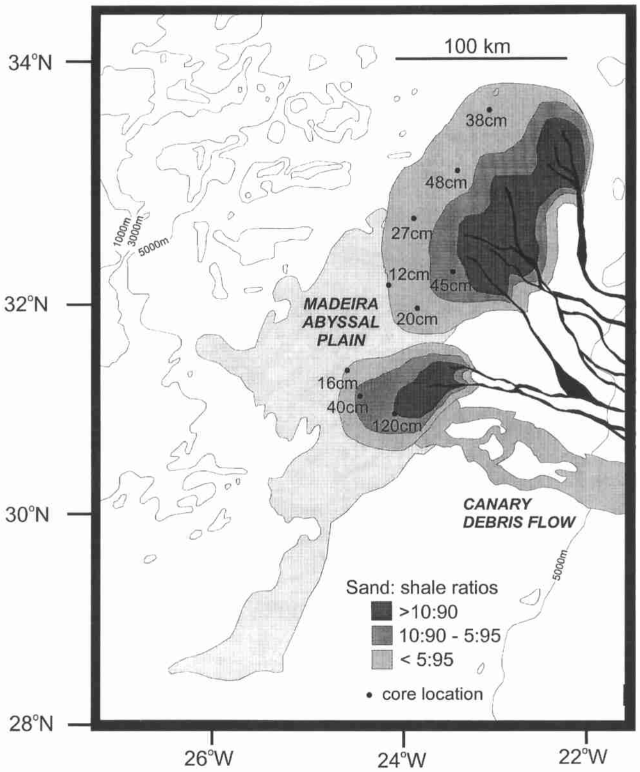

Fig. 5. Turbidite sand distribution on the Madeira Abyssal Plain. Shaded contours show the overall turbidite sand/shale ratios in the cores shown. The thickness of the 'b' turbidite in these cores is also displayed. Note that the sand distribution is closely controlled by the break-of-slope at the base of the lower rise, and that the sands appear to form lobes at the termination of the channel systems.

compared to 60 km^3 of pelagites, have been deposited (Rothwell et al., 1992). Fig. 4 shows the age of turbidite emplacement on the MAP, together with the three distinct subgroups of turbidites. Some of the turbidites are large, reaching 5 m thickness and 120 km^3 in volume (Masson et al., 1992). Fine-grained muds form the bulk of the turbidite deposits, although towards the edges of the plain basal turbidite sands and pelagic muds become more dominant (Weaver et al., 1992). A generalised isopach map, showing sand/shale ratios and sand thicknesses within the cores, has been constructed (Fig. 5). This map has revealed the presence of two large overlapping depositional lobes on the eastern plain. The north-east lobe represents the termination of the northern channel system. Sand/shale ratios can reach 10:90 on the proximal lobe, with a maximum sand-bed thickness of > 50 cm. The sands thin distally, and the limit of sand deposition from turbidites entering the plain from the north-east is about 85 km to the west. The eastern lobe represents the termination of the southern channel system. Sand/shale ratios also reach 10:90 on the proximal lobe, with a maximum sand thickness of > 120 cm. The limit of sand deposition from turbidites entering this part of the plain is about 110 km to the north-west.

6. Discussion

6.1. Does the Northwest African margin fit Stow's (1985) model of a fine-grained clastic slope apron?

According to the model proposed by Stow (1985), the distribution of sedimentary facies on a fine-grained clastic slope apron is highly irregular. Finer-grained sediments (silts, muds, oozes and marls) dominate across extensive smooth or current-moulded areas of the slope. Coarser-grained sediments (sands and gravels) only occur on or near the shelf break, within channels, and in base-of-slope lobes. Slides, slumps and debrites are common throughout. Large canyons and channels may cut across the slope at intervals, and elongate contourite drifts are often constructed near the base-of-slope (Fig. 6a).

The model also states that a typical fine-grained slope apron may be composed of constructional elements, ero-

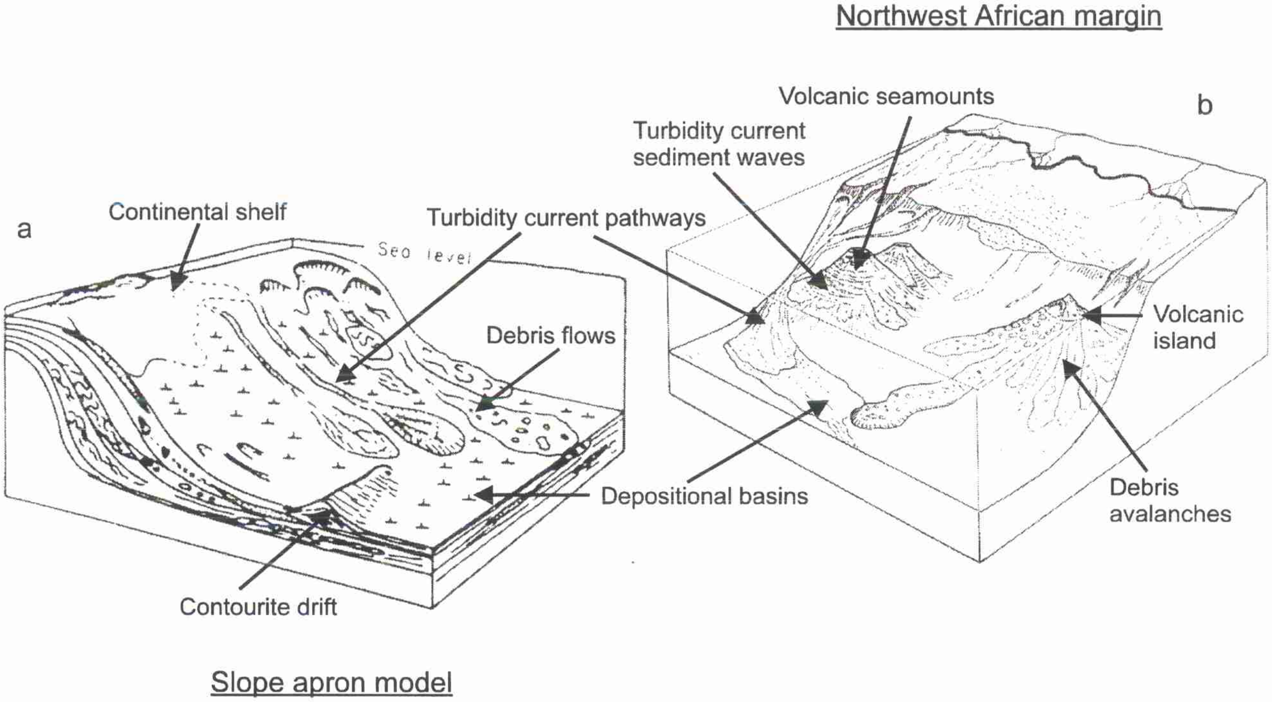

Fig. 6. Sedimentary environment models showing the schematic distribution of facies and morphological elements: (a) the Stow (1985) model of a fine-grained clastic slope apron, and (b) the Northwest African slope apron. Not to scale.

sional elements, or a combination of both. Constructional elements display a relatively smooth convex-concave profile, built upwards and outwards by slope progradation. Low-energy conditions dominate, and the slope tends to be smooth or current-moulded. Erosional elements are heavily affected by erosion (slumping, sliding, etc.) on the face of the slope, causing a steeper and more irregular profile to be developed. The slope is often gullied and slump-scarred, with sediment lobes, debris flow deposits and slump blocks at the foot of the slope.

The sedimentary processes acting upon the Northwest African margin are very similar to those described by Stow's slope apron model. Fine-grained pelagic/hemipelagic 'background' sedimentation is dominant across a large area of the margin, particularly on the lower rise and the adjacent basin plains. These sediments are then modified by alongslope bottom currents, which create bedforms such as furrows, waves and drifts. These deposits are then overprinted by downslope gravity-flows such as debris avalanches, debris flows and turbidity currents (Fig. 6b).

A seismic profile taken across the margin at about 23°N (von Rad & Wissmann, 1982) shows a smooth convex-concave profile, and clear evidence of shelf and slope progradation (Fig. 7a). The dominant sediment type in this area is fine-grained pelagic sediment, and the area is within a zone of sluggish (2–6 cm/s) bottom water flow. This section of the margin is therefore clearly constructional.

In contrast, a schematic profile taken across the margin at 25°N (von Rad & Wissmann, 1982) shows a steep, irregular profile, with numerous slumps and slides cutting the slope surface (Fig. 7b). This profile runs through the area lying above and within the Saharan Slide scar, and is clearly very different from that taken at 23°N, some 200 km to the south. This section of the margin is therefore clearly erosional.

The distribution of sedimentary facies and morphological elements on the Northwest African margin is therefore very similar to that described by Stow (1985) as being characteristic of a fine-grained clastic slope apron. The margin also comprises both constructional and erosional elements. Using these criteria the Northwest African margin can therefore be successfully classified as a fine-grained clastic slope apron.

6.2. How does the Northwest African slope apron differ from the model?

A large number of volcanic islands and seamounts occur along the Northwest African margin, and in some areas this leads to a more complex distribution of sedimentary facies than is accounted for by Stow's slope apron model.

Most of the volcanic islands, and some of the larger seamounts, have a radial distribution of downslope flows around their flanks. The Canary Islands, for example, act as nucleii for a large number of gravity-flows (Fig. 1). These include debris avalanches, debris flows, and turbidity current pathways. In some areas, the volcanic

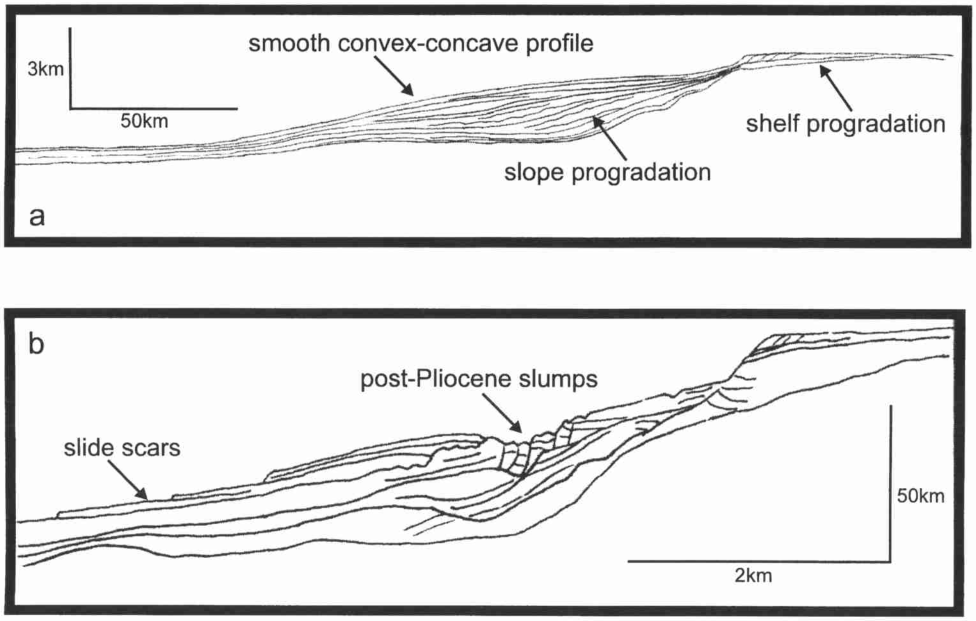

Fig. 7. Schematic profiles of the continental margin off Western Sahara (modified from von Rad and Wissmann (1982)). (a) Profile from around 23° N showing a constructional section of the margin. Note the smooth convex-concave profile, and evidence of shelf and slope progradation. (b) Profile from around 25° N showing a destructional section of the margin. Note the steep, irregular profile, and the numerous slumps and slides cutting the slope surface.

islands and seamounts are also responsible for disrupting and diverting the bottom water flow, leading to a more complex distribution of current-induced bedforms. For example, accelerated bottom water flow around and between the Saharan Seamounts has led to the development of erosional furrows (Jacobi & Hayes, 1992). In addition, the diversion of bottom currents around the Madeiran archipelago has led to the development of sediment wave fields on the Madeira Rise (Jacobi & Hayes, 1992).

It is therefore important to note that seafloor topographic features, (e.g. volcanic islands and seamounts, salt diapirs, and tectonic features such as fault scarps) can have a significant effect on the distribution of sedimentary facies and morphological elements within a slope apron system (Fig. 6b). This has important implications for hydrocarbon exploration in similar systems.

6.3. Sand distribution on the Northwest African slope apron

The Northwest African margin is dominanted by fine-grained sediments, however, sands do occur above the shelf-break, in distributary channels on the slope and rise, and on flat basin floors. In this section we describe the key controls on sand distribution within the system, by linking onshore and offshore sediment transport pathways, and analysing core data from the Madeira turbidity current pathway.

6.3.1. Onshore and offshore drainage systems

Sand distribution beyond the shelf break on the Northwest African margin is largely restricted to TCPs. In this section we investigate the relationship between fluvial input and canyon development along the margin, and discuss some of the other controls on the location of TCPs.

On the Moroccan margin a number of seasonal rivers transport sediments derived from the Atlas Mountain hinterland to the continental shelf. At the shelf break numerous canyons then transport this material to the Seine Abyssal Plain and the Agadir Basin/Madeira Abyssal Plain (Fig. 1). A comparison of onshore river systems and offshore bathymetry indicates a general spatial relationship between fluvial input points and the location of canyon heads at the shelf break. Therefore, the location of canyon heads on the Moroccan margin appears to be influenced by fluvial drainage. In deeper water, on the lower slope and rise, the location of canyons and channels tends to be controlled by the pre-existing topography (seamounts and volcanic islands).

Further south, on the Western Saharan margin, the fluvial input is greatly reduced. The only river sytems that reach the sea are seasonal, and the majority of the margin has no fluvial input at all. This indicates that submarine canyon development on this margin, e.g. the Western Saharan Canyon System, is controlled by other factors (such as tectonic activity). The large Saharan Debris Flow is, however, sourced from this margin, and its location is controlled by a number of factors. A combination of low terrigenous sediment input and the location of the Saharan seamounts appear to inhibit development of linear turbidity current pathways. Seismicity on this margin is rare, so sediments have a long residence time on the shelf and slope. Therefore when a trigger event does occur it will lead to major slope failure, such as the Saharan Debris Flow.

On the Senegalese margin the fluvial input is dominated by the Senegal River which transports sediment to the head of a major turbidity current pathway. Another large turbidity current pathway lies offshore of two seasonal rivers on the Mauritainian margin but little is known about this system (Fig. 1).

There is therefore some evidence of a general spatial relationship between fluvial input points and TCPs on the Northwest African margin. However, other factors such as slope topography, slope angle, and shelf/slope width are also likely to influence the location of TCPs.

6.3.2. The Madeira turbidity current pathway

Analysis of core data from the Agadir Basin (this study), the Madeira Abyssal Plain (Rothwell et al., 1992; Weaver et al., 1992), and the channel system linking the two (Masson, 1994), has allowed us to assess the major controls on sand deposition within the Madeira turbidity current pathway.

An initial investigation of cores recovered from the Agadir Basin (Fig. 3) has revealed that sand/shale ratios are highest in the proximal basin-fill, adjacent to the break-of-slope near the mouth of the Agadir Canyon. The sand/shale ratio decreases westwards in the more distal basin-fill, and is also lower on the slopes to the south of the basin.

Core data from the channel system to the west of the Agadir Basin is sparse. Channels in the northern system contain turbidites mostly derived from the Moroccan margin (via the Agadir Basin), and the southern channel system contains volcaniclastic turbidites derived from the Canary Islands. Overall, there is increased sand deposition within the channels, as opposed to interchannel areas (Masson, 1994). However, it should be noted that large turbidity currents (e.g. the 'b' turbidite of Masson (1994)) can flush out much of the sediment from within the channels on their passage downslope. At the present-day the channels appear to be part of a bypassing system, and are acting as sediment conduits for turbidity currents travelling downslope to the Madeira Abyssal Plain.

Core data from the Madeira Abyssal Plain (Fig. 5) indicate that sand deposition is concentrated at the break-of-slope where the distributary channel systems of the lower rise run onto the flat basin floor. The sandy bases of the turbidites die out within 100 km of the break-of-slope. It is possible to calculate the frequency of turbidites reaching the MAP. In the last 750,000 years the deposition rate has averaged one turbidite every 30,000 years (Weaver et al., 1992). Further investigation reveals that only one turbidite every 150,000 years has reached the MAP from the Moroccan margin via the Madeira TCP. This compares with one turbidite every 14,000 years for the Seine Abyssal Plain (Davies et al., 1997), and 1–3 turbidites every 1000 years for the Horseshoe Abyssal Plain (Lebreiro et al., 1997). Turbidites on the MAP are generally deposited at times of climate/sea-level change at isotope stage boundaries (Fig. 4), and are therefore not linked to lowstands or highstands of sea-level (Weaver et al., 1992).

To summarise, major turbidity current events in the Madeira TCP are relatively infrequent, and tend to occur during periods of climate/sea-level change. Sand/shale ratios within the system are highest adjacent to the break-of-slope, the location of which is controlled by the position of volcanic islands and seamounts. Under the appropriate topographic conditions, substantial sand depocentres can occur far from the continental slope. The Northwest African slope apron may be a useful modern analogue for deep-water hydrocarbon prospects with complex seafloor topography.

7. Conclusions

The Northwest African continental margin is a typical fine-grained clastic slope apron, with pelagic/hemipelagic 'background' sedimentation overprinted by downslope gravity flows and modified by alongslope bottom currents. The slope apron is made up of various architectural elements, and consists of both constructional and erosional sections. The pattern of sedimentation on this margin is made more complex by the presence of numerous volcanic islands and seamounts. These act as nucleii for gravity flows, and as a diversion for bottom currents.

Turbidity currents are relatively infrequent on this margin, and occur during periods of climate/sea-level change. Turbidite sand deposition is largely controlled by the position of the break-of-slope, which in turn is often controlled by the location of adjacent volcanic islands and seamounts. Under the appropriate topographic conditions, substantial sand depocentres can occur far from the continental slope. The Northwest African slope apron may be a useful modern analogue for deep-water hydrocarbon prospects with complex seafloor topography.

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