Mapping of seabed morphology and shallow sediment structure of the Mauritania continental margin, North-west Africa: some implications for geohazard potential

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Seafloor mapping of the Mauritania margin by multibeam bathymetry as well as shallow and high-resolution seismics in combination with core data has revealed a wide variety of seafloor features, which are primarily generated by turbidity currents and landslides. The largest observed features in the study area are two submarine slides, which both have affected over 30,000 km^2 of seafloor. The Cap Blanc Slide is not considered to be a significant geohazard at the present day as it has a minimum age of 165 ka and shows no evidence of recent reactivation. In contrast, the complex Mauritania Slide Complex is characterized by a retrogressive failure style and has an age of only 10.5-10.9 cal. ka B.P. We found no indication for recent reactivation of this slide, but more data are needed to assess the present seafloor stability in this area. Turbidity current activity on the margin is evidenced by numerous gullies, canyons and channels. The largest of these is the >450 km-long meandering Cap Timiris Canyon. During the present Holocene sea-level highstand, however, terrigenous sediment supply to the modern outer shelf has been restricted and most of the conduits are therefore thought to be largely inactive, at least in terms of large sand-rich flows.

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Introduction

The investigation of sediment dynamics on continental margins is of major interest as sediments deposited in these areas can provide a high-resolution record of past climatic changes, and also host some of the World's major hydrocarbon reservoirs. Important architectural elements of continental margins are large submarine slides (e.g. Locat & Mienert 2003, and references therein) and submarine canyons and channels (e.g. Peakall et al. 2000); these elements are two of the major targets for marine geological research at the present time. In particular, the geohazard potential of submarine slides is intensely studied as they can trigger tsunamis and destroy offshore installations, especially as hydrocarbon exploration and production venture into increasing water depths.

The Mauritania margin, which is characterized by the occurrence of major canyons and submarine landslides, is currently a 'new frontier' for hydrocarbon exploration and production. The first detailed maps showing seafloor features on the Mauritania margin and the adjacent margins off Western Sahara and Senegal were published by Jacobi (1976) and Jacobi & Hayes (1982, 1992). These maps were largely based upon 3.5-kHz profiles, although Kidd et al. (1987) also presented GLORIA sidescan sonar imagery from a section of the lower slope. More recently, Wynn et al. (2000) and Weaver et al. (2000) produced seafloor maps covering the entire northwest African and northeast Atlantic continental margins, respectively. However, the map section from offshore Mauritania was largely based upon the previous work by Jacobi & Hayes (1982, 1992) and thus did not offer more detailed information about the local seafloor morphology and the involved processes.

In spring 2003 and summer 2005, RV Meteor cruises M58/1 and M65/2 of the Research Center Ocean Margins (RCOM) at Bremen University collected a suite of new geophysical and sedimentological data from the northwest African margin between 16°N and 23°N (Fig. 1). The primary aim was to survey and sample major landslides and channels in the region, which is in an area of oceanic upwelling and high primary productivity (e.g. Van Camp et al. 1991; Lange et al. 1998). Consequently, the cruises focused on two main features: the Mauritania Slide Complex, previously documented by Jacobi (1976), and the spectacular meandering Cap

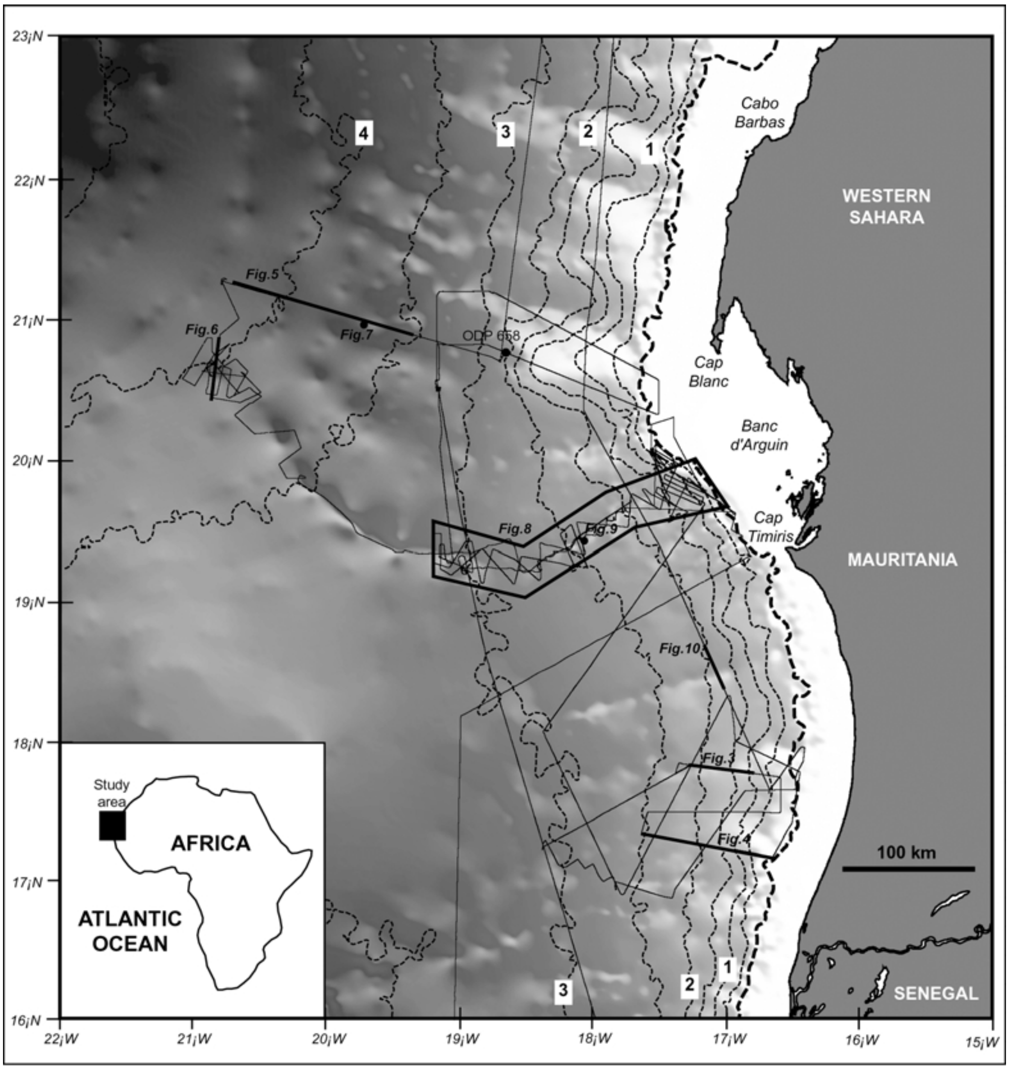

Fig. 1: Location map showing track charts of RV Meteor cruises M58/1 and M65/2 (thin solid line) overlying grey-shaded GEBCO bathymetry. Artificial illumination is from NNE. Inset map shows position of study area on northwest African margin. Bathymetric contours are at 0.5 km intervals (annotated depth in km). Thick dashed line shows shelf break. Locations of Figs. 3-10 are indicated.

Timiris Canyon (Krastel et al. 2004; Antobreh & Krastel 2006a), which had not been surveyed prior to RV Meteor cruise M58/1. PARASOUND shallow seismic profiles were collected continuously along all ship's tracks (Fig. 1), allowing seafloor features to be mapped across a large section of the upper and middle slope.
The main objective of this paper is to present a new map showing the distribution of seafloor features and to discuss the processes responsible for their formation. We also give a first assessment of the geohazard potential associated with the identified features. However, as the data were not primarily collected for such an attempt, we can only present a preliminary estimation of the geohazard potential of our study area. To achieve the goals we summarize our ongoing research off Mauritania and additionally present some new data.

Data collection

Seafloor mapping carried out during the Meteor cruises in 2003 and 2005 was largely based upon a combination of seismic profiling and multibeam bathymetry, with ground-truthing provided by sediment coring in selected areas. A hull-mounted swath bathymetric system, HYDROSWEEP, was used continuously during the Meteor cruises, but was only specifically applied to map the seafloor morphology in the area of the Cap Timiris Canyon. This system transmits 59 beams at a frequency of 15.5 kHz; the angle of the beam array is 90°, producing a total swath width equivalent to 2x water depth.

PARASOUND shallow seismic profiles were collected continuously along all ship's tracks during the Meteor cruises (Fig. 1). The hull-mounted PARASOUND system operates parametrically, and simultaneously transmits two similar frequencies (18 kHz and 22 kHz) to produce a secondary signal of 4 kHz, resulting in a smaller footprint size and improved vertical and lateral resolution (Grant & Schreiber 1990). Vertical resolution is in the order of a few tens of centimeters, and signal penetration is up to 100 m depending on sediment properties.

High-resolution multi-channel seismic reflection profi-

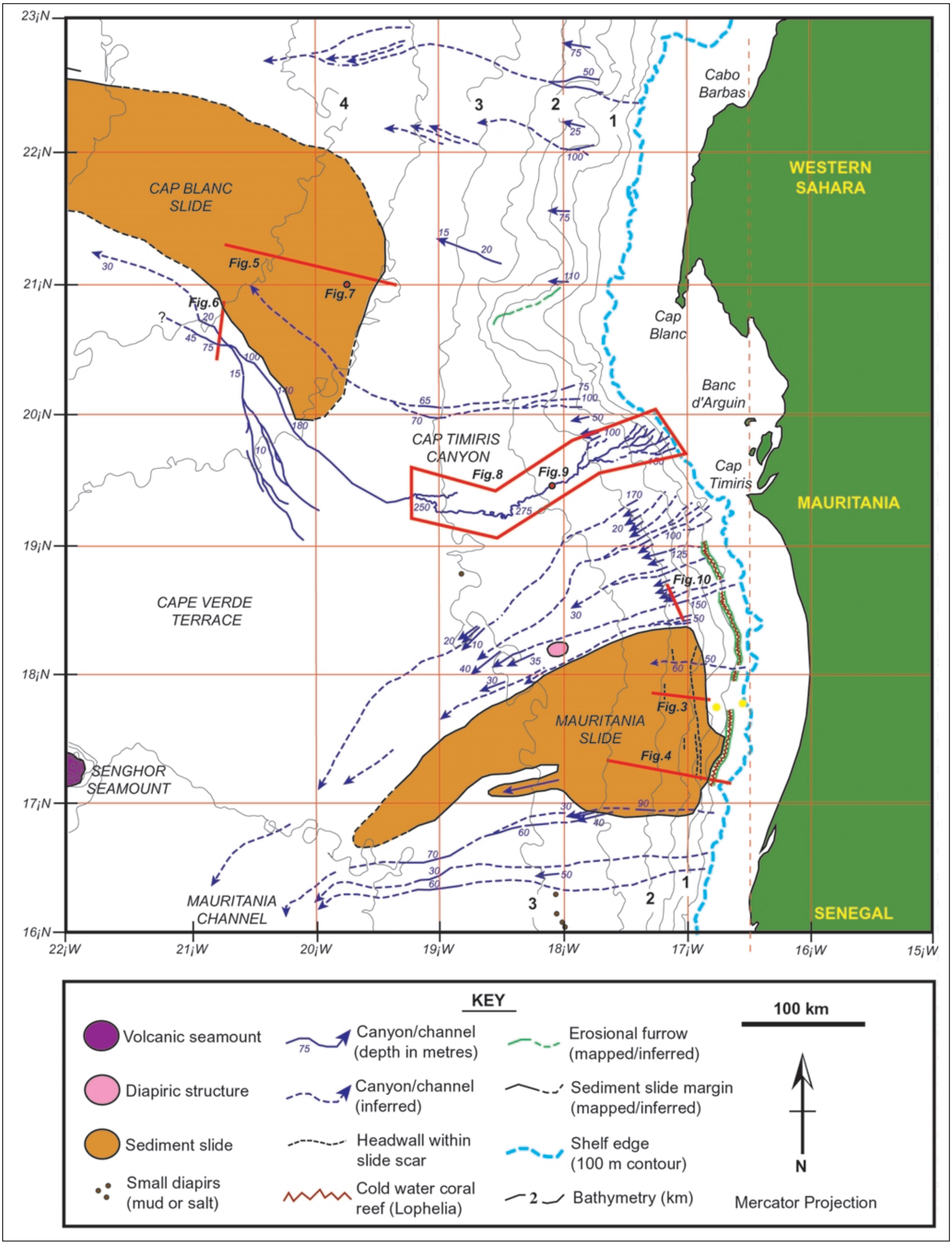

Fig 2: Map showing seafloor features offshore Mauritania, together with locations of Figs. 3-10. Bathymetric contours are at 0.5 km intervals. Thick dashed blue line shows shelf break. Yellow circles above the headwall of the Mauritania Slide Complex show locations of oil/gas fields currently under development (Colman et al. 2005). The courses of the inferred canyons are taken from Wynn et al. (2000). The location of the cold water coral reef upslope of the Mauritania Slide is taken from Colman et al. (2005). See text for the construction of the outline of the Cap Blanc Slide.

les were collected in three areas: the Mauritania Slide Complex, the Cap Timiris Canyon, and the ridge extending offshore from Cap Blanc (Fig. 1). A 1.7l GI-Gun was used as source. The energy was recorded with a 450m-long 72 channel streamer. The processing procedure included trace editing, setting up geometry, static corrections, velocity analysis, normal moveout corrections, bandpass frequency filtering (frequency content: 55/110 - 600/800 Hz), stack, and time migration. A common midpoint spacing of 10 m was applied throughout

Based on the acoustic data, up to 12-m-long gravity cores were taken at selected locations. In addition, a multicorer was deployed in areas where it was important to preserve the sediment-water interface; this produced short cores ~30 cm long.

Margin morphology and sediment supply

The map area extends from 16° to 23°N and offshore to 22°W, covering the entire Mauritania continental margin and also part of the adjacent Western Sahara margin to the north (Figs. 1, 2). The continental shelf in this region is typically 25-50 km wide, although in the Banc d'Arguin embayment between Cap Blanc and Cap Timiris the shelf width is >100 km. The shelf-break is at ~100 m water depth, beyond which lies the continental slope with typical slope angles of 1°-3°. At 2000-2500 m water depth the slope passes to the continental rise, which has gentle slopes of <1°.

At the present day there is very little fluvial input onto the Mauritania margin, but large volumes of wind-blown sediment are transported offshore from the Sahara Desert (Matthewson et al. 1995; Holz et al. 2004). In the Cap Blanc area it has been shown that the present-day aeolian input is largely composed of silt-sized angular quartz, with additional input of assorted clay minerals (Wefer & Fischer 1993). In addition, the northwest African coast around Cap Blanc is the only modern example where active sand dunes directly supply sand to the coast of an open ocean (Lancaster et al. 2002).

High primary productivity is caused by oceanic upwelling, which is seasonally and spatially variable on the margin. Between 20° and 25°N, regional trade winds are strong and persistent throughout much of the year, leading to continuous upwelling (Mittelstaedt 1991; Van Camp et al. 1991). Between 15° and 20°N, the trade wind belt undergoes seasonal migration. Along the whole margin, upwelling, and the associated high productivity, is concentrated along the outer shelf and shelf edge, although satellite images have shown that plumes and filaments of cold upwelling water and the associated high productivity can locally extend for hundreds of kilometers offshore (Van Camp et al. 1991; Gabric et al. 1993).

Seafloor features observed in the study area

Fig. 2 shows a compilation of the observed seafloor features based upon new geophysical and sedimentological data collected during Meteor cruises M58/1 and M65/2. In areas where new data are lacking, some features were adopted from a map covering the entire Northwest African margin published by Wynn et al. (2000).

The new data reveal a wide variety of interesting seafloor features, which are generated by downslope-flowing turbidity currents, landslides, and alongslope-flowing bottom currents. The margin is dominated by gravity-driven sediment transport as demonstrated by numerous canyons and channels as well as two major slides (Fig. 2).

Submarine slides

The Mauritania Slide Complex

The Mauritania Slide Complex is a major area of mass wasting observed on the upper slope in the study area (Fig. 2). It was first discovered by Seibold & Hinz (1974) and subsequently mapped and described by Jacobi (1976). They estimated the area of seafloor affected by mass movements to be in the order of 34,000 km^2, and the total volume of excavated material to be about 400 km^3. A series of new PARASOUND profiles collected across the Mauritania Slide Complex (Figs. 1, 2) suggest that the total area affected by the slide is about 30,000 km^2 +- 4,000 km^2. The volume of the uppermost main debris flow unit is ~600 km^3 +- 100 km^3 and therefore slightly larger than previously estimated. The relatively large uncertainty is caused by poor data coverage of the distal part of the Mauritania Slide complex.

The slope angles above the uppermost headwall range from 1.5° to 2.2° while those within the slide scar range from 0.7° to 1.8°. There is no single headwall at the upper slide boundary; instead there are a series of stepped headwalls at water depths ranging from ~800-2000 m (Fig. 3). Most of the headwalls are 50-60 m high, although the observed height range is from 25-100 m. The cumulative scar height is up to 200m.

PARASOUND profiles show that the character of the slide scar area is highly variable, with areas of relatively intact slide blocks interspersed with layers of blocky slide debris and thin sheet-like debris flow deposits,

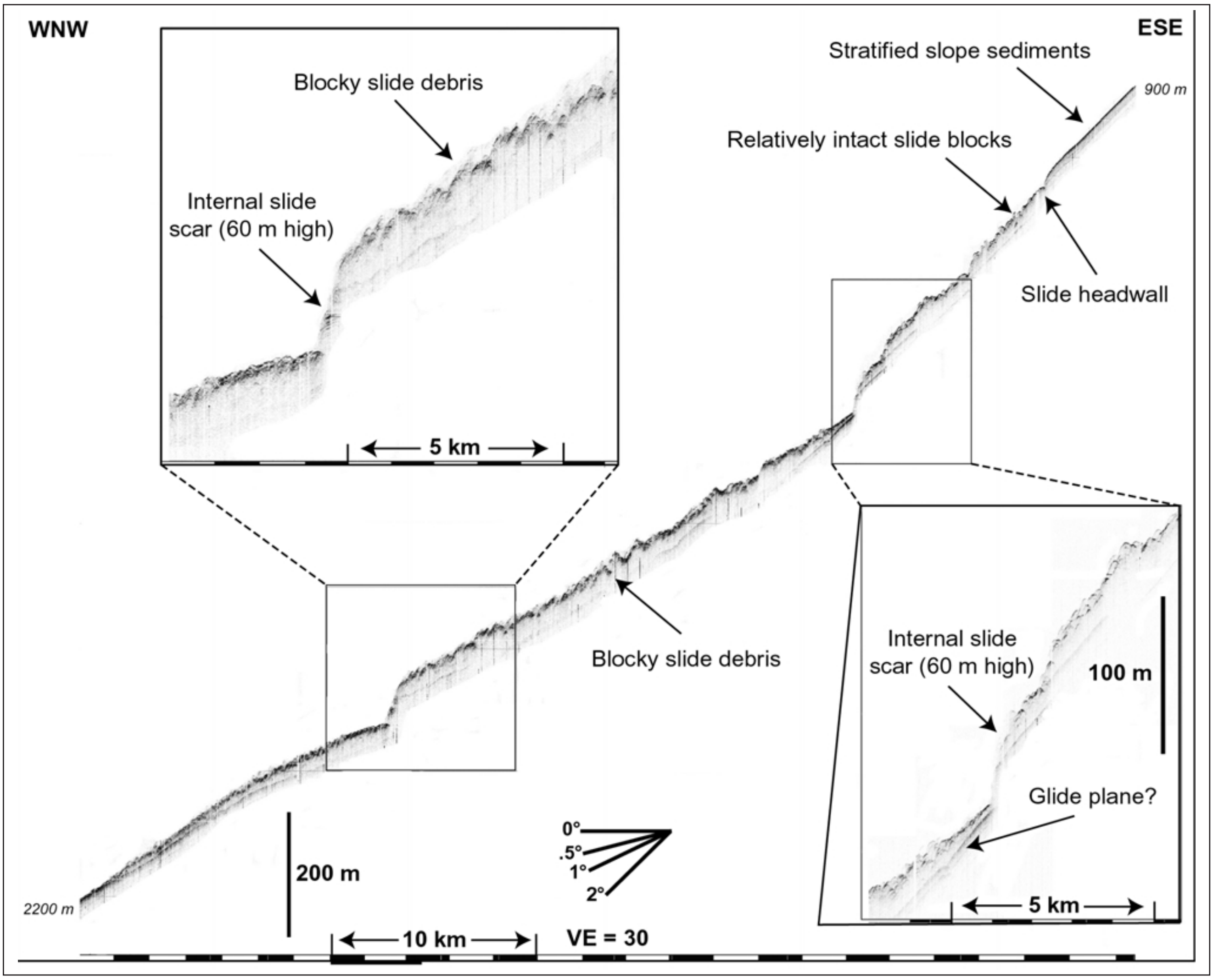

Fig 3: PARASOUND dip profile across the upper Mauritania Slide Complex, showing multiple failure scarps and the bedding-parallel nature of glide planes. For location see Figs. 1 and 2.

suggesting a complex failure history. However, there is a general downslope change in morphology as follows: 1) an upper zone of relatively intact slide blocks (Fig. 3), 2) a middle zone of thin, blocky slide debris some 25 m thick (Fig. 3), and 3) a lower zone consisting of a thick tongue-shaped debris flow deposit with a relatively smooth top (Fig. 4). The transition between the middle and lower zone is associated with a major change in slope gradient from ~1.5° to < 1° (Fig. 4). Zone 3 is the main depositional area of the Mauritania Slide Complex.

A seismic profile illustrates the internal structure of the Mauritania Slide Complex (Fig. 4). About 15 km upslope of the uppermost headwall an isolated sharp ridge ~50m high is visible in the seismic profile. This ridge was identified on almost all profiles upslope of the headwall area of the Mauritania Slide Complex. Two erosional furrows (or moats) are present on either side of the ridge, which extends alongslope for at least 50 km at a water depth of 400-500 m, just upslope from the Mauritania Slide Complex headwall (Fig. 2). Industry 3D seismic and shallow core data have revealed that this ridge is a linear carbonate mud mound covered by deep-water corals, and extends intermittently alongslope for at least 190 km and covers an area of ~95 km^2 (Colman et al. 2005).

The headwall scars in water depths between 800 m and 1200 m truncate well-layered reflectors (Fig. 4). Highly blocky deposits were identified immediately beneath the headwall area. Downslope of a change in slope gradient to <1° the main debris flow depositional area is characterized by stacked chaotic to transparent units separated by thin packets of well-stratified sediments. The stacked chaotic to transparent units in combination with a series of stepped headwalls prove that the Mauritania Slide Complex is a multiple stage failure.

Five gravity cores were recovered from across the Mauritania Slide Complex during Meteor cruise M58/1, both from the center of the main 'excavation zone' and

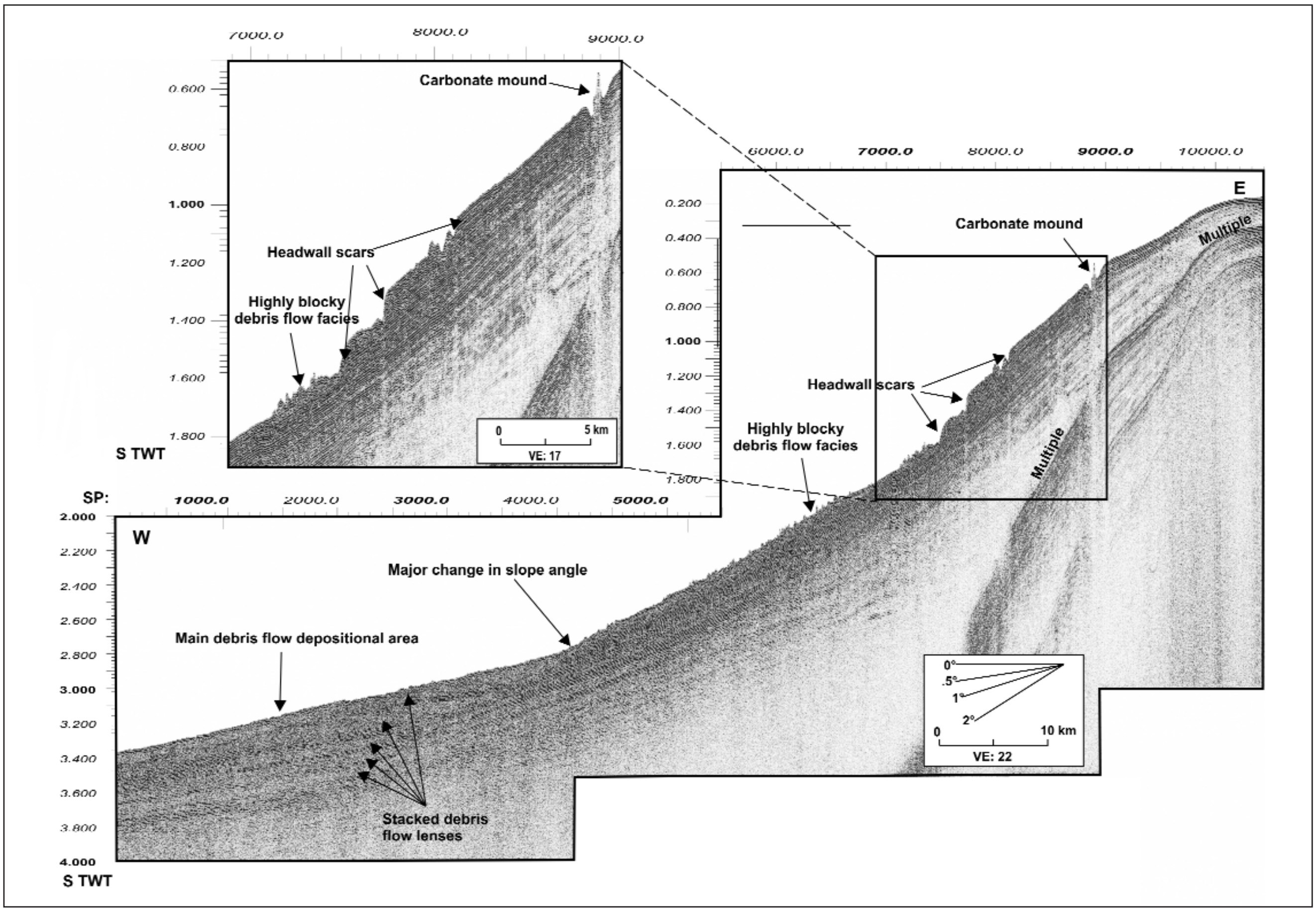

Fig 4: Seismic dip profile crossing a carbonate mound, as well as the headwall area and the main depositional area of the Mauritania Slide Complex. Note the stacked debris flow deposits imaged as transparent units. For location see Figs. 1 and 2. Slightly modified after Antobreh & Krastel (2006b).

from various tongues of the debris flow deposit at its south-western margin. Cores recovered at the edge of the uppermost debris flow unit contain undisturbed sediments (mainly silty foram-bearing mud) on top of and below the debris flow, which shows numerous clasts of various size and includes folded and stretched intact sediment sequences in an olive grey silty mud matrix. Radiocarbon dating of the undisturbed sediments below and on top of the debris flow deposits allows us to date the deposition of the uppermost debrite unit at 10.5 to 10.9 cal. ka B.P. (Henrich pers. comm). At some locations the uppermost debrite sheet is overlain by a 50-cm thick, normally graded, siliciclastic sand turbidite in direct contact with the debrite. We do not see any indication of erosion of the debrite by the turbidity current but, in contrast reconstruct an erosional effect of the debrite flow into the underlying hemipelagic sediments by some 50 cm based on oxygene isotope curves.

The Cap Blanc Slide

Jacobi & Hayes (1982, 1992) mapped a series of slides off Cap Blanc originating at a water depth of ~2000 m. During Meteor cruise M58/1 two survey lines running perpendicular to the slope were chosen to intercept these upper slides (Fig. 1), but despite surveying westwards to a water depth of 3200 m (about 19°10'W) no obvious slide headwall or deposit was located.

The new data, however, show the presence of a deeper slide off Cap Blanc (called the Cap Blanc Slide in this study). The slide headwall is visible on PARASOUND profiles at ~3575 m water depth and is ~25 m high (Fig. 5) though the headwall is not visible as sharp step in the morphology probably due to its age of ~165 ka (see below). The slide deposit clearly thickens from ~18 m thick just below the headwall to >26 m thick some 115 km further downslope. The slope angle of the undisturbed sediments immediately above the headwall is 0.47°, while the upper slide deposit has a slope angle of 0.24°. The southern boundary of the slide is visible on a PARASOUND profile crossing the distal Cap Timiris Canyon (Fig. 6). The Cap Blanc Slide onlaps a well developed right-hand levee of the Cap Timiris Canyon. The slide deposits are up to 25 m thick on this profile. The northern boundary of the slide was identified on GLORIA sidescan sonar and 3.5 kHz profile data presented by Kidd et al. (1987). This boundary is shown on Fig. 2 as solid line at the distal northern

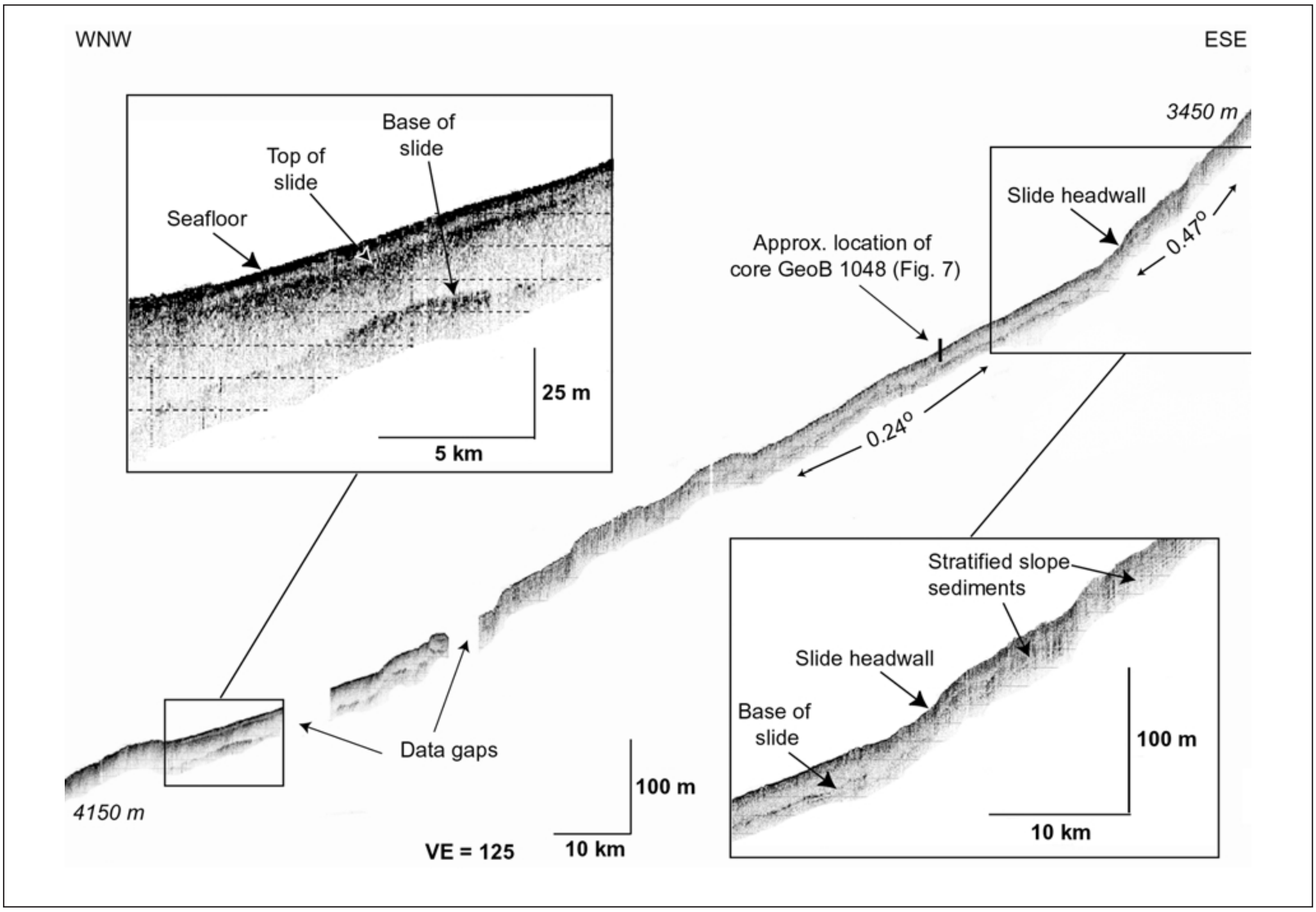

Fig 5: PARASOUND dip profile showing the headwall of the Cap Blanc Slide. Note the layer of draping sediments on top of the slide deposit. Approximate position of core GeoB 1048 (Fig. 7) is indicated. For location see Figs. 1 and 2.

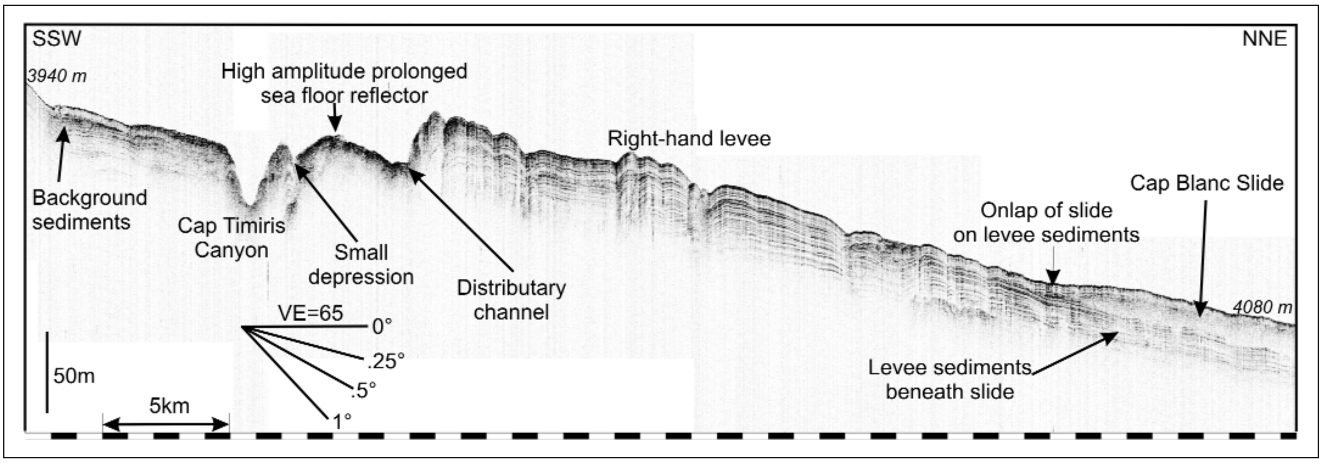

Fig 6: PARASOUND profile crossing distal Cap Timiris Canyon. The well developed right-hand levee is onlaped by the deposits of the Cap Blanc Slide. For location see Figs .1 and 2.

boundary of the slide. Extrapolation of the slide boundary using all available data and the new PARASOUND data suggests that the area affected by the slide exceeds 40,000 km^2, and that the overall width of the slide is ~175 km (Fig. 2). This extrapolation is based upon the assumption that the slide ran perpendicular to the slope, as has been noted elsewhere (e.g. Masson 1994). Geophysical data from the area of the Cap Blanc Slide provide some indication for the age of this event. PARASOUND profiles show a thin drape a few meters thick in places on top of the slide deposit (Fig. 5) suggesting that the slide is not a recent (Holocene) feature.

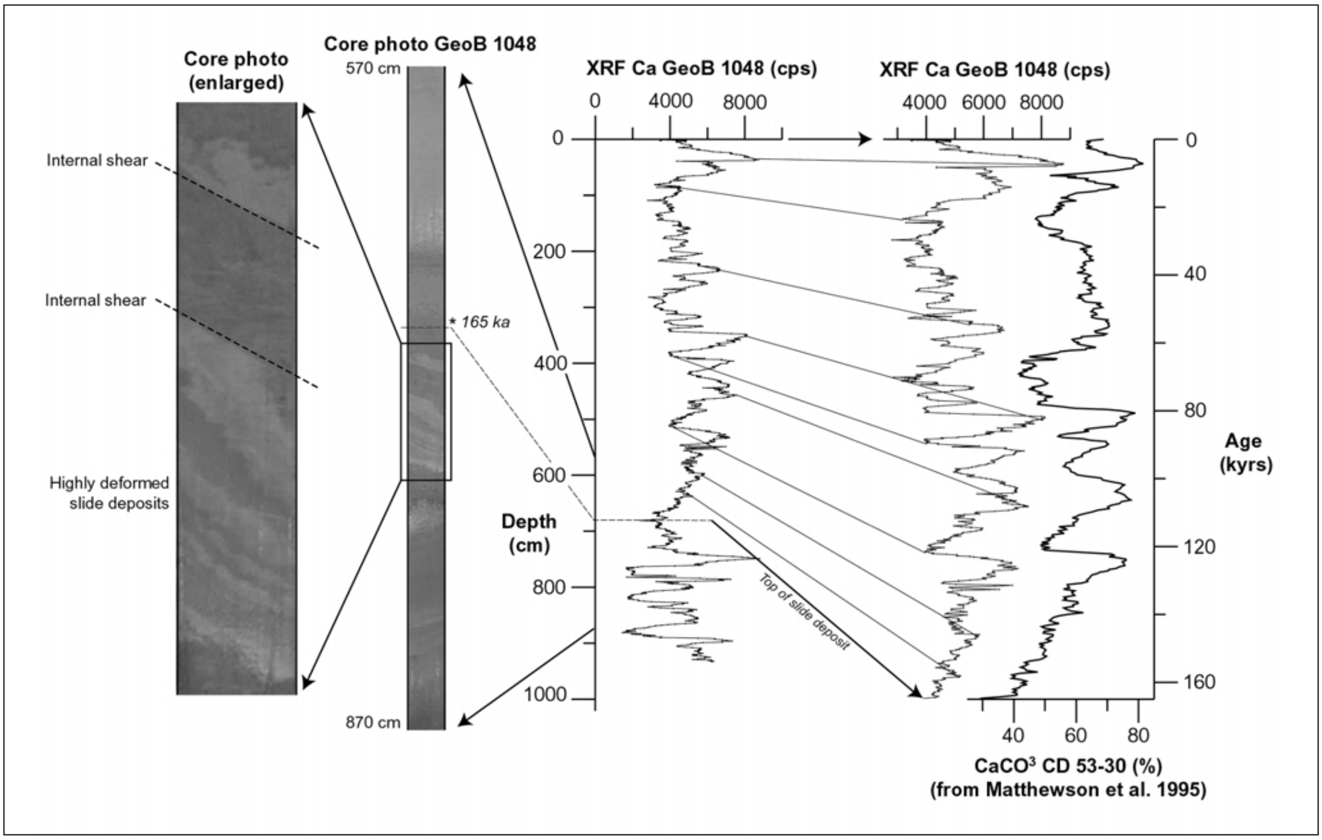

Fig 7: Panel diagram showing the Cap Blanc Slide deposit in core GeoB 1048. Core photos show internal shear boundaries (thick dashed lines) and the overall highly deformed nature of the slide deposit, in contrast with parallel stratified overlying pelagic sediments. Dating of the pelagic sediments immediately on top of the slide deposit (which is shown by a thin dashed line) was achieved by correlating the XRF Ca curve of Core GeoB 1048 above the slide deposit, with the dated CaCO3 curve from a core in background sediments outside of the slide area (taken from Matthewson et al. 1995). The correlation between these two sequences is excellent (thin lines show corresponding peaks), allowing a date of 165 ka to be assigned with confidence as the minimum age for the Cap Blanc Slide. For location see Figs. 1 and 5.

A single core (GeoB 1048) recovered from within the slide at 20°54'N/19°43'W (Figs. 2, 5, 7) confirms that the top of the slide deposit is at a depth of 686 cm below the seafloor, where we found a sharp boundary between highly deformed slide deposits and parallel stratified overlying sediments. Dating control has been achieved by correlating the $CaCO^3$ curve from the pelagic sequence in core GeoB 1048 above the slide deposit, with that from an oxygen isotope-dated core outside of the slide scar ~140 km to the SSW (core CD 53-30 in Matthewson et al. 1995). This indicates that pelagic sediments immediately above the slide deposit can be dated at 165 ka, making this the minimum age for the Cap Blanc Slide (Fig. 7).

Canyons and channels

The Cap Timiris Canyon

One of the most unexpected results of Meteor cruise M58/1 was the discovery of a spectacular meandering canyon-channel system offshore of Cap Timiris (Krastel et al. 2004). The Cap Timiris Canyon runs westwards from the shelf break to a depth of at least 4000 m and is over 450 km long (Fig. 2). The upper part of the system is composed of a series of dendritic canyons and gullies up to 500 m deep that cut back to the shelf break (Fig. 8). These gradually merge downslope into one main canyon at just over 2000 m water depth; which is incised up to 300 m deep in places (Fig. 8). From there on HYDROSWEEP multibeam bathymetry reveals a highly complex sinuous and meandering morphology with a single cut-off meander and several intra-canyon terraces (Antobreh & Krastel 2006a). Levees are poorly developed up to a distance of ~350 km from the shelf break, indicating that most flows are confined within the canyon and do not overspill in this section.

Good bathymetric coverage of the Cap Timiris Canyon is only available up to a distance of ~215 km from the shelf break (Fig. 8) but numerous PARASOUND profiles of the distal channel were collected during Meteor cruise M65/2 in the summer of 2005, (Figs. 1, 6). A PARASOUND profile of the distal canyon (Fig. 6) shows only a ~40m deep V-shaped main channel and two smaller depressions located northeast of the main channel. Well-developed levee sediments are located

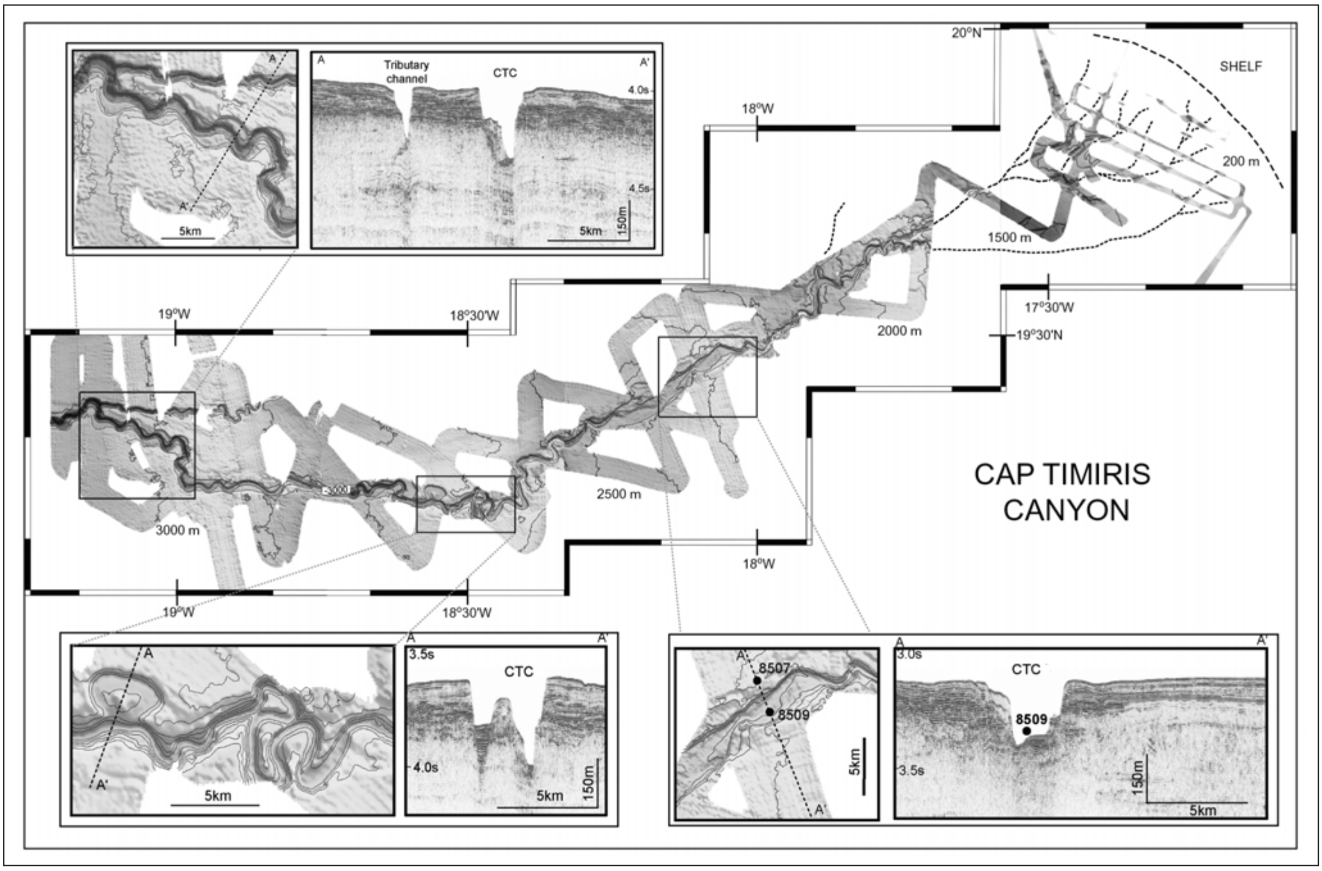

Fig 8: Plan view image showing HYDROSWEEP multibeam bathymetry of the upper and middle Cap Timiris Canyon (modified after Krastel et al. 2004; Antobreh & Krastel 2006a). For location see Figs. 1 and 2. Three inset images show enlarged sections of HYDROSWEEP bathymetry together with multi-channel seismic sections across the channel. Lower right inset shows locations of core 8509 shown in Fig. 9. CTC = Cap Timiris Canyon.

immediately northwest of the second depression. The sediments of the above described Cap Blanc Slide onlap the levee sediments.

Along the Cap Timiris Canyon thirteen sediment cores were recovered from the channel axis, intra-channel terrace and overbank areas. Core GeoB 8509 was recovered from the channel thalweg or a lower terrace of the upper canyon (Fig. 8), and contains a 9 m thick sequence of interbedded sand-mud turbidites and olive-grey hemipelagic muds (Fig. 9). Initial radiocarbon dating indicates regular turbidity current activity over the last 13 ka (Holz 2005).

Other canyons and channels

There is a large concentration of upper slope canyons and gullies extending south from Cap Timiris as far as the northern margin of the Mauritania Slide Complex, between 19°20'N and 18°20'N (Fig. 2). These incisions are typically between 50 and 150 m deep (with exceptions up to 250 m deep) at water depths of 1000-2000 m (Fig. 10), and have a spacing of up to 10 canyons per 100 km at the 2000 m isobath. In between are numerous small gullies <25 m deep (Fig. 10), which are roughly spaced 1-5 km apart at the 2000 m isobath. Further downslope the canyons and gullies merge and open out into shallow channels, often with adjoining depositional levees. These channels are all <70 m deep at a water depth of 3000 m. To the north and south of this highly incised section of slope there are relatively few canyons and channels, e.g. a spacing of three canyons per 100 km between 21°N and 22°N at water depths of 1000-2000 m.

Controls on the distribution of seafloor features and implications for geohazard assessment

Weaver et al. (2000) characterize the Northwest African margin by its low sediment supply from rivers even during glacial times but high sedimentation rates in upwelling areas along the upper slope. Large-scale slides are present but occur infrequently.

The most prominent sedimentary features identified

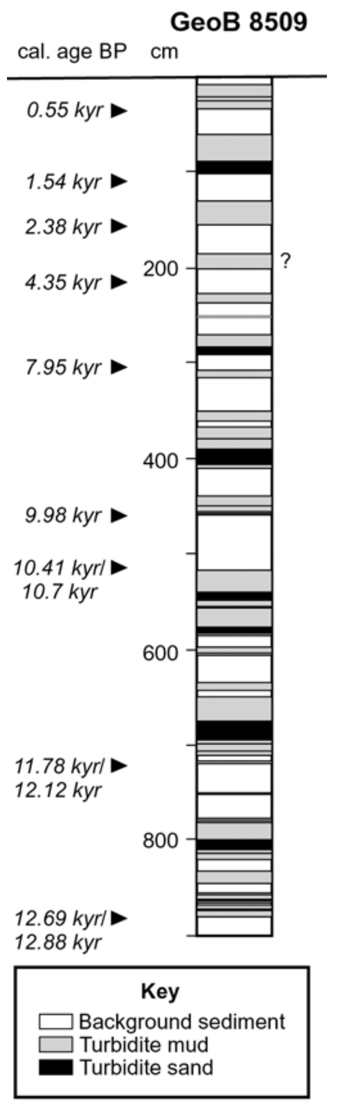

Fig 9: Interpretative core logs showing the sediment sequence of a core recovered from near the base of the Cap Timiris Canyon (GeoB 8509). Radiocarbon dates (Holz 2005), shown in italics, indicate evidence for continuing turbidity current activity through the Holocene within the channel. For location see Figs. 1, 2 and 8.

offshore Mauritania in this study are numerous submarine canyons/channels formed by turbidity currents and two large submarine slides. In the following we will analyze the controls on distribution of these features and discuss the implications for geohazard assessment.

Submarine slides

Large-scale submarine slides are an important potential geohazard as they are unpredictable and can affect large areas of seafloor. The two slides discovered to date do not appear to be linked to any obvious seafloor features, e.g. fault scarps, and the headwalls are at different water depths (Fig. 2).

The Cap Blanc Slide occurs on a section of slope that incorporates only few channels and canyons and is relatively unaffected by turbidity currents. The headwall of this slide is unusually deep at 3575 m and lies over 200 km offshore of Cap Blanc (Fig. 2). However, in this region high sedimentation rates can extend into deep water. Studies on the continental slope off Cap Blanc have shown that, of the whole northwest African margin, it is this section that receives the greatest input of pelagic sediment due to elevated primary productivity (Van Camp et al. 1991) combined with high eolian sediment input (deMenocal et al. 2000). Offshore advection means that the depocenter for most pelagic sediment off Mauritania is located on the upper and mid-slope at water depths of ~1000-1500 m (Fütterer 1983), with sedimentation rates off Cap Blanc at these depths being ~10 cm/1000 yrs (Martinez et al. 1999). However, in the Cap Blanc region, plumes and filaments of cold upwelling water can locally extend for hundreds of kilometers offshore (Van Camp et al. 1991; Gabric et al. 1993), meaning that high sedimentation rates may extend further offshore. This is supported by a record from ODP Hole 658C off Cap Blanc (see Fig. 1 for location), at a depth of 2263 m, which showed a sedimentation rate of 22 cm/1000 yrs over the last ~14 ky (deMenocal et al. 2000). Overall, the age (165 ka) and headwall location (water depth 3575 m) of the Cap Blanc Slide, and the lack of evidence for slide reactivation, suggest that this feature is not a significant geohazard at the present day.

Understanding the location, age and present-day stability of the Mauritania Slide Complex is, however, of potentially greater importance, as the current focus of hydrocarbon exploration offshore Mauritania is actually centered directly upon the upper part of this slide (Fig. 2; Colman et al. 2005).

Values such as the slope angle above the uppermost headwall ranging from 1.5° to 2.2°, headwall heights ranging between 25 and 100 m and headwalls occurring in water depths ranging from ~800-2000 m are in close agreement with median values calculated by Hühnerbach et al. (2004) from a database of over 100 submarine slides on the open slopes of the eastern Atlantic continental margin (although not all slides were included in the statistical analysis due to incomplete datasets). The median slope angle for the upper boundary of the studied slides by Hühnerbach et al. (2004) was 3°, the median water depth was 1175 m, and the median headwall height was 47.5 m. The Mauritania Slide Complex is, however, considerably larger in volume (~600 km^3) and areal extent (~30.000 km^2) than the median values of 30 km^3 and 1550 km^2, respectively. The values for the Mauritania Slide Complex are in the same range as single other large slides on the NW-African margin, such as the Saharan Debris Flow with volume estimates ranging from 600-1100 km^3 (Gee et al. 1999). These data therefore suggest that the Mauritania Slide Complex is typical in terms of its location, but is atypical in terms of its dimensions, probably because it is not a simple single slide. Retrogressive failure is suggested by a series of stepped headwalls in

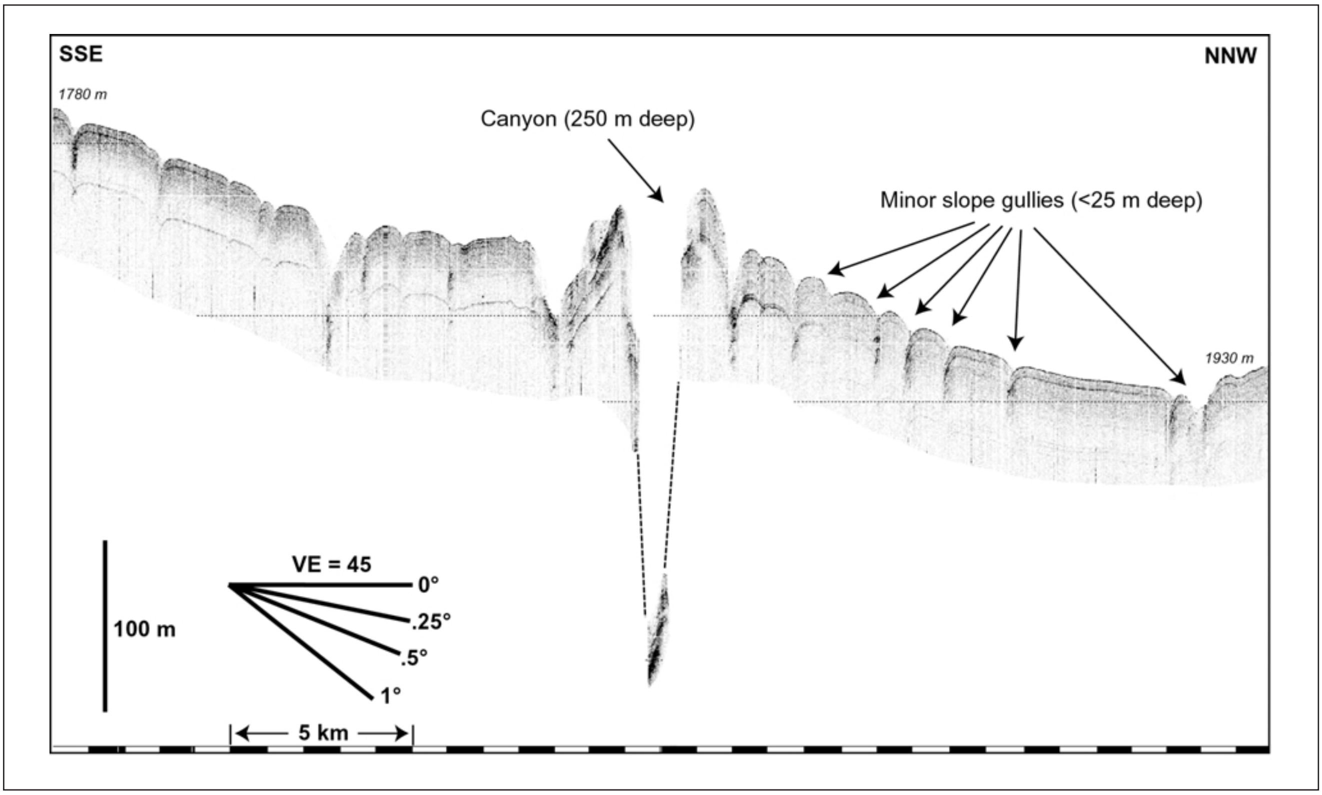

Fig 10: PARASOUND strike profile showing close spacing of gullies on the upper slope, adjacent to a deep canyon. Dashed lines show inferred canyon walls which were not imaged by PARASOUND due to large slope angles. For location see Figs. 1 and 2.

water depths between 800 and 2000 m (Figs. 3, 4). Additionally the seismic data clearly show stacked debris flow units imaged as transparent units, which are generally separated by well-stratified thin reflection packages (Fig. 4).

Without long cores penetrating individual debris flow units we can only speculate about the timing of the failure. Shallow sediment coring showed that the uppermost main debris flow unit was deposited between 10.5 to 10.9 cal. ka B.P. (Henrich pers. comm). We cannot exclude younger slide reactivation though we do not see any indications for such remobilization in our data. The well preserved headwalls between 800 m and 2000 m water depths suggest that the uppermost debris flow unit is probably part of a retrogressive failure which occurred in Late Pleistocene times. In the seismic data we can identify at least five transparent units separated by thin well stratified reflection packages (Fig. 4). The existence of these packages between the debris flow units indicates that the buried debris flow deposits are significantly older than late Pleistocene showing that this part of the northwest African continental margin has been unstable for a long time. The timing of the older events and therefore the recurrence interval, however, remains unclear as it is not possible to correlate key reflectors to any drill site due to missing data.

The reasons for the repeated slope failures in this area might be manifold. The elevated sedimentation rates due to upwelling-induced high primary productivity (Fütterer 1983; Martinez et al. 1999) result in rapid accumulation of poorly consolidated organic rich sediments, which are potentially unstable. Large slope failures on such a relatively unstable slope could be initiated by a variety of triggers. We consider excess pore pressure as a result of high sedimentation rates associated with low permeability sediments and the decay of organic matter as the most likely trigger. Antobreh und Krastel (2006b) noted the presence of widespread and pervasive acoustically transparent vertical linear zones in the main depositional areas of the Mauritania Slide Complex and interpret these features as evidence for the widespread distribution of excess pore-pressure resulting from over-pressurised gas or fluids within the slide complex.

Jacobi (1976) suggested that the Mauritania Slide Complex may be linked to the presence of east-west trending fracture zones, which could act as a focus for earthquake activity or faulting on this section of the margin (Hayes & Rabinowitz 1975) and therefore provide a potential trigger. The volcanically active Cape Verde Islands are another potential location of nearby earthquakes.

Dissociation of gas hydrates can trigger submarine slides as well (e.g., Mienert et al. 1999). The depth of the slide headwall around 800m water depth and the age of the youngest slide event would be consistent with a trigger by gas hydrate dissociation at the end of the last glacial period. Our data, however, do not show evidence for gas hydrates or gas hydrate dissociation such as bottom simulating reflectors, bright spots, or widespread masking of reflectors due to free gas.

It is interesting to note that cores recovered at the edge of the debris flow show that the uppermost debrite sheet is overlain by a 50 cm thick normal siliciclastic turbidite, which is of shelf origin. The occurrence of the siliciclastic turbidite directly on top of the debris flow might be explained by a tsunami, which was triggered by the slope failure. Such a tsunami would have mobilized shelf material, which was transported downslope as a turbidity current. This scenario would mean that the debris flow and the turbidity current were quasi-simultaneous events. Though we do not see any hemipelagic deposits between the deposits of the debris flow and the turbidite, we are aware that the turbidity current might have eroded underlying deposits and that the debris flow and the turbidity current could also be independent events.

The relatively young age of the youngest debris flow event in combination with a long history of large scale sliding in the area of the Mauritania Slide Complex strengthen the importance to asses the geohazard potential of this area, especially as it is an area of active hydrocarbon exploration and production. An interesting feature in this context is the presence of a linear carbonate mound system immediately upslope of the upper headwall as evidenced on our data (Figs. 2, 4) and a study of Colman et al. (2005). The sediments upslope, and directly below, the carbonate mound are characterized by undisturbed deposits without any signs of downslope movement (Fig. 4). If the slide underwent retrogressive failure as suggested above and cut back upslope, the carbonate mound might have stabilized the slope and prevented further upward retrogression of the slope failure. Such a scenario suggests that areas of the slide immediately adjacent to the mound are now largely stable and unlikely to propagate further upslope. The stacked debris flow lenses identified in the seismic data, however, indicate that this part of the continental margin has been unstable for a long time. The main depositional area of all debris flow units is from ~2000 m water depth (Fig. 4) and all slope failures probably occurred in water depths between 800 and 2000 m. The high sedimentation rates in this area result in the quick build up of potentially unstable sediments well below the carbonate ridge, which will fail if the applied forces exceed the shear strength. Therefore the stability of the slope beneath 800 m water depth can only be addressed by geotechnical studies which have not been conducted so far.

To conclude, both geophysical and sedimentological data show no evidence for recent slide remobilization, although local collapse of over-steepened headwalls may still present a hazard. Further studies are therefore required both within and adjacent to the slide to assess present-day stability.

Turbidity currents

The largest concentration of turbidity current gullies, canyons, and channels is situated between 18° and 20°N (Fig. 2). During present-day highstand conditions the majority of these conduits are inactive, as fluvial terrigenous input onto the Mauritania margin has been negligible due to the present highly arid regime in the Sahara Desert (18 – 30°N) which became dominant about 5-6 ka (e.g. deMenocal et al. 2000; Swezey 2001; Kuhlmann et al. 2005). The Cap Timiris Canyon (Fig. 8) was studied in detail (Antobreh & Krastel 2006a). The canyon was probably originated by an ancient river system in the adjacent, presently arid Sahara Desert that breached the shelf during a major Plio/Pleistocene sea level lowstand. Such a system delivered sediments directly into the slope area. Seismic data show that an initial invading unchannelized sheet of sand-rich gravity flows initiated canyon formation by gradual mobilization along linear seafloor depressions and fault-controlled zones of weakness. Several abrupt shifts in canyon direction suggest a strong structural control on canyon location and development.

Seismic and bathymetric data of the upper and middle sections of the canyon show a deeply entrenched canyon without significant levee development (Fig. 8). This observation is supported by core data which do not show abundant overspill turbidites. Flows in the upper and middle sections of the canyon are strongly confined with little or no overspill. In contrast the depth of the distal canyon is reduced to <100 m (Fig. 6). This section is characterized by a well developed right-hand levee indicating that flow overspill becomes more important downslope as channel depth decreases. The minimum age of Cap Timiris Canyon is 165 ka, as the 165 ka old Cap Blanc slide onlaps levee sediments of the distal channel (Fig. 6). The seismic facies of the reflectors beneath the Cap Blanc Slide are also characteristic for levee sediments; hence the canyon is probably significantly older. Wien et al. (2006b) suggested that Cap Timiris Canyon was active for at least the last 245 kyr. Present activity and therefore the geohazard potential of Cap Timiris Canyon is, however, low. The analysis of core GeoB 8509 has shown that margin-derived turbidity current activity decreased markedly at the beginning of the Holocene, and that since then the system has only been supplied by smaller-scale, slope-derived flows (Holz 2005). No Holocene overspill turbidites were found at distal Cap Timiris Canyon.

Conclusions

Geophysical and sedimentological data collected in the spring of 2003 and the summer of 2005 have contributed to the construction of a new seafloor map of the Mauritania continental margin, allowing the spatial distribution of sedimentary features and processes operating in this region to be analyzed in detail for the first time.

Large sections of the upper slope on this margin experience enhanced levels of pelagic/hemipelagic background sedimentation due to upwelling-induced high productivity and offshore transport of eolian dust from the Sahara Desert. These high sedimentation rates, and the lack of frequent triggers such as earthquakes, enables thick sequences of fine-grained sediment to accumulate rapidly. Consequently, large-scale slope failures in the form of submarine landslides occur intermittently and affect vast areas of seafloor. Two major landslides have been mapped during this study, the Cap Blanc Slide and the Mauritania Slide Complex. While the Cap Blanc Slide is relatively old (165 ka) and no indications for younger sediment remobilization were identified in the new data, the Mauritania Slide Complex is a priority for further study as it is a relatively young (~11 ka) large complex slide with evidence for multiple phases of retrogressive failure, which might have been tsunamigenic. Although we did not find evidence for recent slide reactivation, local collapse of over-steepened headwalls may still present a hazard. As our new data were not primarily collected to assess the geohazard potential, further studies are required both within and adjacent to the slide to assess present day stability.

During the early Holocene and preceding Late Glacial Period, the climatic regime in the Sahara Desert was very different to the present-day, with numerous river systems supplying clastic sediment to the outer shelf. These and similar conditions in earlier times have contributed to the formation and maintenance of numerous submarine canyons, gullies, and channels on the margin, particularly between 18° and 20°N. The largest of these is the 450 km-long Cap Timiris Canyon, which displays a spectacular meandering morphology in its upper reaches. Minimum age for Cap Timiris Canyon is 165 ka. This deeply entrenched canyon is an effective pathway for the transportation of shelf and upper slope sediments to the deep sea.

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