REPEATED INSTABILITY OF THE NW AFRICAN MARGIN RELATED TO BURIED LANDSLIDE SCARPS

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Abstract

The Sahara Slide occurred approximately at 50-59 Ka offshore Western Sahara in a mid-slope setting (1900 m water-depth). The existence of several buried and stacked slide events, seen on high resolution seismic profiles, provide new insights into slide location and triggering mechanisms. Buried slide scarps coincide remarkably with scarps and boundaries of the Sahara Slide, presently exposed on the seafloor. The objectives of this work are to examine the long-term stability of this part of the margin and investigate the triggering mechanism(s) that led to these massive events.

Buried slide scarps occur in sediments of Miocene-Pliocene age. Multiple scarps becoming more closely spaced towards a larger scarp that may be the main headwall suggest that most of the buried slides developed as retrogressive slides. The seismic record shows that differential compaction across an area of depression bound by scarps generates compaction hinges (anticlines) leading to oversteepening and possible excess pore pressure. We propose that alignment of ancient and present scarps and vertically stacked slide deposits points towards differential compaction as being a key factor in landslide triggering.

1. Introduction

Submarine slides are an important architectural element of continental margins. Because of their widespread and often episodic nature, mass sediment movement events are important components of the modern stratigraphic record, and have been studied in connection with global climatic cycles, including sea level changes (e.g. McHugh et al., 2002). Several investigations address the geohazard potential of submarine slides (e.g. Locat & Mienert, 2003, and references therein) as submarine slides might destroy offshore infrastructure and trigger tsunamis.

The NW African continental margin is well known for the occurrence of large but infrequent slides (Weaver et al., 2000; Wynn et al., 2000; Krastel et al., 2006). The largest slides are the Mauritania Slide (Antobreh and Krastel, 2006) and the Sahara Slide (Gee et al., 1999; Georgiopoulou et al., in prep). These studies mainly discuss the dynamics of the slides but less is known about trigger mechanisms and why these slides occur at specific locations along the margin while other parts of the margin are stable. Early investigations of the Sahara Slide concentrated on the depositional part of the slide (see Gee et al., 1999 and references therein) but data of the head wall area were lacking.

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New acoustic and gravity core data from the headwall area of the Sahara Slide, off Western Sahara, were acquired during *RV Meteor* cruise M58/1 in 2003 (Fig. 1). These new data in combination with revisited older data allows analysis of the distribution and mechanics of the Sahara Slide form source to sink (Georgiopoulou et al., in prep.). Here we present a set of high-resolution seismic reflection profiles from the headwall area of the Sahara Slide, which document the presence of buried scarps and slide deposits which exhibit remarkable spatial coincidence with the present Sahara Slide headwall. We interpret the buried slide deposits as indicating a long term instability for this part of the margin and analyse the role of old slides for triggering subsequent slides at a similar location.

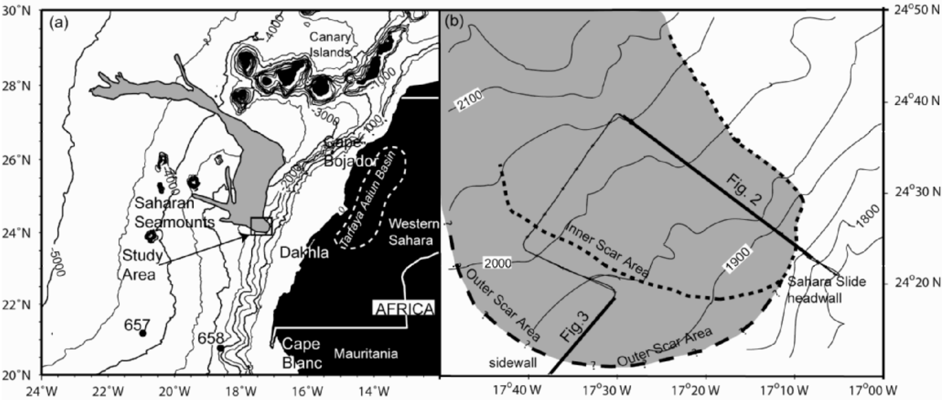


Fig. 1. Location of the study area on the NW African margin (box) and blow up with survey lines (b). (a) Map showing the outline of the Sahara Slide (grey-shaded area) on the NW African margin and the location of ODP sites 657 and 658. Contours are at 500 m. (b) Thin solid lines show the survey lines at the headwall of the Sahara Slide (grey-shaded area) and thick lines the location of Figs. 2 and 3.

2. Geological setting and stratigraphic framework

The continental shelf of the Northwest African margin is composed of seaward-dipping Cretaceous and Tertiary sediments (Summerhayes et al., 1976). Shelf widths are generally 40-60 km, although the maximum width is >100 km off the Western Saharan coast. The shelf-break is at around 110-150 m water depth (Summerhayes et al., 1976; Seibold, 1982; Wynn et al., 2000). Continental slope angles range from 1°-6°, while the continental rise displays gradients of <1° (Masson et al., 1992).

The study area lies in the Aaiun-Tarfaya basin, offshore NW Africa. The marine history of the Aaiun-Tarfaya Basin starts with a Jurassic transgression from the west. Maximum transgression occurred during the Cenomanian invading the Sahara and reducing terrigenous input to the Atlantic (Seibold, 1982). A strong regression and erosion started on the continental shelf and slope during the Oligocene/Miocene, which also marks the first development of submarine incision characterised by accentuated subsidence rates, averaging 6cm/ka off Cape Bojador, and possible sea-level lowering (Seibold, 1982). In post-Oligocene times canyons were filled and re-excavated and local slumping occurred (Seibold, 1982). The early Miocene is a phase of marked global warming at the same time as continuous sea-level rise (Sarnthein et al., 1982). Climate on the Northwest African margin was wet with hardly any aeolian dust input. Sea level continued to rise during the Middle Miocene, while major hiatuses occurred at the upper Early Miocene and end of Middle Miocene. During the Late Miocene (Messinian) there were episodes of cooling which were correlated with a short but marked sea level drop. During the Early Pliocene high sea-level was re-established (Sarnthein et al., 1982).

Quaternary sediments off NW Africa are essentially biogenic due to a continuous upwelling cell (Seibold and Hinz, 1974). Results from ODP site 658 show that the upper Pliocene-Holocene sediment section comprises three major hemipelagic lithologic units, the upper of which is divided into two subunits. Unit I spans the period Pleistocene to Holocene. Unit II represents the period between Upper Pliocene and Lower Pleistocene and Unit III deposited from Lower to Upper Pliocene (Ruddiman et al., 1988). Unit II correlates with an almost transparent unit which has velocities 900-950 m/s indicative of free gas in the sediment (Ruddiman et al., 1988).

3. The Sahara Slide

The Sahara Slide is a large submarine slide that took place retrogressively 50-59 ka on an open slope offshore the arid Western Sahara (Fig. 1) and involved approximately 600 km^3 of sediment. Recently acquired bathymetric data revealed that the scar area is shaped by two headwalls, each up to 100 m high, cut into mid-slope sediments. Between the two main escarpments the scar has a stepped profile consisting of a series of discrete glide planes at different stratigraphic levels separated by internal scarps, suggesting that the slide occurred retrogressively. The main headwall of the slide appears to have been reactivated as recently as ~2000 y.a. as indicated by detailed shallow seismic profiles and sediment cores. High resolution deep seismic data presented in this paper show that the headwall scarps of the Sahara Slide coincide remarkably with buried scarps of ancient slides that occurred at different times in the past.

4. Data and Methodology

High-resolution seismic data were collected using a 1.7L GI-Gun as source and 450 m long 72 channel Syntron streamer for signal recording. Processing included trace editing, static corrections, velocity analysis, normal moveout corrections, bandpass frequency filtering (frequency content: 55/110 – 600/800 Hz), stack, and time migration. A common midpoint (CMP) spacing of 10 m was applied throughout.

5. Ancient scarps and buried slides

Seismic Profile GeoB03-060 crosses the headwall area of the Sahara Slide (Fig. 2). The headwall is characterized by a ~80 m high step in morphology. The headwall cuts well-stratified sediments. A sidewall and an internal scarp each ~20m high were found on Profile GeoB06-057 (Fig. 3). The seismic sections are generally characterized by an interlayering of transparent and well stratified units. The upper most transparent unit represents the slide deposits of the Sahara Slide, which was the last major failure that took place retrogressively at 50-59 ka BP (Gee et al., 1999; Georgiopoulou et al., in prep). Four buried slides have been highlighted on the seismic sections (Fig. 2 and 3), although more can be identified, but either because they are very thin or because they cannot be associated with a prominent scarp, they are not described in detail in this paper. However, their presence contributes to demonstrating the degree of slope instability on this margin and therefore they will be considered in the discussion. The highlighted slides have been letter-coded and this letter is used to refer to them (A, B, C and D, from the deepest to the shallowest). A stratigraphic interpretation of the profile allows assigning approximate times to the major slide events. Seismic profiles published in von Rad and Wissmann (1982), as well as results from ODP sites 657 (Faugeres et al., 1989) and 658 (Ruddiman et al., 1988) helped establish the stratigraphy of the area. Sediment packages a-e correspond to the equivalent sediment packages in fig. 8 of von Rad and Wissmann (1982). Units a and b seem to match in thickness and seismic character with Units I and II at ODP site 658 (Ruddiman et al., 1988). The uncomformity marked on Fig. 2 between Middle and Early Miocene may be the Messinian sea level drop that caused the hiatus during 6.2-4.6 Ma reposted in Sarnthein et al. (1982).

Slide A appears to have taken place within Early Miocene sediments (Figs. 2, 3). The other three also took place in pre-Quaternary times, probably between Middle Miocene and Pliocene.

The headwall scarp of slide A, which is the most prominent feature on the seismic profiles, is characterised by complex morphology (Fig. 2). It is formed by multiple scarps, similar to the Sahara Slide headwall scarp, but those of slide A are higher. They range between 20 m and up to approximately 150 m (calculated using 1500 m/s sound velocity). The total height displacement of the headwall is 470 ms (~320 m). Blocks bounded by those scarps appear rotated and internally deformed (Fig. 2). This morphology indicates that this slide took place retrogressively. The deposit displays the typical chaotic internal seismic signature for slide deposits and also contains intact non *in situ* blocks. The sidewall of this slide can be seen on Fig. 3, where continuous strong reflectors interpreted as hemipelagic sediments can be seen interlayered in the slide deposits, suggesting that this slide is comprised of at least four events, separated by sediment packages of at least 10 m thickness. Considering an average sedimentation rate of 6 cm/ka (Oligocene/Miocene average sedimentation rate according to Seibold, 1982), this thickness indicates time periods of about 170 ka between events. Each of the events may have taken place retrogressively as suggested by the scarp morphology. The interpretation as retrogressive slides is suggested with caution, however, as the scarp morphology may have been the end result of these multiple events. However, we believe that the first event was dramatic enough to form this scarp and re-activation, perhaps because of over-steepening, generated the following events.

A period of general stability followed in the Middle Miocene, with only minor slide events taking place (outlined with green solid lines, Fig. 2), until slide B occurred. This slide does not have a prominent scarp associated with it, but it initiates approximately 5km downslope of what appears to be an anticline over one of the scarps of slide A.

Slide C appears to be the result of a re-activation of the major scarp of slide A as the slide A headwall area had not been fully infilled when slide C occurred and the scarp must have still been exposed on the seafloor. Slide C shows multiple scarps too that cut into slope stratified sediments in different stratigraphic levels.

The headwall of slide D that occurred in the Pliocene, is also situated approximately 5km forward of a forced fold that is formed on the edge of the major scarp.

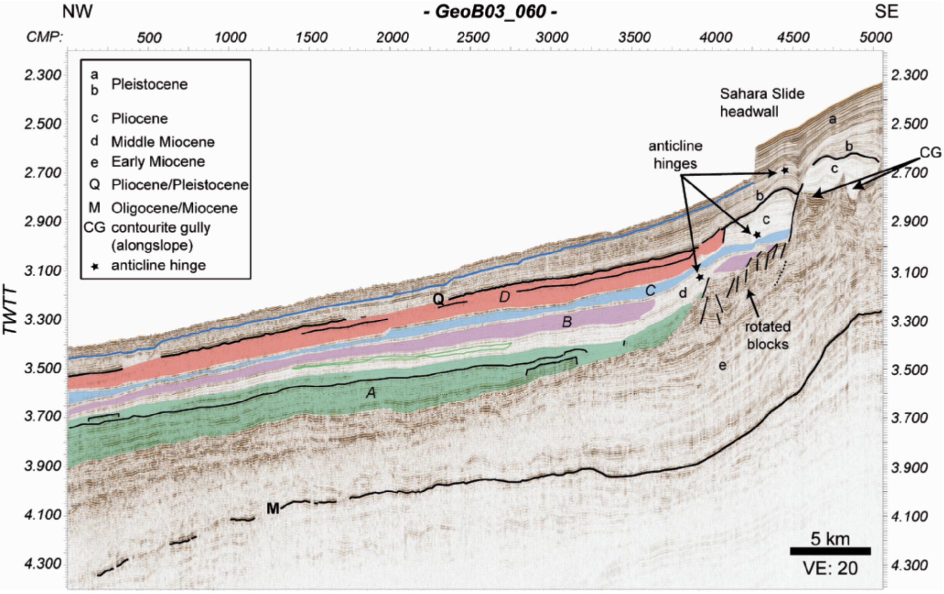


Fig. 2. Seismic reflection profile GeoB03-060 across the headwall area of the Sahara Slide (blue solid line) showing the stratigraphy and the distribution of slides *A*, *B*, *C* and *D*. The black stars indicate the location of anticline hinges. See Fig. 1 for location.

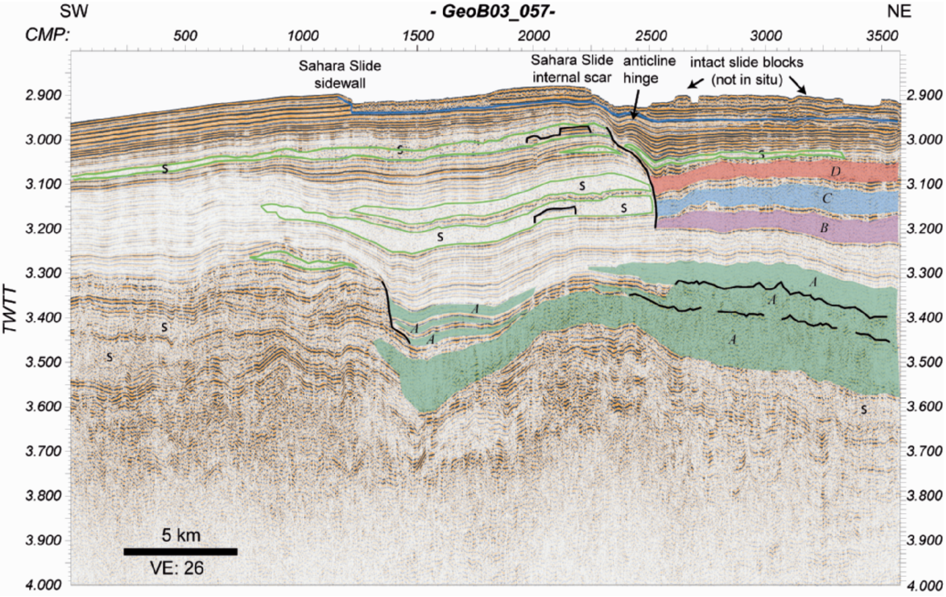


Fig. 3. Seismic reflection profile GeoB03-057 through the sidewall of the Sahara Slide (blue solid line) that shows the distribution of slides A, B, C and D. Note that slide A can be resolved into at least four events on this profile. Slides B, C and D have a common sidewall above which sediments fold gently forming an anticline hinge. More slide deposits are indicated with green solid lines or represented with the letter *s*. See Fig. 1 for location.

The three slides (B, C and D) share a common sidewall seen in Fig. 3, which appears to have propagated upwards through time. Sediments immediately adjacent to the scarp face are gently folded.

6. Triggering and evolution of slope failures

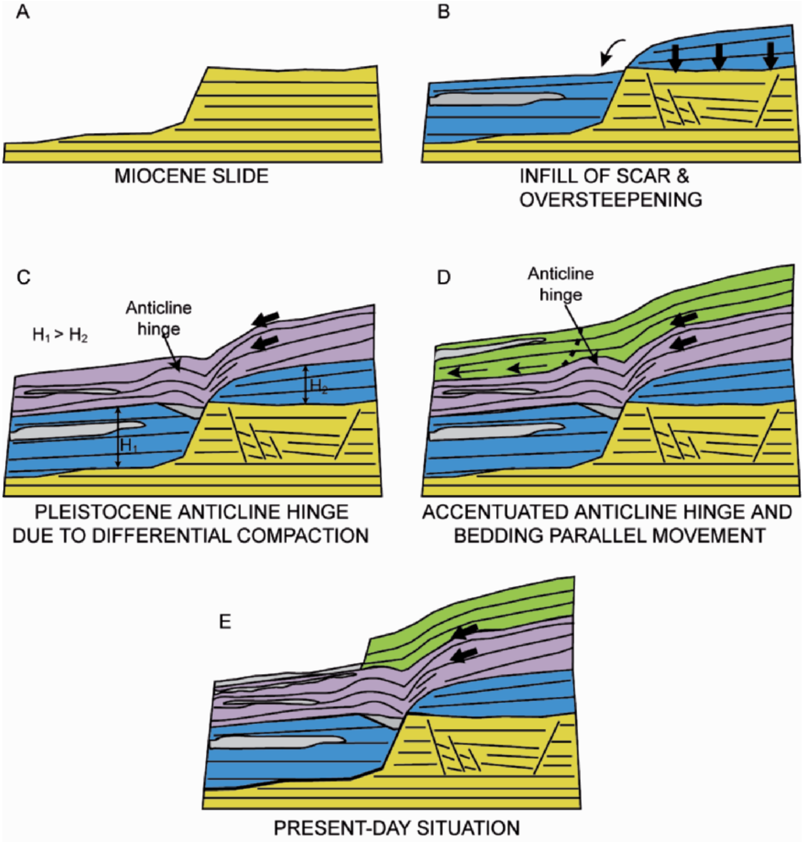
The formation of slide A created a depression surrounded by scarps that subsequently accumulated thick sediments while the adjacent area received thinner sedimentary packages. Post-slide sediments would have been more compactable than those outside the scarp which would have acted as uncompactable relief. Differential compaction across the scarps increased the accommodation space accentuating the topographic differences generating a compaction hinge (anticlne) at the transition between the depression and the adjacent seafloor, in a similar manner as suggested for the Maiella platform margin in the Central Appenines (Rusciadelli and Di Simone, 2007). Continued loading and compaction would have led to oversteepening of the strata seaward of the scarp which would further accentuate the anticline hinge (Rusciadelli and Di Simone, 2007). Oversteepening could cause intra-layer slumping giving rise to the thin slide deposits observed in the data (green solid lines in Figs. 2 and 3). Mechanical compaction of the buried slide sediments would build up pore fluid pressure contributing to the destabilisation of the area. Pore pressure data are not available for this area, but due to compaction such phenomenon is expected to have taken place. The gently folding sediments seen on seismic line GeoB03-057 (Fig. 3) provides further evidence that differential compaction takes place across the scarps. Subsequent sliding seems to regularly occur a few kilometres in front of anticline hinges suggesting that differential compaction across a dramatic scarp promotes repeated instability. A schematic conceptual model about the progress of slide generation is presented in Fig. 4.

Vertically stacked slide deposits are evident underneath the Mauritania Slide Complex as well, which is found further south on the same margin (Antobreh and Krastel, 2006) and has similar dimensions to the Sahara Slide. The vertical stacking of deposits in both areas suggests that the Northwest African margin has suffered a long history of slope instability. Unlike the area of the Storrega Slide complex where repetitive instability has also been reported (Solheim et al., 2005) climatic changes do not seem to be as important for instability on the Northwest African margin. Both in the Sahara Slide area and the Mauritania Slide Complex area the slope remains unstable after the initiation of sliding and differential compaction seems to be the main causal factor, hence explaining the long term instability of specific sections of the NW African continental Margin.

7. Conclusions

The Sahara Slide is one of the mega slides on the NW African continental margin, which occurred at approximately 50-59 Ka offshore Western Sahara. New high resolution seismic data allowed the study of sedimentary features beneath the headwall area of this slide.

- Four major buried and several smaller slide deposits prove large scale mass wasting at this section of the margin since Early Miocene times.



MIOCENE SLIDE

INFILL OF SCAR & OVERSTEEPENING

PLEISTOCENE ANTICLINE HINGE DUE TO DIFFERENTIAL COMPACTION

ACCENTUATED ANTICLINE HINGE AND BEDDING PARALLEL MOVEMENT

PRESENT-DAY SITUATION

Fig. 4. Conceptual model of slide generation due to buried scarps (not to scale). (a) Slide A occurs in Miocene times creating a depression bound by scarps. (b) Infill of the scar with thick, underconsolidated sediments, differential compaction across the scarp begins. Oversteepening at the scarp produces minor failures (grey wedge in C). Lithostatic pressure on the uncompactable sediments outside the scar leads to fracturing (black lines indicating faults). (c) Loading and differential compaction across the escarpment generates an anticline hinge. (d) Continued loading and differential compaction accentuates the anticline hinge and leads to oversteepening and potential excess pore pressure. (e) Present day situation after failure of the Sahara Slide at 50-59 Ka.

- Several buried slide scarps coincide remarkably with scarps at shallower stratigraphic levels as well as the boundaries of the Sahara Slide that is presently exposed on the seafloor.
- Major slide events most likely occurred as retrogressive type failures.
- Loading and differential compaction across escarpments generates an anticline hinge and leads to oversteepening and potential excess pore pressure. Hence specific sections of the NW African continental Margin remain unstable after the initiation sliding.

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