Slope morphologies offshore Dakhla (SW-Moroccan margin)
Morphologies de la pente continentale au large de Dakhla (marge SW marocaine)

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Abstract:

This study explores a portion of the West African margin at the junction between two well-known segments offshore Dakhla and offshore Mauritania with destructional architecture characterized by giant slides. In between these two segments, the Dakhla segment has historically been described as a constructional section. During an oceanographic Dakhla cruise (2002), high resolution seismic data, swath bathymetry and imagery were acquired around latitude 23° N, offshore Dakhla. This new data set reveals the existence of varied and complex morphologies on the continental slope, interpreted as a "shallot-shaped" canyon, seafloor depressions or pockmarks, ridges and scarps. These morphologies are interpreted as clues of sedimentary transfers and rupture processes. A scenario is proposed for the development of these different sedimentary morphologies.

Keywords: African margin, Bathymetry, Seismic interpretation, Pockmarks, Ridges, Scarps
Résumé :

Cette étude s’intéresse à une portion de la marge Ouest Africaine, à la jonction entre deux segments largement étudiés situés au large de Dakhla et de la Mauritanie, caractérisés par une morphologie globale de type destructif avec de larges glissements. Entre ces deux segments, celui de Dakhla est généralement décrit comme une portion de marge de type constructif. Durant la mission océanographique Dakhla (Décembre 2002), au large de Dakhla, de nouvelles données de sismique haute résolution, de bathymétrie et d’imagerie ont été acquises autour de la latitude 23°N. Ce nouveau jeu de données révèle l’existence de différentes morphostructures du fond telles qu’un canyon, des dépressions plus ou moins circulaires (pockmarks), différents types de rides et des escarpements, structures interprétées comme autant de témoignages de processus de transferts sédimentaires et de rupture de pente.

Mots-clés : Marge africaine, Bathymétrie, Interprétation sismique, Pockmarks, Rides, Escarpements

1. Introduction

The study of slope stability along passive continental margin is important to understand 48 sediment transfer from the shelf to the oceanic basin and to approach potential geo-hazards. 49 Among them, submarine landslides affect all types of continental margins and landslides are 50 relatively larger on passive margins than along active margins [Masson et al., 2009]
Compared to all passive margins, the North-western African continental margin is characterized by large submarine landslides (>400 - 600 km³) such as the Sahara Slide, the Cape Blanc Slide, the Mauritania Slide, and the Complex Dakar Slide, which are intensively studied since the 1970's [e.g. Antobreh and Krastel, 2006; Embley, 1982; Gee et al., 2001; 1999; Georgiopoulou et al., 2010; 2009; Hühnerbach et al., 2004; 2004; Jacobi and Hayes, 1992; Krastel et al., 2012; Wynn et al., 2000]

In the northern part of the west African coast, south of the Canary Islands and offshore Dakhla, around 25°N, the margin shows a destructional margin architecture [Ranke et al., 1982] with a steep irregular profile and numerous slumps and slides cutting the slope surface such as the Sahara slide [Georgiopoulou et al., 2010; Wynn et al., 2000]. In the southern zone, south of 21°N and offshore Mauritania, two slides have been described by Krastel et al., [2006] and Antobreh and Krastel [2006], the Cap Blanc slide and the Mauritania slide.

Between these two zones, where instabilities are related to relatively high accumulation rates but rare triggers, [Ranke et al., 1982] described a constructional section of the margin with smooth convex/concave shape and evidences of shelf and slope progradation.

During the Dakhla cruise [2002] devoted to deep investigation of the margin on the R/V Suroit, high resolution seismic data together with swath bathymetry were additionally acquired on a relatively unknown portion of the margin, at 23°N offshore Cap Blanc and Dakhla (Fig. 1). This new data set reveals new morphologies linked to different types of sedimentary transfer processes, that are described in this paper. A scenario is proposed to link these different morphologies, with relative ages.

**GENERAL SETTINGS**

The West African margin is one of the oldest passive margins in the world: the rifting phase of this margin occurred between the late Triassic and the Early Jurassic and was followed by
oceanic spreading initiated around 195 Ma [Labails, 2007; Labails et al., 2010; Sahabi et al., 2004]. Earthquakes are rare and have been recorded in the old weakness zones created during the opening of the Atlantic Ocean [Hayes and Rabinowitz, 1975]. From Jurassic to Early Cretaceous, carbonate platforms have been constructed, followed by marine clastic infill between Cretaceous and Tertiary. Since the late Cretaceous, erosive cycles have shaped the margin [Labails, 2007; Labails et al., 2010] and a major eocene erosional surface [Labails, 2007], observed on the opposite American margin by Mountain and Tucholke, [1985], is associated to a succession of gullies and canyons perpendicular to the margin.

On the Dakhla coast (Fig. 1), the shelf-break is located at 100-200 m of water depth. Beyond, the continental slope has a width of 50-250 km [Wynn et al., 2000], and displays slope angles of 1-6°. In some areas, e.g. adjacent to the Sahara Canyon System, slope angles may reach 14°. The slope evolves to the continental rise at water depths of 1500-4000 m, with gradients decreasing from about 1° on the lower slope/upper rise, to 0.1° on the lower rise [Masson et al., 1997]. The rise is generally 100-1500 km wide and terminates at water depth of 4500-5400 m, the deep abyssal plains.

Offshore the Dakhla margin, quaternary deposits are constituted of pelagic and hemipelagic sediments [Georgiopoulou et al., 2010; Wynn et al., 2000]. This fine-grained clastic slope apron, with pelagic/hemipelagic ‘background’ sedimentation is overprinted by downslope gravity flows, shaped by along slope bottom currents [Wynn et al., 2000]. Zühlsdorff et al., [2008] showing successions of turbiditic and hemipelagic deposits in the Cap Timiris Canyon system that were correlated to the alternation of arid and humid climatic conditions. They explained that both atmospheric systems: the northerly Trade winds and the southerly African monsoon, interact with each other and with seasonal shifts: northwards during times of boreal summer (or climatically forced on larger time scales) due to Trade winds weakening and southwards when the Trade winds strengthen. The effect for western Africa is humidification
when monsoonal pattern prevails and aridification when Trade winds become stronger [Zühlsdorff et al., 2008].

Offshore Mauritania, high accumulation areas of biogenic detritus have also been observed at water depths of 1000-1500m in relation with intense upwelling activity in the area [Fischer et al., 2009; Henrich et al., 2008]. Oceanic upwelling is seasonally and spatially variable on the northwest margin [Mittelstaedt, 1991; Van Camp et al., 1991] with a major upwelling zone as seen on figure 1. The region off Cap Blanc is dominated by a persistent upwelling and strong activity of small-scale eddies, filament and jets [Karakaş et al., 2006]. The area between 26°N and 21°N shows that a permanent upwelling has been recorded since 2002 and reported by the Bulletin of Upwelling, [2015]. High sediment accumulations areas of biogenic detritus are also observed at 1000-1500 m water depths (mwd) in relation with intense upwelling activity in the area [Fischer et al., 2009].

Thus, the large open-slope landslides (>400-600 km$^3$) occurring on this continental slope (Fig. 1), like the Mauritania, Cap Blanc and Sahara Slides [Embley, 1982; Gee et al., 1999; Georgiopoulou et al., 2009; Georgiopoulou et al., 2007; Henrich et al., 2008; Krastel et al., 2006] largely consist in remobilized hemipelagic sediments [Gee et al., 1999; Krastel et al., 2006].

The Canary Islands contribute to the sedimentation by an input of volcaniclastic material by both large-scale landsliding [Wynn et al., 2002] and slow fallout through the water column into the hemipelagic sediments.

Together with the presence of these islands and seamounts, the existence of deep-water bottom currents locally influence the sedimentation pattern of this margin.

The general water mass structure of the northwest African margin includes at about 600-700 mwd the southward-flowing North Atlantic Central Water (NACW), at 2000-3800 mwd, the North Atlantic Deep Water (NADW) flowing in a southerly direction, and below 3800m, the
Antarctic Bottom Water (AABW) flowing in a northeasterly direction. These bottom currents have velocities ranging from 1 to 6 cm/s [Lonsdale, 1982; Sarnthein et al., 1982]. Oceanic upwelling is seasonally and spatially variable on the northwest margin [Mittelstaedt, 1991; Van Camp et al., 1991] (blue dashed line on Fig. 1). A major and persistent upwelling center in the region off Cap Blanc is characterized by strong activity of small-scale eddies, filament and jets [Karakaş et al., 2006] and between 26°N and 21°N a permanent upwelling has been recorded since 2002 and reported by the Bulletin of Upwelling [2015].

DATA AND METHODS

EM300

The EM300 is a multi beam swath sonar mapping system which gives a high-resolution bathymetry and an acoustic backscatter imagery. This system uses a single 30 kHz Mills Cross array and is able of swath mapping at depth ranges between 10 and 5000 m. When operated down to approximately 5000 m depth swath widths are about 5000 m. It runs with up to +/- 75° angular swath with 135 beams per ping, and features dynamically variable beam with configuration range from 1° to 4°, to achieve both high spatial resolution in deep and shallow waters. The Bathymetry of Dakhla Cruise is processed with Caraïbes software (developed by Ifremer) and have a spatial resolution better than 50 m (in water depths <2000 m).

Chirp

The Chirp is a hull-mounted sediment echosounder. The signal is characterized by a long impulse (50 ms), lineari modulated in time and frequencies. Thus, its frequency spectrum ranges 2-5.2 kHz with an average at 3.2 kHz. This frequency bandwidth allows a very high resolution (dm) in surficial layers (high frequency) and a deep penetration with the lower frequency that may reach about 100 m. 39 profiles (Fig. 1) have been recorded equivalent to
229 hours of data. For display purposes the envelope of the signal is computed and low-pass frequency filtered (2000 Hz). No automatic gain control is applied to the data, to avoid blanking features close to the seafloor reflection.

**Multichannel seismic data**

A total of 1500 km of multichannel seismic profiles (Fig. 1) were shot during the Dakhla cruise on board the N/0 Suroit in 2002 [Klingelhofer *et al.*, 2009; Labails 2007; Labails *et al.*, 2010]. The system was composed of a 4.5 km long streamer of 360 channels, with a 12.5 m group interval, which was towed at 15 m immersion. The data were sampled at 4 ms.

Two different marine seismic sources were used during the cruise. For the deep crustal targets a large (8100 in$^3$) airgun array was used in the single bubble mode consisting of 12 airguns between 250 in$^3$ and 976 in$^3$ (16 l). The airgun array was shot at a constant interval of 150 m.

Processing of the multichannel seismic data was performed using the Sispeed package. It included spherical divergence correction, FK-filtering, band-pass filtering (3-5-50-60 Hz), internal mute and dynamic corrections. The last processing steps included applying an automatic gain control and a Kirchoff migration using water or stacking velocities.

**RESULTS**

**Morpho-sedimentary structures**

The study area is characterized by a broad continental shelf, with a width ranging from 50 to 80 km and a shelf break at a water depth of 100-120 m. The swath bathymetry map of the continental slope, with a 100 m grid cell size resolution, reveals a complex seafloor morphology from the shelf break at 120 m to 3000 m (Fig. 2).
The bathymetric map (Fig. 2) shows an undulating morphology that can be described as a bulge-like structure with a large radius of curvature of around 40 km shown on the profile (ef) (Fig. 2). This undulating morphology is oriented NW-SE, perpendicular to the shoreline. Based on the slope map and the bathymetric profiles, we divide this portion of the continental slope in three sections (Fig. 2 – profile (ab):
- the first section, between 120 and 500 m water depth, is characterized by a slope angle of 5° and corresponds to the lower slope.
- the second section, between 500 and 2100 mwd, is characterized by a slope angle ranging from 2° to 4° , with a convex longitudinal shape from 1000 to 2000 (profiles ab and cd, Fig. 2) and a complex bulged shape seen on transversal profiles (ef) and (gh) (Fig. 2).
- the third section, between 2200 and 3000 mwd, is characterized by a gentle slope, less than 2°, with well-marked scarps (S1 and S2, Fig. 2). The southern part of the study area, between 2600 and 3000 mwd, is characterized by the presence of a meandering channel.

From upslope to downslope, four sea floor features are identified, on the morphobathymetric map (Fig. 3), 1) the "shallot-shaped" canyon, 2) the sea floor depressions, 3) different ridges types and 4) scarps which will be described in the following paragraphs.

**Scars**

The morphobathymetric map shows the presence of two scarps (i.e. S1 and S2, Fig. 3) that cut the downslope part respectively between 2400 and 2600 mwd and between 2100 and 2600 mwd (Fig. 3). They both show a general N-S trend, with a complex broken shape almost imbricated.
Dakhla "shallot-shaped" canyon:

This canyon deeply incises the northern portion of the studied area, between 800 and 2200 mwd (Fig. 4). This canyon, named the "shallot-shaped" canyon because of its specific shape, is globally oriented E-W and can be spitted in three sub-parts: a proximal part, a median part and a distal part.

The proximal part of the canyon runs from 800 m down to 1000 m axial depth (Fig. 4) and displays a V-shaped with a steep flank to the South (4°; 100 m-deep axial incision) and a terrace to the North (Fig. 4 profile ab).

The median part, from 1000 m to 1400 mwd (Fig. 4), corresponds to the enlargement of the incising feature reaching up to ten kilometers with smoother slope (axial incision <2°) and edges. Profiles (cd) and (ef) show a 40 m-deep axial incision.

On the distal part, from 1400 to 2200 mwd (Fig. 4), the incision narrows down to a single channel seen on profile (gh).

Ridges morphologies:

Two groups of ridges may be observed on the figure 5. The first one, from 1000 to 1300 m, is only visible on the bathymetric map (nor on the chirp profiles because of the rough weather and neither on the slope map), in the eastern part of the central bulge (5A). These small scale ridges reveal a regular morphology of 3 to 5 m high for a wavelength of 50 m, with a N30 orientation, thus oblique to the main slope (Fig. 5A).

A second group of ridges, larger and irregular, occur between 1500 and 1800 mwd. These ridges are larger, with 1-12m high with kilometric lengths (2-20 km) and spaced by 1 to 5 km. They show a perpendicular orientation to the main slope (Fig. 5A, western part).
Seafloor depressions:

Asymmetric seafloor depressions have been observed in the central part of the area around 1500 mwd (Fig. 5B). Three types of seafloor depressions have been mapped and detailed on figure 5B: 1) circular (Fig. 5 – profiles 3 and 4) with a diameter varying from 0.5 to 1 km, 2) troughs 0.5–1.5 km wide, 6–9 km long and up to 45 m deep; oblique to the slope, oriented SW/NE and 3) troughs parallel to the slope.

Echo Types classification

The studied area can be divided into several zones based on the dominant echo types. Five echo types (Fig. 6 - for location see Fig. 3) have been identified and grouped within the four main classes following the classification of Damuth [1980] and Damuth and Hayes [1977]: distinct (I), hyperbolic (II), transparent (III), indistinct (IV). Each acoustic facies is described using amplitude, lateral continuity, frequency and geometry of the sub-bottom echoes (Fig. 6).

Distinct echoes (I)

Those echo types are characterized by a distinct sharp continuous bottom echo with parallel sub-bottom reflectors. It has been further subdivided into two sub-types (Fig. 6).

Facies I-1 is a laminated facies constituted by alternation of parallel continuous thin high and low amplitude reflections up to 60 ms thick.

This facies covers a large part of the study area, from the base of the continental slope to the western most part of the area. The reflections have slightly higher amplitude than in deeper water depths, between 800 to 2200 and 2200 to 3000 mwd. This facies covers the wavy morphologies (ridges area), seafloor depressions and scarps.
Facies I-2 is similar to facies I-1 with alternation of parallel continuous thin high- and low amplitude reflectors, but is topped by a transparent upper layer (0.0025 ms), with a thick and diffuse seafloor reflector. This facies is mapped between 1600 and 2200 mwd.

Hyperbolic echoes (II)

This echo is characterized by irregular overlapping hyperbolae with chaotic sub-bottom reflections of relatively high amplitude. The signal shows slight even none sea-floor penetration (Fig. 6). It is restricted to the area of the shallot-shaped canyon.

Hard echoes (III)

It has been subdivided into two sub-types (Fig. 6)

Facies III-1 is characterized by high-amplitude reflectors with no sub-bottom echoes and/or diffuses returns on seismic profiles and a rough seafloor. It occurs on the upper continental slope and shelf break.

Facies III-2 displays hard echoes with subbottom reflectors, this echo type shows discontinuous and inclined subsurface reflectors, appearing as discontinuous patches. Facies III-2 is mainly represented on the continental shelf of our study area.

INTERPRETATION

Sedimentary structures

High-resolution multibeam and bathymetry data show a highly-complex superficial morphology described above. In order to understand the origin of those sedimentary structures, we use deep penetrating multichannel seismic profiles (Figs. 7 and 8). The seismic profile AB (Fig. 7) can be divided in two parts: the lower part, below the cretaceous reflector [Labails, 2007], displays long amplitude undulations that are related to the presence of a tectonic bulge described by several authors [e.g. Jolivet et al., 1984; Patriat and Labails, 2006]. On the other hand, the upper part of the profile AB (Fig. 7) shows undulations of the
sedimentary layers with wavelengths of about 40 km, probably related to a geological heritage with the presence of numerous canyons and interfluves (Fig. 7). This large-scale undulating morphology is locally complemented by peculiar features described in previous paragraphs: two scarps, the "shallot-shaped" canyon, the ridges and the seafloor depressions. The aim of the discussion will be to try to understand each of the sedimentary process triggering these deposit features.

The scarps morphologies

The two scarps (S1 and S2) correspond to 30-40 m steps which are observed on the seismic profile CD (Fig. 8). The seabed and shallow reflectors are separated by shallow faults or hydro-fracturing due to fluid pressure that connect to surface discontinuities (sliding surfaces; Figs. 7 and 8). The scarps morphologies have affected the continuous echoes i.e. seismic facies I-1 and I-2 (Fig. 8). According to the literature, Facies I-1 and I-2 generally correspond either to an alternations of pelagic/hemipelagic (muddy/silty) sediments or to turbidites deposits [e.g. Damuth, 1980]. The reflectors (pelagic/hemipelagic facies) that drape S1 are cut by S2 can be observed on the seismic profile (Fig. 9). This observation proves that Scarp S1 is older than S2.

Shallot-shaped canyon

The "shallot shaped" canyon (Fig. 4) corresponds in its proximal part, to a group of V-shaped incisions similar to the gullies described on other continental slope by [Twichell and Roberts, 1982]. They are issued from the shelf edge and further join together into a single canyon going downslope and finally reach the abyssal plain in its distal part. The sharp incision of the canyon (ab) does not show any sedimentary pelagic drape on the chirp profiles, The median part of the shallot-shaped canyon is characterized by an hyperbolic echo (type II, Fig. 6)
interpreted by several authors [Damuth, 1980; Jacobi, 1976] as a rough seafloor covered with coarse elements such as blocks or mass-transport deposits so-called debrites [Lee et al. 1999]. The chaotic nature of the echo in the shallot-shaped canyon suggests a high degree of sediment remobilization and thus deposition from turbidity currents or debris flows. Collapse of the canyon flanks (see Fig. 3 for location) may contribute to the widening of the channel and to the irregular deposit morphology. Following Lonergan et al., [2013], we propose that the gullies channelize turbidity currents originating from the shelf, supplying sediments downslope in relation with intermittent activity. The coarser elements are deposited in the median part (Fig. 4), while the rest flowing down evolves into turbidity currents by incorporating water and transforming its matrix into a fluid, which goes through the canyon (profile gh – Fig. 4), in the distal part of the system like the scenario described by Mulder and Alexander [2001].

No clear scar, headwall or departure zone has been identified on bathymetric data to explain mass wasting processes on the upper slope, therefore the simplest way to explain the presence of debris flow deposits would be the connection with a continental supply system with sporadic but intense and extreme events.

Turbidity current pathways where inferred in this area but not connected to permanent present day drainage system on land because of the saharian desertic climate [Wynn et al., 2000]. Thus, the origin of many submarine canyons, on this continental margin of north-west Africa between 15°N and 26°N, like Cap Timiris Canyon, are assumed to be related to a major subaerial river system that was active in the past in relation with "green sahara" periods since Plio-Pleistocene times [Antobreh and Krastel, 2006; Larrasoña et al. 2013; Vörösmarty et al., 2000]. Recent studies [McGee et al., 2013; Skonieczny et al., 2013] revealed that eolian dust fluxes varied a lot during the last 20 ka, with maximum values during Heinrich Stadial 1
and the Younger Dryas, and minimum fluxes during the end of the African Humid Period between 8 and 6 ka.

The seafloor depressions

Sea-floor depressions observed around the 1500 m isobath reveal two types of shape (Fig. 5). The circular shaped depressions may be assimilated to pockmarks features. Pockmarks are circular to elongated seafloor depressions which are often associated with fluid gas escape flow from the subsurface [Judd and Hovland, 2007]. The bright amplitudes seen on the figure 9 may correspond to hard lithology like seep carbonates which would likely be associated with gas venting [Cathles et al., 2010; Çifçi et al., 2003; Çifçi et al., 2003; Gay et al., 2006; Hovland et al., 2010; Hovland et al., 2002; Judd and Hovland, 2007]. An unconformity is observable on the seismic chirp profile (Fig.9) around 1.95 twt (s) (1500 mwd).

To explain the formation of the second type of depressions, the elongated ones (Fig. 5), we examine three hypotheses. The concentration of circular pockmarks can cause the formation of the elongated pockmarks observed at 1500 m. The Fig. 5B shows an outstanding example of the evolution of pockmarks from circular to elongated shape. The addition of two pockmarks may be observed before complete coalescence on the profile 2 (Fig. 5C) and a detailed observation show that the large pockmark (Fig. 5B) is composed of a coalescence of ten to twenty smaller depressions. This first hypothesis corresponds to groups or long chains of pockmarks described by [Hovland and Judd, 1988].

Another hypothesis is that these linear depressions reflect the surface expression of a deeper structure such as a meandering channel or a subjacent fault draped by sediment, as suggested by the third cartoon on the top of the figure 8. Meandering paleo-channels are clearly seen on the figures 3 and 5A and may explain the occurrence of some of the elongated seafloor depressions.
The dissymmetry or "en échelon" or "festooned" appearance of this succession of holes and troughs depressions have already been observed on a portion of this margin, between Cap Timiris and Nouakchott by Yang and Davies [2013]. They described troughs, either parallel or oblique to the slope dip, with elongate en-echelon plan-forms. These troughs have variable length, ranging from 0.5 to 10 km and are related to 2 types of gravity-driven faults: tear faults and normal faults. Based on 3D seismic data, these authors analysed a set of times slices with amplitude maps and suggest that the "en echelon and linear" troughs were formed as a result of multiple episode of down slope creep and have propagated through 60-140 m of sediments. These observations area in close agreement with our data, suggesting that the seafloor depressions may be assimilated to a potential rupture line and represent the surface expression of tear and/or linear faults affecting the upper sedimentary column. The location of "en echelon and linear" troughs at the slope inflexion (around 1500m) may suggest the departure zone of a sliding event.

**Ridges areas:**

The two ridges areas are observed on both sides of the sea-floor depressions area (Figs. 5). Upper slope ridges, smaller in size and presenting an oblique orientation to the slope are assimilated to sediment-wave morphology, which would be in agreement with the existence of numerous sediment-wave fields mapped in the northern part of the margin by [Wynn et al., 2000]. These morphologies are commonly reported on the continental slopes of passive margins [Faugères et al., 2002; Faugères et al., 200; Viana and Rebesco, 2007] and active margins [Lee and Chough, 2001]. The bad weather prevent any further investigation of these small ridges features on the chirp data and thus, our observations are only based on the bathymetry map.
The second group of ridges, larger in size are located from 1500 to 1800 mwd. These undulations are parallel to the bathymetry and occur just below the seafloor depressions area (Fig. 5), traducing a deformation of the superficial sedimentary cover. We suggest they may be interpreted as compressional ridges.

DISCUSSION

All those sea-floor features, pockmarks, compressive ridges and scarps, canyons, reveal the existence of sediment transfer and instability processes from upslope to downslope. Here we suggest a potential link between these specific morphologies.

According to the literature, non-random pockmarks show spatial arrangement related either to complex underlying geology or to local disturbance of the seabed, whereas random distribution of pockmarks is commonly displayed on the lower slope where sediments are generally fine-grained and tectonic structures are rare [Pilcher and Argent, 2007]. In our study area, pockmarks are arranged along a "festooned line" on a N-S direction parallel to the bathymetry. However the seismic SMT profiles (Figs. 7 and 8) do not show deep faults or tectonic structures with complex underlying geology. The only visible fault is the one displayed in the scarp S2 (Fig. 8 - cartoon 2) and it appears to shift the first three reflectors). This fault is therefore considered as superficial and might be rooted in a layer which constitutes a sliding surface (basal detachment) seen on the figure 8.

Pilcher and Argent [2007] described linear pockmark trains which are associated with listric slump faults in different cases of continental slope instability. We suggest that scarps S1 and S2 are former zones of pockmarks alignments (Fig. 10).

The "festooned line" or "en-échelon" line of coalescent pockmarks could witness a weakness zone on the slope which could evolve into a future detachment area and form a new scarp S3.
This phenomenon of high concentration of pockmarks (causing their fusion) is widely observed e.g. in the Congo Basin [Gay et al., 2006; Gay et al., 2003], Nigeria margin [Sultan et al., 2014; Wei et al., 2015] in the Northwestern Atlantic [Fader, 1991], the Ionian Sea, Greece [Hasiotis et al., 2002], the North Sea [Hovland, 1984; Hovland et al., 1987; Hovland and Sommerville, 1985] and the Mediterranean [Dimitrov and Woodside, 2003].

The occurrence of compressive ridges below the pockmarks area also evidence initiation of gravitory movement.

The main triggering mechanism for slope instability and thus gravity mass movements processes, across the NW-African continental margin, is believed to be the overload of sediment [Georgiopoulou et al., 2010; Masson et al., 2010]. Whereas, other triggers such as earthquakes, free gas, gas hydrates or diapirism are believed to be of minor importance [Georgiopoulou et al., 2010; Krastel et al., 2006].

During the late Pleistocene, the repeated slope instabilities appear as a common characteristic of NW African margin [Antobreh and Krastel, 2006; Georgiopoulou et al., 2010; 2007]. This margin has also been strongly affected by Quaternary sea-level cycles [Church and White, 2006; Wien et al., 2006]. According to Georgiopoulou et al. [2010], sea level changes appear to be important and giant slides appear to coincide with periods of deglaciation. During the latter periods, the sedimentation occurred in the vicinity of the present shore line [Georgiopoulou et al., 2010]. Thus, major sedimentary events on the northwest African margin appear coincident with glacial - to - interglacial transitions [Church and White, 2006; Georgiopoulou et al., 2010]. According to Riboulot et al. [2014; 2013; 2012], the upper-Pleistocene 100 ka cyclicity sea-level changes are the predominant driving factor of pockmark formation in the Gulf of Lions and Nigeria. On the basis of these observations, we suggest that Pleistocene sea level and sediment load associated with fluids escapes are the main process for soft-sediment deformation off Dakhla.
No core or drilling wells are available in the study area, however we propose correlations based on sea-level curves. The main goal of this correlation is to propose an age for the scarps morphologies and pockmarks formation (Fig. 10). Riboulot et al., [2013] have estimated the formation of a pockmark to last ~100 ka. Based on that assumption, we correlate morphologies with the sea-level curve from Waelbroeck et al. [2002] and propose the following chronology (Fig. 10):

- A) During the Marine Isotopic Stage MIS8 to MIS7: formation of the first generation of pockmarks caused by sedimentary load at 2600 mwd, that induced the formation of a sliding plane of the scarp 1. This scarp is draped by hemipelagic deposits;
- B) During the MIS 6 to MIS 5: formation of the second generation of pockmarks at 2200 mwd, that induced the formation of a sliding plane of the scarp 2. And folding of the hemipelagic layer.
- C) During the MIS 4-2 to MIS 1: formation and the alignment pockmarks at 1500 mwd and future scarp S3 (?). This area of pockmarks is contemporary to Sahara Slide, El Golfo / Canary Debris Flow and the Mauritania Slide [Siddall et al., 2003].

During low sea level phases, cannibalization of the shelf combined with "green sahara" periods since Plio-Pleistocene times (Larrasoña et al. 2013) induced an overload of sediment on the slope that may have favored sediment failures. The slope destabilization might also be linked to the liberation of hydrate dissociation by variation of temperature and pressure, linked to glacial/interglacial phases.
CONCLUSION

The analysis of multibeam bathymetry, high-resolution sub-bottom and seismic data on the continental slope of the off Dakhla allowed us to identify several morphologies such as shallot-shaped canyon, pockmarks, wavy morphologies and two scarps (S1 and S2). A detailed observation of these morphologies on chirp sub-bottom profiles and seismic data shows evidences rupture processes and transfer of sediments. Compressive ridges is primary linked to deformation mechanisms and creeping movements. This deformation is probably enhanced by the presence of fluids or gas associated with internal discontinuities acting as basal shear planes for creeping events. The scarps S1 and S2 indicate at least two generations of slides on this margin. We suggest that slide development was caused by rapid sea level rise after glaciation periods when sedimentation rate was maximum on the slope. This sedimentary load induced fluid or gas migrations along unconformities and superficial faults in the sediment. Fluid migration has lead to the formation and concentration of aligned pockmarks in weakness zones. These slides are believed to be 100-ka cycle events controlled by sea level variations during the second half of the quaternary period.

However, more regional studies using high resolution but deeper seismic penetration are needed in the area as well as coring and geotechnical studies to fully assess the timing of the events, the existence of gas hydrates and to determine whether creeping is still active today.

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Imbert and the editor O. Lacombe are thanks for their fruitful comments that helped us to improve this paper.
REFERENCES


FIGURE CAPTIONS:

Figure 1: Bathymetry and global relief map from [Smith and Sandwell, 1997] (Mercator projection, WGS84) of the NW Africa margin showing the study area (Dakhla zone) and the main morphologic features, described in literature like slides and debris flows (with a color code depending on authors), canyon and channel systems and the upwelling location of NW Africa. A green line underlines the isobath 1500 m. Insert box shows the profiles (seismic and bathymetry) position retrieved during the Daklha cruise.

Figure 2: Bathymetric map of the offshore Dakhla from SIMRAD EM300 acquired during the Dakhla cruise and Slope-gradient (in degrees) map calculated from the bathymetry data. A synthetic bathymetric profiles shows the global morphology of the continental slope from upperslope (- 80 m) downslope (- 3000m).

Figure 3: Morphobathymetric interpretation on shaded relief map showing the main morphological features and echo-character mapping showing the distribution of the different echo types (see Figure 6) in the study area. Dakhla canyon is shown (in yellow), ridges areas, the depressions shown (in dark blue) on the mid-slope, scarps S1 and S2 (in read) on the lower slope and a meandering canyon is still visible on the south western part.

Figure 4: Detailed bathymetric map of the Dakhla shallot-shaped canyon. The Dakhla canyon is divided into 3 parts: the "proximal part" upslope which groups several incisions, the "median part" which shows the enlarged part of the structure and the "distal part" which channelises turbidites issued from the median part. The bathymetric profile (ab) across the proximal part shows the sharp incision. Bathymetric profiles (cd) and (ef) across the median
part show the large morphology of incision. Bathymetric profile (gh) across distal part shows
the main enlarged canyon downslope.

**Figure 5:** Focus on the mid-slope area with the wavy morphologies (ridges) and depressions.
(B) Shaded relief map showing the examples of the evolution of depression (pockmarks) from
a circular to an elongated giant shape. Synthetic bathymetric profiles (1, 2, 3 and 4) show the
different bathymetric sections on 1) the wavy morphologies (ridges) 2) the combining two
depressions (pockmarks) ; 3) a circular depression (isolated pockmark), 4) elongated
depressions (giant pockmarks).

**Figure 6:** List of the main chirp "echo types" described in the investigated area: distinct
echoes (I) with facies I-1 and I-2, hyperbolic echoes (II) and Hard echoes (III) with facies III-
1 and facies III-2. The description of the echo and the area where it occurs are detailed in the
main text.

**Figure 7:** Dakhla seismic profile (AB profile) and interpretation showing the global
morphology of the continental slope and the main sedimentary layers (main surfaces; top
Jurassic, Cretaceous surfaces and Eocene surface [Labails, 2007]. The seismic profile shows
significant seismic undulations of the sedimentary layers parallel to the seabed (location of
the seismic profile AB on figure 1).

**Figure 8:** Dakhla seismic profile (CD profile) and interpretation showing the global
morphology of the continental slope and the main surface sedimentary layers (main surfaces;
top Jurassic, Cretaceous surfaces and Eocene surface in [Labails, 2007]. Seismic profile across
scarp S1, scarp S2 and depressions. Insert box shows (Chirp subbottom seismic) profiles
across the scarp S1, scarp S2 and depressions. The seismic profile shows significant bulge of
the basement (location of the seismic profile CD on figure 1).

Figure 9: The chirp profiles P02 and interpretation (location on figure 5A) shows the
seafloor depression and bright spots in this depression and overpressure ridges. The
uncomformity surface truncates the subjacent reflectors and is recovered by parallele
reflectors.

Figure 10: Schematic illustration of the influence of pockmarks on seafloor stability and
relationship with sea-level [Sea-level curve from Waelbroeck et al., 2002]. The model is
based on seismic profiles and bathymetry interpretation, A): formation and the alignment
pockmarks at 2600 mwd during stage MIS 8 then sliding (scarp 1) event during stage MIS 7.
B): formation and the alignment pockmarks, at 2200 mwd during stage MIS 6 then sliding
during stage MIS 5 (scarp 2); C) (MIS 2 to 0) : formation and the alignment pockmarks at
1500 mwd during stage MIS 2 and probable future sliding (S3).
Figure 4
Figure 5
<table>
<thead>
<tr>
<th>Type</th>
<th>Type - Example</th>
<th>Zone</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>distinct echoes (I)</td>
<td></td>
<td>base continental slope and large part of the studied area</td>
<td>continuous and parallel reflectors of high amplitude and medium frequency</td>
</tr>
<tr>
<td>facies I.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>facies I.2</td>
<td></td>
<td>continental slope between 1600 and 2200</td>
<td>continuous and parallel reflectors with a transparent thin upper layer</td>
</tr>
<tr>
<td>hyperbolic echoes (II)</td>
<td></td>
<td>mass transport deposits &quot;troughs and holes&quot;</td>
<td>is characterised by dense irregular overlapping hyperbolae</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hard echoes (III)</td>
<td></td>
<td>upper continental slope</td>
<td>Hard facies is characterised by a dark surface reflector, with few or no sub-bottom reflectors</td>
</tr>
<tr>
<td>facies III.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>facies III.2</td>
<td></td>
<td>continental shelf</td>
<td>Hard subsurface with oblique reflectors (bed rock)</td>
</tr>
</tbody>
</table>

Figure 6
Figure 7
Figure 9
Figure 10

MIS8 ← A → MIS7 (slide 1)

(a) sediment load
-linear pockmarks (1)
fluid escape
overpressure ridges

(b) hemipelagic drape

(c) meandering channel
listric faults

MIS6 ← B → MIS5 (slide 1)

(a) linear pockmarks (2)
unconformity

(b) scarp S1

(c) scarp S1
meandering channel

MIS2 ← C → at present

water depth (m)

shallot-shaped canyon
-linear pockmarks (3)

scarp S2

scarp S1
overpressure ridges

Relative sea level (m)

-150 -100 -50 0 50 100 150 200 250

MIS2
MIS4
MIS6
MIS8

N 23°
N 22° 20
N 22° 40
W 17° 20
W 17° 40
W 18° 20
W 18°

40 km