Chapter 17

Large-Scale Mass Wasting on the Northwest African Continental Margin: Some General Implications for Mass Wasting on Passive Continental Margins

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Abstract The continental margin off Northwest Africa is shaped by a complex interplay of sediment transport processes, directed both downslope and alongslope. During several recent cruises, sediment transport processes between 12°N and 29°N off Senegal, Mauritania, and Western Sahara were investigated by means of geophysical and sedimentological methods. Sediment transport on the Northwest African continental margin operates with different rates and styles: some sections of the margin show a large concentration of upper slope canyons but no indication for significant mass wasting, whereas other sections are characterized by large-scale mass wasting with no canyons or gullies. Four mega-slides, each affecting over 20,000 km^2 of seafloor, have been identified along the continental slope off Northwest Africa. All slides are complex in morphology and show a stepped headwall pattern typical for retrogressive failure. Several buried mass transport deposits are seismically imaged beneath all near-surface slides indicating a long history of mass wasting for some sections of the margin. Two of the mega-slides show headwalls at atypically large water depths, deeper than 3,000 m.

Keywords Submarine landslides • Canyons • Geohazards • Acoustic imaging

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17.1 Introduction

The passive continental margin off Northwest Africa (south of 26°N) is characterized by low sediment supply by rivers, even during glacial times, but high primary productivity caused by oceanic upwelling results in relatively high sedimentation rates exceeding 10 cm/ka in places (Martinez et al. 1999; Weaver et al. 2000). In addition, the margin is characterized by significant dust import from the Sahara desert (Sarnthein and Koopmann 1980). The margin shows several large-scale landslides and numerous canyon/channel systems (Weaver et al. 2000). Acoustic imaging off Northwest Africa began more than 30 years ago; the first maps showing the distribution of seafloor features were published by Jacobi (1976) and Jacobi and Hayes (1992). Updates of these maps were presented by Wynn et al. (2000), Weaver et al. (2000), and Krastel et al. (2006).

This study presents a new map covering the African margin from Senegal to the Canary Islands (Fig. 17.1). New geophysical and sedimentological data allowed the area off Senegal to be included in these maps for the first time; several other seafloor features (e.g.,off Cap Blanc, headwall area of the Sahara Slide, see Fig. 17.1) are characterized in more detail. We combine the work of previous studies with these new data in order to discuss sediment transport processes and potential geohazards off Northwest Africa, and finish by drawing some general conclusions for mass wasting at passive margins.

17.2 Results and Interpretations

The new map (Fig. 17.1) covers an area from 12°N to 29°N, showing numerous seafloor features mainly generated by turbidity currents and landslides. Most of the features are interpreted from acoustic data collected during a variety of research cruises during the last 10 years. Where new data do not exist, features were adopted from a map covering the entire Northwest African margin published by Wynn et al. (2000). The new map shows four major landslides and numerous canyon/channel systems. Slide margins are marked “inferred” if data coverage is too sparse for a robust reconstruction.

17.2.1 Sahara Slide

The Sahara slide is a mega-slide with a run-out distance of 900 km and an estimated volume of 600 km^3 (Embley 1976; Masson et al. 1993; Gee et al. 1999; Georgiopoulou et al. 2010). The Sahara slide is a complex landslide, comprising elements of translational sliding as well as debris flow. The headwall area is located at ~1,900 m water depth. Bathymetric data show two major headwalls, each about 100 m high (Fig. 17.2).

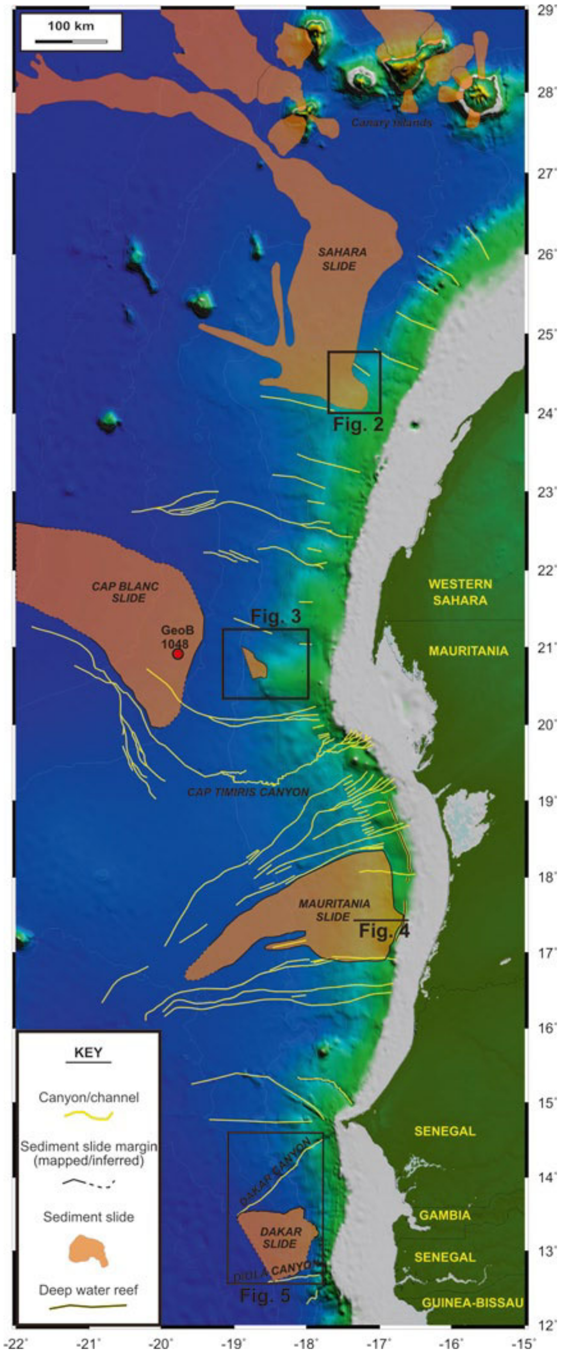

Fig. 17.1 Map showing the distribution of sea-floor features on the Northwest African continental margin. Volcanic landslides around the Canary Islands are shown but not discussed in this manuscript (Some features adopted from Wynn et al. 2000)

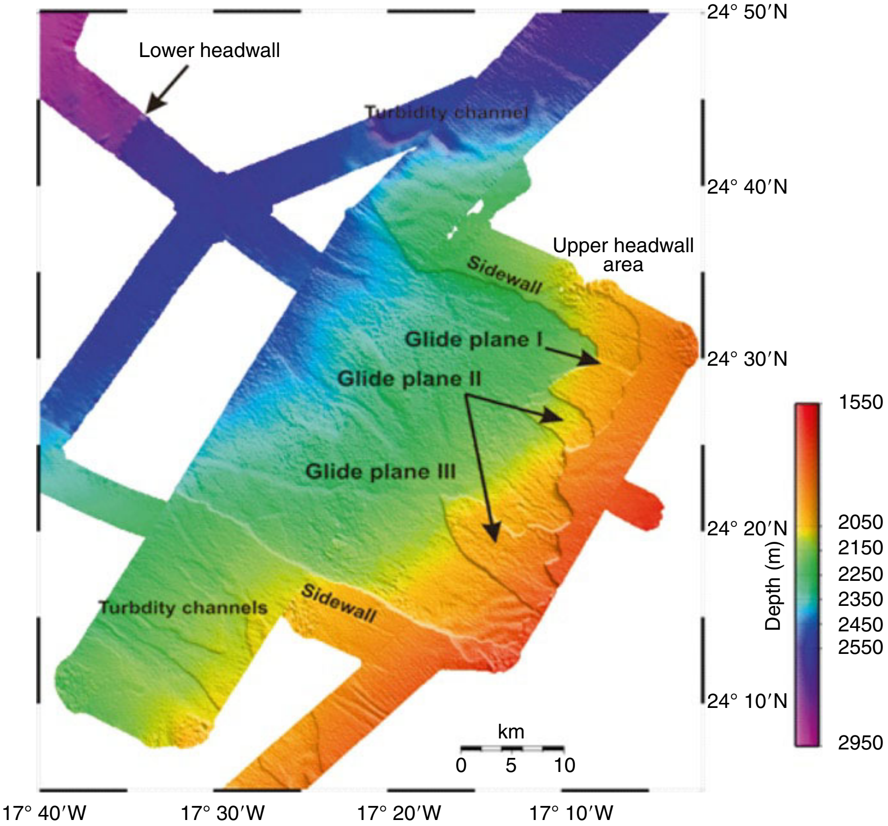

Fig. 17.2 Bathymetric map showing the headwall area of the Sahara Slide. See Fig. 17.1 for location of image

Detailed images of the upper headwall (Fig. 17.2) reveal a complex morphology typical for a retrogressive slab-type failure, with multiple headwall incisions and at least three levels of glide planes (Fig. 17.2). The evolution of the Sahara slide on its way downslope is summarized by Georgiopoulou et al. (2010). The initial failure rapidly disintegrated and transformed into a debris flow. While passing close to the Canary Islands, the debris flow incorporated volcaniclastic sand from the substrate, forming a two-phase flow structure: a pelagic debris flow phase that was carried on top of a basal volcaniclastic debris flow phase. Gee et al. (1999) suggested that the volcaniclastic debris flow phase acted as a low friction layer, thereby explaining the unusually long run-out distance of the Sahara slide. The age of the main slide event is estimated to be ~60 ka, occurring during rapid sea-level rise after a significant lowstand (Gee et al. 1999). However, Georgiopoulou et al. (2009) also presented evidence for late Holocene reactivation of the headwall. Multiple buried events beneath the present-day headwall suggest large-scale mass wasting in the area of the Sahara slide since at least Miocene times (Georgiopoulou et al. 2007).

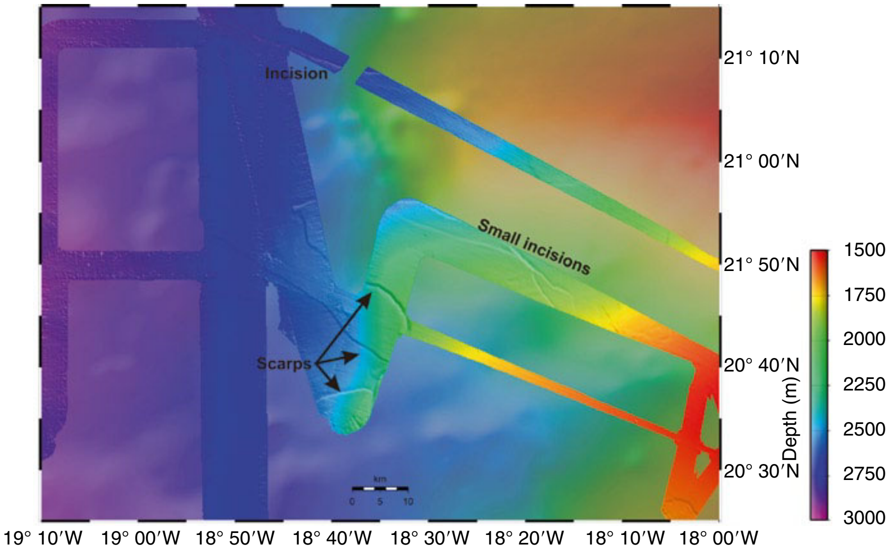

Fig. 17.3 Bathymetric map off Cap Blanc showing a relatively small headwall scarp. The large Cap Blanc Slide originates further downslope. See Fig. 17.1 for location of image

17.2.2 Cap Blanc Slide

A very large mass transport deposit off Cap Blanc (called Cap Blanc slide, Fig. 17.1) is bounded by a 25 m-high headwall at ~3,575 m water depth, on a slope angle of ~0.4° (Krastel et al. 2006). The margins of the Cap Blanc slide are only visible at specific locations (solid lines on Fig. 17.1) but, taking all data into account, a slide area exceeding 40,000 km^2 and a slide width of ~175 km can be reconstructed. Acoustic data show a drape of several meters on top of slide deposits. The boundary between undisturbed and slide sediments occurs at a depth of 686 cm in core GeoB1048, recovered from within the slide area (see Fig. 17.1 for location of core). Undisturbed sediments immediately on top of the highly deformed slide deposits are dated at 165 ka by correlating the $CaCO_3$ curve from the pelagic sequence with that from an oxygen isotope-dated core outside of the slide scar (Krastel et al. 2006). 165 ka is the minimum age of the slide corresponding to a sea-level lowstand.

Jacobi and Hayes (1992) also mapped a series of slides off Cap Blanc originating further upslope, at ~2,000 m water depth. This observation is only partly confirmed by new data. Bathymetric data show numerous small incisions and canyons as well as some local <50 m-high scarps at ~2,000 m water depth (Fig. 17.3). The volume of the evacuated area surrounded by the scarps shown on Fig. 17.3 is difficult to reconstruct due to incomplete bathymetric coverage but the lateral extent of the evacuated area is less than 400 km^2 and the thickness of the missing sedimentary succession is

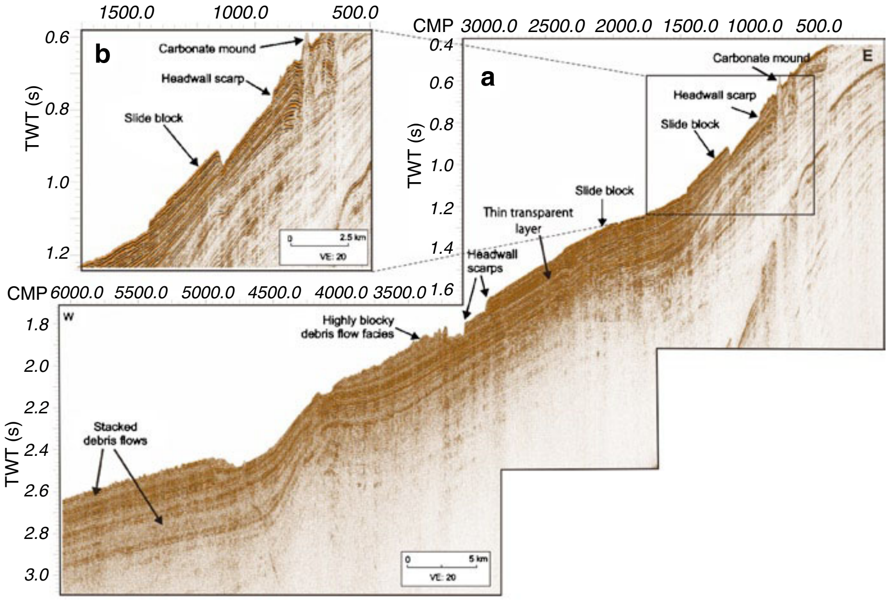

Fig. 17.4 (**a**) Seismic profile crossing the headwall area and the main depositional area of the Mauritania Slide Complex. (**b**) Enlargement of the headwall area (Modified after Antobreh and Krastel 2007). See Fig. 17.1 for location of profile

at most 50 m. Hence 20 km^3 is the maximum volume and therefore significantly smaller compared to the large-scale slides at this margin, which all have volumes exceeding 100 km^3.

17.2.3 Mauritania Slide Complex

The Mauritania Slide Complex was first discovered by Seibold and Hinz (1974) and subsequently mapped and described by Jacobi (1976). This slide was investigated in detail by acoustic methods and sediment coring (Antobreh and Krastel 2007; Henrich et al. 2008; Förster et al. 2010). The slide has affected an area of ~30,000 km^2 (Fig. 17.1); the estimated volume of the deposits is 400–600 km^3. The headwall scarps commonly occur as a series of steps ranging between 25 and 100 m high, between 600 and 2,000 m water depths (Fig. 17.4). A chain of deep-water reef mounds is found immediately upslope of the headwall scarps (Colman et al. 2005). The area beneath the headwall scarps is characterized by blocky debris, while thick tongue-shaped debris flows with relatively smooth surfaces dominate the lower (depositional) area (Fig. 17.4). The uppermost debris unit is dated at 10.5–10.9 ka (Henrich et al. 2008), which occurred at the end of Last Glacial Maximum

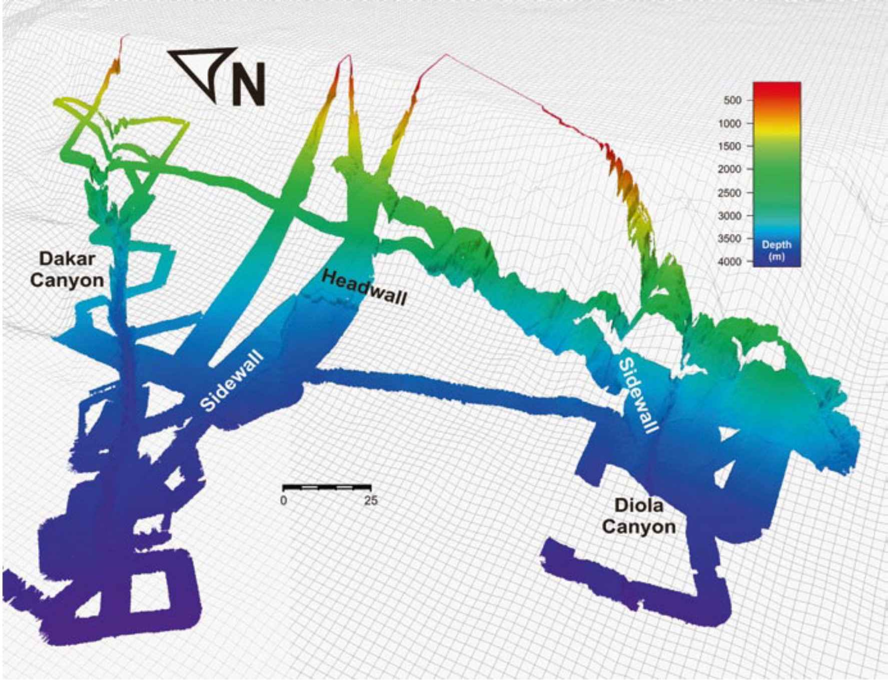

Fig. 17.5 3D-perspective view of the Dakar slide. See Fig. 17.1 for location of image

sea-level rise. Förster et al. (2010) suggest an additional slide, dated at <24 ka, occurred during the glacial lowstand. Seismic data show several buried slide units, indicating a long history of instability on this part of the margin.

17.2.4 Dakar Slide

Dakar slide, located off southern Senegal, is described in detail by Meyer et al. (2012) so only a brief description is given here. The headwall occurs at a water depth of 3,100–3,400 m; no indications for mass wasting are found on the upper or middle continental slope (Fig. 17.1). Slope gradients in the headwall area are as low as 1°. Dakar slide is bounded by two major canyons: Dakar Canyon to the north and Diola Canyon to the south (Fig. 17.5). The full extent of Dakar Slide is not yet mapped, but a clearly visible sidewall runs from the northern edge of the headwall for about 90 km to the Dakar Canyon, which seems to be locally destroyed by the slide (Fig. 17.5). The age of Dakar slide is currently unknown, but a 50 m thick hemipelagic drape suggests a minimum age of 1 Ma. Multiple large-scale mass wasting deposits, reaching back to Miocene times, are found beneath the youngest deposits (Meyer et al. 2012).

17.3 Discussion

17.3.1 Mass Wasting Off Northwest Africa: Where and Why?

Extensive areas of the NW African continental margin are dominated by large-scale mass wasting, although some sections show a concentration of upper slope canyons with no indication for widespread failures (Fig. 17.1). Similar distributions of canyons and slides are found at other passive margins, e.g., along the U.S. Atlantic continental margin (Twichell et al. 2009). It remains unclear why only specific sections of the margin off NW Africa show repeated failure. Jacobi (1976) suggested that earthquakes associated with fracture zones might play a role, but comprehensive analyses of the earthquake history are not available for this region. High sediment accumulation rates caused by upwelling definitely play a key role as a pre-conditioning factor. Rapid sediment build-up leads to sediment instabilities arising primarily from underconsolidation of deposited sediments and widespread lithological weak layers (Antobreh and Krastel 2007). In this context it is interesting to analyze the role of upper slope canyons and gullies. Canyons off NW Africa represent an important pathway for downslope sediment transport (Hanebuth and Henrich 2009; Henrich et al. 2010; Pierau et al. 2010); however, large submarine slides are preferably found in regions with no major canyons. There is no evidence that canyons are destroyed by slides, i.e. no prominent canyons are found upslope of slide headwalls or buried beneath slide sediments. Some slides are actually bounded by major canyons (Fig. 17.1). Hence we believe that canyons represent an effective pathway for regular downslope sediment transport by turbidity currents, evacuating sediments away from the slope, while the areas without canyons become increasingly burdened by deposition of thick sedimentary successions (Masson et al. 2010). Infrequent triggers, especially the lack of regular earthquakes, result in long periods of undisturbed sediment accumulation; these thick sedimentary packages occasionally fail as large slides.

Two of the slides off NW Africa originate at water depths >3,000 m on slope angles around 1° or less. These water depths are unusually large compared to other slides along Atlantic margins, which typically originate in water depths of 800–2,500 m (Hühnerbach et al. 2004; Twichell et al. 2009). For the Cap Blanc region, the continental rise shows high sedimentation rates because filaments of cold upwelling water can locally extend for hundreds of kilometres offshore (van Camp et al. 1991). We assume that such a depocenter controls the location of Cap Blanc slide, whereas the location of Dakar slide is probably controlled by canyon systems bounding the slide and turbidity channels above the central slide (Meyer et al. 2012).

All sections of the NW African margin that are affected by mass wasting show a long history of mass wasting. Sediments deposited above buried scarps are potentially unstable. For the Sahara slide, Georgiopoulou et al. (2007) suggest that differential compaction across bounding escarpments generates compaction hinges, leading to oversteepening and excess pore pressure. A similar process is suggested by Alves and Cartwright (2010) for a slide area offshore Brazil. They show that differential compaction along landslide strata can control depositional systems well after generation of the initial slide event. In addition, landslide scars form depressions where rapid deposition of contourites may occur. It is well known, that excess pore pressure may develop within contourite units that are sandwiched between impermeable horizons (Laberg and Camerlenghi 2008), thus further promoting differential compaction. The causes of initial failure in the sections affected by mass wasting offshore NW Africa remain unclear, but successive failures seem to be controlled by differential compaction across previous landslide scarps, thereby explaining the long history of mass wasting for some sections of the margin.

17.3.2 Timing of Landslides and Geohazard Potential

It is important to assess the geohazard potential related to submarine mass wasting off NW Africa, especially as the area offshore Mauritania is a current focus for hydrocarbon exploration and production (Colman et al. 2005). No age information are available for the Dakar slide but all other slides occurred during periods of low or rising sea level. Direct linkage between sea level and slide occurrence in this region is not well understood, but indirect effects include spatial variations in primary productivity and hence the maximum sedimentation rate (Georgiopoulou et al. 2010). The probability of future large-scale slope failures during the current highstand is generally considered to be low. However, our new data indicate a relatively recent (<2 ka) large-scale reactivation of the Sahara slide headwall (Georgiopoulou et al. 2009), which needs to be considered for future risk assessments.

Despite the relatively low probability of voluminous mass wasting off NW Africa in the near future, we also discuss the tsunami potential of such slides. Volume and initial acceleration are considered as the most important parameters influencing tsunamigenesis, but other factors (e.g., flow dynamics, water depth, velocity, length, thickness) may also be important (Harbitz et al. 2006). Both Dakar and Cap Blanc slides occur in deep water on gentle slope; it is very unlikely that they reached high velocities and triggered a tsunami. Georgiopoulou et al. (2010) concluded that the Sahara slide was a slow-moving slide, as the absence of a related turbidite indicates that the slide was not moving sufficiently quickly to generate shear mixing between the slide and the overlying water. In addition, the relatively large water depth of 1,900 m in the headwall area is also not in favour for generating a tsunami. The water depth of 600–1,500 m in the headwall region of the Mauritania slide is more typical for landslide-generated tsunamis. The initial acceleration of the Mauritania slide is unknown but a turbidite containing shelf sands, deposited immediately above the slide deposits, might indicate mobilization of shelf sands by a tsunami (Krastel et al. 2006; Henrich et al. 2008).

17.4 Conclusions

The NW African continental margin is characterized by large-scale but infrequent mass wasting. Mass wasting off NW Africa is a geohazard but the probability for major events in the near future is low. New acoustic data allow us to draw several conclusions for mass wasting off NW Africa, which might be relevant for other passive margin settings: (i) Open slope areas without major incisions allow rapid and undisturbed sediment accumulation beneath zones of high primary productivity, which in turn leads to sediment instabilities arising primarily from underconsolidation of deposited sediments and widespread lithological weak layers. In contrast, canyons and gullies act as effective pathways for regular downslope sediment transport by turbidity currents, preventing extensive slope failure. (ii) Vertical stacking of mass wasting events suggests that sediments deposited above buried scarps are potentially unstable. (iii) The large size of the slides off NW Africa is caused by high sedimentation rates but infrequent triggers, with all major slides in the last 200 ka occurring during sea-level lowstands or periods of sea-level rise. (iv) Mega-slide headwalls at water depths >3,000 m on the Northwest African continental margin expand the known depth range of large-scale North Atlantic slides.

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