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# Analysis of past seafloor failures on the continental slope off Nice (SE France)

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**Abstract** Three types of failure are present on the continental slope off Nice: superficial slumping, deep-seated failure, and gullying of the canyon walls. Only deep-seated failures displace large sediment volumes and represent an important geological hazard. Triggering mechanisms for failure are variable and include earthquake loading, undercutting, and increasing pore pressure through sediment loading. A combination of failure type, depositional setting, and triggering mechanism suggests six different failure scenarios that have to be taken into account if geotechnical modeling is to reproduce the variability and pattern of seafloor failure of Nice.

## Introduction

Mass wasting processes are common phenomena on submarine slopes in general and the continental slope in particular. They may involve a variety of processes ranging from sediment creep to turbidity currents (e.g., Nardin et al. 1979; Mulder and Cochonat 1996). As a consequence, submarine slopes have to be considered unstable on geological time scales. Increasing economic activity on the continental slope, however, has also increased the need for a better understanding of sediment failure and mass wasting processes in order to predict future events that might occur on human time scales and affect coastal installations or anthropogenic structures on the seafloor. Unfortunately, due to the nonperennial nature of failure events, direct observations and/or measurements of these processes are generally not possible. Indirect observation and geotechnical modeling are therefore commonly used in slope stability studies. A geotechnical approach uses shear strength measurements and infinite slope analysis in order to determine the safety factor of a given deposit (Skempton 1964; Almagor and Wiseman 1977; Karlsrud and Edgers 1982; Lee and Edwards 1986). Such an approach is generally limited by the spatial distribution of sediment cores and/or in-situ measurements and restricted to the uppermost sediments that are accessible by sediment gravity cores. A geological approach, on the other hand, tries to reconstruct the history of a given area in order to use the magnitude, frequency, and distribution of past failure events for predictions about future events (Bugge et al. 1987; Prior et al. 1987). The two approaches have to be used together for a thorough understanding of geohazards in a given area, although, this is rarely done.

In the Baie des Anges on the continental slope off Nice, SE France (Fig. 1), the geotechnical approach has been used in the past based on many short piston cores and in-situ measurements (Mulder 1992; Schieb 1992; Mulder et al. 1992, 1994; Cochonat et al. 1993) resulting in a synthetic regional map of offshore hazards (Fig. 2). In this paper, we present acoustic data (side-scan sonar imagery, multibeam bathymetry, and high-resolution seismic profiling) that allow us to distinguish several types of seafloor failure based on their geometry, size, triggering mechanism, and the depositional environment in which they occur. We will show that seafloor failure is widespread in the area, affecting almost any kind of deposit and, thus, confirming the results of previous geotechnical modeling. However, at the scale of the individual failure event, important differences occur, underlining the necessity for more detailed geotechnical data in order to choose the appropriate model of soil mechanics to model the event.

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## Geological setting and previous work

The continental slope off Nice is characterized by a very narrow shelf, generally less than a few kilometers wide,

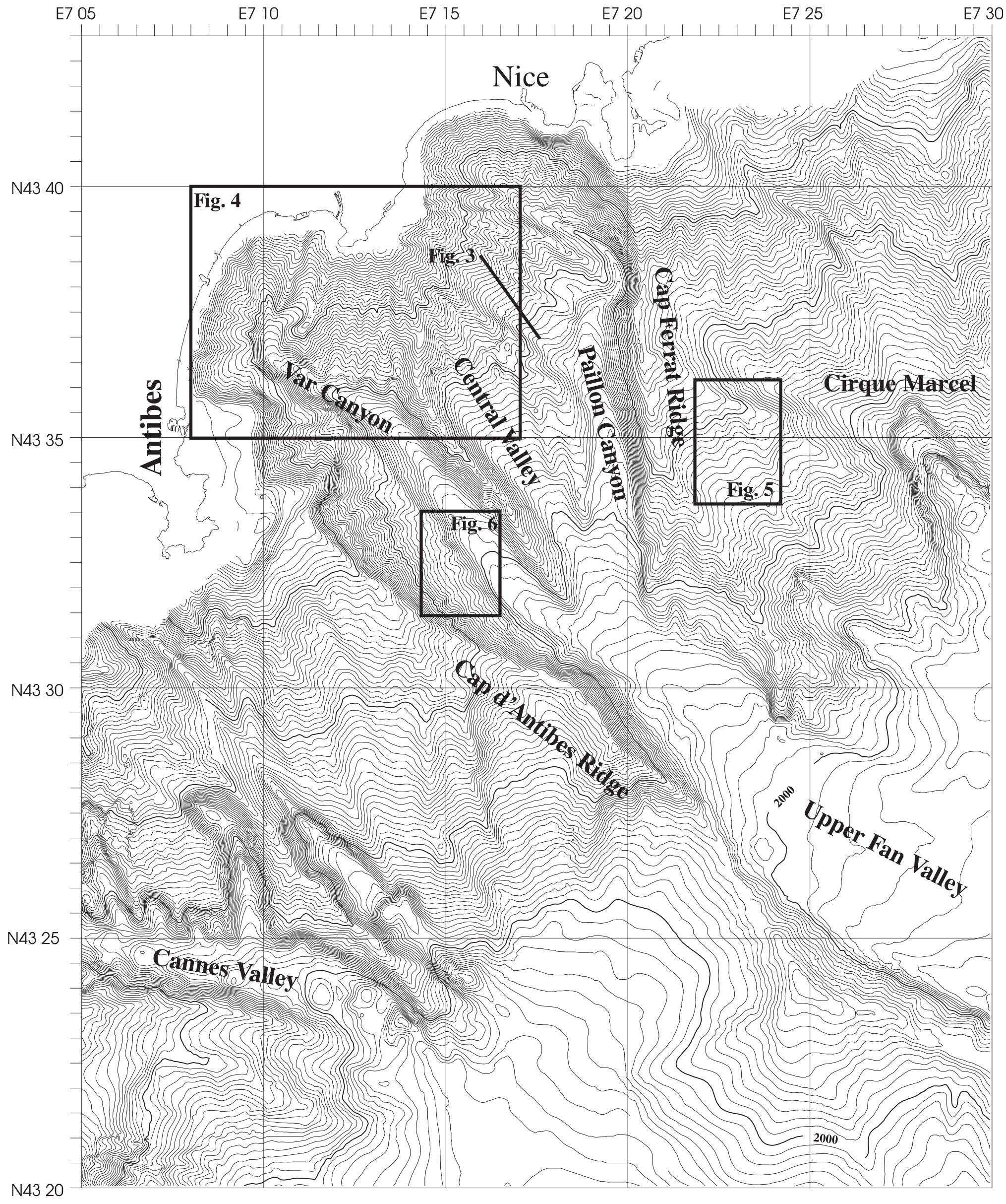


**Fig. 1** Bathymetric chart of the continental slope off Nice showing major physiographic features mentioned in the text. Depth contours are at 25 m intervals with major isobaths (bold) at 500 m intervals

and a steep continental slope, having an average gradient of more than 11° (Fig. 1). The slope is deeply eroded and dissected by several canyons, of which the Var and Paillon Canyons are the most important (Pautot 1981). Both canyons are directly connected to the Var and Paillon Rivers and coalesce downslope to form the Upper Fan Valley of the Var Submarine Fan (Savoye et al. 1993). The canyons are bound by two prominent ridges that delimit the Baie des Anges offshore: the Cap d'Antibes Ridge in the west and the Cap Ferrat Ridge in the east.

Early observation of turbidity-current activity in the Var Canyon led to the idea that portions of the seafloor in the Baie des Anges are unstable (Gennesseaux 1962), but major interest in the area has been triggered by a submarine landslide in 1979 that affected parts of Nice International Airport and generated a turbidity current that broke two telecommunication cables further offshore (Gennesseaux et al. 1980). Subsequent studies investigated the pathway of this particular event (Malinverno et al. 1988) or tried to establish the causes of failure. Studies of the consolidation state of superficial sediments from sediment cores and in-situ measurements (Schieb 1992; Cochonat et al. 1993) concluded that major portions of the uppermost continental slope and the Cap d'Antibes Ridge are unstable because of the underconsolidated nature of the sediments. However, deposits on most of the ridges are overconsolidated, interpreted as being the result of erosion related to failure of the overlying sediments (Mulder et al. 1992; Cochonat et al. 1993). The average thickness of missing overburden on the Central Ridge has been calculated to be 7 m and is considered to be the mean thickness of sediment failure in that area. Based on the regional

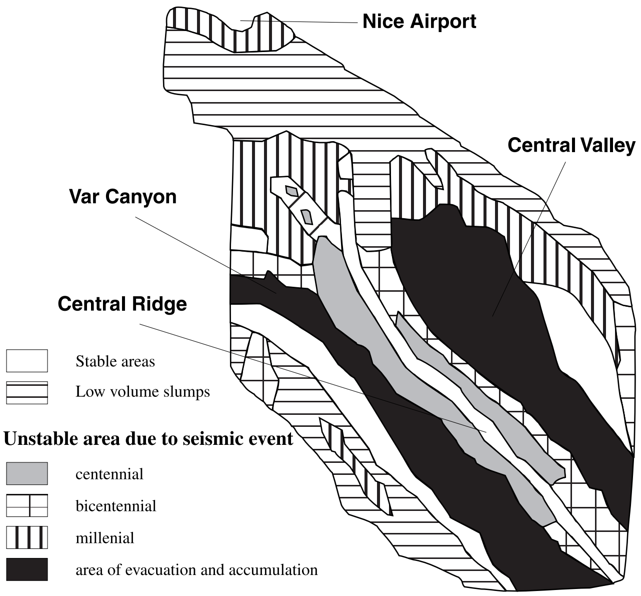


**Fig. 2** Synthetic regional map of offshore hazards in the Baie des Anges (redrawn from Mulder et al. 1994, Fig. 14)

distribution of the consolidation state of the surficial sediments, local slope gradient and shear stress due to earthquake loading, Mulder et al. (1994) determined safety factors. These authors compiled a synthetic map of offshore hazards (Fig. 2), indicating that only a few areas can be considered stable and that most areas are prone to failure, especially considering the steep slopes and seismic activity in the area. However, verification of this analysis in light of the geological record has not been carried out prior to the present study.

## Materials and methods

The present study is the result of a detailed geomorphologic and sedimentologic investigation of the seafloor off Nice based on deep-towed side-scan sonar imagery and 3.5-kHz profiles, collected during the SAME1 cruise in 1986 with the French SAR (Système Acoustique Remorqué) system. The SAR data have been reprocessed recently and a mosaic has been generated allowing the identification of slump scars and other erosional features on the continental slope. Uncertainties in the correct positioning of the tow-fish have been overcome by careful comparison of the side-scan sonar imagery and multibeam bathymetry data (SeaBeam and EM12d), including high-resolution data (Simrad EM1000) of the uppermost continental slope less than 1000 m deep. However, due to relatively uniform surficial sediments and a lack of clearly defined geomorphic features (in particular on the Cap Ferrat Ridge), the exact location of many of the slump scars is still problematic and will make further (more detailed) investigation difficult. The surface extent of the scars, as seen on sonographs, together with the thickness of failed sediment (estimated from 3.5-kHz profiles), provided a rough estimate of the volume of sediment involved in the events. On the uppermost slope, multibeam bathymetry data allowed direct determination of the size and depth of slump scars, as well as the volume of failed sediment. In addition, numerous sediment cores, in-situ measurements and submersible observations have been used to calibrate the acoustic data and to determine the general distribution of superficial sediments.

## Types of failure events

Detailed analysis of side-scan sonar imagery, 3.5-kHz profiles and multibeam bathymetry allowed to distinguish three types of sediment failure. These include superficial slumping, deep-seated failure (often associated with successive rotational slides), and gullying of the canyon walls.

### Superficial slumping

This type of sediment movement is restricted to the uppermost layer of sediments. It generally involves only the most superficial sediments and occurs in areas of relatively low slope gradients (1:20), such as the broad central valleys within the Baie des Anges and on the Cap Ferrat Ridge. In plan view, these slump scars are ellipsoidal with a more or less well-defined neck and generally are associated with a well-defined, erosive flow path (Fig. 3). This path may be up to 2 km long and is generally about as wide as the initial slump scar. There are no indications for deposition at the end of the path. In some cases on the Cap Ferrat Ridge, only the flow path could be clearly identified on the side-scan sonar imagery. The surface extent of this type of mass wasting, as indicated on side-scan sonar images, is less than 20,000 $m^2$ (Fig. 3A) and depth of failure less than 10 m (Fig. 3B), resulting in total volumes of slumped sediment of less than 200,000 $m^3$.

### Deep-seated failure

Slump scars of this type appear in various ways on the data sets. First, they appear on multibeam bathymetry data, where they are underlined by sudden increases in slope gradient of the chutes on the uppermost continental slope (Fig. 4). Side-scan sonar data are not available for this area and slumps scars are defined only morphologically. The slump scars are up to 35 m deep and most are amphitheater-shaped. As the chutes on the uppermost continental slope are not connected to direct input of sediment (rivers), they must have been carved by sediment gravity flows resulting from failure on the slope itself. These sediment gravity flows are highly

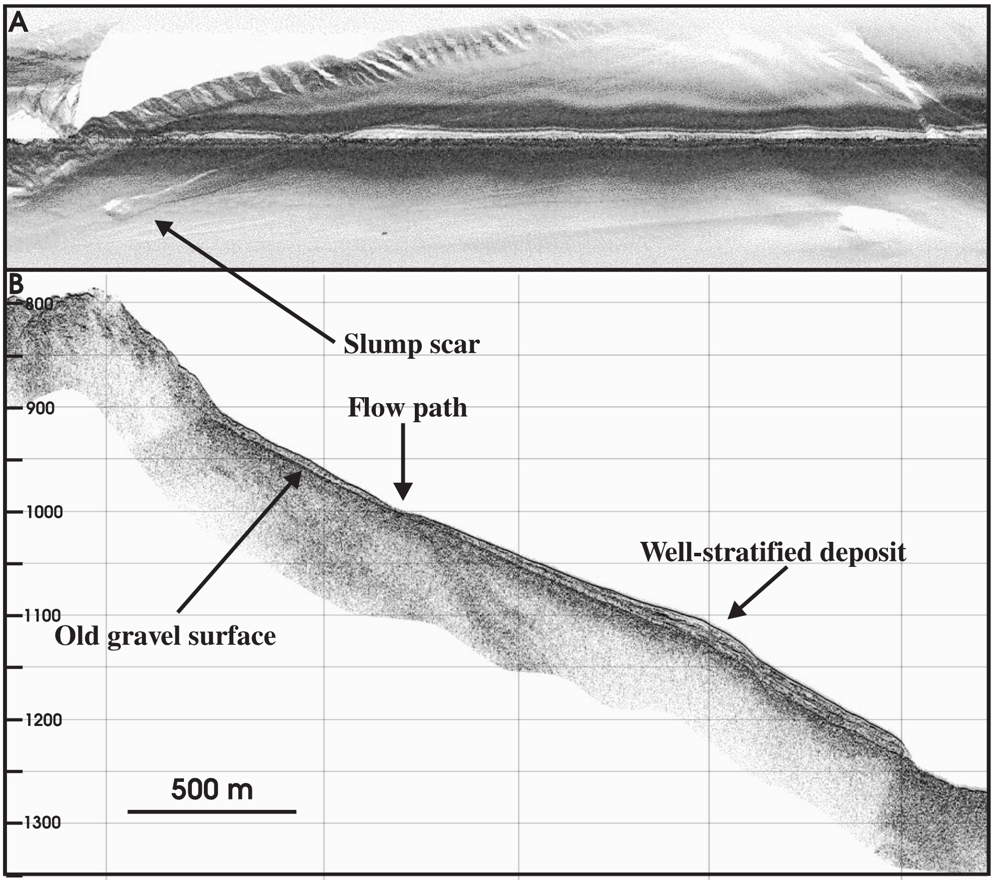


**Fig. 3** Side-scan sonar imagery and associated 3.5-kHz profile illustrating an example of a superficial sediment slide. Failure occurs in well-stratified sediments overlying an older gravel surface. For profile location see Fig. 1

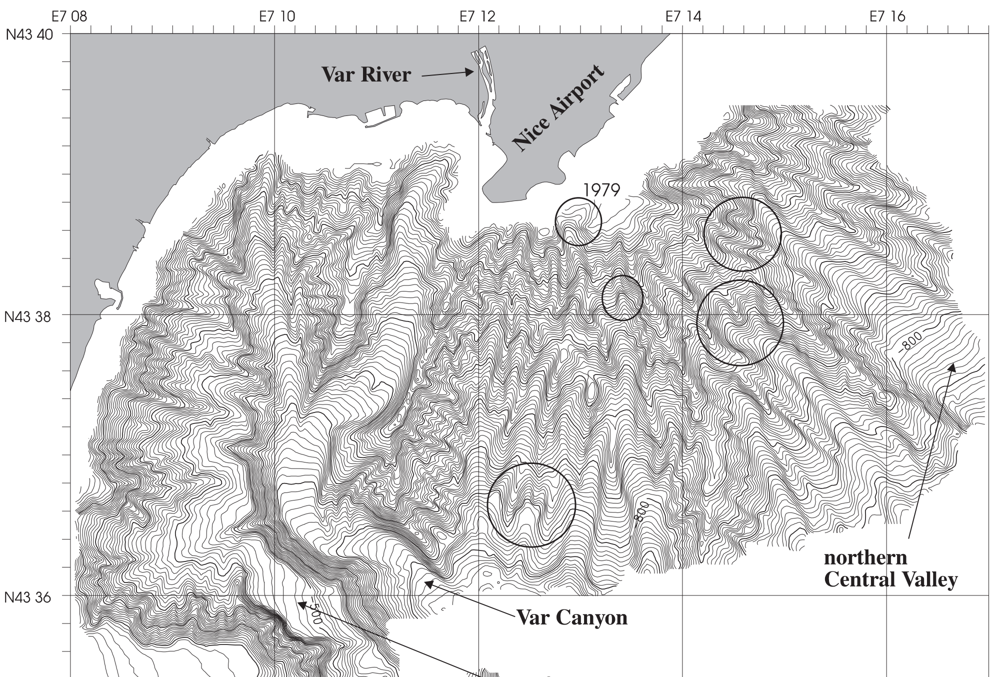


**Fig. 4** High-resolution bathymetric chart (EM1000) of the uppermost continental slope (less than 1000 m water depth). Contour lines are at 10 m intervals. Note the sudden increase in slope gradient in some of the chutes on the uppermost slope (circled). The presumed origin of the 1979 submarine landslide is also shown

erosive, as cross-cutting of the chutes on the uppermost slope suggests. The submarine landslide of October 1979 is part of this group of sediment failures (Fig. 4). Depth of failure for this particular event has been inferred to be 25 m and the initial slump volume to be $8 \times 10^6$ $m^3$ (Habib 1994), but this initial volume has increased through erosion along the flow path by an order of magnitude (Mulder et al. 1997a). The initial slump scar of this event, like those of other deep-seated failure events on the uppermost continental slope, is not visible on the side-scan sonar images. However, the erosive and sinuous flow path of the 1979 event can be identified. Similar evidence for sediment failure, although with much larger dimensions, exists at the base of slope (Cirque Marcel) and within canyons of the Golfe de Cannes–La Napoule (Fig. 1). Here, amphitheater-like steps in slope are up to 150 m high.

Deep-seated failures are also shown on the side-scan sonar imagery at various locations. They are identified as areas of slightly lower backscatter intensity associated with marginal shadows (Fig. 5). The shape of these slump scars is variable. Many show a rounded, catfoot-like outline while others are more elongate in shape (Fig. 6). There is frequent evidence for successive slumps or intense gullying of the headwall of these slump scars (Fig. 6), but in contrast to superficial slumping, the flow path is generally not visible. It is possible that these successive slumps correspond to different events, but destabilization of underlying sediments due to erosion by the initial slump is also a possibility. Gullying of the headwall of the slump scar is definitely more recent than the initial slump and has been generated by undercutting. Slump scars of this type are also much larger than superficial slumps with a surface extent of up to $10^7$ $m^2$. Depth of failure for these slump scars is difficult to determine with precision due to a lack of high-resolution bathymetric data. Available data suggest a depth of several tens of meters, which would correspond to total volumes of slumped sediment of up to $3.5 \times 10^8$ $m^3$, i.e., up to 40 times the 1979 event. Although the actual size of the slump scars may be the composite of several generations of failure, it seems clear that submarine landslides much larger in size than the 1979 event did occur in the past.

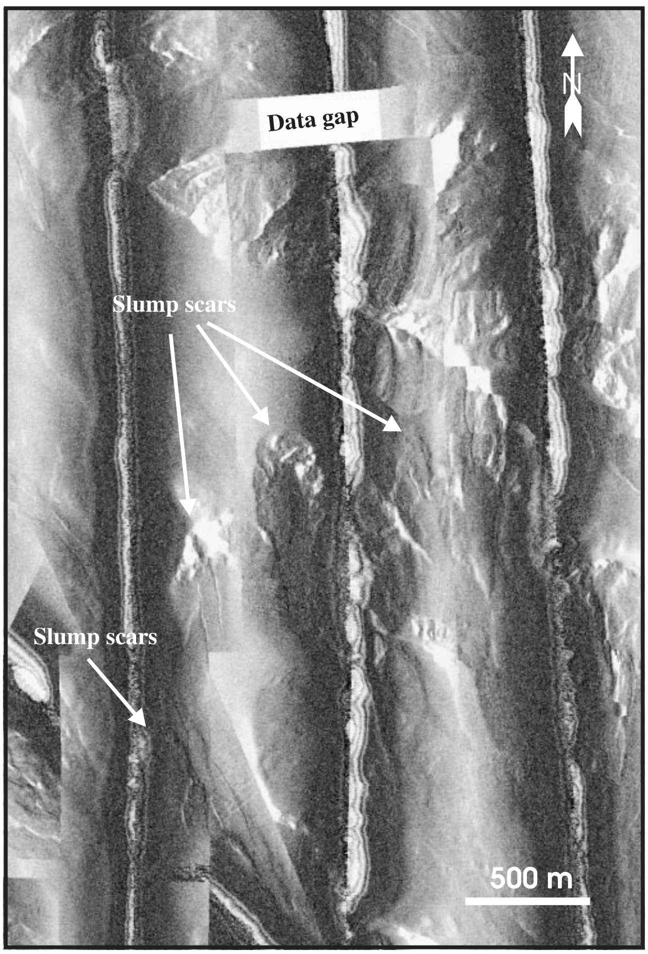


**Fig. 5** Side-scan sonar image showing an example of deep-seated failure on the Cap Ferrat Ridge. Location of the image is shown in Fig. 1

### Canyon-wall gullying

Canyon-wall gullying can be observed on both side-scan sonar images and bathymetric charts (Figs. 4 and 6). Although slump scars are not identifiable, canyon-wall gullying appears as numerous V-shaped incisions on 3.5-kHz profiles and as a unique dendritic pattern on the side-scan sonar images (Fig. 6). The magnitude of the events shaping the canyon walls is difficult to evaluate, but the regularity of the gullies seems to point towards small-scale events in well-consolidated sediments. The sediments on the ridges are overconsolidated (Cochonat et al. 1993), which is also underlined by step like outcrops of older deposits at the base of the canyons. The missing overburden responsible for the overconsolidation of the surficial sediments has been calculated to be 7 m (Mulder et al. 1992; Cochonat et al. 1993), but it is unlikely that this material has been taken away by a single event. In fact, slope gradients across the canyons are extremely high (up to 1:2), and superficial deposits are highly unstable, producing almost continuous sediment flow. The slightest perturbation will generate small-scale sediment flow, as submersible observations indicate (B. Savoye personal communication 1996).

## Distribution of failure events

The three types of sediment failure are not evenly distributed on the Nice continental slope, but correspond to specific depositional settings. Superficial slumping occurs mainly within fine-grained, very homogenous deposits that cover most of the uppermost continental slope and that are the result of sediment plumes generated at the Var River mouth (Sage 1976). These plumes

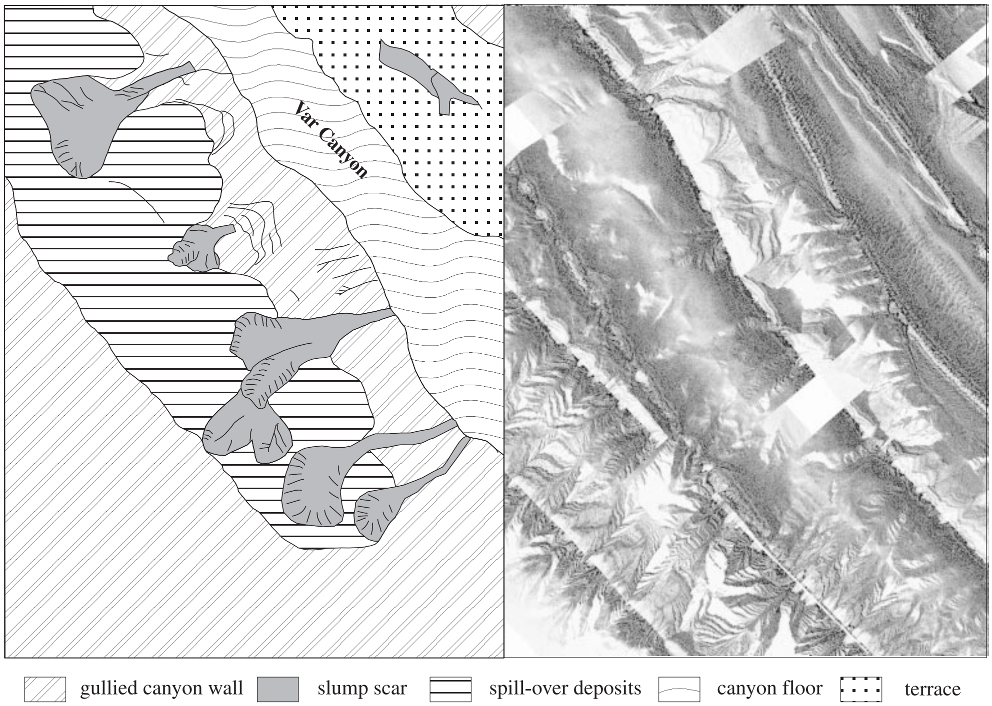


**Fig. 6** Side-scan sonar imagery showing deep-seated slumping east of the Cap d'Antibes Ridge and gullying of the canyon walls. These slump scars probably represent incipient stages of canyon-wall gullying. For image location see Fig. 1

may have formed at the surface or at intermediate water depths as mesopycnal plumes (Mulder et al. 1997b), depending on their sediment load and density. However, occurrence of superficial slumping within these deposits seems to be restricted to the broad, flat-floored valleys (Fig. 7), where these deposits reach the greatest thick-

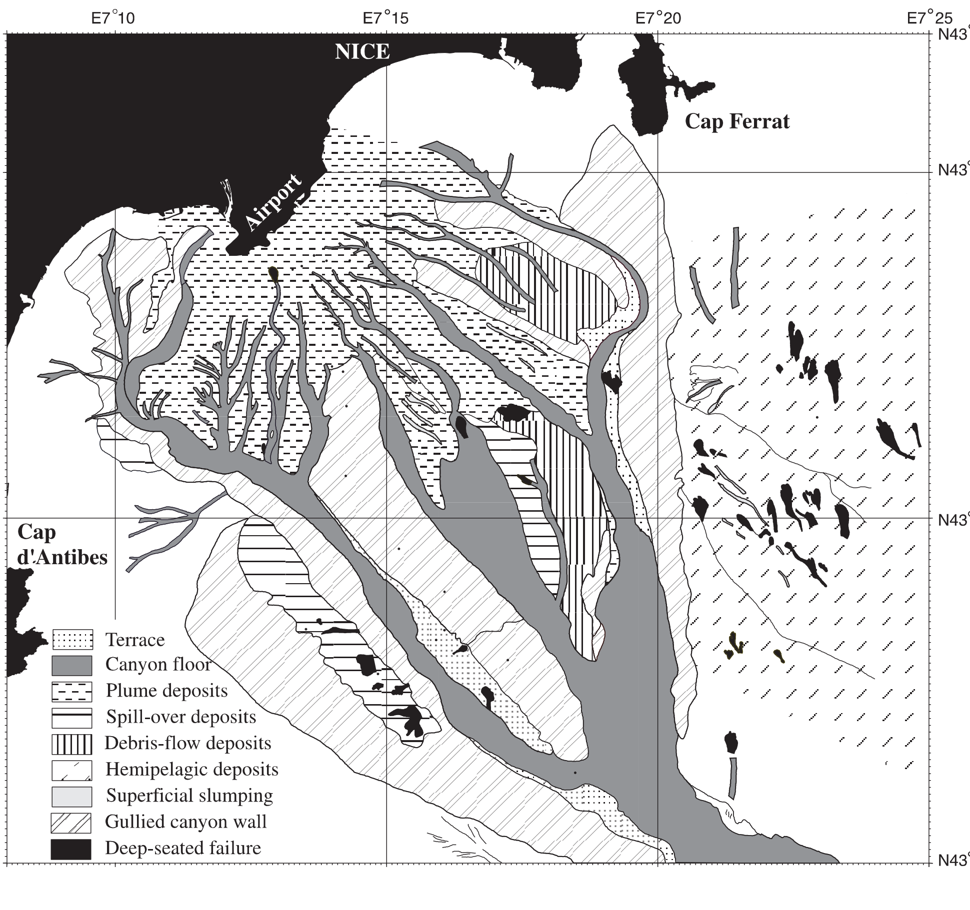


**Fig. 7** Simplified interpretative map of the continental slope off Nice showing the spatial distribution of different types of failure event and their depositional environments. Note that the extent of canyon-wall gullying also represents recent spill-over deposition

ness. Additional superficial slumps exist in hemipelagic deposits east of the Cap Ferrat Ridge. Hemipelagic deposits, in contrast to plume deposits, result from much lower sedimentation rates and lack sediment coarser than fine silt. Canyon-wall gullying, on the other hand, is restricted to the walls of major canyons (Fig. 7) that have eroded deeply into already well-consolidated sediments. Erosion of the canyons, together with frequent failure of spill-over sediment on the canyon walls, precludes the formation of thick accumulations of recent deposits on the canyon walls. Deep-seated failure, finally, occurs in three different depositional settings: (1) the uppermost continental slope beyond the Nice Airport that is characterized by mainly fine-grained deposits from surface or hyperpycnal plumes, (2) a mid-height terrace on the Cap d'Antibes Ridge, where thick accumulations of fine-grained spill-over deposits are found, and (3) the continental slope beyond the Cap Ferrat Ridge (Fig. 7) that is now disconnected from major sediment sources and covered by mostly hemipelagic deposits.

## Discussion

### Distribution of failure

The distribution of failure events appears to be strongly controlled by slope gradient, by grain size of the deposits, and by sediment accumulation rates. High slope gradients are clearly an important factor in sediment failure (Karlsrud and Edgers 1982; Mulder et al. 1994), but if gradients are too high, the frequency of failure events will be too high to allow thick, unstable deposits to accumulate. Under these conditions only small events are possible. In order to produce voluminous, potentially hazardous sediment failure, thick deposits of fine-grained sediment are necessary. This condition is present at the three locations mentioned previously. However, the reasons for sediment accumulation are different. While the slope beyond the Cap Ferrat Ridge and the mid-height terrace of the Cap d'Antibes Ridge have low to medium gradients (between 1:20 and 1:10), the uppermost continental slope off the Nice Airport is very steep (1:5). On the other hand, it is also the area showing the highest sediment accumulation rates. We suggest that the conditions of high sedimentation of fine-grained material on steep slopes are the most likely to produce frequent, voluminous sediment failure and that low sedimentation rates and gentle to moderate slopes will also generate voluminous, but less frequent sediment failure.

Temporal distribution of failure events is more difficult to evaluate in the absence of exact dating. At present it is not clear if submarine landslides were more frequent during periods of lowered sea level. It seems likely, however, that submarine landslides occurred at all times, because lowered sea level did not fundamentally change the physiography of a region lacking a continental shelf and with a steep continental slope. In addition, the occurrence of failure in the well-stratified sediments covering a gravel layer in the large central valleys may well point towards sediment failure during the Holocene, since these deposits are most likely of Holocene age, covering older (possibly Pleistocene) gravel deposits.

### Variability of failure events

Bathymetric and acoustic data from the steep seafloor off Nice indicate a great variability in size and morphology of past failure events. Depositional setting and triggering mechanism determine this variability. In fact, six main scenarios may exist, each with its specific frequency and risk (Table 1).

Canyon-wall gullying occurs in spill-over deposits covering older deposits that have been exposed by canyon erosion. The main triggering mechanism in this case is undercutting, and although these events are very frequent, they do not present a great risk due to their small size. Superficial slumps may occur in plume or hemipelagic deposits, but seem to be restricted to moderate slopes. This makes earthquake loading the best candidate as a triggering mechanism. Although these events displace larger amounts of sediment than canyon-wall gullying, their risk potential remains low. As well, they appear to be frequent with, maybe, slightly more fre-

**Table 1** Summary of slope failure types on the continental slope off Nice

| Failure type | Depositional setting | Triggering mechanism | Event frequency | Hazard potential |
|---|---|---|---|---|
| Canyon-wall gullying | Spill-over deposits | Undercutting | Very high | Low |
| Superficial slumps | Plume deposits | Earthquake loading | Low–medium | Low |
| | Hemipelagic deposits | Earthquake loading | Low | Low |
| Deep-seated failure | Plume deposits | Sedimentary loading (earthquake loading) | High | High |
| | Hemipelagic deposits | Earthquake loading (undercutting ?) | Low | High |
| | Spill-over deposits | Undercutting (earthquake loading) | Medium | High |

quent events in plume deposits that probably have higher accumulation rates. Deep-seated failures always represent a great risk as they displace large volumes of sediment. In plume deposits with high accumulation rates, sediment loading is the dominant triggering mechanism, but earthquakes can also act as triggers (Mulder et al. 1994). The frequency of these events is high. Earthquake loading is the main triggering mechanism for hemipelagic deposits that are characterized by low accumulation rates, which explains why the frequency of these events is low. At present it is not clear if undercutting also plays a role in triggering failure in these deposits. Extremely large events, such as those forming the Cirque Marcel (Fig. 1), may have destabilized other deposits further upslope. Undercutting is, however, the most important triggering mechanism for deep-seated failure in spill-over deposits. Thick accumulations of spill-over deposits in the Baie des Anges result from alternating phases of canyon erosion and terrace formation due to variations in sediment transport activity in the area, otherwise this depositional setting would not exist. The frequency of deep-seated failure in spill-over deposits should be moderate.

Table 1 indicates that only deep-seated failures represent a significant risk. In order to produce such events, thick accumulations of fine-grained sediments are necessary. As a consequence, differences in accumulation rates have to be used to explain the differences in event frequency for deep-seated failures in hemipelagic, spill-over, and plume deposits.

### Comparison to geotechnical modelling

The results presented here confirm that seafloor failure may occur in virtually any setting of the continental slope off Nice. Mulder et al. (1994) reached similar conclusions by using infinite slope analysis based on a number of short piston cores and in-situ measurements (Fig. 2). While this agreement is true on a regional scale, marked differences appear in the type and distribution of individual failure events.

Infinite slope analysis suggests that major portions of the upper continental slope are subject to very superficial failure (< 2 m thick), due to the underconsolidation of deposits in this area. Larger events (5–15 m thick) should occur on the steep ridges under the influence of additional shear stress due to earthquake loading (Mulder et al. 1994). The thickness of failure postulated in this model strongly depends on the depth of available geotechnical measurements (2 m for in-situ measurements, 5–15 m for piston cores). The distribution of failure events as they appear in our data-sets does not confirm these conclusions (Fig. 7), probably for two main reasons. First, the continental slope off Nice is morphologically extremely complex, making extrapolation of geotechnical measurement to other, "similar" environments very risky. Acoustic investigation of the seafloor suggests a greater diversity of depositional environments than that reflected in previous geotechnical zonations (Cochonat et al. 1993). A second reason for the inadequacy of infinite slope analysis to reproduce the pattern of seafloor failure lies in the variability of types, geometries, settings and triggering mechanisms of failure events. Each case must be treated individually with its own model of soil mechanics in order to reproduce conditions of stability and failure and to describe post failure behavior. This requires measurement of geotechnical parameters that are not available at present, such as in-situ shear strength across the failure plane.

## Conclusions

Analysis of side-scan sonar imagery, multibeam bathymetry data, and 3.5-kHz profiles has shown a variety of failure types based on geometry and volume, depositional environment, and triggering mechanism. Evidence for past failures of different types on the continental slope off Nice is widespread and not restricted to the Baie des Anges area. Geoacoustical investigation therefore confirms previous regional assessments of slope stability based on infinite slope analysis. The complexity of the morphology of the continental slope off Nice and the variability of failure types, however, requires the choice of appropriate soil mechanics models in order to determine failure conditions at the scale of the individual slump. In general, geotechnical data for such detailed analyses are not available. Detailed geological investigations, such as the one presented here, are a prerequisite for determining the geometry of a specific failure event: knowledge that is important for the choice of appropriate sites for geotechnical measurements and of the model of soil mechanics to be used. Future research should be directed towards an improved understanding of seafloor failures at the scale of the individual event. This requires in-situ measurements of geotechnical parameters over important depths (ideally to the depth of the failure plane).

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