Slope Instability of Continental Margins

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Abstract: Giant submarine landslides occur on almost every contintental margin. Individual slides involve up to 20,000 km^3 of slope material and cover an area of up to 113,000 km^2. Their wide spread distribution and their large dimensions make them important geological features, particularly as many of them are located within hydrocarbon exploration areas. The factors that are controlling slope stability are still poorly understood in spite of significant research efforts, and there are only few landslides for which the trigger is known with certainty. It appears that ground motion due to earthquakes, rapid sedimentation, and slope destabilization by gas hydrates are among the most important factors, whereas slope angles seem to be less important.

Introduction

Submarine landslides are a global phenomenon. They occur in the sedimentary successions of continental margins and within the basaltic edifices of volcanic ocean islands. In the scope of this book we concentrate on landslides on continental margins. Submarine landslides have been reported from passive, active and sheared margins (Fig. 1), and they occur on all scales. Factors such as sedimentation, earthquake loading, and gas hydrates have proven to be of variable importance for submarine slope stability. The goal of this paper is to review the recent development and current understanding of slope stability based on examples from active and passive continental margins.

During the last decade research on submarine mass wasting has increased significantly for a number of reasons: (1) hydrocarbon exploration moves into deep-water areas where slides occur (Fig. 1), and where even small slides can have the potential to endanger installations on the seafloor, (2) public awareness of climate change demands understanding of the interrelationship of slope failure and gas hydrate stability, (3) regional side-scan sonar and seabeam bathymetry acoustic images have revealed the importance of erratic down-slope transport of sediments for understanding ocean margin systems, and (4) submarine mass wasting provides the means to transport large amounts of sand into the ocean basin. Recent discoveries of hydrocarbon in ancient sand deposits of deep-water areas makes an understanding of its distribution important for hydrocarbon reservoir assessment in the ocean deep-water domain.

There are three major types of gravity driven processes: generation of transport by slides or slumps, transport of sediments in laminar motion by debris flow, and transport of sediment in turbulent motion by turbidites. Because it is often difficult to determine from the acoustic images whether a mass movement is a slump or debris flow the terms "blocky" or "cohesive" are used. Here "blocky" describes failures that leave rubble at the base of the eroded sea floor. Another term is the "disintegrative" landslide, which has a distinct scar at the upper source area of gravity-driven transport, but lacks the failure evidence at the base of the failure. Traditionally rotational and translational slide deposits, debris flow deposits, and turbidites have been associated with distinct slope failure processes. However, this might not be true as submarine slides evolve dynamically, for instance slumps frequently turn into debris flows and these into turbulent flows during the downward passage of the involved material (Fig. 2).

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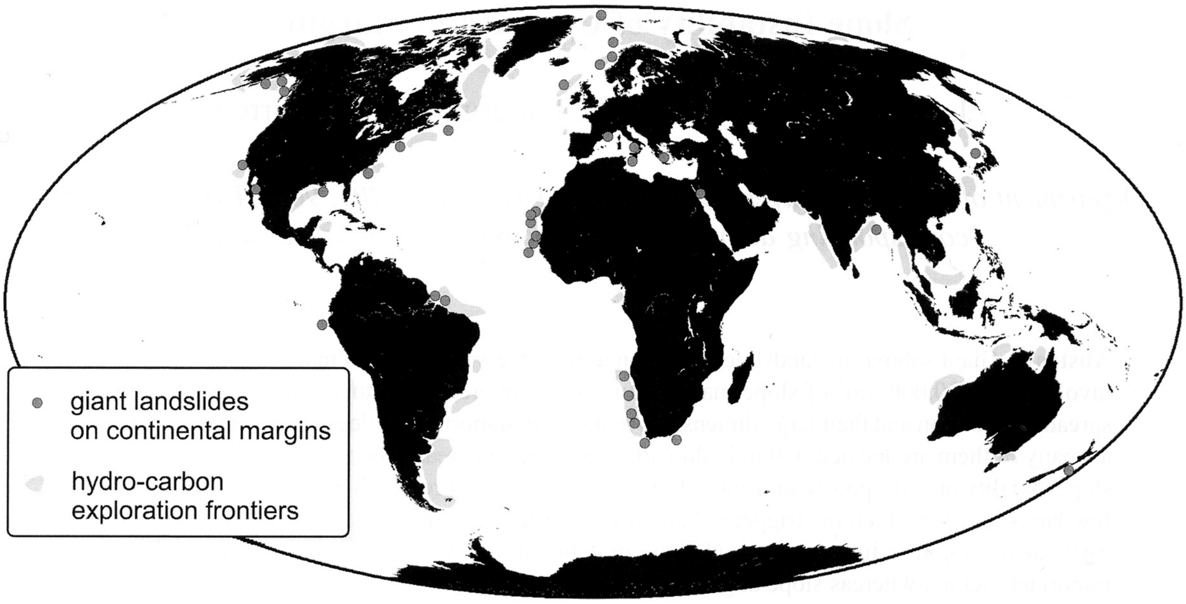

Fig. 1. Global distribution of major submarine landslides on continental margins and location of frontier areas of hydrocarbon exploration (modified after Stow and Mayall 2000). Note, that landslides are found in all well investigated margins, and that they coincide with today's exploration activity.

Modeling of submarine slope failure has improved significantly during the last decade. We will touch on the modeling results, but a thorough review would be beyond the scope of this paper, and we refer the reader to recent publications (Mohrig et al. 1999; Huang and Garcìa 1999; Mello and Pratson 1999; Dimakis et al. 2000) and references therein.

Giant landslides on continental margins

Global distribution

Compilation of major landslides (> 1000 km^2) reported in the literature (Fig. 1 and Table 1) shows that landslides occur on virtually every continental margin. However, the large number of known small landslides (< 1000 km^2) and the expected high number of still undiscovered small landslides, which escape the resolution of acoustic mapping systems, may be equally important in area and volume. Gaps are rather caused by poor data coverage than by the absence of landslides. Evaluation of side-scan sonar data (McAdoo et al. 2000) shows that approximately 10 % of the U.S. continental margins (in the Gulf of Mexico up to 27%) are influenced by submarine slope instabilities. Two inferences can be directly drawn from these observations. First, landslides are an important phenomenon for understanding sediment transport rates from the upper continental slope to deep-sea basins as well as for maintaining the slope angle. Secondly, the geological processes that are responsible for causing landslides cannot be deducted from their spatial distribution alone. Therefore, we focus in the following on areas with data coverage dense enough to address the individual processes. These areas are the N-American, the European and the NW-African margin. They include active and passive margins, fluvial dominated and non-fluvial dominated, and glaciated and non-glaciated margin segments.

Geomorphology of submarine landslides - an example

Submarine landslides are downslope movement of sediments above a basal shear surface and can result in little-deformed to intensely folded, faulted and brecciated masses that have translated downslope from the original site of deposition.

Location, Name	Area (km²)	Volume (km³)	Run-out (km)	Reference
North America				
Grand Banks, Canadian east coast	27500	150 -200		Piper et al. 1999
Continental slope off Maryland	2000			Embley and Jacobi 1977
Gulf of Mexico	5509			McAdoo et al. 2000
Gulf of Mexico	2913			McAdoo et al. 2000
Gulf of Mexico	2460			McAdoo et al. 2000
Gulf of Mexico	1394			McAdoo et al. 2000
Gulf of Mexico	1098			McAdoo et al. 2000
Icy Bay, Alaska	1080			Schwab and Lee 1986
Sur submarine landslide, California	~1000	35	70	Gutmacher and Normark 1993
Middle and South America				
Amazon Fan	10000	1000		Piper et al. 1997
Peruvian Margin	1000	250		Duperret et al. 1995
Africa				
Agulhas, S Africa	79500	20300		Dingle 1977
Chamais, SW Africa	69000	17400		Dingle 1980
Cape Town, S Africa	48000	10000		Dingle 1980
Childs Bank, SW Africa	28500	3800		Dingle 1980
Spanish Sahara	18000	1100	700	Embley 1975
Dakar, W Africa	6577	395		Jacobi 1976
Dakar, W Africa	4952	495		Jacobi 1976
Walvis Bay, SW Africa	3500	90		Summerhayes et al. 1979
Concepcion Bay, SW Africa	2500	150		Summerhayes et al. 1979
Dakar, W Africa	1102	66		Jacobi 1976
Europe				
Western Mediterranean	60000	500		Rothwell et al. 1998
Storegga Slide, Norway	112500	5600	800	Bugge et al. 1988
Trænadjupet Slide, Norway	14100			Laberg and Vorren 2000
Andøya Slide, Norway	9700			Laberg et al. 2000
Gela Slide, Mediterranean	1500			Trincardi and Argnani 1990
Rockall Bank	1100	300		Faugeres et al. 1981
Asia				
Bassein Slide, Bay of Bengal	3940	960		Moore et al. 1976

Table 1. Reported submarine landslides involving areas larger than 1000 km^2.

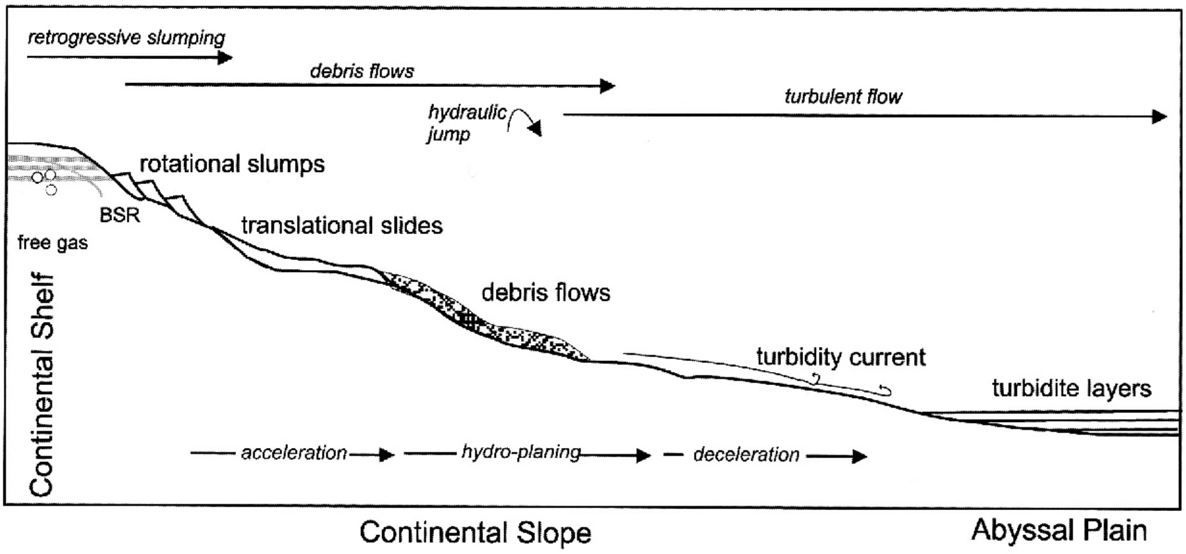

Fig. 2. Schematic diagram for downslope mass movements on continental margins.

Once initiated, the shear surface will propagate upslope from its nucleation point leading to a scoop-shaped, concave-downslope slide scar, often with an irregular outline (Martinsen 1994).

The Towed Ocean Bottom Instrument (TOBI) of the Southampton Oceanography Centre, UK, is a high-resolution side-scan sonar which produces sea-floor images of much higher resolution than previously (Fig. 3). It is now possible to study submarine slides almost at the same level of detail as onshore landslides. Based on TOBI data part of the Trænadjupet Slide offshore Norway was studied. The slide probably occurred during the mid-Holocene, sometime prior to 4 ka BP (Laberg and Vorren 2000).

The headwall of the Trænadjupet Slide is up to 150 m high and 20 km long and controls the nature and location of the shelf break in front of a large transverse shelf trough. Immediately downslope from the headwall initial sediment disintegration produced detached sediment ridges. Near the headwall the ridge spacing is relatively dense, but the ridges increase in spacing and decrease in size downslope. The downslope decrease in size involves breakdown of the ridges into sediment blocks. The sediment ridges moved by back-tilting or through basal deformation (Fig. 3). Transition to sediment streams comprising more-or-less disintegrated sediments occurred over some kilometres. Areas dominated by sediment streams are imaged as marked downslope lineations which represent an interplay of erosion by the downslope-flowing sediments and the formation of smaller escarpments delineating lobes of sediments (Fig. 3).

The slide deposits are characterised by what are interpreted to be four prominent debris flow lobes terminating in the southern Lofoten Basin. The lobes have a maximum height of about 150 m above the surrounding sea-floor. GLORIA images indicate small and large blocks. Thus some of the failed mass characterised by the longest run-out distance, probably the most-consolidated sediments, were not remoulded completely during the downslope flow.

Processes influencing landslides

Slope stability depends on the shear strength of the slope material and the applied forces, i.e. primarily gravity. Slope failure occurs if the applied forces exceed the shear strength. The forces applied to a slope will rarely change in nature. Although sea-floor ground motions due to earthquakes are difficult to quantify (Spudich and Orcutt 1982), it

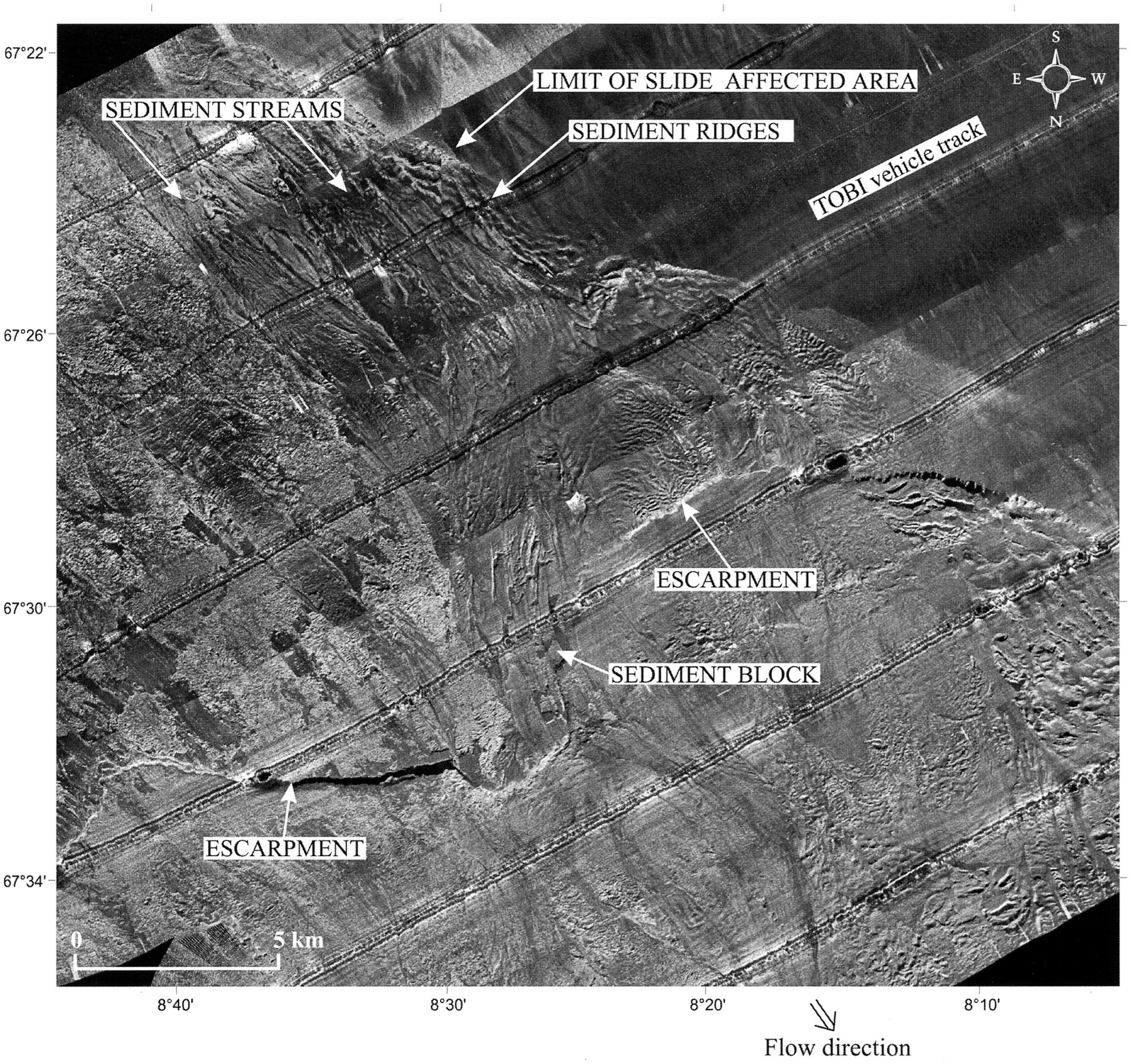

Fig. 3. Sea-floor image of Towed Ocean Bottom Instrument (TOBI) side-scan sonar covering the upper, western part of the Trænadjupet Slide. A prominent escarpment up to 100 m high can be followed from the lower left part of the image across the slide. Sediment ridges near the sidewall, areas of sediment stream and a large sediment block are also visible. Sediment flow direct into the lower right and TOBI vehicle tracks are indicated.

may be possible that they can generate forces strong enough to start landslides (Keefer 1993).

It is widely accepted that landslides initiate when the shear strength of the slope material decreases in a short time. The most efficient way to decrease the shear strength is the increase of pore pressure because the effective stress is the applied stress, i.e. gravity, minus the pore pressure (Scheidegger 1982). Mechanisms that increase the pore pressure include sedimentation rates that are high enough to trap fluids, wave loading, earthquake loading, and localized transport and accumulation of gas and fluids. Schwab and Lee (1988) demonstrated for the Gulf of Alaska that wave loading primarily occurs at shallow water depth on the shelf and leads to rotational slumps, whereas earthquake loading dominates at water depth greater than approximately 50-100 m and is responsible for debris flows. Dissociation of gas hydrates on the continental slope due to changes in sea level or increase in bottom water temperature may produce large amounts of free gas within sediment layers (Mienert et al. 1998; Bouriak et al. 2000). This increase of free gas within the sediment column will decrease the bulk shear strength of the slope material and can potentially lead to slope failure (Paull et al. 1996; Mienert et al. 1998). Finally, erosion of the slope foot by bottom water currents will decrease the stability of the slope, e.g. in deltaic environments. However, so far it has not been demonstrated that the latter process can lead to major landslides on continental margins. In the following we will refer to and discuss the most quoted triggering mechanisms earthquakes, (rapid) sedimentation, and gas hydrates on landslides.

Seismicity and landslides

North American Atlantic and Pacific margins

Seismicity on North American margins is distinctly more frequent and stronger at the active margins on the west coast than at the passive margins of the east coast and in the Gulf of Mexico (Fig. 4). Gloria side-scan sonar and bathymetric data provide evidence of wide spread slope failures on both the active and the passive margins (McAdoo et al. 2000). It is important to note that the active Oregon margin generally has a lower seismic activity than for example the active Japanese margin. Therefore it may not be ideally suited as a type location for an active margin. However, the detailed studies on the Oregon margin allow a first comparison of landslides on passive and active margins using similar data sets.The seismically active margins like the sheared margin of southern California and the margin off Oregon with its subduction zone show landslides only on 7.1 and 3 % of their area, respectively. The passive margin of the Gulf of Mexico has 27 % and the passive New Jersey Margin 9.5 % covered by landslides. This observation indicates that earthquakes, which not only have a high frequency but also a high magnitude may not be the sole triggers for landslides (Fig. 4a).

On the other hand, the North American margins also include the most widely accepted example for a landslide that was caused by earthquake-related ground motion. In 1929 a major submarine landslide occurred south of the Grand Banks immediately after a 7.2 magnitude earthquake had happened (Piper et al. 1999). Temporal proximity and the seismic quiescence of the area at other times, which excludes earthquake loading as a possible release mechanism, make it likely that the slope instability was a direct result of a single earthquake-related ground acceleration.

Norwegian margin

Most of the earthquake foci on the passive Norwegian Margin are at depths less than 25 km and thus generally much shallower than earthquakes with high magnitudes on the active N-American Margins. The locations of epicenters of earthquakes with magnitudes greater than 4 correspond approximately to the outer boundary of postglacial rebound (Fjeldskaar et al. 2000; Byrkjeland et al. 2000) (Fig. 4b).

It is not likely that the pattern of seismic activity was distinctly different during the Early Holocene when the slides occurred, because most workers believe that post-glacial rebound is still the dominating reason for seismic activity on the Norwegian Margin. Comparison of the epicenters of earthquakes (Ms > 4) along the margin with the location of large slides shows that the main center of seismic activity during the 20th century is located south of the Storegga Slide off the Norwegian coast. Additional seismic activity is scattered over the entire margin with a small concentration east of the Trænadjupet Slide. The relation of earthquakes and slides is ambiguous and earthquakes may not be the most important reason for the initiation of slides in this area.

Mediterranean margins

Tectonic activity causes earthquakes with magnitudes greater than 4 in the Mediterranean. A locally destructive earthquake of magnitude 6.1 in the eastern Mediterranean, the Gulf of Corinth, Greece, caused small sized submarine landslides

(Papatheodorou and Ferentinos 1997) in fan delta deposits. The sediment movements occurred on bedding planes. The failures are located about 9 km from the former epicentre. The three dominant instability mechanisms considered in association with this earthquake are liquefaction of a shallow sub-surface horizon (Papatheodorou and Ferentinos 1997). Secondly, a multi-block rotational slide is considered to be caused by remoulding and/or liquefication, and thirdly an elongated slide happened by a combination of shear stress changes of the unconsolidated sediments. The slope failure conditions in the eastern and northeastern Mediterranean Sea most likely have been generated by cyclic loading resulting from earthquakes. A combination of earthquake loading, undercutting, and increases in pore pressure is considered for past sea floor failures on the continental slope of the western Mediterranean. In general, the western Mediterranean Sea landslides and possibly the Adriatic Sea landslides took place during low sea level stands (Rothwell et al. 1998) in regions of high sediment input and prograding wedges. There is little evidence for seismically triggered slope instabilities in the western Mediterranean Sea.

Sedimentation and landslides

NW-African margin

The trade wind driven upwelling belts of the NW - African Margin receive a considerable amount of biogenic material from ocean productivity and high inputs of aeolian sediments, which in turn cause high sedimentation rates, between 5-10cm/kyr (Ruddiman et al. 1987). There is a very low seismicity on this passive margin. Dating of turbidites with biostratigraphic methods (Weaver et al. 1992) shows that mass-movement events occurred during times of climate change, and not at times of low or high sea level stands. While the Senegalese margin receives fluvial input to the head of one of the major turbidity current pathways, the Mauritainean Margin receives seasonal fluvial input. Here also lies one of the major turbidity current pathways. The giant slides and slumps observed on the NW-African margin have occurred

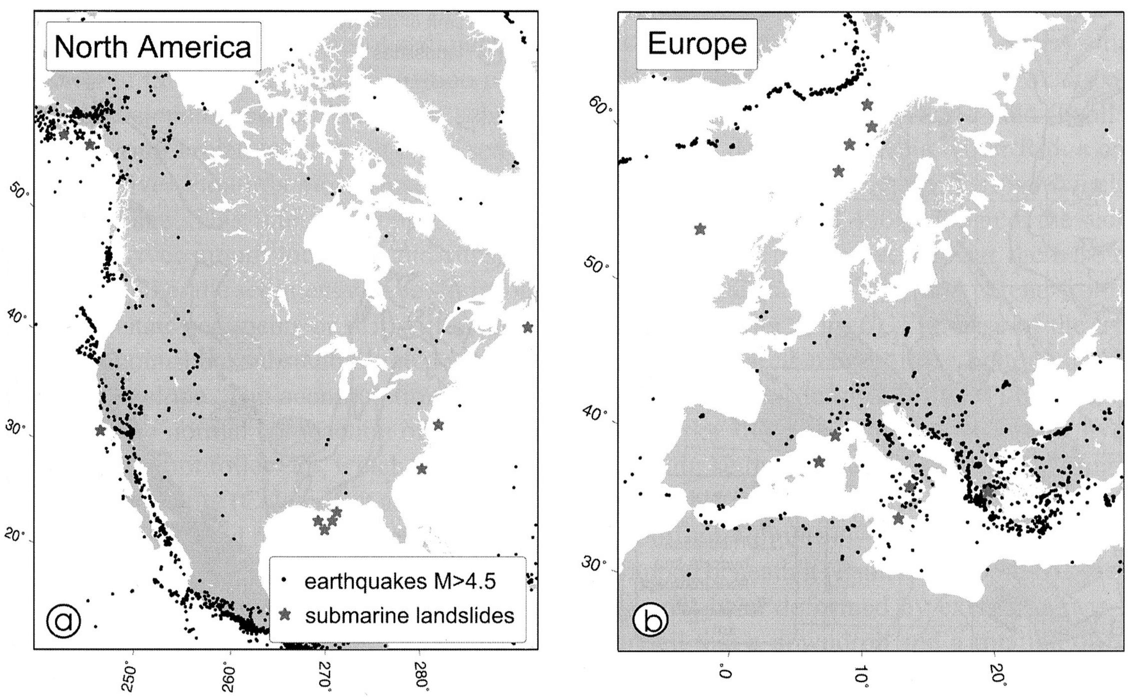

Fig. 4. a) Location of earthquakes M > 4.5 from 1990-2000 in North America based on the CNSS catalog. **b)** Location of earthquakes M > 4 from 1990-2000 in Europe based on the CNSS catalog. Location of landslides based on the literature cited in Table 1 and references therein.

in water depths greater than 2000 m on slopes less than 1.5 ° (Embley and Jacobi 1977). The slides occurred both in pelagic sediments rich in organic matter, and in terrigeneous sediments. No consistent relationship has yet been established between the landslides and the sedimentary systems in which they were initiated.

Norwegian margin

The formerly glaciated margin of Norway experienced sedimentation rates exceeding 10 cm/kyr during advances of the Fennoscandian Continental Ice Sheet to the shelf edge. The late Cenozoic depocenters comprise eight trough-mouth fans (TMF) varying in size between 2700 and 215,000 km^2 (Vorren and Laberg 1997). These fans are dominated by debris flows. It is suggested that each stacked debris flow unit documents an ice-sheet advance to the shelf break (Vorren et al. 1998). Of the four large late Quaternary landslides on the Norwegian margin (Bjørnøyrenna-, Andøya-, Trænadjupet- and Storegga slides) (Fig. 5), one is located on a fan (Bear Island TMF), one is located on the flank of a fan (North Sea TMF), and two are located in the inter-fan areas. AMS^{14}C datings indicate that the acoustically imaged Storegga, Trænadjupet, Bjørnøyrenna, and Andøya slides all occurred during the last 10,000 years in Holocene times (Haflidason et al. 2001; Laberg et al. 2000; Laberg and Vorren 2000). Also, much older slides are observed in seismic reflection profiles in various locations pointing towards prolonged margin instability (Evans et al. 1996).

The two largest fans (Bear Island TMF and North Sea TMF) also contain several large buried slides (King et al. 1996). Thus, it is quite evident that the high sedimentation rate areas, represented by the TMFs, are sites of frequent slide events. The

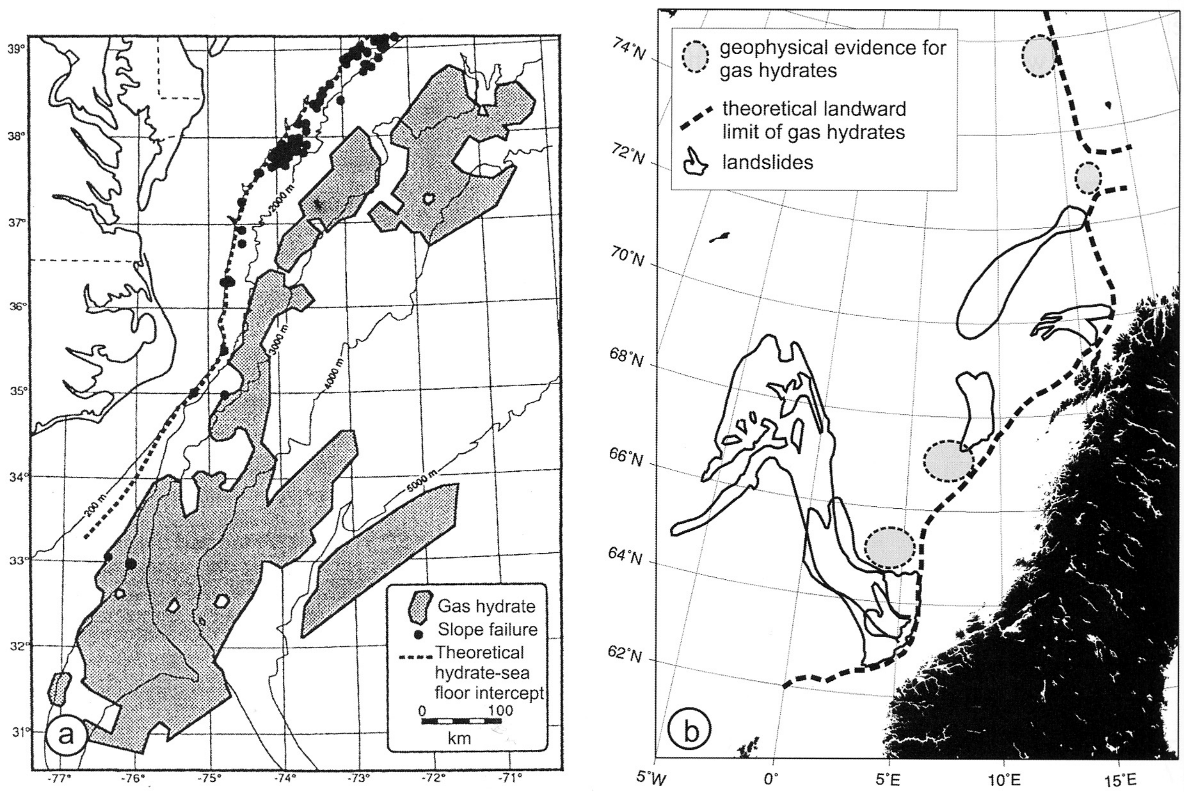

Fig. 5. a) Location of mapped gas hydrates and landslides on the US east coast (after Booth et al. 2000) and **b)** location of gas hydrates and major landslides on the Norwegian margin.

two late Quaternary slides in the inter-fan areas are situated in front of transversal troughs. The troughs were important drainage routes for active ice streams during the late Cenozoic glaciations. It is not clear why TMFs did not develop in these areas. Possibly it relates to the steeper slopes in these areas, or possibly it is due to frequent sliding activity that evacuated the material delivered by the ice-streams.

Gulf of Mexico margin

The sedimentary system of the Gulf of Mexico Margin is characterized by salt tectonics along the entire margin and high sedimentation rates at the Mississippi Delta. Salt diapirs are distinctive tectonic features that create vertical movements including uplift over the diapirs and subsidence between them. These movements change locally the dip of the slope (McAdoo et al. 2000). The most important factors determining location and rate of sediment deposition are tectonics, subsidence, slope channel switching and sea level changes (Bouma et al. 1992). The channel and delta switching occurs over periods from 1000 to 2000 years. It has a substantial influence on the rapid transport of enormous amounts of sediments from the shelf to the deep-sea, the deposition of sediments and slope instability. Sediment supply increases during a relative lowering of the sea level, when the river mouth is more closely located at the shelf edge. This interactive process of sea-level fall, river mouth location, and subsidence dictates whether the sediment will be stored on the shelf as deltaic sediments or if it will bypass the shelf and contribute substantially to a prograding continental slope. The accumulation may be so rapid that the normal compaction of fine grained sediments cannot follow up, which may easily result in slope failure (Coleman et al. 1983). Rather steep headscarps and retrogressive slumping may be formed, which in turn cause the classical processes resulting in debris flows and muddy and sandy turbidites (Bouma et al. 1992). This describes the frequently proposed process of instability of continental margin sediments during sea level lowering. However, we still cannot quantify the relative importance of the different processes during the different phases of a complete sea level cycle. The largest landslides occur in the vicinity of the Mississipi Canyon where sedimentation is high. This is an interesting candidate for comparable studies between the N-American and European Margin such as the Rhone Canyon.

Gas hydrates and landslides

Blake Outer Ridge

Circumstantial evidence indicates landslide initiation by gas hydrate decomposition on the east coast of the United States (Booth et al. 2000). On this continental margin gas hydrates and submarine landslides are abundant (Fig. 5). The landslides are exclusively located within the gas hydrate stability zone, although gas hydrates have not been observed in the direct vicinity of many of the landslides. However, it is possible that gas hydrates have existed at the head of the observed landslides before the last glaciation during which most of the landslides occurred, because a glaciation and corresponding sea level lowering might have resulted in dissociation of much of the gas hydrate.

One of the best localities to observe the effects of gas hydrate dissociation exists on the Blake Outer Ridge gas hydrate field (Paull et al. 1996). A depression of the Outer Ridge crest is clearly seen in a seismic profile (Fig. 6) including faulting in the upper 400 to 500 m of the sediment column. The faults develop near the base of the gas hydrate stability zone and extend from there to the seafloor (Fig. 6). The base of the hydrate stability zone is marked by a bottom simulating reflector drilled during Leg 164 (Paull et al. 1996). It marks the boundary between the hydrate-bearing sediments above and gas-bearing sediments below. Gas hydrates may also exist without a bottom simulating reflector if no free gas is trapped beneath it (Paull et al. 1996). As the ridge has not been deformed by extension it is interpreted that a downdrop and a rotation of blocks caused the observed features (Dillon et al. 1998), where also mobilisation of sediments is indicated. Pockmark-like depressions exist at the location of the major faults, which are potential gas escape

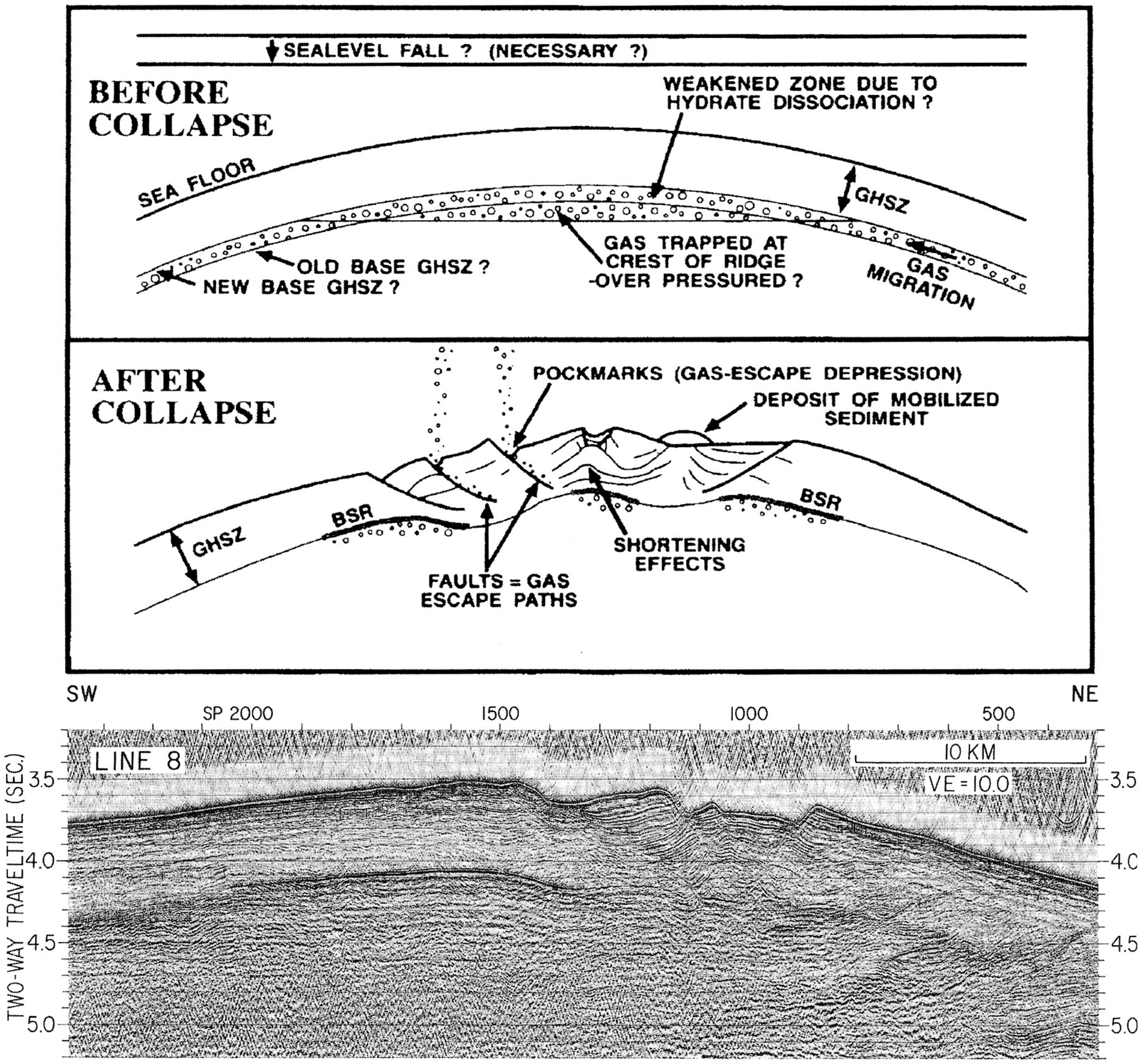

Fig. 6. a) + b) Development of the gas hydrate related collapse structure on the Blake Outer Ridge. **c)** Seismic line of the same structure at a different location (after Dillon et al. 1998).

paths (Fig. 6), documented for other sea floor environments (Hovland and Judd 1988). The Outer Ridge collapse structure was likely caused by the conversion of sediments at the base of the gas hydrate stability zone into a liquefied layer. It seems likely that gas hydrate-induced sediment mobilisation of this order of magnitude can cause submarine landslides in an area more prone to slope failure than the relatively flat top of the Blake Outer Ridge.

Norwegian margin: Storegga

The Norwegian-Barents Sea Margin presents good examples of gas hydrates, and venting-type processes such as diapirs, pockmarks and mud volcanism (Mienert et al. 1998; Bouriak et al. 2000). This margin has experienced some of the world's largest known slides such as the Storegga, Trænadjupet and Andøya Slides (Bugge et al. 1988; Laberg et al. 2000). Laberg et al. (2000) have suggested that the triggering mechanism for the Andøya Slide is earthquake loading. Bugge et al. (1988) discuss the possibility that the Storegga Slide is related to gas and gas hydrates, because a well-defined bottom simulating reflector occurs on seismic profiles from the north-eastern flanks of the current slide scar (Posewang and Mienert 1999). Seismic reflection profiling and ocean bottom hydrophone wide angle seismic experiments suggest that the bottom simulating reflector in this area represents the gas hydrate to free gas interface (Mienert et al. 1998). Mienert et al. (2000) have shown that the gas hydrate stability zone on the Norwegian Margin shifted by about 200 m between glacial and interglacial times. Also, a collapse structure similar to the one on the Blake Outer Ridge is located directly at the northern fault scarp (Fig. 7). The associated sediment mobilisation might have triggered the slide. A main factor for causing a weakening of sediment strength in hydrated areas is the decomposition of gas hydrates. The decomposition of hydrates is causing a solid hydrate to transform into a fluid and free gas that increases the pore fluid pressure. It is important to note that the distribution of present-day gas hydrates on the Norwegian Margin has been recognised by seismic investigations (Posewang and Mienert 1999) but only in a few in-

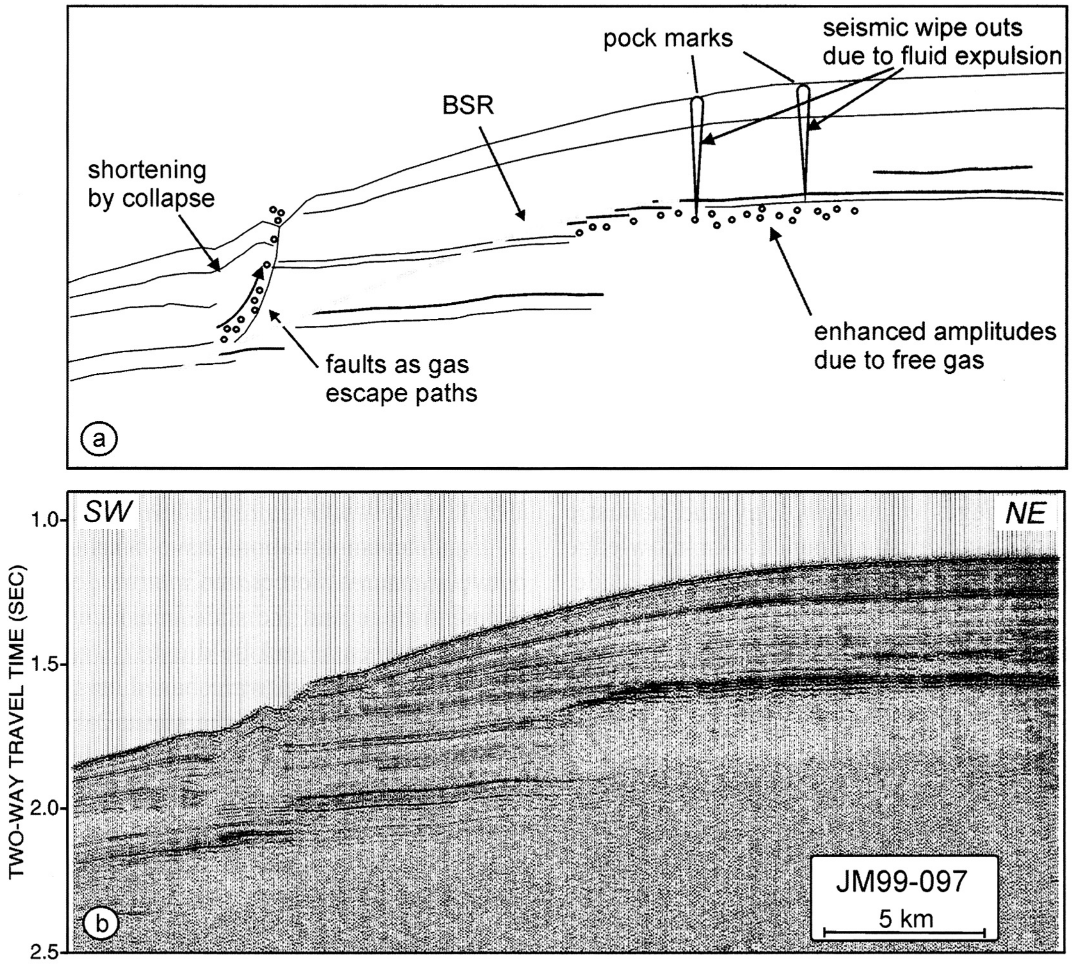

Fig. 7. a) Interpretation of **b)** seismic line JM99-097 on the northern rim of the Storegga Slide, off Norway.

stances by gas hydrate sampling. Past distributions of hydrates are inferred from modeling results (Mienert et al. 2000).

Modeling of the hydrate stabiltity zone (HSZ) as a function of temperature and pressure shows a distinct decrease of the HSZ at the Norwegian margin from the Last Glacial Maximum (LGM) to the present time (Mienert et al. 2000). Important is that the inflow of warm Atlantic Water at the end of the deglaciation 13.000 - 9600 yrs BP caused a thermal wave from the ocean into the seafloor, which has since strongly affected the hydrate reservoirs of shallow and moderate water depths (less than 1500 m). The proposed dissociation of gas hydrate fields within several thousand or even less years depending on the position of the gas hydrate stability base beneath the seafloor places it near or well within the observed slide frequencies. During this period, some of the major slides of the Norwegian margin have taken place. The southern Norwegian margin sites where water mass temperatures increased more distinctly in the upper 800 meters indicate not only a larger change in gas hydrate stability fields (Mienert et al. 2000) but also a much more unstable margin (Vorren et al. 1998).

Discussion and outlook

Acoustic images of morphology and acoustic backscatter have greatly expanded our knowledge about submarine landslides in the last decade. However, the information is biased towards more recent failures, and generally the slide triggers cannot be decided with certainty. Information is even sparser for buried sediment failures observed in seismic reflection profiles.

Recent work by McAdoo et al. (2000) documents that the slope angle is not the most important factor in determining where a slope failure will occur. Sedimentation, erosion, and local geology affect the location of a landslide much more. Moreover, sediment rheology appears to affect the size of landslides. Although most of the commonly called triggers for submarine landslides are earthquakes, it is becoming increasingly evident that there are large segments of the world's continental margins which show slope failure and are far away from seismically active regions.

In the past, many of the failure mechanisms along passive margins have been assumed to have the greatest probability of triggering slope failure during sea level lowstands (Piper et al. 1997). However, it is now becoming clear that the largest acoustically imaged slope failure events on the Norwegian Margin have all occurred during the last 10000 years, in a period of rapid sea level rise. This weakens the hypothesis that slope failure is directly related to slope erosion or decompression of gas hydrates, that have been proposed for low sea levels.

Despite substantial mapping efforts in the frame of various research programmes on the North American (McAdoo et al. 2000; Hampton et al. 1996), North West African (Wynn et al. 2000) and European Margin (Mienert et al. 1998; Vorren et al. 1998), there are very few examples of submarine landslides on continental margins for which we can name with confidence the release mechanism (Piper et al. 1999). The geomorphic products of submarine landslides are well described, but due to the dynamics of landslides evidence of the release mechanisms can rarely be obtained directly from the observed landslide deposits. Therefore, it is necessary to find methods that can constrain these processes. Numerical modeling can be one way to exclude impossible scenarios (Mello and Pratson 1999).

Equilibrium equations have been established between external forces and internal forces at the failure surface and the slide interfaces based on both experimental and field data (Elverhøi et al. 1997). However, software based on this theory takes only into account the static 2-D case and does not have the ability to model the dynamic evolution of slides and retrogressive sliding mechanism. Thus further developments of dynamic modeling techniques for retrogressive sliding mechanism in sensitive and gassy sediments are required. Also, the initiation of slides may be closely related to the presence of weak layers, which we need to identify and investigate in upcoming studies. The commonly used undrained shear strength and standard slope analysis may thus have underestimated the risk of sliding. Improvements and major advances can be achieved through a combination of field stability analysis, laboratory experiments and finally modeling of observations.

Risk assessment needs to incorporate all available information for a potential slide area such as the geologic evolution, the seismicity, the abundance and potential for gas hydrates, glacier loading, weak layers, and bottom currents. The overall goal should be to develop a procedure for the quantification of the probability (yearly return period) for a specific area to be affected directly by slope instabilities or impacted by the long run out distance of individual slides. This will reduce statements such as "the above observations suggest that triggering of large slope failures identified on the margin may have been caused by a large earthquake".

Conclusions

The large number and the extensive amount of involved slide material make submarine mass wasting one of the most important geological processes shaping the continental margin architecture. Today's knowledge of acoustically mapped continental margin areas is not sufficient to draw firm conclusions on the stability or risk neither on passive nor on active margin areas. Integrated 3-D seismic interpretation and visualisation methods are therefore requested for future stability analysis.

The complex relationship between tectonic and sedimentary processes that are active on different time scales, i.e. tectonic evolution of the margin to almost instantaneous earthquakes, high sedimentation rates to low sedimentation rates due to rapid climatic changes, make it extremely difficult to assess the ultimate reason for an individual slide. Observations without improved modeling of mass movement mechanics and release mechanism only lead to more speculation about the importance of individual or a combination of different processes.

The dynamic evolution from rotational slumps, to translational slides, to eventually turbidity currents destroys the initial structure of the involved sediments, and often obscures evidence of the release mechanisms. Therefore, it is difficult to deduct the release mechanisms just from the geomorphic products of slides. We need new methods to improve "backstripping" of the sea floor observations to improve our understanding of the old slope failures.

Some of the most important questions await more firm answers: (1) What are the specific triggers that decide where slope failure will occur? (2) What are the specific triggers for slope failures on continental margins? (3) Why will one region of seafloor fail while neighbouring regions remain undisturbed? (4) What determines the location of the slip planes? (5) What is the role of gas hydrates in slope stability?

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