Submarine Landslides: Advances and Challenges

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ABSTRACT

Due to the recent development of well-integrated surveying techniques of the sea-floor, significant improvements were achieved in mapping and describing the morphology of submarine mass movements. Except for the occurrence of turbidity currents, the aquatic environment (marine and fresh water) experiences the same type of mass failure as found on land. Submarine mass movements however, can have run out distances in excess of 100 km so that their impact on any offshore activity needs to be integrated over a wide area. This great mobility of submarine mass movements is still not very well understood, in particular for cases like the far reaching debris flows mapped on the Mississippi Fan and the large submarine rock avalanches found around many volcanic islands. A major challenge ahead is the integration of mass movement mechanics in an appropriate evaluation of the hazard so that proper risk assessment methodologies can be developed and implemented for various human activities offshore, including the development of natural resources and establishment of reliable communication corridors.

RÉSUMÉ

Le développement récent de techniques de levés hydrograhiques pour les fonds marins nous a permis d'atteindre une qualité inégalée dans la cartographie et la description des glissements sous marins. À l'exception des courants de turbidité, on retrouve dans le domaine aquatique les mêmes types de mouvements de terrain que sur terre. Par contre, les glissements sous-marins peuvent atteindre des distances excédant 100 km de telle sorte que leur impact sur les activités offshore doit être pris en compte sur de grandes étendues. La grande mobilité des glissements sous-marins n'est pas encore bien comprise, comme pour le cas des coulées de débris cartographiées sur le cône du Mississippi ainsi que pour les grandes avalanches sous-marines retrouvées au pourtour des îles volcaniques. Un défi majeur auquel nous faisons face est celui de déterminer les aléas associés aux divers types de mouvements sous-marins ainsi que les risques associés à l'activité humaine, telle que l'exploitation des ressources naturelles et l'établissement de routes de communications fiables.

INTRODUCTION

The continuing development of natural resources, oil and gas in particular, either closer to the continental slope or in deeper water, the growing need for seafloor transport and communication routes, the pressure on coastal development (cities, harbors), the protection of the marine environment and the impact of global changes are all responsible for the major advances in our understanding of the phenomena of submarine mass movements and their inherent consequences. In this context, we wish to report on major advances made over the 1984-2000 period but also on the challenges still ahead.

The year 2000 coincides with the completion of the International Decade on Natural Disaster Reduction (IDNDR). Over the last 10 years many opportunities (*e.g.* symposia, workshops or conferences) were provided to underline the significance of land sliding not only as a morphological agent but also as a natural phenomenon with economical and societal significance acting both on land and underwater. During this period, we have held two international symposia: Christchurch (1992) and Trondheim (1996). However, the last opportunity to review submarine mass movements, as a part of the International Symposium on Landslides, was provided by Prior at the Toronto meeting (Prior, 1984). During this period, reviews related to submarine mass movement and related phenomena are provided by Lee (1989, 1991), Schwab *et al.* (1993), Hampton *et al.* (1996), and for some physical considerations by Leroueil *et al.* (1996) and Locat (2000).

We would like to approach this review by first revising the various causes of submarine mass movements and their mobility. Then we will briefly mention the major research projects which have or will be related to submarine mass movements. We will illustrate the rapid development of the geomorphological analysis of submarine mass movements using multibeam techniques. Thereafter, we wold like to approach our review in the manner proposed by Leroueil *et al.* (1996), that is, to look at the pre-failure and failure stages and the final post-failure stage. We will end our work by discussing some elements of hazard and risk assessment related to submarine mass movements. At each step, we will try to underline achievements and remaining challenges.

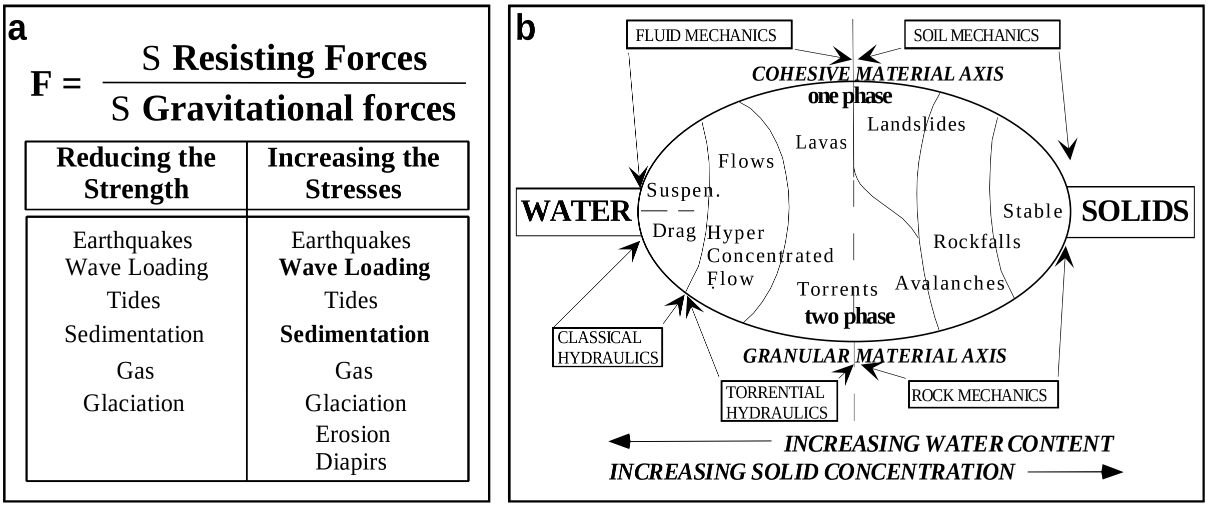


Figure 1. (a): Causes of submarine landslides; elements in bold are commonly most significant. (b): a schematic view of mass movements made of mixtures of solid and water at various stage of mixing and as a function solid characteristics (one or two phase flow) with indication of the physics involved in the phenomena (Modified from Meunier 1993).

CAUSES OF SUBMARINE MASS MOVEMENTS AND THEIR MOBILITY

A compilation on the possible elements that can initiate a submarine landslide is presented in Figure 1a. Some causes are peculiar to the marine environment: role of gas charging, diapirism, and wave action. Materials involved in submarine mass movements are as diverse as those on land, *i.e.* rock, soils, mud and mixtures of both. A submarine mass movement can also be analyzed from a geotechnical characterization standpoint (Leroueil *et al.* 1996), considering the various stages from pre-failure conditions to the run out and depositional phase, as will be shown later. The complexity of submarine mass movements can be great and we must now consider their possible various phases which are: initiation, transition into debris flow (Norem *et al.* 1990), the subsequent formation of a turbidity current (Normark and Piper 1991) and its movement on the sea floor until final deposition. Here we must distinguish the cases where turbidity currents can be directly generated by hyperpicnal flows originating at mouths of major rivers entering the ocean, as often seen in fjords (Syvitski *et al.* 1987, Mulder and Syvitski 1995), from those originating from mass movements or debris flows. To illustrate the continuity of the mass movement phenomena, we borrowed a diagram proposed by Meunier (1993 Figure 1b). This diagram has two axes: granular and cohesive. It also takes into account the relative proportion of solid and water. Therefore, depending on the type of mixture (one or two phases), its behavior will be best analyzed by soil/rock mechanics principles, fluid mechanics or torrential hydraulics. This means, for example, that for mud flows, where the rate of movement is fast enough so that there is no time for excess pore water dissipation, the mechanics of the movement cannot be adequately explained by soil mechanics but rather we must apply fluid mechanics principles. For a comprehensive review of debris mechanics, the reader is referred to the work of Iverson (1997).

A first observation based on the above presentation is that if we wish to carry out a risk assessment related to submarine landslides, we must take into account the various components of the phenomenon, *i.e.*, from failure initiation to the final deposition, which will require scientific consideration covering all the physics involved.

Another way of representing the physics involved in a submarine mass movement is to present the classification of mass movements proposed by the ISSMGE (International Society for Soil Mechanics and Geotechnical Engineering) Technical committee on Landslides (TC-11) and adjust it to the submarine environment (Figure 2). In this case, the main difference is the development of turbidity currents from mobile types of mass movements such as avalanches, debris and mud flows. Clearly, one could introduce subdivisions (*e.g.* Prior 1984, Mulder and Cochonat, 1996) but the terms presented in Figure 2 can cover most of the observed phenomena. We will see later that the widespread use of multibeam surveys shows us that mass movements are occurring in various environments and involve all types of earth material from mud to hard rocks.

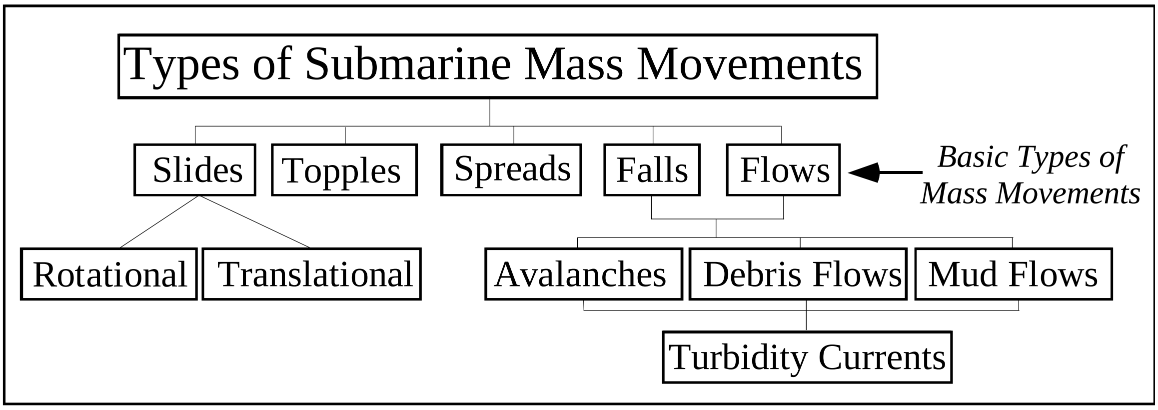


Figure 2. Classification of submarine mass movements adapted from sub-aerial classification proposed by the ISSMGE Technical Committee on Landslides (TC-11).

MAJOR RESEARCH EFFORTS SINCE 1984

Over the last decade, some major national and international projects have been directly related to the study of submarine mass movements. These projects have various acronyms: ADFEX (Arctic Delta Failure Experiment, 1989-1992), GLORIA (1984-1991), STEAM (Sediment Transport on European Atlantic Margins, 1993-1996), ENAM II (1996-1999), STRATAFORM (1995-2001), COSTA (Continental slope Stability, 2000-2002).

Project ADFEX (Arctic Delta Failure Experiment) involved scientists from Canada, France, Norway and Poland (Couture *et al.* 1995). The main goal of ADFEX was, for the first time, to obtain real time data on debris flow and turbidity current generation and dynamics. The site selected was the Kenamu Delta in Lake Melville, Labrador and a blasting method was used to trigger the initial slide (Figure 3, Couture *et al.* 1995). Due to the combined effect of gas in the sediments and last minute changes in the blasting design, only a slope failure occurred without any significant debris flow generation. Although the field experiment itself failed to meet the main goal, this project resulted in many achievements including: a unique cooperation between geoscientists and hydraulic researchers from both sides of the Atlantic, the transfer of knowledge from snow avalanche to submarine debris flows (Norem *et al.* 1990). the development of analytical tools to study the generation of tsunami from submarine slides (Jiang and Leblond, 1992) and a better understanding of the effect of blasting on loose sediments (Couture *et al.* 1995). A lesson learned from this attempt to trigger a submarine slide is that Nature is difficult to master !

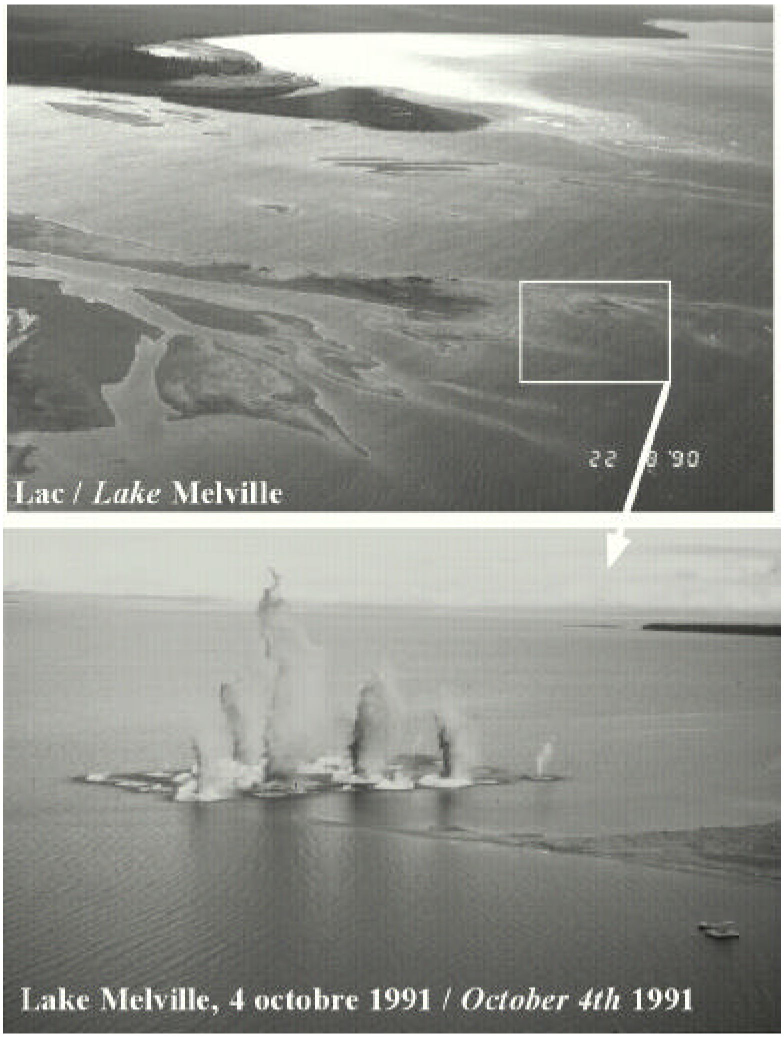


Figure 3. Attempts to generate a submarine slide and debris flow at the Kenamu delta, Lake Melville, October 1991

The STRATAFORM project (1995-2001) was aimed at developing a better understanding of the formation of sedimentary strata by studying the various processes responsible for it, including mass movements. The research was carried out on an active margin, the Eel River Margin off the coast of California, and a passive margin, off New Jersey. The STRATAFORM project strongly involved field surveys, in situ monitoring and observations, laboratory testing and numerical modeling (see Nittrouer 1999a and 1999b). Concerning submarine mass movements, this study established hydroplaning as a physical explanation for some highly mobile submarine debris flows (Mohrig *et al.* 1999).

The ENAM II and STEAM projects, sponsored by the European Community, had a strong component dedicated to submarine mass movements with a particular reference to those in the North Sea and the NW African continental margin respectively. The ENAM II work presented an integrated approach to the study of submarine landslides in the context of oil resources development. A major contribution of this project was an intensive study of the Storrega Slide (Figure 4) which is one of the largest submarine landslide along with those found along the NW African margin (Embley 1976, 1982, Embley *et al.* 1978, Masson *et al.* 1992, 1993, 1998). At the completion of ENAM II, European researchers developed a new project, COSTA (2000-2002), which deals primarily with coastal slope stability and will look into submarine mass movements in the North Sea, as well as in the Mediterranean Sea. Project COSTA has identified the following objectives (Mienert 2000, personal communication):

1. Assessment of historical records of slope instability, slope parameters, seismicity, and tectonic setting.
2. Understanding of seafloor failure dynamics through 3-D imaging of sediment architecture and geometry of slope failures.
3. Understanding of sediment physical, mechanical and elastic properties of slip planes and areas prone to slope sliding.
4. Determination of presence of gas hydrate and its significance for slope stability.
5. Modelling of forces and mechanical processes that control the initiation of slope instabilities (release mechanisms), flow dynamics and initiation of tsunamis.
6. Assessment of risk-fields related to slope stability.

It is hope that other countries like the United States and Canada will be able to join this major concerted effort (project COSTA) dedicated to the study of submarine mass movements.

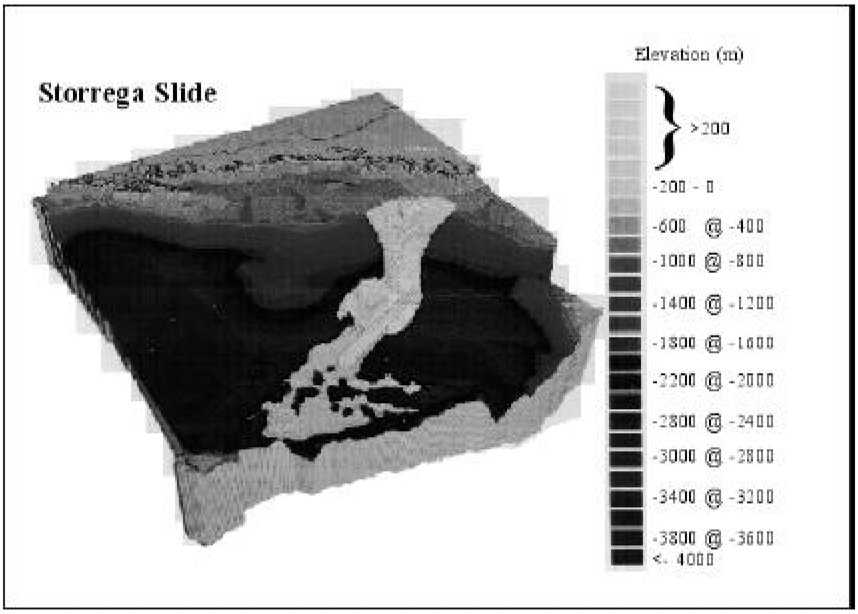


Figure 4. A 3D view of the Storrega slide, off the coast of Norway. The slide extends on the sea floor over a distance of more than 160 km (Mienert, personnal communication)

SEAFLOOR GEOMORPHOLOGY (USING MULTIBEAM TECHNIQUES): THE FINAL STAGE

The initial knowledge of potential problems, in a given area, is often revealed by a morphology, suggesting that the sea floor or slope has been modified in a catastrophic manner. In fact, the actual geomorphological setting of a landslide constitutes its final stage (unless it is re-activated, Leroueil *et al.* 1996) and is a major revealing factor. This is why one of the major achievements of the last decade has been the rapidly increasing use of multibeam surveys over the whole water world, *i.e.* both marine and fresh (Locat *et al.* 1999) to produce air-photograph type quality descriptions of the sea floor. The analysis of sub-aerial landslides has typically been done with an adequate knowledge of the morphology and stratigraphy, not withstanding the mechanical properties and pore water conditions. For submarine landslides, it is only recently that we could count on a similar quality of data. Instead, most of the analyses had to rely on side-scan sonar and sparsely spaced single-beam echo sounder lines, which had major limitations. Physiographic features were identified only by interpolating between a series of survey tracks. The resulting mapped morphologies bore only a crude resemblance to the actual seafloor features. This was particularly true for large landslides (Moore and Normark 1994, Schwab *et al.* 1991).

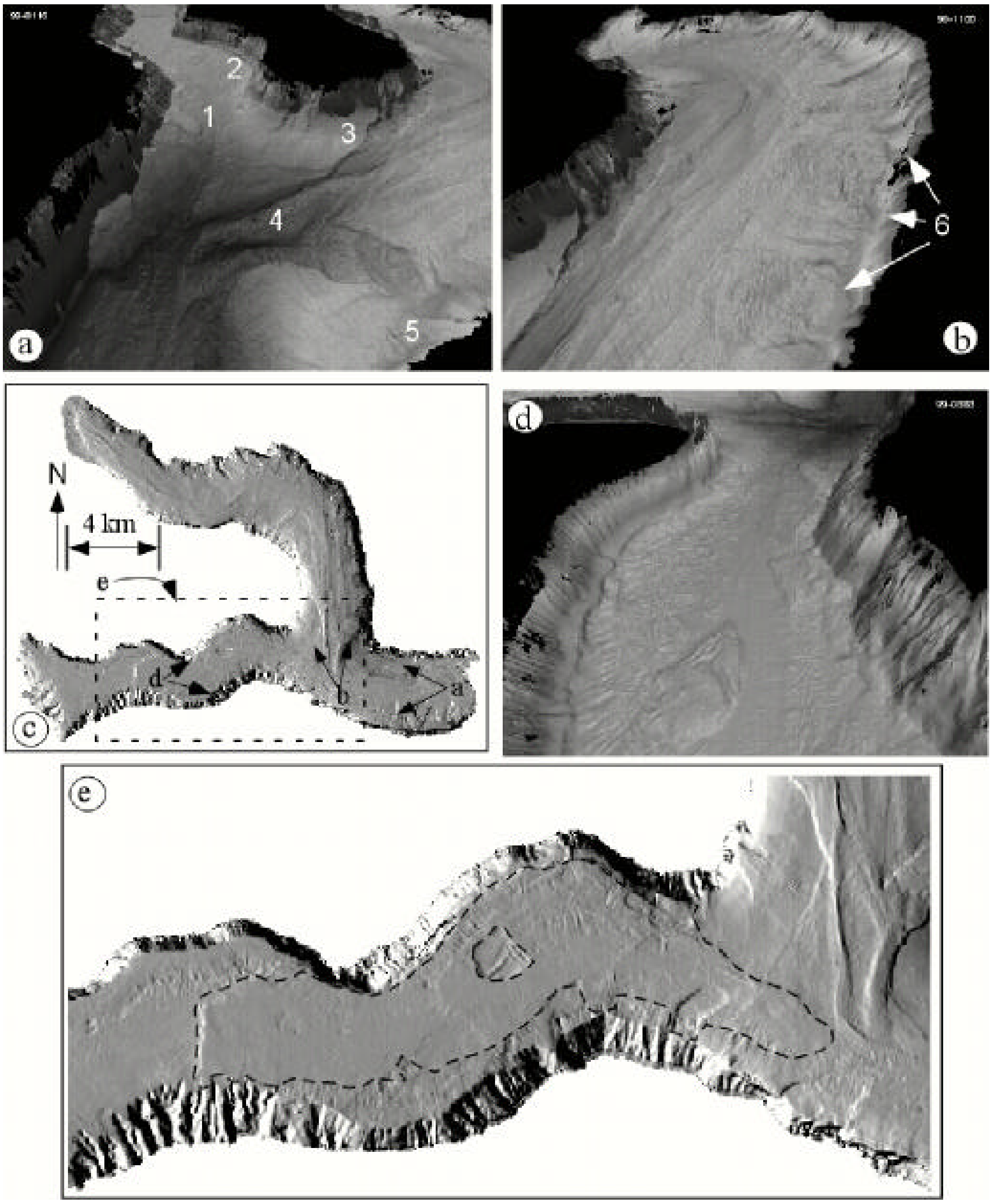


Figure 5. Morphological of the upper part of the Saguenay Fjord, Québec, Canada, showing a 3D representation of multibea bathymetry from the 1999 survey. In (a): spread (1), slide (2), and flows (3 and 5), a major fan (4). In (b): three spreads (6) originating from the East wall. The width in the middle of (a) is about 6 km, and about 4 km in (b). In (e): a large liquefaction failure, a fault controlled escarpment to the West (Locat and Sanfaçon 2000). The water depth ranges from 0 to 225 m, and view angles of (a), (b), and (d) are given in (c).

With the development of multi-beam techniques and Differential Global Positioning Systems (DGPS, Lee *et al.* 1999, Mitchell 1991, Li and Clark 1991, Prior 1993, Hughes Clarke *et al.* 1996) we can now produce precise bathymetric maps of near air-photographic quality (Bellaiche 1993, Urgeles *et al.* 1997). Precise differential positioning, tide data and data correction related to ship movement are essential. In addition, the acoustic velocity in the water column is corrected by a series of acoustic profiles taken during the survey. If space permits, onboard post processing can be completed for a quick map production. The recently developed EM3000 is a portable system which will provide nearly a tenfold improvement in bottom morphology definition for water depths less than 100m. The overall approach of data reduction and analysis has been presented by Hughes Clarke (1997).

Saguenay Fjord, Québec, Canada

The Saguenay Fjord was one of the first sites where a multibeam sonar survey was carried out to map submarine landslides (Couture *et al.* 1993, Hampton *et al*. 1996). The fjord is located 200 km Northeast of Québec City, Canada. The area provides a fairly quiet environment so that sea conditions are nearly perfect so as to ensure the best results. The same area was also re-visited in 1997 after a major flood event (Kammerer *et al.* 1998) and in 1999 (Figure 5). The Saguenay Fjord survey covers the upper part of the fjord at water depths ranging from 0 to 225 m.

The Saguenay Fjord region has had frequent major earthquakes (*e.g.* 6.3 in 1988), the largest historic one occurring in 1663 (Locat and Leroueil 1988, Locat and Bergeron 1988, Pelletier and Locat 1993, Syvitski and Schafer 1996) for which an equivalent Richter Scale of 7 was given. It is believed that this earthquake triggered a series of major land and submarine slides, the largest sub-aerial one being the St. Jean Vianney slide totaling a volume of more than 200 million cubic metres. At the same time, major submarine landslides took place in the upper reaches of the fjord. The complex morphology of this part of the fjord is related to (1) catastrophic sedimentation into the fjord of sub-aerial mass movement material, (2) synchronous occurrence of many submarine landslides and (3) their related derivative mass movements (see Figure 5, 1: flow, 2: slump, 3: flow, 4: fan accumulation, 5: flow, 6: slides and spreads). This major catastrophic event is responsible for the deposition of a 5 to 15 m thick turbidite in the deeper part of the fjord, a few kilometres to the East (Perret *et al.* 1995, see also later in Figure 21).

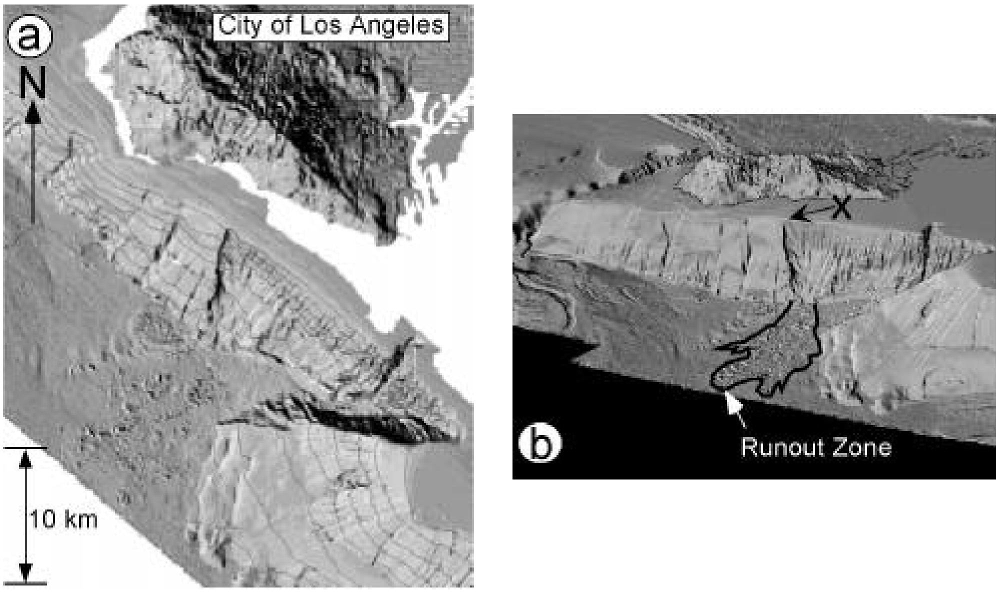


Figure 6. Palos Verdes slide. “a”: plane view, “b” 3D view. The “x” identifies the northwest extent of the detachment area (Source USGS).

Palos Verdes slide, California, USA

The Palos Verdes slide (Figure 6), off Los Angeles, had long been recognised based on seismic reflection logs (Gorsline *et al.* 1984). The slide took place along a steep escarpment, mobilized into a debris avalanche and traveled a distance of about 10 km out onto the adjacent basin floor. The head scarp is about 500m high and the slope varies between 15-20°. The debris was dispersed over a wide area shown in figure 4b. From seismic records (Hampton *et al.* 1996) the thickness of the debris deposit varies from about 20 m in the lower part of the slope to less than 1m, 10 km away from the base of the slope, with an average thickness of 5 to 10m.

The image shown in Figure 6 appears to illustrate a process of continuing instability development towards the northwest. The precise nature of the material involved in the slide remains to be determined. According to the slope geometry and the blocky morphology still observable in the run out zone, the material appears to be made of stiff sediments or rock. The presence of these landslide scars and others in the area have triggered an interest in the study of slide-related tsunamis, in particular for populated areas (Locat *et al.* 2000b, see also Kulikov *et al.* 1996, 1998, Thomson *et al.* 2000).

Humboldt Feature, Eel River Margin, California, USA

An example of a possible landslide feature in the Eel River Margin was investigated as part of the STRATAFORM Project (Nittrouer 1999a and 199b). One component of this study is to understand sediment stability and transport (Lee *et al.* 1999, Orange 1999). Accordingly, a detailed description of the morphology is an essential part of any analysis (Goff *et al.* 1999).

The 3D bathymetry picture shown in Figure 7a represents the study area which can be divided into two parts. The northern part, located to the north of a breached anticline (a small sea mount in the middle on the slope), is represented by a fairly smooth slope with more or less regularly spaced gullies. The southern sector is characterized by a semi-circular amphitheater, containing a series of hummocks (Fig. 7b), which may be either the result of a large deep-seated submarine failure (as interpreted by Gardner *et al.* 1999) or a series of migrating sediment waves (an alternate interpretation described by Gardner *et al.* 1996). The water depth range in this image is from zero to about 200 m near the shelf break and about 500m near the base of the slope. The slope itself is at an angle of about 1° to 6° and the slope break is at about 20 km from the shoreline. This example illustrates both the application of state-of-the-art technology to undersea mass-movement processes and the difficulty in some cases in discriminating between seafloor failures and seafloor depositional bed-form features.

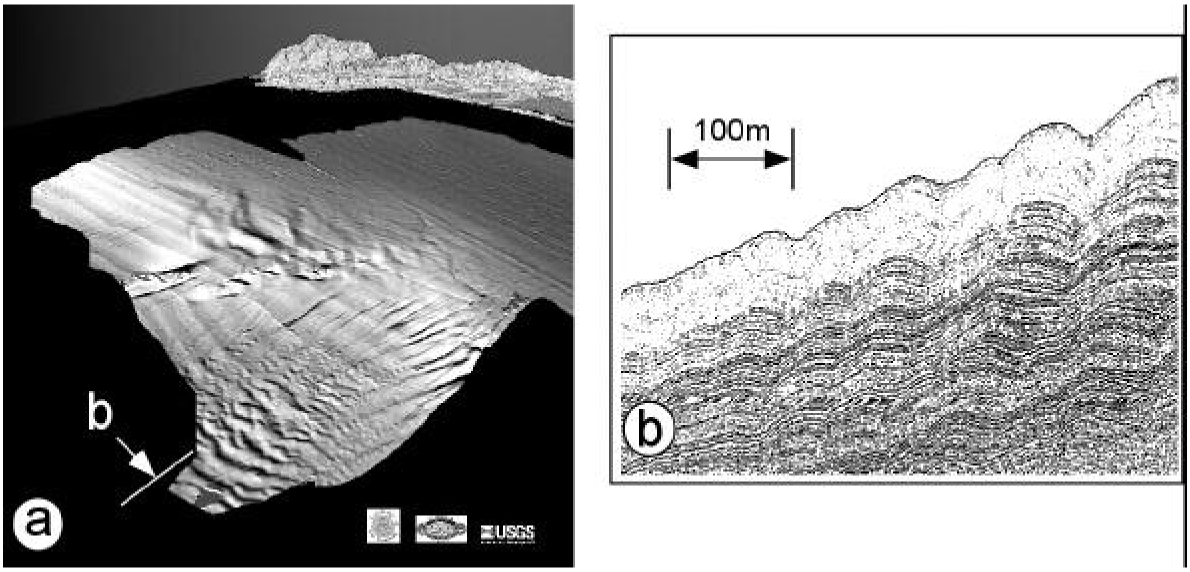


Figure 7. Humboldt Feature, Eel River Margin, California (see Gardner *et al.* 1999 and Lee *et al.* 1999 for discussion), a: swath bathymetry sun illuminated 3D map; b: Huntec seismic section with the location shown in "a".

Lake Tahoe Rock Avalanche, California/Nevada, USA

Lake Tahoe, located along the boundary between California and Nevada, is at an elevation of 1900m. A multibeam sonar survey (Figure 8) of the lake was carried out in 1998 (Gardner *et al.* 1998). For this work, the EM1000 was mounted on a small vessel (8 m long). Lake Tahoe, one of the deepest lakes in the United States, is located between two major faults, including the Sierra Nevada fault which is located about two kilometres west of the lake.

Most rocks in the area were produced by volcanic activity. The landscape itself has been locally modified by glaciers.

The head-scarp of this large rock avalanche is about 5 km wide and the debris traveled a distance to a point near the center of the lake. Some lumps of isolated debris are of the order of 100 m in length. The north flank of the rock avalanche, in the starting zone, appears to be limited by strong lineament systems intersecting at an angle of about 130° (see arrows in Figure 8a).

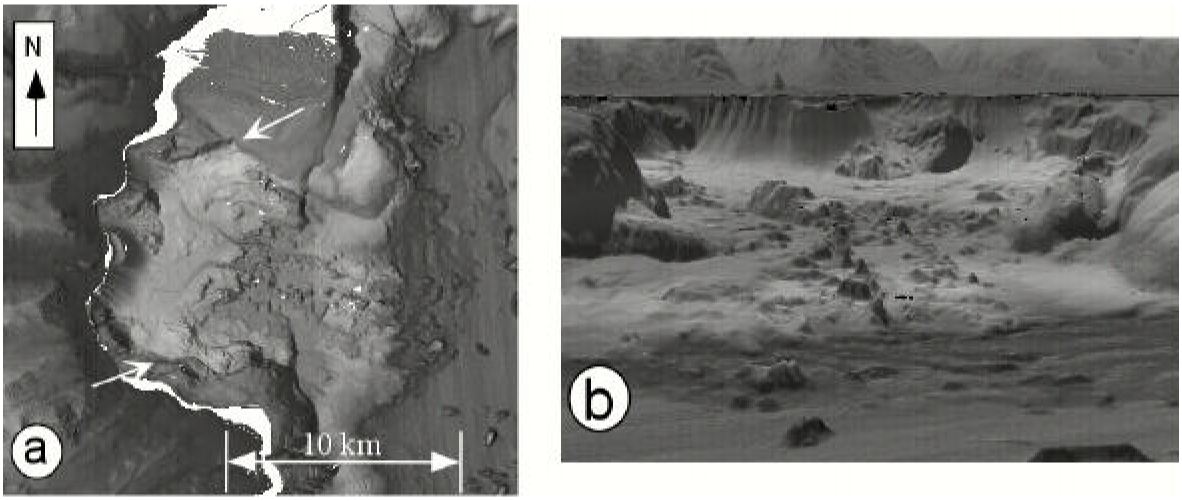


Figure 8. Lake Tahoe debris avalanche (see Gardner *et al*. 1998 for details); a: plan view of the debris avalanche area, with the arrows pointing at lineament intersections, b: 3D view looking towards the west.

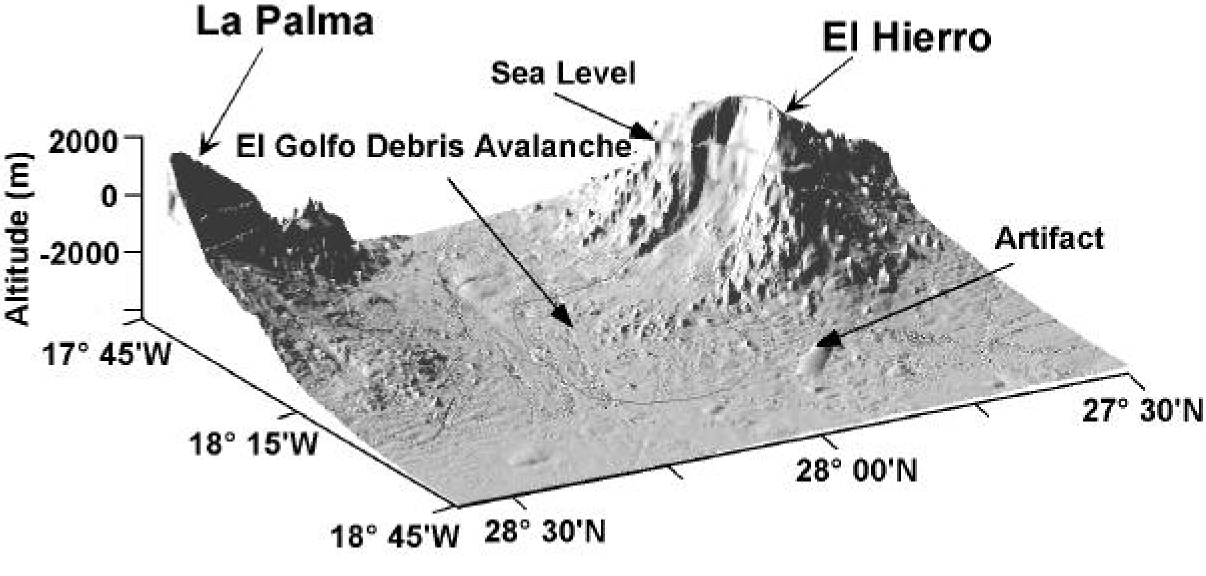


Figure 9. El Golfo debris avalanches off El Hierro Island (Canary Islands, Spain, Urgeles *et al.* 1997), and the western tip of the Cumbra Nueva debris avalanche in La Palma on the left side of the image.

Canary Islands Rock Avalanches, Spain

The Canary Islands rock avalanches have been initiated on the non-buttressed flanks of the island, which is bounded by the rift systems where most eruptions take place (Figrue 9). The avalanche spreads almost to the top of the island (1500 m) in El Hierro, 2400m in La Palma or 3700 m in Tenerife, which holds the third highest oceanic volcano on earth after Mauna Loa and Mona Kea in Hawaii (Moore *et al.* 1992, 1995). These avalanches travelled distances of beteeen 50 to 100 km down to ocean depths of up to 4000 m and involved volumes of up to several hundred of cubic kilometers (Urgeles *et al.* 1997, 1999; Watts and Masson, 1995, 1998). This type of mass movement is very similar to those reported by Moore and Normark (1994) for the Hawaiian Islands. Major rock avalanches are now reported around many volcanic islands (*e.g.* Elsworth and Voight 1995; Voight and Elsworth 1997, F. Giocci, personal communication, Stromboli island).

Comments on Morphology

In addition to bathymetry, the multibeam systems also commonly measure the backscatter intensity, which is related to the quantity of acoustic energy being returned from seafloor (Borgeld *et al*. 1999). Acoustic backscatter depends, at least in part, upon the physical properties of the seabed, including the density and grain size. A reliable method for estimating sediment density and grain size from acoustic backscatter values has not as yet been developed and remains one of the challenges to maximizing the usefulness of multibeam information.

Seismic methods are also being more and more integrated with the morphological data. In this sense, the development of 3D analysis of sediment architecture has recently been of growing interest and has been initiated by the oil industry. More recently, 2D and 3D seismic data have been integrated in the study of sediment deposition (Driscoll and Kramer 1999). In parallel, the development of synthetic seismograms has provided a bridge between modelers and geophysicists. It is hoped that these techniques will also be integrated in the study of submarine mass movements.

GEOTECHNICAL INVESTIGATIONS OF SUBMARINE LANDSLIDES

Submarine landslides occur in various environments, like on land mass movements. While seismic and multibeam surveys can be carried out on a cost effective manner, sampling and *in situ* testing, on the other hand, are not as easy and often much more costly for the same level of quality. Except for cases involving offshore resources such as oil and gas, in most situations sampling is done by means of gravity methods: Calypso (up to 60 metres, mounted aboard the Marion Dufresnes II, IFREMER), Long Coring Facility (up to 30, metres, Geoscience Atlantic, Canada), Lehigh (up to 3 metres), Kastin corer (up to 3 metres), box corer (0.6 metre) and surface sampler (Shipek, VanVeen). The best coring method is the box corer but it has a very limited penetration! All other methods have their intrinsic difficulties mainly related to the partial remolding of the soil during the penetration in the sediment. Ongoing research efforts are being directed toward developing a remotely operated drilling equipment, called the PROD. This coring tool is designed to sample to 100 metres below the seabed in any kind of material (soil or rock). Such depth ranges would be satisfactory for most of the submarine mass movement investigations.

In situ techniques have been developed for general purposes but can be used in submarine landslide investigations. The Lancelot and Excalibur probes were designed as piezocone, which can also collect gas samples (limited to about 10 metre in soft sediments, Christian *et al*. 1993, 1994).

MECHANICS OF SUBMARINE LANDSLIDE INITIATION: PRE-FAILURE AND FAILURE STAGES

Researchers have specified many possible triggers for the initiation of submarine landslides including: 1) oversteepening, 2) seismic loading, 3) storm-wave loading, 4) rapid accumulation and underconsolidation, 5) gas charging, 6) gas hydrate disassociation, 7) low tides, 8) seepage 9) glacial loading and 10) volcanic island processes (Figure 1a). Seismic loading and oversteepening were considered in the early work of Morgenstern (1967), and many submarine landslide initiation prediction procedures have focused on these triggers ever since (*e.g.*, Lee *et al.*, this meeting). However, recent work (Boulanger *et al.* 1998, Boulanger 2000) has shown that repeated, non-failure, seismic events can actually strengthen the sediment column through development of excess pore water pressures during earthquakes and subsequent drainage and densification during intervening periods. By carrying out a series of cyclic-loading tests on normally consolidated specimens, we observed (Figure 10d) that the sediment begins to exhibit overconsolidation and a significant strength increase if a period of drainage is allowed between repeated earthquake simulations. This figure illustrates the dynamic response (10a, b and c) of a soil sample from Eel River margin tested under cyclic loading under a cyclic stress ratio of 0.242 and an effective stress of 50 kPa. Figure 10 (a to c) shows the three ways used to define the failure criteria: (1) pore pressure, (2) deformation and (3) failure envelope. Figure 10d presents the test results on a normally consolidated specimen which has been taken through repeated cyclic loading (below the failure point) and drainage periods. The specimen clearly exhibits a decrease in the void ratio and an increasing shearing resistance to liquefaction after each cycle. We propose to call this build up of shearing resistance, seismic strengthening, and suggest that this mechanism partly explains the paucity of shallow submarine landslides on the Eel River Margin, the most seismically active margin in the continental U.S., and possibly in other areas with similar sediment and tectonic settings.

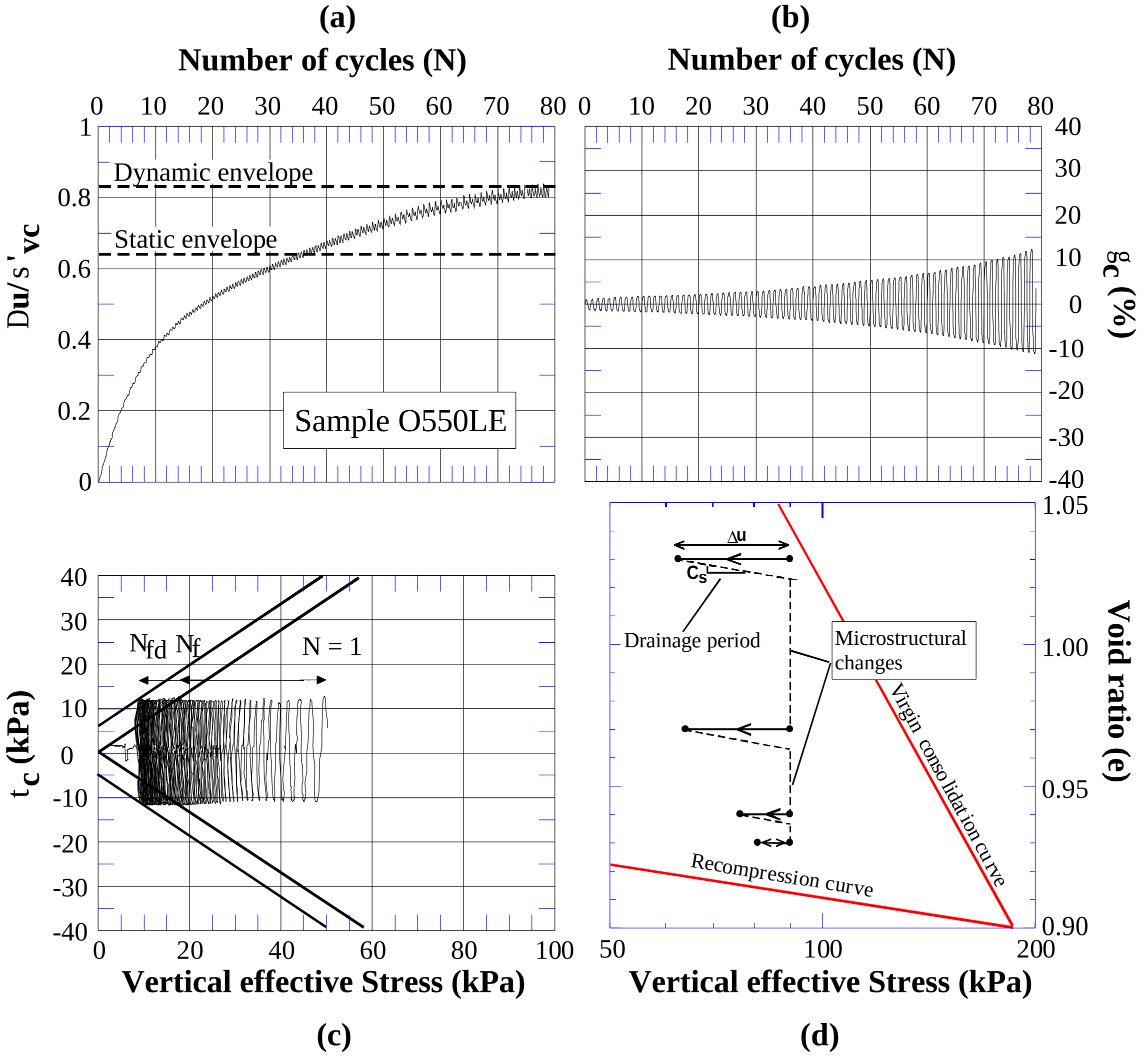


Figure 10. (a, b, c): Dynamic response of a natural sample from Eel river Margin (California) showing the number of cycles to failure in an undrained case using different methods. (d): effects on void ratio of only few cycles of cyclic loading and drainage (Boulanger *et al.* 1998; Boulanger 2000). Symbols specific to this figure are as follows: σ'_{vc}: vertical effective consolidation stress; γ_c: cyclic deformation, τ_c: horizontal shear stress; N: number of cycles; N_f: number of cycles to failure, Δu: excess pore pressure.

Storm-wave loading and underconsolidation became recognized as major factors in causing submarine landslides following the failure of or damage to several offshore drilling platforms when Hurricane Camille struck the Mississippi Delta in 1969 (Bea *et al.* 1983). Further work (*e.g.*, Whelan *et al.* 1977, Hampton *et al.* 1982) showed that bubble-phase gas charging can degrade sediment shear strength and contribute to slope failure. Other studies (*e.g.* Kvenvolden and McMenamin 1980) have shown the existence of gas hydrates underlying many submarine slopes. Such hydrates are icelike substances, consisting of natural gas and water, which are stable under certain pressure and temperature conditions that are common on the seafloor. When temperatures increase or pressures decreases, the stability field changes and some of the hydrate may disassociate and release bubble-phase natural gas. Unless pore water flow can occur readily, this gas charging leads to excess pore pressures and degraded slope stability. Kayen and Lee (1991) suggested that worldwide lowering of sea level during glacial cycles could lead to numerous slope failures because of gas hydrate disassociation. Of more immediate interest, warming of the seafloor through changes in current patterns or global warming could potentially cause a similar effect (Figure 11). The impact of oil and gas offshore production in areas where gas hydrates are present poses difficult questions regarding the effect of these activities on the gas hydrate stability and its link to slope instability or the potential re-activation of older mass movements.

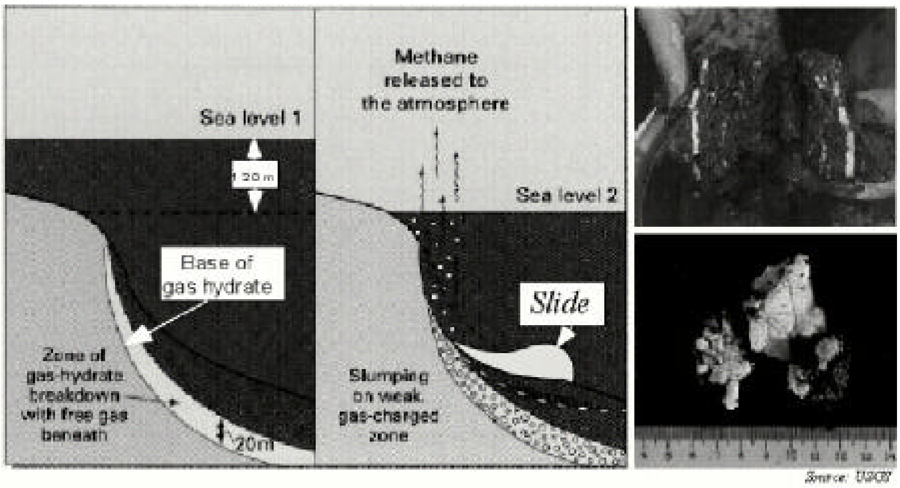


Figure 11. The role of gas hydrates on slope instability development as a results of sea level lowering.

Coastal landslides frequently occur during low tides through a mechanism similar to the rapid drawdown condition in earth dams or of failure at delta fronts (Mulder *et al.* 1993). The Kitimat Arm failure (Prior *et al.* 1982), which occurred in British Columbia in 1975, is a classic example of such a mechanism, as is a more recent failure in Skagway, Alaska, that was responsible for killing a worker (George Plafker, personal communication, Cornforth and Lowell 1996, Kulikov *et al.* 1996). Low-tide-induced failures are part of a larger group of submarine landslides that are caused by water seepage effects. Seepage can occur beyond the immediate coastline through coastal aquifers (Robb 1984) and other pore fluid migration processes, including sediment subduction at plate boundaries (Paull *et al.* 1990, Orange and Breen 1992). Under appropriate conditions, such seepage can lead to failure and potentially to the ultimate development of submarine canyons (Orange *et al.* 1997).

Continental glaciation may play a significant role in inducing landslides (Mulder and Moran 1995). Factors that may be important include loading and flexing of the crust, greatly altered drainage and groundwater seepage, rapid sedimentation of low plasticity silts, and rapid emplacement of moraines and tills. A particularly dense set of large submarine failures off New England (O'Leary 1993) could be related in part to nearby continental glaciation.

Volcanic islands constitute an environment within which submarine landslides are extremely common as well as being among the largest, if not the largest, mass movement features on the surface of the earth (Moore and Normark 1994, Holcomb and Searle 1991, Voight and

Elsworth 1997, Masson *et al.* 1998). The landslides include debris avalanches with runout distances exceeding 200 km and giant slumps that can produce M7 or greater earthquakes as they deform (Lipman *et al.* 1985) or could have been produced by them (Moore *et al.* 1994). The extent of these features has only been recognized since the development of such long range sidescan sonar devices as GLORIA. The immediate hazard to volcanic islands from failures such as these is clear as is the hazard to more distant locations through the production of tsunamis. The cause of the failures is not well understood although it must be related in part to the presence of magma near the failure surfaces, the physical properties of rapidly emplaced volcanic rock, and magma or gas pressures within the core of the islands. A challenge to submarine landslide research is to determine whether any of the giant slumps could convert to catastrophic debris avalanches and to evaluate the likelihood of any giant landslide activity with a timeframe that is relevant to present coastal and island populations.

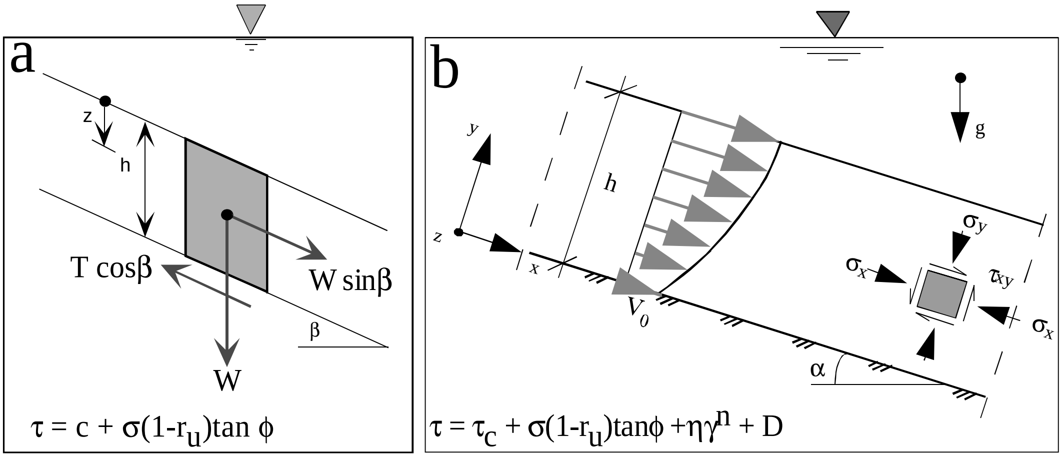


Figure 12. The failure (a) and post-failure (b) mechanics along an infinite slope (D: drag)

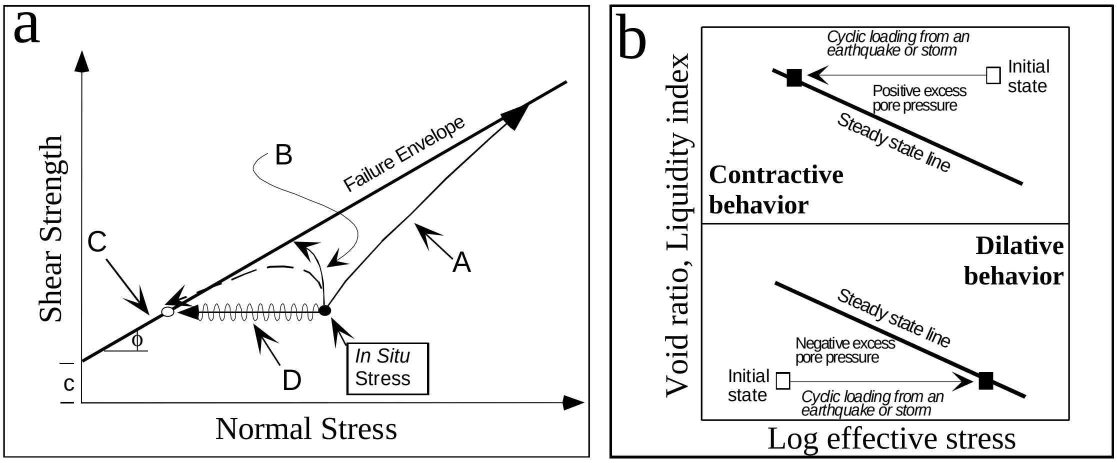


Figure 13: A mechanistic illustration of conditions leading to: (a) failure in soils (A: dilative failure, B: contractive failure, C: liquefaction failure, D: cyclic loading failure), (b) onset of liquefaction.

Following initial failure (Figure 12a) some landslides mobilize into flows (Figure 12b) whereas others remain as limited deformation slides and slumps. The mechanisms for mobilization into flows are not well understood but at least one factor is likely the initial density state of the sediment (Poulos *et al.* 1985, Lee *et al.* 1991). If the sediment is less dense than an appropriate steady state condition (contractive sediment) the sediment appears to be more likely to flow than one that is denser than the steady state (dilative, Figure 13b). The ability to flow may also be related to the amount of energy transferred to the failing sediment during the failure event (Leroueil *et al.* 1996). This particular aspect of mobility is addressed in more details in the following section.

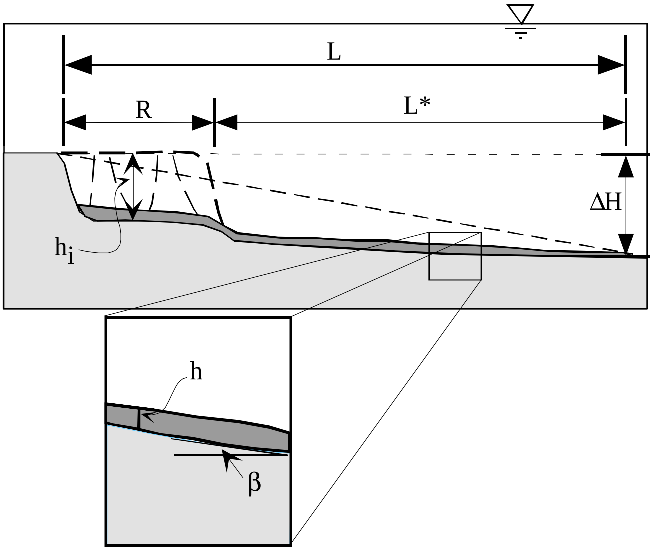


Figure 14. Geometrical description of mobility (h_i: initial height, h: flow thickness).

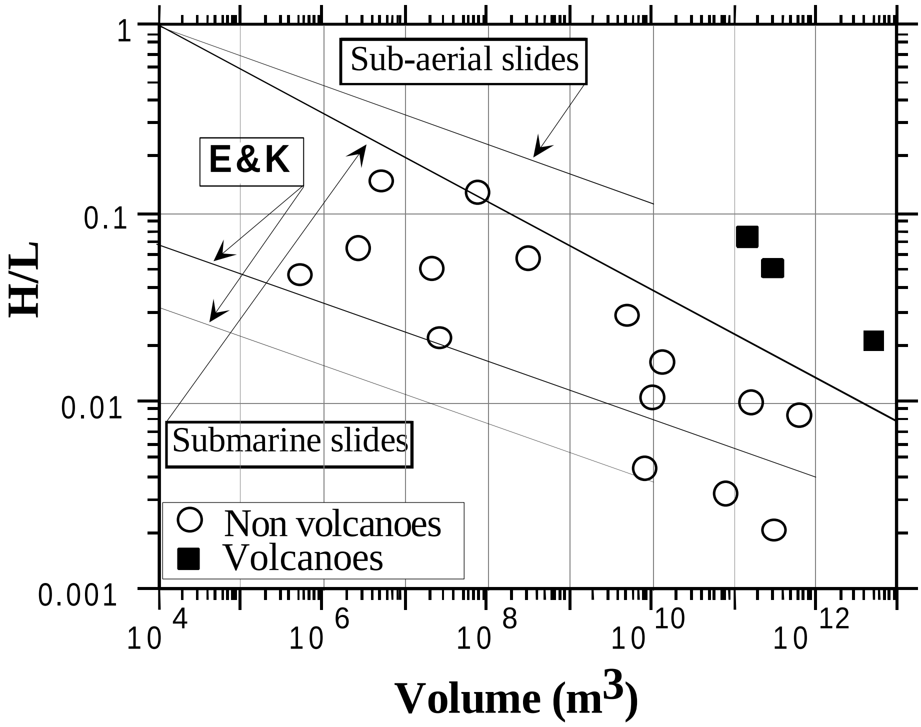


Figure 15. Mobility of submarine mass movements as a function of the H/L ratio and the volume (E&K: Edgers and Karlsrud 1982, see Hampton *et al.* 1996 for landslides data).

MECHANICS OF SUBMARINE LANDSLIDE MOBILITY: POST-FAILURE STAGE

In considering the mobility of a mass movement, we can distinguish two components: the retrogression (R, in Figure 14) and the runout distance (L). Heim (1932) first proposed to look at the mobility of a given mass involved in a landslide in terms of the geometry of the deposits before and after the slide event. Heim (1932) proposed the use of the term Farboschung (F = H/L), which represents the angle of the line joining the escarpment to the maximum distance reached by the debris. The Farboschung is commonly used to characterize the mobility of a mass movement. In such a definition, the term, L, would also include R. For slides in sensitive clays, R has been related to the ratio of Cu/γH (Mitchell and Markell 1974, where Cu is the undrained shear strength and γ the bulk unit weight). The R parameter has also been linked to the liquidity index (I_L) by Lebuis *et al.* (1983). The term, R, although not well constrained in the case of submarine landslides, becomes negligible for long travel distances but still remains a critical element for the positioning of sea floor structures.

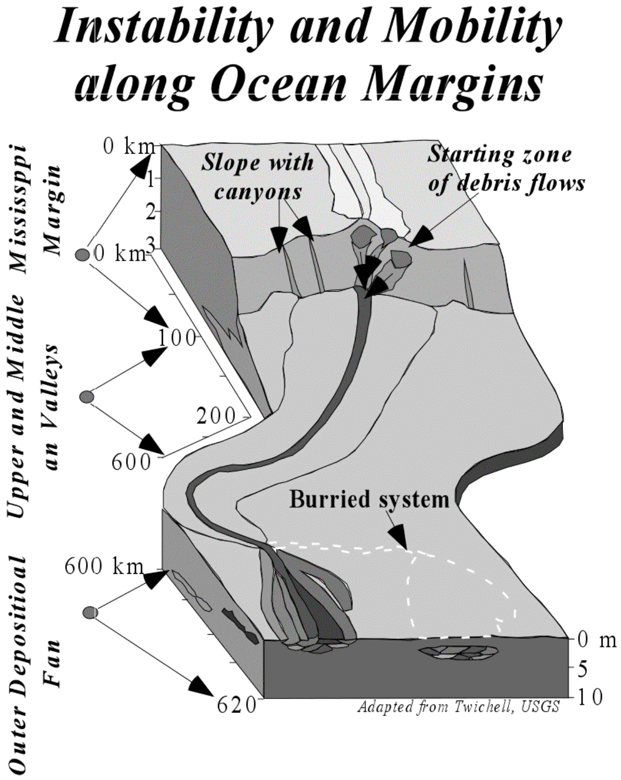


Figure 16. Schematic view of far-reaching debris flows deposited on the Gulf of Mexico Fan (modified after Twichell, USGS).

Heim (1932) observed that for sub-aerial slides, the value of F was inversely proportional to the initial volume (V) of the sliding mass. Edgers and Karlsrud (1982) reviewed the extent of submarine slides and compiled data on values of F and V for submarine landslides, which has been updated by Hampton *et al.* (1996, Figure 15). Figure 15 does not distinguish cases where flow is channelized, for which case it would tend to provide much greater run out distances. In comparison with sub-aerial slides, submarine landslides are much more mobile and tend to involve larger volumes (Figure 15). The (F vs V) relationship results directly from the transformation of the potential energy (E_p) of a given mass into other forms of energy, including kinetic energy (E_k) such as:

[1]

$$E_p + E_s = E_k + E_f + E_D + E_v + E_r$$

Where E_s is the seismic energy resulting from an earthquake, E_f the friction loss, E_D the friction loss due to drag effects on the upper surface of the flow, E_v the loss due to viscous effects and E_r the energy used to remold or transform the intact material. During the course of a submarine slide event (or also a sub-aerial slide), there appears to be a process by which there are some changes in solid to water ratio which provides a sufficiently low strength to allow flow to take place (see also the Figure 1b). Whatever the exact nature of the phenomenon, it is embedded in the remolding energy (E_r). Many hypotheses are proposed to explain the development of flows, including: (1) it must take place at the time of, or soon after, failure, (2) the transformation of the original mass can result from fragmentation associated with inter-collision in rock masses (Leroueil *et al.* 1996, Davies *et al.* 2000), and (3) it may include the effects of impact with the sea floor of the rock mass (*e.g.* case on chalk along the coast of England, Hutchinson 1988) or soil (Flon 1982, Tavenas *et al.* 1983).

Similarly, to explain far reaching debris flows reported by Schwab *et al.* (1996), Locat *et al.* (1996) invoked a significant loss in strength of the soil mass in the starting zone to account for the very low remolded shear strength required for the observed mobility (up to 400 km, Figure 16).

Possible boundary conditions during a flow event are illustrated in Figure 17. As for snow avalanches (Norem *et al.* 1990), the flowing material is divided into two components: dense and suspension flows. The dense flow could be either a rock avalanche, a debris flow or a mud flow. The suspension flow, which is generated by the drag forces acting on the upper surface of the dense flow will transform into a turbidity current once the dense flow stops or moves slower than the suspension flow. This phenomenon can take place on slopes as low as 0.1° (Schwab *et al.* 1996). Recently, Mohrig *et al.* (1999) have shown that once a critical velocity is reached, around 5 to 6 m/s, hydroplaning could also induce added mobility by reducing the shearing resistance at the base of the flowing mass (Figure 17). This process of hydroplaning is similar to what has been observed by Laval *et al.* (1988) for density surges and turbidity currents. This process will tend to lift the frontal portion of the dense flow thus reducing the shearing resistance at the interface with the underlying immobile layer. During the flow, we should expect some erosion or sedimentation to take place but these phenomena still remain to be described more fully and integrated into numerical models. In some environments, *e.g.* the Gulf of Mexico, the flow will be channelized and if the channel is filled and the flow height in excess of the critical flow height, flow can proceed over long distances (Johnson 1970).

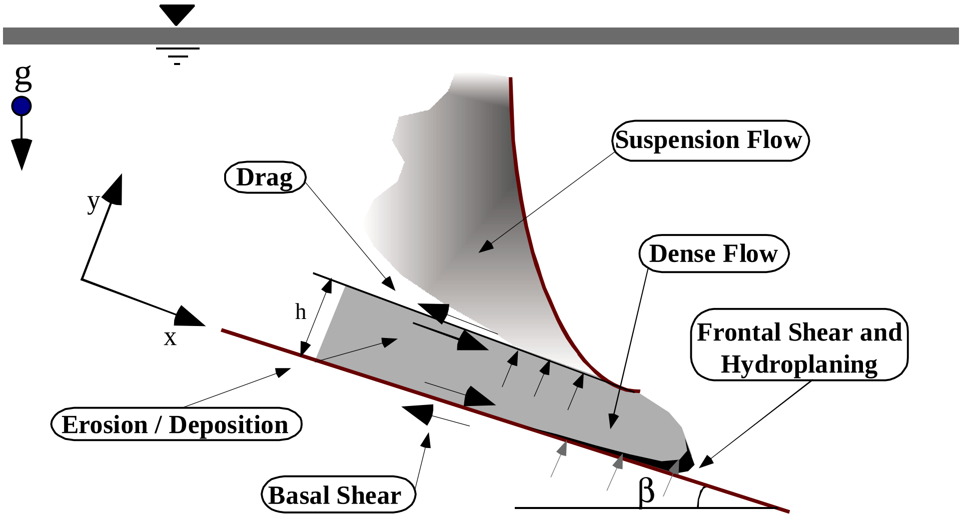


Figure 17. Schematic diagram showing the generation of a turbidity current (suspension flow) for drag forces on the surface, potential lifting of frontal lobe leading to the process of hydroplaning, the basal shear stress causing erosion and deposition.

Once a mudflow or a debris flow is generated, the velocity of the flowing mass is such that the flowing material remains under undrained condition. In such a case, and considering the high rate of movement, the phenomenon is best described by means of fluid mechanics rather than soil mechanics. In the case of mudflows or muddy debris flows, the flow behavior can be represented by three types of fluids (Locat 1997):

A Bingham fluid (see also Johnson 1970, Huang and Garcia 1999):
[2]

$$t = t_c + hg^n$$

A Herschel-Bulkley fluid (see also Coussot and Piau 1994):
[3]

$$(t - t_c) = Kg^n$$

A bilinear fluid (see also O'Brien and Julien 1988):
[4]

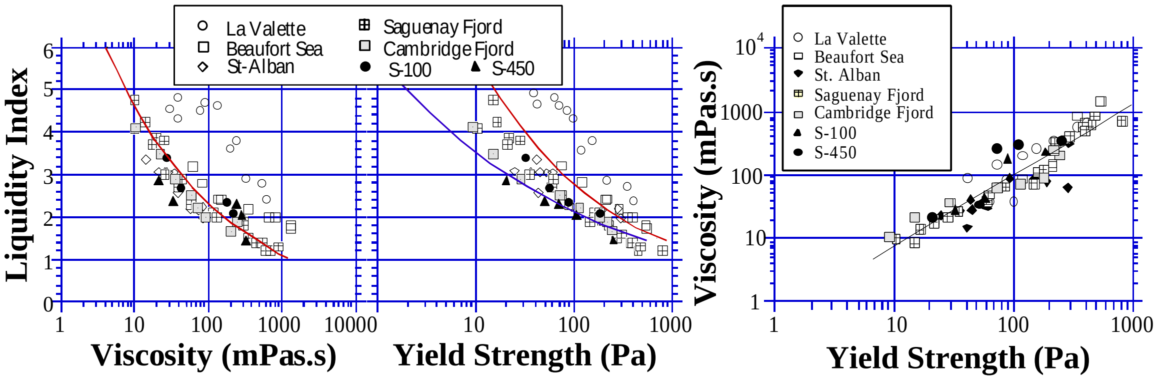
$$t = t_c + hg + \left(\frac{c}{g + g_0} \right)$$

where τ is the resistance to flow, τ_c the yield strength, η the dynamic viscosity (mPa.s), γ the shear rate (not to confuse here with the unit weight in soil mechanics) and γ_0 the shear rate corresponding to the yield strength of the bi-linear fluid. K has units of mPa.s and is equivalent to the viscosity once the mixture is analyzed as a non-yield-stress fluid. The fluid is qualified as pseudoplastic for $n < 1$, as a dilatant fluid for $n > 1$, and as a Bingham fluid for $n = 1$.

For the study of various submarine slides, Norem *et al.* (1990) proposed to use a visco-plastic model as described by:
[5]

$$t = t_c + s\,(1 - r_u)\tan f' + hg^n$$

where σ is the total stress, r_u the pore pressure ratio ($u/\gamma h$) and ϕ' the friction angle. This constitutive equation is a sort of hybrid model, similar to what has been proposed by Suhayada and Prior (1978). The first and third terms of the equation are related to the viscous component of the flow, as in equations [2], [3] and [4]. The second term is a plasticity term described by the effective stress and the friction angle. An interesting aspect of such an approach is that it can be adjusted to various flow conditions. For example, if we consider a rapidly (undrained) flowing granular flow we would be mostly using the third term of [5] with a value of "n" greater than 1. In the case of a mud flow (undrained), terms one and two of [5] would be used but the value of "n" in [5] would be less than or equal to 1. For flows where the velocity and the material properties are such that excess pore pressure can dissipate, than the second term could dominate and the equation would approach the sliding-consolidation model proposed by Hutchinson (1986). For rock avalanches, the last two terms of [5] would be considered.



(a) (b) (c)

Figure 18. Using the liquidity index (I_L) to estimate the rheological parameters of mudflows or muddy matrix of debris flows. (Note that water, at 20°C, has a viscosity of 1 mPa.s).

In many cases, we consider the mixture as a yield stress fluid so that the rheological behavior of the matrix can be represented by a yield strength and a viscosity parameter. It has been proposed that the yield strength and viscosity could be related to the liquidity index (Locat and Demers 1988, Locat 1997). Results obtained for various soils or sediments are given in Figure 18. The results are partly influenced by the floc size and also by salinity in the case of the yield strength (Locat 1997). Nevertheless, for a single sediment or soil, the quality of the relationship is quite reasonable. An interesting observation is that the yield strength contributes about 1000 times more than the viscosity to the resistance to flow of the fluid. The results in Figure 18 are used hereafter to provide a first approximation of the relationships between liquidity index and rheological parameters (see also Locat 1997):

[6]

$$h = \left(\frac{9.27}{I_L} \right)^{3.3}$$

[7]

$$t_c = \left(\frac{5.81}{I_L} \right)^{4.55} \text{ for a salinity of about 0 g/L,}$$

[8]

$$t_c = \left(\frac{12.05}{I_L} \right)^{3.13} \text{ for a salinity of about 30 g/L.}$$

[9]

$$h(mPa.s) = 0.52 t_c^{1.12} (Pa)$$

Recently, these relationships have successfully been used by Elverhoy *et al.* (1997) to analyze the behavior of debris flows along the coast of Norway. For mudflow or matrix controlled debris flows, Hampton (1972) has shown that the minimum thickness of the flowing material (H_c, in metre) for flow to take place can be defined by the following relationship:

[10]

$$H_c = \left(\frac{t_c}{g^{'} \sin b} \right)$$

where γ' (in kN/m^3, not to confuse here with the shear rate in fluid mechanics) is the submerged unit weight and β the slope angle (note that here the unit of τ_c is given in kPa). From a series of tests results on density and liquidity index measurements (Locat *et al.* 2000a) we can propose the following relationship to relate liquidity index and unit weight (γ, in kN/m^3):

[11]

$$I_L = \left(\frac{17.60}{g} \right)^{6.80}$$

or

[12]

$$g = 17.60 I_L^{-0.147}$$

and modifying [8], for seawater, to adjust τ_c in kPa so that:

[13]

$$t_c = 2.42 I_L^{-3.13}$$

we can rewrite [10] as a function of the liquidity index:

[14]

$$H_c = \frac{2.42 I_L^{-3.13}}{\left(17.60 I_L^{-0.147} - g_w\right) \sin b}$$

where γ_w is the unit weight of water. Equation [14] is a generalization of the approach already proposed by Schwab *et al.* (1996) for debris flows in the Gulf of Mexico. Equation [14] could easily be re-organized to express the H_c solely as a function of density but the transformation from the unit weight to the liquidity index also provides access to many other empirical relationships (see the above equations). To illustrate the use of [14], let us consider a case where a mudflow can take place on a slope inclined at 0.06° (case of the Gulf of Mexico, Schwab *et al.* 1996). Considering a unit weight of between 13.5 and 14 kN/m^3, we can compute the liquidity index from [11] and find that the I_L varies between 5 (from [12], $\gamma = 13.9\ kN/^3$) and 6 (from [12], $\gamma = 13.5\ kN/m^3$). Entering these results in [14], we obtain a value for H_c, at 3.7m and 2.1 m respectively.

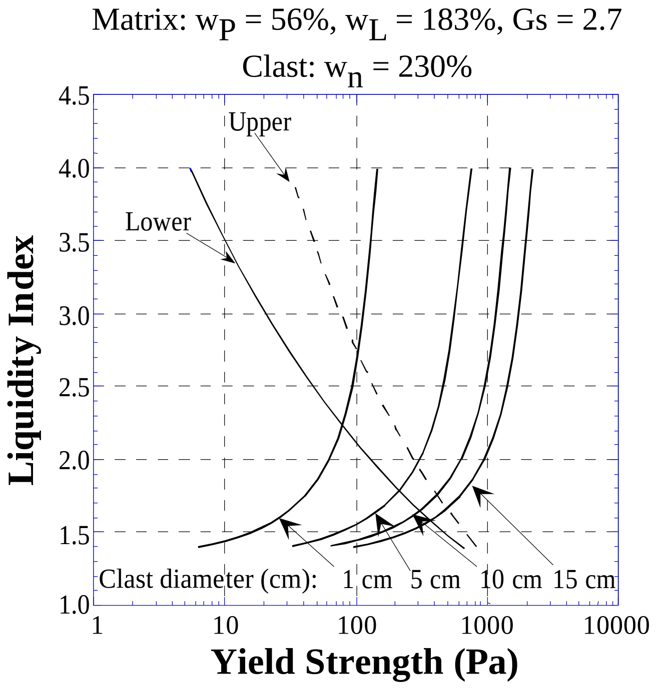


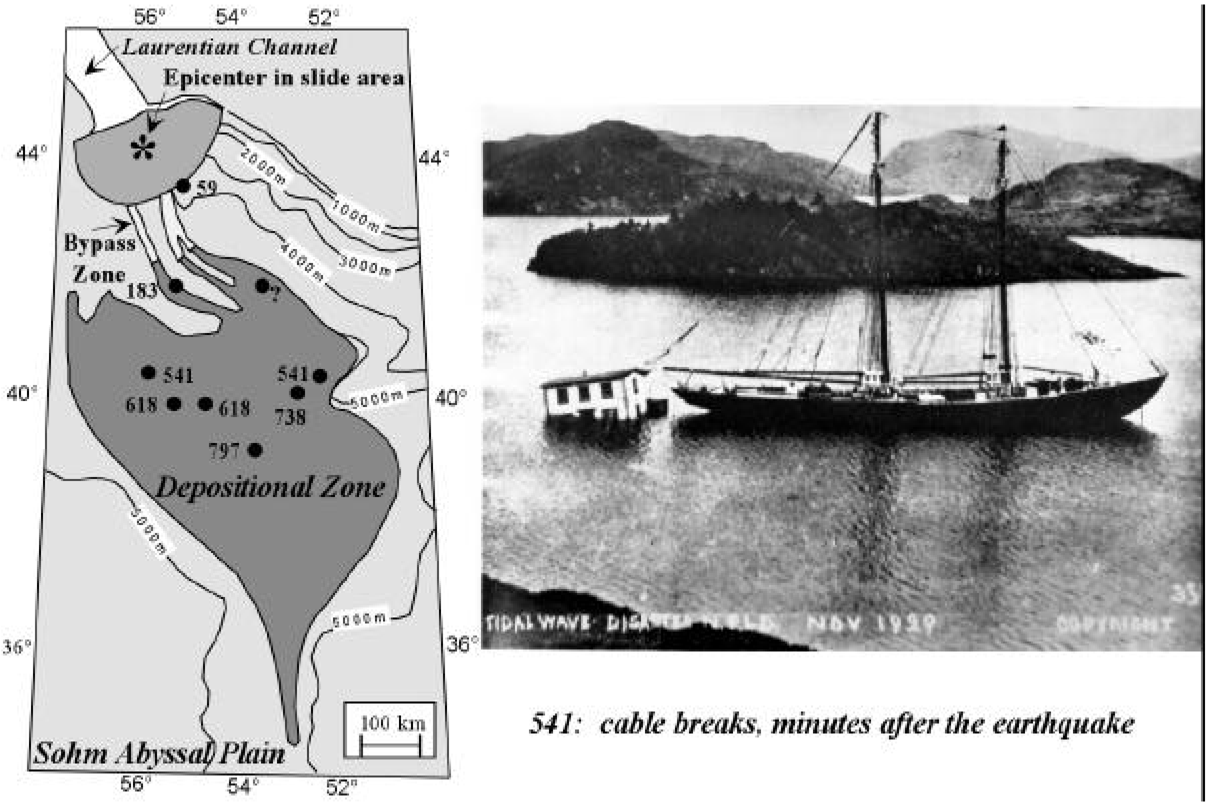
Figure 19. Using the liquidity index/yield strength relationship to estimate rheological properties at the time of debris flow formation. Index properties are given for this computation (w_p: plastic limit; w_L: liquid limit; G_s: grain density, w_n: natural water content of the clast).

Similarly, the liquidity index-yield strength relationship can also be used to back-calculate the yield strength of a debris flow at the time of the event for as long as the water content of the clast is greater than the matrix (Figure 19). This assumes that no consolidation of the clast took place since deposition. Such an approach, based on the work of Hampton (1975) has been used successfully by *Schwab et al.* (1996) to analyze the mobility of debris flow on the Gulf of Mexico fan. Hampton (1975) considers the mixture like a Bingham fluid so that the largest diameter of the clast (D_{max}) which can be supported by the clay-water slurry is calculated with the following relationship:
[15]

$$D_{\max} = \frac{8.8t_c}{g\left(g'_c - g'_m\right)}$$

where g is the acceleration due to gravity, γ'_c and γ'_m the submerged unit weight of the clast and the matrix respectively (adapted from Schwab *et al.* 1996). The results shown in Figure 19 are illustrating the use of the above empirical relationships to generalize the approach proposed by Hampton (1975). The example in Figure 19 has been developed for the type of sediments indicated in the figure. We have represented the two extreme curves relating the liquidity index and the yield strength (from [7], [8]) which provide the realistic range of values for both liquidity index and yield strength. Also shown in Figure 19 is the computation of [15] for different values of D_{max} (here given in centimeters). For example, if the maximum observed clast diameter is 10 cm, the only possible ranges of liquidity index and yield strength values of the matrix would have to fall inside the area bounded by the so-called *upper* and *lower* curves. In addition, and has shown above (Figure 18), if for a given sediment the relationship between I_L and τ_c has been obtained using the viscometer, than the potential range of values can be greatly reduced. The end result can be quite useful in trying to determine the rheological conditions under which a mud flow or a debris flow has taken place (provided that the water content of the clast has not change since deposition, or could be estimated properly).

The above analysis of the submarine mass movements indicates that these phenomena are as diversified as they are on land, that they can be very mobile and involved very large volumes of material while still moving at significant velocities. By its own nature, the marine environment is not easily accessible, in particular for achieving a detailed description of the material involved. Therefore, the complexity of the submarine mass movements will have to be taken into account for hazard and risk assessment.



541: cable breaks, minutes after the earthquake

Figure 20. This sketch is adapted from Piper *et al.* (1985) who illustrated the extent of the Grand Banks slide of 1929. Note that the total travel distance affected by the slide and the resulting turbidity current extends as far as 1000 km from the epicenter. The water depth range here is from about 1000m to 5000m. The total event lasted more than 12 hours. The mass movement generated a tsunami that destroyed part of a village killing 27 people (see photograph where a schooner is towing a house in the harbor, GSC Archives).

HAZARD AND RISK ASSESSMENT

Evaluating the risk posed by submarine landslides and predicting the regional variation of future landslide events is in its infancy. The main questions raised about the hazard are (1) where did mass movement occur and where will it occur, (2) how frequently, (3) what are the triggering mechanism(s), (4) what is their area of influence and (5) can previous failures be re-activated ? These questions are similar to the one asked for terrestrial mass movements, but our actual knowledge is far from what has been already achieved for on land landslide risk assessment (Cruden and Fell 1997). As shown above, the extent of submarine mass movement can be well documented and some initial attempts (see below) are being made to predict the potential for landsliding on a regional scale. The other elements of the problem are not at all well constrained at the moment. The case of the Grand Banks slide (Piper *et al.* 1988) provides a good example to illustrate the various components which must be taken into account for a proper risk assessment (Figure 20). The 1929 Grand Banks earthquake triggered a major submarine slide which transformed into a debris flow travelling over a distance of not more than 80 km (Locat *et al.* 1990). The debris flow initiated a turbidity current which covered a distance of at least 1000 km ! Cable breaks data were used to indicate that the initial velocity was as high as 25 m/s and that it was still about 5 m/s at a distance of more than 500 km from the starting zone. In addition, the submarine landslide generated a 20m tsumani wave which moved toward the coast of Newfoundland killing 27 people (Piper *et al.* 1985, 1988). Here the triggering mechanism is clear: an earthquake. The observed area affected by the phenomena is huge: hundreds of square kilometers !

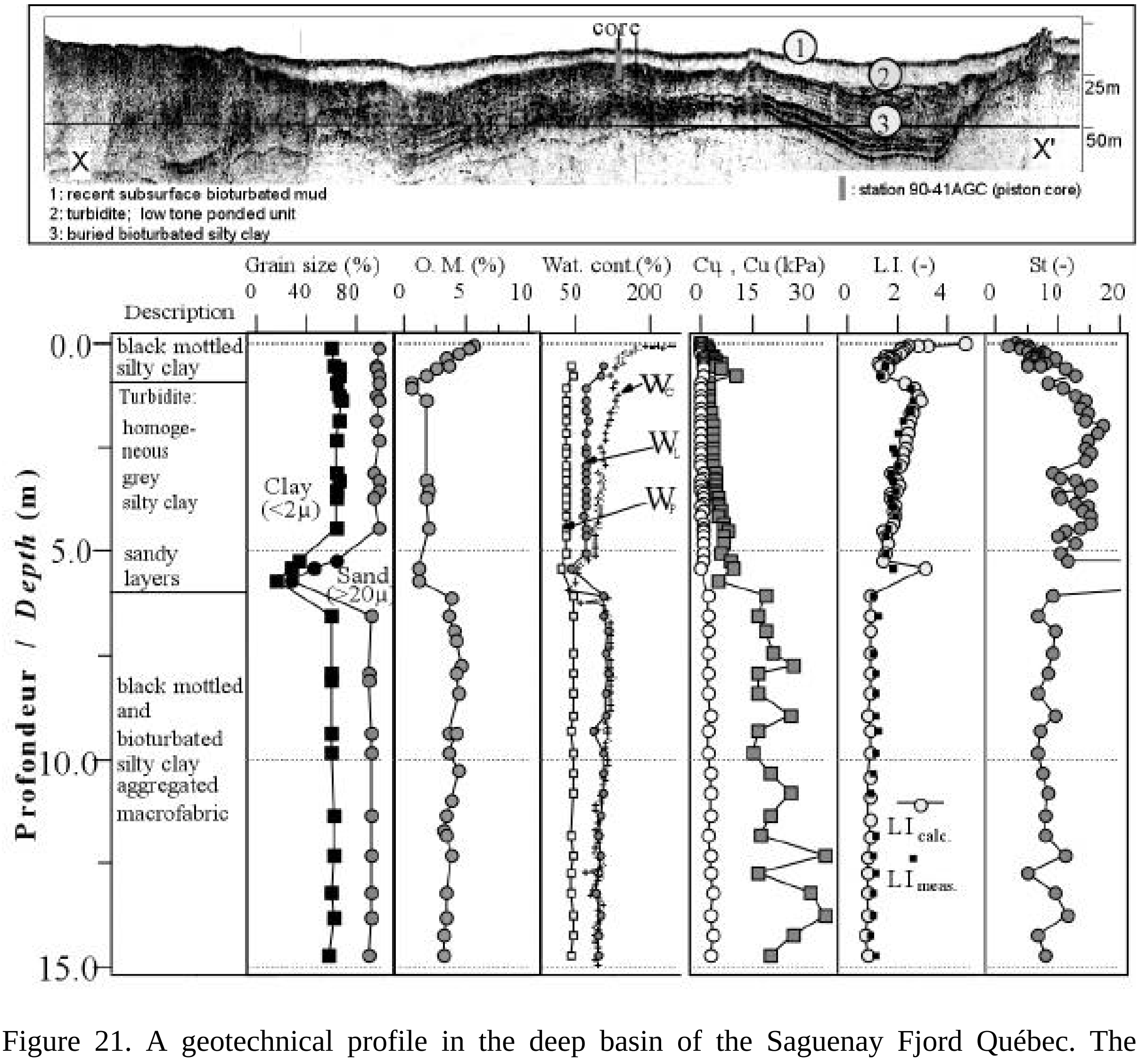


Figure 21. A geotechnical profile in the deep basin of the Saguenay Fjord Québec. The transparent layer near the surface (see geophysical profile at the top) is the turbidite layer clearly identifiable on the geotechnical profile below (modified after Perret *et al.* 1995)

The generation of the turbidity current is indicative of an initially rapid mass movement. On the other hand, the observed cable breaks suggest that the flow was still able to generate damage even at a distance of nearly 1000 km from the source. It is difficult to know if the earthquake and the slide itself did re-activate older mass movements or how frequent such events could be. The answer is likely to be written in the sediments either as "seismites" (sediment layers resulting from earthquake related sediment deposition, *e.g.* Perret *et al.* 1995, Figure 21) or by tsunami related sediment deposits (Clague and Bobrowsky 1994). As shown in Figure 21, turbidites will have a characteristic “geotechnical” signature. The upper part of the geotechnical profile (Figure 21) consist mostly of a 5m turbidite showing a regular increase in the shear strength. This turbidite layer covers a bioturbated unit which has a very different signature as shown by the higher variability of the shear strength. In the case of the Saguenay Fjord, if the turbidite has an organic content less than 1% it indicate that most of the material comes from on land mass movements; for the opposite case, it indicates an earthquake related submarine landslide (Perret *et al.* 1995). Therefore, longer cores of good quality are essential if one wishes to identify catastrophic layers which can than be dated or correlated in order to establish the submarine landslide hazard in a given area.

In terms of risk assessment, and apart from the work of Favre *et al.* (1992), little has been done about submarine landslides. The most recent activity has been a special Workshop on seabed slope stability and its impact on oilfield drilling facilities (International Association of Oil and Gas Producers 1999). One sentence (p. 3) from this workshop report says it all: “No one understands how to cope with big or deep slides, except by avoiding areas prone to this type of behavior”. This field is clearly new and requires methodological developments.

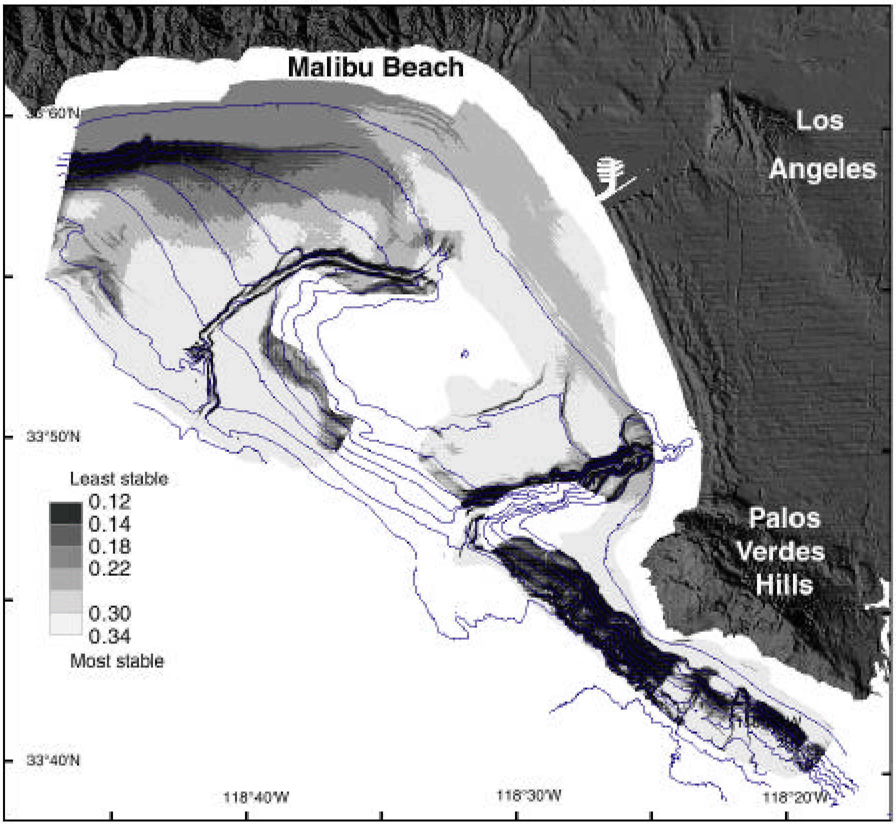


Figure 22. Example of a regional map showing landslide susceptibility from integrated geotechnical and seismic databases, the case of the Los Angeles area, California.

Referring to the above questions, we would like to propose the use of the geotechnical characterization of mass movements (Leroueil *et al.* 1996). Lee *et al.* (this meeting) have made a step in that direction by incorporating a variety of regionally varying data into a Geographic Information System (GIS) to develop predictions of relative landslide susceptibility for two offshore areas, Santa Monica Bay in southern California and the Eel Margin in northern California. The map shown in Figure 22 is produced by mapping the calculated values of the ratio of the critical horizontal earthquake acceleration (k_c) to the peak seismic acceleration with a 10% probability of exceedance in 50 years in the Los Angeles area.

The approach requires detailed bathymetry and acoustic backscatter information, such as are obtained from state-of-the-art multibeam systems. It also requires statistical information on loading functions, such as the probability of particular seismic accelerations. An example of the latter is available for much of the U.S. margin (Frankel *et al.* 1996). Perhaps most significantly, information on sediment properties and state is needed along with the variability of both of these with sub-bottom depth. Also desirable is the confidence one can place on this information given measurement errors and the limited availability of samples and in situ measurements (see also Favre 1992). Lee *et al.* (1999) deal with these requirements by mapping surface character using shallow sediment cores and then relying upon normalized soil parameters (Lee and Edwards 1986) to define the response of the sediment to burial. Such an approach cannot be used to extrapolate to sub-bottom depths greater than a few meters and limits the approach to only shallow landslides. The approach also relies upon infinite slope stability analysis (*e.g.* Fig. 12a) and thus is incapable of handling complex geometries. In spite of all of these limitations, the approach does provide an estimate of shallow landslide susceptibility that roughly mirrors the occurrence of such features on the margins investigated (Figure 22). A challenge to extending this approach to other situations is to make better quantitative use of remotely sensed data and to incorporate more sophisticated slope stability analysis techniques using predictive models for shear strength and burial (Locat *et al.* 2000a).

It is hope that the development of better coring methods and the use of 3D seismic will be integrated, along with modeling of soil properties, in a general approach which would provide the variability and distribution of the necessary properties or parameters. This, along with the other available tools for both static and dynamic analysis of slope stability, will provide the necessary information to evaluate both the hazard and the risk assessment related to submarine mass movements.

CONCLUSIONS

The above presentation was aimed at providing an overview of the achievements made since the early 1990s and presents some of the major challenges still facing us. With M. Hampton, in 1996, we published a general review on submarine landslides (Hampton *et al.* 1996). We therefore took this opportunity to look in greater details on the geomorphological and engineering aspects. When considering the intense research activities initiated over the last 5 years, a lot more could be said. We assembled a document which, we believe, represents a fair description of the major achievements made over the last ten years or so. A lot more could be said and many fascinating problems are still facing us. As a summary, our main conclusions on achievements and challenges are presented hereafter.

The major achievements were:

- Development of surveying techniques providing aerial photograph-like quality images of the sea-floor.
- Physics of rapid mass movements with a description of post-failure behavior, in particular for debris and mud flows.
- Determination of the rheological parameters and the use of the liquidity index.
- Recognize the role of gas hydrates in the development of slope instability.
- The introduction of the concept of hydroplaning to explain some of the large run-out distances achieved by debris or mudflows.

The major challenges facing us are:

- Improving sampling and in situ measurement techniques.
- Integrating 3D seismic methods into slope stability analysis.

- Use of long cores to provide estimates of the frequency of catastrophic events in the aquatic environment.
- Modification of mass properties to provide mobility to the flowing mass: the transitions from failure to post-failure behavior and from debris flow to turbidity current.
- Generation of tsunami from submarine mass movements.
- Hazard assessment: frequency and extent in particular.
- Monitoring the movement and mobilization of actual landslides.
- Determining the role of subsurface water flow in initiating submarine landslides.
- Integrate the role of gas hydrates in the analysis and prediction of submarine slope stability.
- Evaluating the mechanics of giant landslides and improving our understanding of the causes of their great run out distances.
- Developing criteria to determine the cause of seafloor deposits that have been described as either landslides or migrating sediment waves.

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