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Section 1

Role of submarine slides in margin development
Section 1 - Role of submarine slides in margin development

NORWEGIAN MARGIN OUTER SHELF CRACKING NORTH OF STOREGGA SLIDE


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Outer shelf cracks and elongated gas blow out features have been first discovered along a 40 km long section of the U.S. Atlantic margin. Her, individual cracks are several km long, 1 km wide and up to 50 m deep (Driscoll et al., 2000, Hill et al., 2004). The cracks and depressions seem to be caused by “gas blow outs” related to the release of shallow trapped gas. The precise age of the blowouts and the origin of the gas remains unknown, but post-LGM formation of the blowout features suggest that ocean warming triggered methane hydrate dissociation processes. The fact, that the gas hydrate outcrop zones of the largest gas hydrate provinces in Europe are on the Norwegian-Barents-Svalbard (NBS) margin makes the U.S. Atlantic margin – Norwegian Atlantic margin reaction of potential gas hydrates fields to post- Last Glacial Maximum (LGM) climate conditions particularly important for studies of submarine slope failures, i.e. geohazards. The NBS margin is not only an important gas hydrate province but also an area where numerous seeps are documented, and we thus know that there is gas migration in the sediments. In particular the area, where the theoretical outcrop zone of the base of the gas hydrate stability zone (BGHS) and the geophysical evidence as a bottom simulating reflector (BSR) lies, we observe outer shelf cracking, shallow faulting and fluid escape features such as pockmarks. A system of cracks associated with high pockmark density features occurs along the northern extension of the giant and retrogressive Storegga slide on the Mid-Norwegian Margin. The cracks exhibit a 50 km long and up to 3 km wide zone of approx. 10 m deep depressions. They line up with the northern edge of the Storegga headwall elongating in N-S direction. Within the uncertainty of the BGHS modelling the approx. 50 ms TWT cracking zone corresponds well to a zone of the BGHS outcrops, where it intersects the upper continental slope. Radiocarbon age dating of the cracking reveals the same age on the main crack as the Storegga Slide event, but due to the 14C dating uncertainties it remains unknown whether the cracking predates, occurs at the same time, or postdates the Holocene giant submarine sliding event. The cracks are possibly associated with fluid escape indicated by pockmarks typically 50-300 m in diameter and 1-5 m deep. The presented post-LGM formation of cracks, faults and gas blow out features along U.S. and Norwegian Atlantic margin outer shelf areas may be the result of a time dependent response of ocean clathrate reservoirs to climate change (Mienert et al., 2005) and therefore a “climate induced geohazard”.

The statistics of submarine mass movement inventories are poorly characterised in comparison to those of subaerial mass movements. In this study we investigate the aggregate behaviour of the Storegga Slide by carrying out a statistical analysis of its constituent mass movements. By using area as a proxy for mass movement magnitude, we demonstrate that the non-cumulative frequency-magnitude distribution of mass movements within the Storegga Slide is a power law with an exponent of 1.52. The Storegga Slide has the characteristics of a dissipative system in a critical state, where the input of sediment is continuous in the form of hemipelagic sedimentation and glacial deposition, and the output is represented by mass movements that are spatially scale invariant. We conclude that the Storegga Slide may be modelled as a large-scale geomorphic system that exhibits self-organised critical (SOC) behaviour. In comparison to subaerial mass movements, the aggregate behaviour of submarine mass movements is more comparable to that of the theoretical ‘sandpile’ model. The origin of SOC may be linked to the retrogressive nature of the Storegga Slide. Since SOC is an emergent feature, the large-scale behaviour of the Storegga Slide should be autonomous of the smaller-scale elements. A power law distribution also implies that incomplete submarine mass movement inventories may be extrapolated within the limits of power law behaviour, which is important in terms of hazard management.
THE SOUTHERN FLANK OF THE STOREGGA SLIDE:
IMAGING AND GEOMORPHOLOGICAL ANALYSES
USING 3D SEISMIC

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The Holocene Storegga Slide is one of the world’s largest exposed slides and also the most studied of all the Norwegian slides. However due to its complexity it is far from being fully understood. Three-dimensional (3D) seismic combined with swath bathymetry data from the southern flank of the Storegga Slide have been used to study mass movement processes occurring in the region. The high spatial resolution provided by the 3D seismic data has allowed a detailed geomorphological analysis of sedimentary and deformational structures. The Holocene Storegga failure affected a significant part of the studied area. The predominant feature is a compression zone, comprising two lobes, where the seabed shows marked parallel ridges. Down slope it is possible to identify another compression zone. A relative chronology of events was established and it is proposed that these two compressions zones are the result of gravity-driven slope failures related to different stages of the Holocene Storegga Slide.

Keywords: 3D seismic, Storegga Slide, North Sea Fan, glacial debris flow, frontally confined submarine landslide.
The slope along the SW Labrador Sea is a prospective exploration frontier with limited legacy data and geoscience knowledge. Newly acquired seismic reflection and multi-beam bathymetry data provide a better understanding of mass failure processes. A semi-continuous seismic section along the upper slope from Flemish Pass to north of Hamilton Spur shows an alternation of major morphological elements that includes canyons and failure corridors, inter-canyon ridges, ice-outlet trough mouth fans (TMFs), and sedimentary spurs. Preliminary geohazard investigation shows a wide variety of Plio-Pleistocene mass failure products including shallow detachment faults, head-scarps, creep folds, decollement surfaces, and a preponderance of mass transport deposits (MTDs) of various origins. Particularly noteworthy are two newly identified fans outboard the Hawke Saddle and Notre Dame Channel (believed to be TMFs constructed of mass wasted material), and a large shallow buried failure complex north of the Hamilton Spur, which contains many km-scale slide blocks dispersed over thousands of square kilometers.

Keywords: SW Labrador Sea, slope morphology, mass failures, giant slide blocks
The morphology of two lower – middle Pleistocene paleo-slope surfaces within a muddy glacigenic succession was studied on 3D seismic data. The lower surface is characterised by irregular relief. It terminates upslope by an escarpment that represents the upper part of a paleo-slide scar. The slide scar morphology is relatively similar to that of modern slide scars and failure is inferred to have occurred during or after a glacial maximum when the ice reached the paleo-shelf break. A large area immediately outside the paleo-slide scar was affected by sediment creep or sliding, thus the area of unstable sediments extends beyond the paleo-slide scar. The upper surface morphology is dominated by three straight to slightly meandering paleo-channels, at least one of them formed by mass wasting. Together, the two paleo-surfaces exemplify slope morphology that may result from sediment instability on glaciated margins.

Keywords: paleo-slide scar, paleo-channels, glaciated margin, Barents Sea.
The Krishna and Godavari rivers have formed the Krishna-Godavari delta where they enter the ocean. Both the rivers, which drain a significant part of the Indian peninsula, and the delta are influenced by a seasonal sediment supply controlled by the monsoon rains. The delta system receives nearly all its sediment during this annual flushing of the river system.

The slope instabilities on the delta are most likely driven by excess pore pressure induced by rapid sedimentation and therefore reflect sedimentation history and distribution. The overall geometry of delta shows that the Pleistocene subsidence on the inner part of the sub-aqueous delta is associated with toe-thrusts in more distal regions and that the morphology of the delta front is comprised of channel-levee systems with overbank and mass transport deposits. The climatically induced fluctuations in sea level have probably shifted the main depocentre through time with the more distal sedimentation occurring during sea-level lowstands.

This study is based on 2D and 3D-seismic data that has been combined with geotechnical information from boreholes. This investigation demonstrates the role regional geology has for the distribution and timing of mass movements.

**Keywords:** Submarine landslides, East Indian margin, delta deposits
REPEATED INSTABILITY OF THE NW AFRICAN MARGIN RELATED TO BURIED LANDSLIDE SCARPS

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The Sahara Slide occurred approximately at 50-59 Ka offshore Western Sahara in a mid-slope setting (1900 m water-depth). The existence of several buried and stacked slide events, seen on high resolution seismic profiles, provide new insights into slide location and triggering mechanisms. Buried slide scarps coincide remarkably with scarps and boundaries of the Sahara Slide, presently exposed on the seafloor. The objectives of this work are to examine the long-term stability of this part of the margin and investigate the triggering mechanism(s) that led to these massive events. Buried slide scarps occur in sediments of Miocene-Pliocene age. Multiple scarps becoming more closely spaced towards a larger scarp that may be the main headwall suggest that most of the buried slides developed as retrogressive slides. The seismic record shows that differential compaction across an area of depression bound by scarps generates compaction hinges (anticlines) leading to oversteepening and possible excess pore pressure. We propose that alignment of ancient and present scarps and vertically stacked slide deposits points towards differential compaction as being a key factor in landslide triggering.
The Cook Strait submarine canyons occur at the transition from the westward dipping oblique subduction zone adjacent to the SE North Island and the zone of continental transpression in NE South Island of New Zealand. Slopes in this area are deeply incised with several canyons heading into the shelf and to within 1500 metres of the coast in less than 50 m water depth. High resolution bathymetric data collected with Simrad EM300 multibeam technology allow seafloor geomorphic expression to be assessed at a level of detail not previously possible.

Extensive areas of the Cook Strait canyon walls and adjacent margin slopes are affected by bedrock landslides of a variety of styles, including: i). translational landslide complexes of up to several cubic kilometres failing on multiple low angle (<5 degree) bedding planes on the landward dipping back-limbs of active thrust propagated anticlines; ii). multiple juvenile slope failures in the head zones of gully systems located on the steep slopes of the leading fore-limbs of thrust propagated anticlinal structures; and deep-seated (hundreds of metre) collapses occurring adjacent to principle canyon channels. Other erosional processes including current/tidal scour and gulley erosion are also widespread throughout the area. Multiple active fault traces occur on the frontal slopes, shelf areas and cutting through canyons. These are large magnitude, high frequency earthquake sources and define zones of very high ground shaking expected to contribute to triggering of slope failures.

This paper provides an overview of the morphostructure of an active canyon system, focused on categorisation and quantification of landslide processes driven by active tectonic forcing in the form of high ground shaking levels and active faulting and folding. Bedrock landslides are playing an important role in canyon development and sediment transfer, and are subsequently having a significant influence the morphology of this obliquely convergent margin.
Section 1 - Role of submarine slides in margin development

QUATERNARY AND RECENT SUBMARINE LANDSLIDES ON THE LIGURIAN MARGIN (NORTHWESTERN MEDITERRANEAN): DISTRIBUTION AND TRIGGERING MECHANISMS. MALISAR PROJECT

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Submarine landslides are one of the major gravity process affecting the slope of continental margins (Canals et al., 2004; Hampton et al., 1996; Locat, 2001). They occur preferentially in areas that present conditions prone to failure: sediment under-consolidation, high-slope gradient, high sedimentation rates, variability in the texture and physic-mechanical state of the sediment strata (Sultan et al., 2004). Landslides can also have a strong impact on coastal environments by generating tsunamis (Fine et al., 2005; Fryer et al., 2004).

The Ligurian Basin experienced recently such phenomena: in 1979, a failure (8 x 10⁶ m³) occurred in shallow-water depth during infilling operations seaward of the Nice airport (Gennesseaux et al., 1980) and generated three successive waves, 2-3 m height, that broke along the coastline between Nice and Antibes. Three historical tsunamis are also well-known in the area (1564, 1817, 1887). They have been generated during historical earthquake events (1564, 1817 and 1887). Based on the 1979-event experience, earthquakes could have been responsible for tsunamogenic failures on the Ligurian slope.

To analyse the distribution of failures on the slope, and to study their triggering mechanisms and their relationship with tsunamis, the MALISAR cruises acquired multibeam bathymetry, various types of geophysical data, and cores in the area between Nice and Genova, from about 100 m to 2500 m water depth. The dataset reveals numerous buried or fresh scarps and mass-transport deposits involving several km³ of sediment.

Offshore the Nice city (France), mass-wasting events mainly affect the upper part of the slope, in areas close to the Var and Paillon river mouths, where volume of fresh sediment delivered by rivers is the highest. Small-scale failures (< 100 m wide) are mainly located near the shelf break; they are the most abundant and are restricted to the uppermost layers (up to 10 m) of slope sediment. Larger-scale failures (up to 400 m wide) are located deeper on the slope and they affect deposits over greater thickness (up to 40-50 m). Smaller failures mainly result from the under-consolidation state of slope sediment during periods of high sedimentation rate, while the triggering of larger failures probably requires an external constraint such as an earthquake-induced acceleration of the seafloor.

Between Nice (France) and Imperia (Italy), failures are several kilometres wide and affect slope deposits over 100 to 300 m. They are located near the base of the slope, between 1300 and 2000 m of water depth. The location of these failures seems to be mainly controlled by the presence of numerous active faults related to the salt tectonic affecting the basin or of deeper crustal origin. Three impressive scarps are located in the epicentral area of the 1887 earthquake. One of them is still clearly visible of the present seafloor and could be related to the 1887 event. The two others are partly buried under draping hemipelagite-type deposits and could be related to the recurrent activity of earthquakes in that area.

Between Imperia and Genova (Italy), submarine landslides are mainly restricted to the flanks of the numerous canyons that erode the slope. A major scarp, 7 km long and about 100 m
height, is located in an interfluve area between two major canyons, offshore Savona. The failure exhibits large blocks of well-layered deposits in its upstream part, then a chaotic mass several km long in its downstream part. The absence of draping hemipelagite deposits suggests the failure has been triggered recently.


A morphometric analysis of submarine landslides on the continental slope of north Colombia – south Ecuador convergent margin provides insights into hazards, including mass movements locations, size of failures and location control. Bathymetric and seismic data acquired in 2005 revealed three distinctive types of locations with the occurrence of potentially tsunamogenic submarine landslides: 1) the erosive margin toe is characterized by three 5-6-km wide and up to 1500m high semi-circular scarps. The toe is also affected by a 35-km long area of linear scarps resulting from the imbrication of successive failures, 2) canyon walls are affected by five up to 500m high scarps, 3) the deformation front exhibits a 50x20km potentially destabilized area characterized by intensive fracturation. All these features are controlled by active tectonics, Slope oversteepening is a key parameter facilitating the onset of slope failure for the two first types, and is associated with 1) seamount subduction, 2) subsidence related to basal erosion of upper plate, and 3) uplift along active tectonic structures. Regarding the third type, the destabilisation area is influenced by the intensive fracturing at the vicinity of a splay fault.
The 1929 Grand Banks earthquake, landslide and tsunami were pivotal in geologic history as they led to the first unequivocal recognition of a landslide-triggered tsunami and turbidity current. The event is well constrained in terms of trigger, timing, sequence of events and impact. The landslide site was surveyed in September of 2006 with a 12 kHz multibeam echosounder. Regionally, these bathymetric data show canyons, valleys and gullies, somewhat typical of the continental slope in the region. No major headscarp related to the event is recognized (cf. the Storegga Slide). Most significant are a series of shallow gullies with small headwalls about mid-slope. Upslope from these is a series of shallow escarpments that probably represent upslope retrogression of the failure. The landslide appears to have been relatively shallow (top 5-100 m) and laterally extensive. There is no evidence of a single massive submarine landslide with major headscarp and debris lobe. The landslide presumably evolved rapidly into turbidity currents that flowed along existing canyon and valley corridors. In the case of the 1929 Grand Banks event, a damaging tsunami was generated following a landslide for which the bathymetric signature is not clearly identifiable from most of the regional sea floor of the Canadian East Coast margin. The tsunami was generated either by widely distributed, shallow sediment failure, or by the ensuing turbidity current. In either case, remnant morphology is difficult to distinguish. This fact suggests that assessment of tsunami hazard based on recognizable morphologic evidence alone may underestimate the landslide and tsunami risk.

Keywords: Submarine landslide, mass-failure, tsunami, multibeam, geohazard, seafloor geomorphology, submarine canyon, submarine valley, submarine fan
LANDSLIDE AND GRAVITY FLOW FEATURES AND PROCESSES OF THE NAZARÉ AND SETÚBAL CANYONS, WEST IBERIAN MARGIN

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The Nazaré and Setúbal Canyons of the west Iberian margin are highly complex seafloor environments, displaying a range of sedimentary features and processes that reflect the transition from erosive upper to depositional lower canyon. Upper sections are characterised by a deeply incised, narrow, V-shaped thalweg, and frequent localised intra-canyon slope failures. Lower sections have a U-shaped floor with heterogeneous sediment distribution. Two types of gravity flow are observed: thin-bedded, fine-grained deposits that may be the result of frequent turbidity currents generated by high sediment supply to canyon heads, and thicker, siliciclastic coarse sandy turbidites, probably generated by larger earthquake-triggered slope failures on much longer timescales. Our results highlight the complex interplay of sedimentary processes operating within major canyon systems.

Keywords: Nazaré, Setúbal, submarine canyon, continental margin, mass wasting, turbidity current
INTERACTION BETWEEN MASS-WASTING PROCESSES AND DEPOSITIONAL FEATURES PRODUCED BY GLACIO-EUSTATIC SEA-LEVEL CHANGES, AS A TOOL TO DEFINE THEIR STATE OF ACTIVITY

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High-resolution seafloor mapping (mainly but not solely multibeam soundings) allows a rather precise definition of presence, geometry and volumes of past seafloor instabilities and this data are very valuable for the depiction of marine geohazard. However the knowledge of the age of the instability event is essential for a correct hazard assessment but dating the instability is not always simple. In fact: 1) a favorable stratigraphic situation is required, such as the presence and a clear correlation of the debris produced by the instability event; 2) seafloor coring is only possible for limited thickness and in fine-grained material (unless very expensive rotary drilling); 3) mass wasting features can be very common in certain span of continental margin, so that a resource-consuming activity such as seafloor coring and sediment dating can not be applied extensively.

If the mass wasting occurs in upper-slope and/or in continental shelf environment, however, it develops within sediment whose structure and stratigraphy is deeply influenced by glacio-eustasy. Sea-level changes in the order of 100-120m caused the alternance of emersion and submersion of the continental shelf as well as dramatic changes in rate and kind of depositional processes in the upper slope.

Therefore a possible indication of state-of-activity of instability process can be derived by the fact if they affect features produced by glacioeustasy e.g. at sea level lowstands. If the process is continuous through time, the alterance of period of starvation and high sedimentation rate on the upper slope, can also produce the progressive burial and re-incision of the same feature.

Of course the interaction of instability and depositional features only gives a general age indication, as it depends on local conditions such ad sedimentation rate and kind of depositional processes. However the indication is extremely valuable in comparative analysis (i.e. within the same area to define the relative state of activity of different features) and can be the only not expensive tool to map the instability and the correlated marine geohazards on very large span of continental margins.
Mass Wasting Processes in the Western Wilkes Land Margin: Implications for the East Antarctic Glacial History

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Multichannel seismic data collected off Western Wilkes Land (East Antarctica) reveal a variety of scales sediment mass movements in the form of slide blocks, creep-like features and mega debris flow deposits on the lower slope and rise. Slide blocks affect mainly the lower slope, whereas creep-like features have been identified at the transition between slope and rise. Slide blocks are coherent sediment blocks displaced on low-angle, small throw listric faults that sole out into a basal glide plane, which, especially in the western sector of the study area, corresponds to a Bottom Simulating Reflector (BSR), possibly related to a silica diagenetic front. Slide events appear to be mostly coeval with mega debris flows deposited on the continental rise, which, in places, have seaward extend of more than 200 km and thickness up to 400 m. Locally they contain large outrunner blocks. Fluid migration features have been also identified above the debris flow deposits, possibly as a consequence of their dewatering. The long run out distances of these deposits suggest that they were probably characterized by high water content and low shear strength. Stratigraphic correlation with DSDP Site 268 suggests that slope failures in the Western Wilkes Land occurred during the Middle-Late Miocene. The uppermost part of the Western Wilkes Land post-rift sequence, corresponding to sediments attributed to Unit 4, Pliocene to Recent in age, is not affected by major slope failure. Sediment waves form locally, as a consequence of both turbiditic and contouritic processes. In some areas, debris flow units are separated by thin deposits of well-stratified facies, interpreted as glaciomarine mixed contourites and distal turbidites, and hemipelagic deposits. These thin, laterally continuous, fine grained and low permeability sediments provided perfect potential weak layers and may hence have represented a key factor for slope instability. We infer that high sedimentation rates, due to large amounts of sediment delivered from a temperate, wet-based ice sheet, and consequent excess pore pressures may have played a major role in Western Wilkes Land sediment failures. Moreover the distribution of mass wasting-related features appears to have been related to the amount of meltwater discharge, with debris flows deposition occurring in areas were meltwater possibly played only a minor role. We also infer that the final trigger mechanism may have been related to the high dynamism of the ice sheet, characterized by large fluctuations during the Miocene. Isostatic rebound following major ice sheet retreats may have been at the origin of earthquakes, leading to the failure of sediments already prone to slide.
Submarine turbidity currents are highly destructive and unpredictable events that pose a significant geohazard to seafloor infrastructure. However, we know surprisingly little about the erosive power of such flows. Here we quantify erosion by large sediment volume (>100 km$^3$) turbidity currents in the lower Agadir Canyon off northwest Africa, and show how sinuous canyon morphology influences location and depth of erosion. On the outside of a right-angled bend, where centrifugal force is greatly enhanced, individual flows erode up to 1 m of cohesive fine-grained sediment at a height of 335 m above the canyon floor. Flow overspill beyond this outer bend has led to development of a large erosional channel. Further downstream, the maximum height of significant erosion decreases in response to an increase in canyon width and a decrease in sinuosity. Intense canyon floor erosion produces kilometer-scale scours up to 10 m deep. Cores in the adjacent Agadir Basin show that individual flows can still erode 1 m-deep scours at a distance of ~550 km from source. These unique data provide new insights into erosion by large-volume flows, revealing that significant erosion occurs at great distance from source and at considerable heights above the canyon axis.
The main morphological features of the continental slope on Australia’s eastern margin

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Historic seismic and bathymetry data identified a morphological feature interpreted as a submarine failure surface on the continental slope off eastern Australia. It had been named the Bulli Slide. A recent multidisciplinary marine survey was designed to test this hypothesis, and to determine whether other slides might have occurred in the region. The survey undertook a swath mapping program (4000 line km), augmented with Seismic and (341 line Kms) sub bottom profiles (3414 line Kms). This assisted in the positioning of 12 gravity cores aimed at dating the inferred failure surfaces along the continental slope. The new data show that the Bulli Slide has an arcuate plan shape with a maximum width in the upper erosional slide area of 11.35 km, and a relief of 380 m from water depths of 1330 to 1710 m. The slide feature descends from 950 m to over 3300 m water depth over a distance of 22.3 km indicating a seabed slope of 5.9°. The lower part of the slide widens up to 14.5 km and has a maximum relief of 660 m from 1800-2460 m. Due to significant variation of the slide morphology, a 30% down-scaling has been applied to the total volume of the Bulli slide, resulting in a value of ~100 km3. The swath data reveal a continental slope with long term, widespread, multiphase mass wasting history.
The Gulf of Cadiz is located in the SW margin of the Iberian Peninsula and hosts the convergent boundary between the European and African Plates. The area is characterized by a significant seismic activity source of the largest events in Western Europe, such as the 1755 Lisbon Earthquake and Tsunami (Mw 8.5) and 1969 Horseshoe Earthquake (Mw 8.0) (Buforn et al., 1995). Successive marine geophysical surveys carried out in the area since 1998 in the framework of national and European research projects (e.g. BIGSETS, HITS, EuroMargins SWIM, IMPULS) revealed several active thrusts and strike-slip faults accommodating present-day deformation (e.g. Gràcia et al., 2003a,b; Terrinha et al., 2003; Zitellini et al., 2004). Associated with active faulting, slope failures are common (Gràcia et al., 2003b, Vizcaino et al., 2004, 2006). Here we present an overview of all submarine mass movements identified within the Gulf of Cadiz.

The available data for this study comprises swath-bathymetry, acoustic backscatter, high-resolution and multi-channel seismic reflection profiles and sediment cores. A high-resolution bathymetric compilation of the area (Diez et al., 2005) allows us to identify evidences of complex systems of mass-movements seafloor morphologies. Gully-incised slope failures, amphitheatre headscarps along submarine valleys, mass slides and gravity flows have been recognized at different depths, shaping both slope and abyssal plain domains. The most frequent mass movements observed are retrogressive translational slides, debris flows and turbidite deposits. Headwalls, scars morphologies have been measured and catalogued, and a detailed characterization (i.e. area, volume, age) of the deposits involved in the gravitational processes has been carried out on the basis of seismic profiles and core data.

Submarine mass-movements play a significant role in shaping the Gulf of Cadiz morphology since the upper Miocene (i.e. Giant Chaotic Body, Torelli et al., 1997) to the present-day. A strong relationship between landslides and tectonic activity is evidenced, with earthquake activity as the most likely mechanism to trigger the observed mass transport deposits, as in the case of the Marques de Pombal Slide (Gràcia et al., 2003b, 2005, Vizcaino et al., 2006). In the SW Iberian Margin, submarine landslides have important implications in defining seismic hazard models, as synchronous widespread turbidite deposits are a proxy for paleo-earthquakes (e.g. Garcia Orellana et al., 2006), and may also contribute in defining parameters to assess tsunami hazards along the coasts of the Southern Iberian Peninsula. We acknowledge funding from the Spanish national Projects IMPULS (REN2003-05996MAR) and EVENT (CGL2006-12861-C02-02), and European Commission FPVI STREP Project NEAREST (037110).


Section 1 - Role of submarine slides in margin development


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storical landslides deeply modify the structural properties and topography of the sea
floor. Therefore, it is likely that even years after the mass failure event, structural and
functional properties of benthic communities inhabiting landslides exhibit significant
differences when compared with the adjacent slopes. In order to investigate the effects of
mass failure events on benthic biodiversity and ecosystem functioning, sediment samples
were collected in two twin landslides located in the Gela Basin (Mediterranean Sea) and in
unstable slopes in the Portuguese margin. At each area, landslides were compared with the
adjacent open slopes (used as controls). We analysed meiofaunal abundance, biomass, com-
munity structure, taxa richness and nematode species diversity in relation to the quantity
and quality of food sources in a total of 38 stations. At all transects, both in the landslide
and the adjacent slope, sampling stations were located at increasing water depth (from 183
to 807 m, in the Gela basin and from 500 to 5000 m, in the Portuguese margin). Results will
be discussed in order to assess the influence of historical mass failure events on benthic
biodiversity and to identify different impacts exerted by landslides exhibiting different mor-
phological settings.
A very high-resolution shallow-seismic survey along the central part of the fault-bounded Corinth Gulf southern margin (offshore Xylocastro town) revealed that three morphological zones characterize the area: the shelf, the slope and the basin. Three E-W trending, right stepping basin bounding faults define the basin-slope contact, producing a step like configuration along the base of slope. Steep scarps, caused by mass failures, sculpt the fault plane surfaces, which act as part of the slope. The shelf and the slope are dissected by submarine canyons and numerous minor channels. The largest canyons are located immediately off the river mouths, run perpendicular to the slope and are linear. Seismic profiles across the canyons suggest that some of them are fault controlled. The head and the walls of the canyons are affected by mass failures. It is estimated that about 1.1 km$^3$ of mass failed sediments have been removed from the canyons and transported downslope to the basin floor.

**Keywords:** submarine failures, fault-bounded margin, escarpment, canyon, Xylocastro, Corinth Gulf.
Detailed morphological studies of the Andøya canyon reveal that along-slope sediment transport by ocean currents entering the Andøya canyon from the W-SW subsequently determines the mass wasting processes and the morphogenesis on the western canyon walls, while gully development dominate on the eastern side wall in stiff sediment material and on steeper slopes. Missing infill of the canyon thalweg indicates frequent flushing events evacuating sediments from the canyon to the Lofoten basin. The chronological framework established for the Late Glacial and the Holocene strata from the Andøya Canyon accumulation area in the Lofoten Basin has revealed that three main turbidite events identified are bracketed to the Younger Dryas-Preboreal (early Holocene) period, the 7.3-7.9 ka 14C period and the ca. 4 ka 14C period. The interplay of sediment transport to a slide area on the western canyon side via contour currents and its deposition and erosion at the headwalls may be a controlling factor for the long-term formation of a new canyon system by retrogressive erosion. Alternatively, if the faults surrounding the slide scar area are reactivated, further retrogressive failure on the northwestern flank may occur contributing to canyon formation on a shorter time scale.
DETECTING SEAFLOOR INSTABILITY AND GEOHAZARD MAPPING ON CONTINENTAL MARGINS: THE MAGIC PROJECT (MARINE GEOHAZARD ALONG THE ITALIAN COASTS)

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The Italian Civil Protection Department funded a 5-year mapping program of the outer shelf and upper slope for assessing marine geohazard due to rapid changes occurring at the seafloor. The MaGIC Project (Marine Geohazards along the Italian Coasts) will therefore co-ordinate the acquisition of ~60,000 nautical miles of high-resolution swath bathymetry all along the Italian continental margins. The main objective of this project is to produce a bathymetric database and 1:50,000 maps of geohazards at the seafloor. The continental margins of Italy, even if different in their tectonic setting, display morpho-structural features that reflect long-term tectonic history, including past and recent volcanic activity, and late Quaternary geomorphological evolution during climate–driven sea level changes. Active geologic processes therefore include seafloor faulting, volcanic vents, mass failure features ranging in scale from large debris avalanches to small but widespread rockfalls at canyon heads. These features represent geohazard scenarios that require extensive monitoring for risk assessment and managing. Examples from selected areas will be presented for elucidating the structure of the MaGIC Project, including interpretative and mapping criteria, as well as for highlighting critical aspects in constraining the occurrence and consequences of sediment mass wasting processes at different scales.
Section 2

Mass waste evolution: From slump to distal turbidites
A series of comparable subaerial and subaqueous debris flow experiments of sand-clay-water mixtures has been performed at the St Anthony Falls Laboratory (SAFL) at University of Minnesota. Different compositions were tested and velocities measured in detail using PIV (Particle Image Velocimetry) techniques. The experimental series provides a unique data set highlighting the effects of the ambient and interstitial fluid in comparable subaerial and subaqueous debris flows. Based on our experimental data we emphasize the differences in the dynamical behaviour associated with the two environments and suggest important mechanisms to be included in numerical models.

Keywords: Subaerial debris flows, subaqueous debris flows, experiments, velocity, PIV.
Deep sea turbidity currents, mud flows, and debris flows have been the subject of a number of industry and government studies over the past two decades. While evidence of these flow events are common in a wide variety of continental slope and rise locations, the mode, scale, and frequency of these events have been shown to vary widely from place to place. Based on over more than a dozen field and modeling projects, we present an overview of the controls, scale, flow type, and flow behavior. The most general controlling factors are the type and scale of the triggering event, the slope and morphology of the seafloor, and the material properties of the flow. In this overview we focus on details of the evolving flows that need to be included in quantitative analyses with numerical models.
SUBMARINE SPREADING: DYNAMICS AND DEVELOPMENT

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Spreading is a pervasive type of ground failure in subaerial environments, but its occurrence has hardly been documented in submarine settings. However, recent advances in seafloor imaging techniques show that repetitive extensional patterns of parallel ridges and troughs, oriented perpendicular to the direction of mass movement and typical of spreading, are widespread offshore. A spread develops via the failure of a surficial sediment unit into coherent blocks. These blocks are displaced downslope along a quasi-planar slip surface. Two modes of failure can be identified: retrogressive failure of the headwall, and slab failure and extension. Mechanical modelling indicates that loss of support and seismic loading are the main triggering mechanisms. The extent of displacement of the spreading sediment is controlled by gravitationally-induced stress, angle of internal friction of sediment, pore pressure escape and friction. The resulting block movement patterns entail an exponential increase of displacement and thinning of the failing sediment with distance downslope. A deeper insight into submarine spreading is important because of the widespread occurrence of ridge and trough morphology in numerous submarine slides, particularly in the vicinity of submarine infrastructures.
In Hudson Bay and Hudson Strait, the rapid collapse of the Laurentide Ice Sheet (LIS) culminated in the catastrophic drainage of proglacial Lake Agassiz into the North Atlantic around 8500 cal BP. It has been suggested that this catastrophic event may have triggered the 8200 cal BP cold event recorded in Greenland ice cores. Evidence for that outburst flood was the identification of a centimeter to decimeter-thick hematite-rich red layer that was observed in Hudson Strait sediments around 8000 yr BP. In this paper, we have identified a sequence of two flood-induced turbidites (i.e., hyperpycnites) in a reddish layer from two cores collected in northern Hudson Bay (core AMD0509-27bLEH) and western Hudson Strait (core AMD0509-28PC) in 2005 onboard the ice-breaker CCGS Amundsen. These two reddish layers can be correlated to a red bed previously identified as a regional isochron in Hudson Strait and associated with the final drainage of Lake Agassiz around 8500 cal BP. Regardless of the exact timing of the catastrophic drainage, the hyperpycnites described in this paper suggest that they were deposited following two pulses, which is in agreement with the one of the scenarios proposed by Clarke et al. (2003) [Science 301, 922-923] for the drainage of Lake Agassiz. Finally, this study demonstrates for the first time the turbiditic and the flood-induced nature of the Hudson Strait red bed isochron.

**Keywords:** hyperpycnites, turbidites, Lake Agassiz, outburst flood, 8.2 ka event, Hudson Bay, Hudson Strait
The marine environment presents various settings in which talus slopes are formed via a rock fall process similar to what exists on land. This is the case along fjords and submarine canyons in particular. Although many studies have been carried out on land, surprisingly very little is known for the submarine environment. We propose here the first kinematics analysis of underwater rockfall. It is postulated that the block have a diameter of more than one meter. As it can be expected, the main addition to the subaerial case is the consideration of the role of water (e.g. density or current). For submarine rockfall analysis, the effect of the ambient fluid cannot be neglected. Hydrodynamic constraints are controlled by the speed, shape, and size of the moving mass. Wind does not have a significant role in subaerial rockfall analysis, but currents must be considered in the subaqueous environment. In addition, coefficients of restitution are not only controlled by the elastic properties of the material, but also by impact Stokes number. This paper provides a summary of underwater rockfall kinematics in order to formulate underwater rockfall governing equations.
An 8 km long active sand lobe system has been discovered in a small deepwater intraslope basin, at a water depth of 1500 m, in the Gulf of Cadiz, eastern Atlantic Ocean. The lobe system was mapped in its entirety using a multibeam echosounder, a deep-towed high-resolution sidescan sonar (100 kHz) and a seismic profiler (5 kHz). Integration of these datasets has provided an insight into the morphology of the lobe, with source, by-pass and depositional areas resolved on a meter scale.

Observations from both depositional and source areas allows the characterisation of sand mobilisation and deposition processes within the system. The depositional area on the basin floor comprises a complex bifurcating system of narrow aggradational sinuous channels with characteristic marginal levees. According to their morphology, and by comparison with subaerial analogues, they are formed by sustained sand-rich hyperconcentrated gravity flows.

The source area is represented by a small, potentially fault-related, valley which cuts into a sand-rich sequence. Multiple scours and slabs of sand of up to $1.5 \times 10^6 \text{ m}^3$ in volume displaced by shear failures are recognised on acoustic images on the slopes and floor of the valley, indicating frequent failures of outcropping sands. Volumetric calculations suggest that the valley alone could have been the major source for the sand deposited within the lobe system.

The character of the failures as well as measurements of local slopes and grain-size data of sands suggest that multiple gradual retrogressive failures or “breaching” [1, 2] are responsible for mobilisation of large volumes of sand and generation of sustained gravity flows. The sustained character of the flows is a particularly good agreement with the features observed in the depositional area.

The results of this study are applicable to other depositional systems with sand-rich sources where breaching can be a common process of sand mobilisation and which potentially can lead to subsequent formation of sand-rich depositional bodies further down slope.

LANDSLIDE AND GRAVITY FLOWS ALONG THE NE ATLANTIC CONTINENTAL MARGIN, FROM BISCAY TO MAURITANIA

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Landslides and gravity flows (debris flows and turbidity currents) dominate sediment transport along much of the NE Atlantic continental margin. Here, we review current knowledge relating to location, timing and frequency of these events, from Iberia to NW Africa. We then identify gaps in knowledge where future research should be focussed. The study area comprises a 3500 km-long section of continental margin that is affected by a variety of different climatic, tectonic and morphologic regimes. Several major research programmes, e.g. EU-EUROSTRATAFORM, HERMES and UK-TAPS, have collected new datasets allowing us to better assess the relative influence of these factors on downslope sediment transport. Several case studies are presented here in order to highlight these recent advances, but also with the specific aim of identifying outstanding gaps in our knowledge base. We plan to start filling in some of these ‘data gaps’ through a new NERC core strategic programme that begins in 2007. Our initial aim is to 1) collate and integrate all existing turbidite frequency data covering the last 100-200 ka in the Biscay, Iberia, Tagus, Horseshoe, Seine, Agadir and Madeira Basins, and 2) undertaking a coring cruise to fill in gaps where new core data are considered essential. The ultimate objective is to produce a comprehensive dataset with which we can assess the timing and frequency of landslide and gravity flow events along this margin, and assess the potential future geohazard to adjacent coastal communities.
EVIDENCES THAT THE MAY 2003 BOUMERDES EARTHQUAKE REACTIVATED THE DELLYS AND SEBAOU SUBMARINE CANYONS (CENTRAL ALGERIA MARGIN)

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On 21 May 2003, a damaging earthquake of Mw 6.9 struck the region of Boumerdes 40 km east of Algiers in northern Algeria. The main shock, which lasted ~36–40 sec., had devastating effects and claimed about 2300 victims, caused more than 11,450 injuries, and left about 200,000 people homeless. The main shock was widely felt within a radius of ~400 km in Algeria. To the north, an associated tsunami was felt in southeastern Spain, including the Balearic Islands, and also in Sardinia and in southern France. The main shock location is clearly offshore Boumerdes.

We recently investigated the submarine area encompassing the epicenter using high-resolution swath bathymetry, high resolution seismic, deep-tow side-scan sonar images and Kulkenberg and interface cores. Déverchère et al. (2004) found that the two main slip patches of the 2003 Mw 6.9 Boumerdes earthquake are spatially correlated to two segmented cumulative scarps recognized on the slope and at the foot of the margin.

Five submarine broken telecommunication cables were reported after the earthquake at different locations close to the epicentral area and also far away in the basin on a front which is about 150 km long (France Telecom Marine report). However, no big submarine landslide has been observed close the active faults area, suggesting a multiple source for turbidity currents rather than a single source.

Multibeam bathymetry and deep tow side-scan sonar survey, over the Dellys and Sebaou canyons which are close to the 2003 epicenter, suggest that these canyons have been reactivated very recently. We observe huge scours, furrows and gravels waves on canyon floors, suggesting that high and powerful turbidity currents flowed down the canyons. These turbidity currents could have broken submarine cables, which are located northward in the deep basin.
ANTHROPOGENIC TURBIDITY CURRENT DEPOSITS IN A SEismically active graben, the gulf of corinth, greece: A USEFUL TOOL FOR STUDYING TURBIDITY CURRENT TRANSPORT PROCESSES

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A detailed marine survey in Antikyra Bay in the northern margin of the Gulf of Corinth graben in Greece was carried out to examine the distribution and dispersion of bauxitic “red mud” tailings. The red mud tailings have been discharged at a rate of 500,000 to 640,000 tonnes/year via submerged outfalls on the shelf at a water depth of 100 m. The red mud tailings at the mouth of the outfalls have formed three oval shaped mounds. These mounds have a maximum thickness of about 27 m and thin out radially in the downslope direction along the longitudinal axis of the bay in a south-southwestward direction forming a common depositional lobe. The “red mud” tailings are transported by turbidity currents, via channels which incise the slope, to the basin floor at a water depth of 800 m and over a distance of 17 km, where they form small sheet-like deposits. High-resolution sedimentological analysis of 30 short cores using visual inspection, X-radiography, grain size measurements, X-ray diffraction and smear slides have shown the presence of seven (7) distinct turbidity flow events which were activated on the shelf and the slope and have occurred during the 24 years of tailing discharge. Five of these have their source at the “red-mud” mounds at the mouths of the outfalls and two of them have their source at the shelf break and the upper slope. The analysis revealed that the former consist of (a) graded structureless red mud deposits and/or bioturbated red mud deposits, or (b) laminated red mud deposits, whereas the latter are mostly structureless and poorly graded.

Keywords: anthropogenic turbidity currents, Gulf of Corinth, mud, tailings
Giant crater-like structures have been discovered in and around the Storegga Slide scar in the Norwegian Sea, offshore Norway. These structures are tens of kilometres wide. Here we utilise three 3D seismic cubes and one 2D seismic data set to review the distribution of these structures with respect to the regional geology, and to investigate their potential relationship with mass wasting events in recent times.

Mapping of these structures show that they are always found at the top of the Oligocene-Middle Miocene Brygge Formation. This unit consists of bio-siliceous oozes. The structures are found where the overlying Middle Miocene-Late Pliocene Kai Formation is either thin or absent. These structures have a base that is either coincident with the Opal-A–Opal-CT transition, or a little above this transition.

It is postulated that the Opal-A–Opal-CT transition may be related to the formation of the structures. As a bio-siliceous ooze goes through the transition from Opal-A to Opal-CT it will undergo a porosity reduction of around 20%. Thus a large amount of fluid may be released by this reaction. If this fluid is trapped, it will migrate up-dip towards the crests of anticlines. It is hypothesised that this seal undergoes failure near the crests of anticlines, leading to the formation of crater-like structures.

These crater-like structures are filled by an overlying slide deposit, and large mounds of ooze rest atop this slide deposit. This suggests a relationship with mass wasting. Were these structures responsible for a mass wasting event on the Norwegian margin, or was a mass wasting event the trigger for the formation of these structures?
MEGA-TURBIDITES OF THE WESTERN NILE DELTA: ORIGIN, FREQUENCY AND IMPLICATIONS FOR GEOHAZARDS

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Large-scale slope failures can disintegrate and mix with ambient sea water to form turbidity currents. Turbidites deposited by such flows potentially record the frequency, timing relative to sea level, location and dynamics of slope failure.

A series of unusually thick 'mega' turbidites have been cored within the Herodotus Abyssal Plain. The terrigenous composition and extremely large volume (~72, 25, 126, 80, 6 and 2.4 km³) of six of these turbidites suggests they originated from slope failure on the Nile submarine delta (Reeder et al., 1998, 2000 & 2002). Each of these mega-turbidites contains orders of magnitude more sediment than that supplied to the ocean in any historical flood, even from rivers with much higher sediment concentrations than the Nile. These six megaturbidites were emplaced between ~ 14 and 7 ka during a period of rising sea level.

This contribution describes a series of older Chain 119 pistons cores from locations on the Nile submarine fan, upslope from the Herodotus abyssal plain. These cores are held at the USGS Core repository at Woods Hole. The assistance of staff at this core store is gratefully acknowledged. These cores also contain a series of thick turbidites, comprising more than 1.5 metres of sand in two cases. One thick sand layer is ungraded and contains mud chips, and may represent a sandy debris flow deposit.

The work aims to understand the origin and frequency of megaturbidites, and hence the location of slope failures on the Nile submarine delta. Lateral correlation of turbidites provides insight into the evolution of these destructive flow events, and potentially the dynamics of the original slope failure. The timing of the flows helps to constrain the mechanisms for triggering slope failure. This work provides a firmer framework for assessing the frequency and magnitude of regionally destructive events on the Nile submarine delta.


Orphan Basin is a perched continental rise basin located northeast of the Grand Banks of Newfoundland. It is surrounded on its southern and western side by slopes of 3°. The slope and floor of the basin consists of widespread tongues of mass-transport deposits (MTDs) and turbidites. The age of the failures was determined by the establishment of an accurate stratigraphic scheme from the cores, which was integrated with sparker seismic-reflection profiles that have a resolution in the order of 0.3-0.4 m. During the last glaciation (22-75 cal ka) five sediment failure events occurred at ~25, 37, 46, 58, and 70 cal ka, yielding a periodicity of ~12 ky. The last glaciation is characterized as a period of multiple millennia-scale fluctuations in the sea-level stand, with the most prominent one occurring during the last glacial maximum (28-22 cal ka). Each of the failures occurring in this time interval coincides with a drop in the sea-level stand. The frequency of failures was highly increased during the last deglaciation, with 3 events occurring at 12.5-14 cal ka, and two at ~17 and 19 cal ka. The youngest failure event occurred during the Holocene, at ~7.5 cal ka.

None of the failures defined in this work coincide with periods of intense glacier melting and ice-calving. The 7.5, 58, and 70 cal ka failures are represented by in-situ deformation in cores on or at the flank of an elevated bedrock structure on the basin floor. The 7.5 ka failure is widespread on the southern slope. These lines of evidence suggest that at least some failures were triggered by earthquakes. The coincidence of the failures during the last glaciation with low sea-level stands suggests that dissociation of gas hydrates may have also played an important role in their production.
Section 3:

New techniques, approaches and challenges in submarine slope instability analysis
Most of the parameters used in slope stability analyses, in particular the mechanical soil properties, are uncertain. Probability theory and reliability analyses can provide a rational framework for dealing with uncertainties. Different methods for doing reliability analysis for slopes are discussed in this study and applied to case studies. The results obtained from FOSM, PEM, and FORM via response surface method combined with the finite element method are compared, and the parameters which contribute most to the uncertainty in the factor of safety are identified.

Keywords: Submarine slope, probability analysis, reliability index, factor of safety.
A submarine landslide west of Spitsbergen could induce a destructive tsunami in the North Atlantic. Here we suggest an effective tool for early warning of tsunamis generated by huge underwater landslides. The method is based on the fact that a displacement of ~1000 km$^3$ of sediment produces a permanent and detectable deformation of earth’s lithosphere.

We numerically model the ground tilting imposed by the hypothetical Spitsbergen landslide. Virtual inclinometers, positioned at the three distinct locations at Spitsbergen, show tilts up to 1000 nrad. The actual size of the submarine mass movement is assessable as soon as the sliding ceases, i.e. approximately after one hour, thus leaving another one hour warning time for northern Norway and two hours for Iceland and southern Norway.
Section 3: New techniques, approaches and challenges in submarine slope instability analysis

TRIGGERING OF SUBMARINE SLIDE UNDER MULTIDIRECTIONAL SEISMIC EXCITATION

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The extraction of natural resources on the continental shelf, continuing coastal development, and the need for protection of the submarine environment have contributed to the increasing interest to better understand the behavior of submarine slopes. Due to the large masses involved, the instability of natural submerged slopes may result in devastating direct and indirect consequences to offshore and coastal facilities as well as a potential trigger for local tsunamis. There are many factors contributing to the risk of submarine slope instability and this paper focuses on seismic excitation. A submarine slope can become unstable during and after earthquake loading. If the earthquake intensity is high enough and the applied shear stress exceeds the available undrained shear strength, the slope can fail during the earthquake. On the other hand, if the earthquake intensity is not sufficient to trigger failure during an earthquake but it has induced large amount of excess pore pressure, slope can fail sometime after the end of the earthquake as a result of pore pressure redistribution (Biscontin, 2001) and/or drained or undrained creep processes (Anantanavanich, 2006). It is postulated that the amount of pore pressure generated at the end of the earthquake is a key parameter for identifying post-earthquake instability of submarine slopes. This work examines the response of normally-consolidated to lightly-overconsolidated soft clay in submerged slopes subjected to multidirectional seismic excitation under simple shear stress condition. Experimental studies of the multidirectional effects on both monotonic and cyclic behavior of soft clay were performed. The SimpleDSS model (Pestana et al., 2000) was refined to describe the response of anisotropically consolidated clay under multidirectional cyclic simple shear loading. The model is able to describe changes in undrained shear strength due to different initial conditions and directions of loading. In particular, the new version of the model has capabilities in predicting the rate-dependent behavior of soft clay by adjusting some material parameters. The proposed constitutive laws were implemented in a dynamic finite element program to solve the problem of multidirectional shear wave propagation. Numerical simulations were performed to investigate important factors affecting seismic response of submarine slope such as: earthquake motion characteristics, soil shear stiffness and shear strain dependent modulus, soil plasticity, thickness of soil profile, and consolidation stress history. The capability of the model allows one to include the effects of the slope inclination and multidirectional shaking in the analysis. Multidirectional effects result in a 20 to 30% higher excess pore pressure developed at the end of the earthquake than in the case of uni-directional shaking. This result is consistent with previous studies on cohesionless soils showing that multidirectional effects are important and are associated with larger deformation potential and excess pore pressure generation (e.g., Kammerer et al., 2002)

Kammerer, A., J. P. Pestana, and R. B. Seed (2002). Undrained response of Monterey 0/30 sand
under multidirectional cyclic simple shear loading conditions. Geotechnical Engineering Research Report UCB/GT/02-01, Department of Civil and Environmental Engineering, University of California, Berkeley.

Gas hydrates are crystalline compounds which can form when water or ice and suitably sized molecules are brought together under favourable conditions. The pressure-temperature conditions for their formation depend mainly on the composition of the gas and of the water-rich phase. The necessary conditions for gas hydrate formation prevail in some marine environments and permafrost regions. Such an environment, where conditions are favourable for gas hydrate formation, is known to exist on the Anaximander sea-mountains in the south Mediterranean. Gas hydrates have been discovered in sediments collected from the mud volcanoes at an average depth of 2000 m below sea level and at water temperatures of 12-14 °C. By using δ¹³C measurement and gas chromatography, it was confirmed that the gas enclathrated in the hydrate state was of thermogenic origin. This type of gas consists of several hydrocarbon components and forms mainly structure II hydrates, sometimes in coexistence with structure I hydrates.

While several studies have been conducted on the behaviour of pure methane hydrates in sediments, which forms structure I crystals, the behaviour of multi-component gas hydrates in sediments, possibly of mixed crystal structure, has not yet been adequately described. Based on previous experimental work, a series of tests were conducted with sediment recovered from the Anaximander’s area mud volcanoes, in order to evaluate the effect of gas hydrate dissociation on the stability of the bearing sediment. The sediment was initially saturated with hydrates at a pressure of 20 MPa, using gas of similar composition to the one found in the area. Subsequently, it was subjected to a gradual dissociation of the hydrate content, either by isothermal depressurization, or by isobaric heating. As a measure for its stability, the strain of the sediment is recorded over a range of overburden pressures. The hydrate phase boundary and sediment displacement results of these tests were compared against the results from similar tests with artificial porous media composed from glass beads. The comparison of the experimental data revealed different cementing characteristics of the hydrate according to the nature of the porous media. Significant differences were also observed of the displacement of the sediment as a result of the degree of hydrate dissociation.

The results indicate that gradual dissociation of the hydrates could bear significant impact on the deep-sea sediments in which they are contained, confirming thus the role of hydrate dissociation as a possible cause to subsea landslides.
ESONET AND GEOHAZARDS

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ESONET is a Multidisciplinary European Network of Excellence (NoE) associating 50 partners (research centres, universities, industrials and SMEs) from 14 countries. More than 300 scientists and engineers will participate to its activities.

The goal of the ESONET NOE is the lasting integration of European research on deep sea multidisciplinary observatories. Over the initial 4 years, the approach will be to merge the programmes of members Organisations through marine research activities addressing the scientific objectives and networking activities specially designed for integration and spreading Excellence.

The NoE will work towards establishing sea floor and water column infrastructure which will provide power for instruments and real-time two-way data communications. Key areas around Europe have been identified from which specific targets are selected for relevant science programmes of potential hazards, geo hot spots and ecosystem processes. Sea floor infrastructure will provide platforms for instrumentation deployed throughout the water column and the geosphere below.

From the beginning of the project, lasting integration is in perspective through the construction of a permanent structure able to provide a set of ESONET CORE SERVICES, related to ESONET REGIONAL LEGAL ENTITIES. All of them will be linked for their implementation scheme as well as for a scientific and technical improvement process.

Earth sciences, geohazards and seafloor interface are one of the main objectives of ESONET. The NoE will structure the resources of the participating institutes to create the necessary critical mass, remove barriers and through a joint programme of activities arrive at durable solutions for this future organisation.

A lot of nodes will be implemented in crucial areas for observing geophysical processes. More precisely, 6 objectives were identified in earth sciences: Transfers from the Earth's interior to the crust, hydrosphere and biosphere; Earthquake hazards; Tsunami hazards; Slope instability and sediment failures; Fluid flow and gas seepage through sediments and gas hydrates; Sediment transfer to the deep sea and climate change.

8 of the 11 deep sea sites of ESONET will contribute to these objectives.

Two work packages are in charge of integrating activities. One is devoted to networking activities in the field of integration of regional observatory initiatives and multidisciplinary efforts, data infrastructure, sharing facilities and link with international observatory programmes. Another one builds up standardisation and interoperability in the field of sensor and scientific package, quality assurance, data management and underwater intervention.

Jointly executed research activities will consists in 3 work packages. In the first one, scientific objectives are specifying for the observatory design including generic and specific science modules. A second one is devoted to demonstration missions. In the third one, the long term funding plan strategy will be issued from implementation strategy tasks on economical and legal models, site assessment and environmental constraint evaluation.
CENTRIFUGE MODELLING OF SUBMARINE LANDSLIDE FLOWS

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Landslides occur both onshore and offshore, however little attention has been given to offshore landslides (submarine landslides). These submarine landslides have significant impacts and consequences on offshore and coastal facilities such as oil and gas production wells, platforms, pipelines and seafloor communication cables. The unique characteristics of submarine landslides include huge mass movements and large travel distances at very gentle slopes.

A series of centrifuge tests in which simulations of submarine landslide flows on a very gentle slope was conducted. Experiments were conducted at different gravity levels to understand the scaling laws involved in simulation of submarine landslide flows in centrifuge testing. The slope was instrumented with miniature sensors for measurements of pore pressure and soil stresses beneath the landslide flows. A series of digital cameras were used to capture the landslide flow in flight.

The results from the experiments give an insight into the flow mechanism involved in submarine landslide flows. The results also provide a better understanding of the scaling laws that needs to be adopted for centrifuge experiments involving landslide flows.
The in situ measurement of seafloor physical properties such as pore pressure, shear strength or compressibility poses a challenge to engineers, in particular in the marine realm. We present the design and first use of a marine, deep-water free-fall instrument for cone penetration testing (CPT). The probe can be operated in up to 4000 m water depth to measure cone resistance, sleeve friction, deceleration, temperature and tilt as well as pore pressure in u1 and u3 position. In this paper we discuss the advantages and disadvantages of the current prototype design, and dwell on the differences between quasi-static versus dynamic cone penetration testing.

Keywords: CPT, free-fall instrument, shear resistance, pore pressure
GAS HYDRATE DISSOCIATION UNDER UNDRAINED UNLOADING CONDITIONS

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Gas hydrates are known to be a potential factor in the initiation and propagation of submarine slope failures. Gas hydrate dissociation is associated with release of water and gas which eventually results either in an increase in pore water pressures or an increase in volume. The release of gas and water has the potential to weaken the sediments resulting in a drastic reduction in effective stress. In other words, gas hydrate dissociation reduces soil strength. Gas hydrate dissociation may take place due to pressure reductions or increases in temperature. Of interest to this work is the hazard created by dissociation of gas hydrates under undrained unloading conditions triggering submarine slope failures. An experimental program was carried out in order to study the response of hydrate laden specimens to temperature/pressure variations in undrained conditions. Of specific interest was quantification of the strength reduction as a function of hydrate content and specimen properties as well as rate effects on these results. This paper presents the experimental results and draws some conclusions regarding the effect of gas hydrate dissociation on the stability of submarine slopes.
Section 4

Monitoring stress on submarine slopes and sediment physical properties
Section 4: Monitoring stress on submarine slopes and sediment physical properties

OVERPRESSURE AND SUBMARINE SLOPE FAILURE IN RAPIDLY DEPOSITED QUATERNARY SEDIMENTS: URSA BASIN, GULF OF MEXICO

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Integrated Ocean Drilling Program (IODP) Expedition 308 was dedicated to the study of overpressure and fluid flow on the Gulf of Mexico continental slope. In the Ursa Basin Expedition 308 tested a flow model by examining how physical properties, pressure, temperature, and pore fluid composition vary within low-permeability mudstones that overlie a permeable and overpressured aquifer. Large parts of the mudstone sections have been involved in submarine mass transport, manifested by sequences of deposits (MTDs) of variable thickness. Frequency and intensity of MTD is larger near the downslope termination of the Ursa Basin sedimentary prism, indicating intrabasin redistribution as a prime mechanism. Downhole penetrometer measurements, made at two sites, define the spatial variation in pressure in low permeability mudstones in the shallow sedimentary section. Sites U1322 and U1324 were located ~10 km apart on an E-W transect traversing the clastic sediment prism of Quaternary age, and were drilled to 234 and 608 meters below seafloor, respectively. (fluid overpressure divided by hydrostatic effective stress) is approximately 0.6 in both locations (i.e. the pore pressure lies 60% of the way between hydrostatic and lithostatic). Near the base of a series of stacked MTD at Site U1322 at the downslope end of the traverse, overpressure reaches values near the lithostatic pressure, defining a horizon of potential future slope failure. The overpressured section may begin at a shallower depth at Site U1322 than at Site U1324. The similar overpressure gradients present at both sites in spite of the almost 3-fold difference in sedimentation rate imply a component of lateral fluid flow between them: this flow increases the pressure at Site U1322 relative to a system with only vertical fluid migration. In the subjacent Blue Unit, composed of interbedded sheet sands and mudstones and underlying the Ursa mudstones, fluid overpressures generated by rapid loading at Site U1322 may be partially dissipated by efficient lateral fluid migration. Viewed on a basin scale, this pattern of lateral fluid flow may be the prime locator for cold seeps, mud volcanoes, and a trigger for repeated submarine landslides having generated major mass transport deposits within the past 50000 years.
COMPARISON OF SIMPLE SHEAR BEHAVIOR OF FINE-GRAINED MARINE SEDIMENTS

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The response of submarine slopes to seismic or storm loading has become an important element in the risk assessment for offshore structures and local tsunami hazard. Evaluation of submarine slope stability requires many soil parameters and relies on the selection of appropriate shear strength values. Offshore sediment sampling is very expensive; therefore, geotechnical data for offshore marine sediments is limited. Experimental information on marine clays mostly comes from marine deposits that are now onshore and easily accessible, such as Boston Blue Clay (BBC) and San Francisco Young Bay Mud (YBM), however, these deposits have a different stress history than offshore deposits. Additionally, most experimental results in the literature for fine grained soils concentrate on one-dimensional response, both for monotonic and cyclic tests. Although the traditional simple shear device has been used to investigate cyclic loading effects on marine clay, it does not allow for complex loading conditions which often contribute to the failure on submarine slopes.

A new multi-directional simple shear device developed at Texas A&M University allows loading along three independent axes, two perpendicular horizontal directions to allow any stress or strain paths in the horizontal plane, and a third in the vertical direction. This device is used to compare the response of different marine clays (BBC, YBM, and Gulf of Mexico deposits) to different loading conditions. One-dimensional monotonic and cyclic shearing of $K_c$ consolidated specimens was used to simulate level ground conditions, whereas the effect of the slope was simulated using $K_0$ consolidation for both monotonic and cyclic tests.
The Pointe-du-Fort submarine mass movement likely took place at the time of the February 5th 1663 earthquake as a sidewall slope failure which generated a mudflow with a run out distance of 1070m and a final flow thickness of 10-15m resting on a slope of 1.4 degrees. The slide involved about 1.95 Mm$^3$ of clayey sediments from an original slope of 24 degrees. The slide took place in normally consolidated sediments composed of stratified low organic Laflamme Sea clay at the base overlain by progressively more organic rich recent sediments. In situ strength testing and sampling on the tidal flat, morphological analysis and remolded strength of the debris lobe can be related to rheological tests to model the mobility of the debris. For the first time, it has been possible to link the mobility of a submarine slide with the characteristics of the sediments at the time of failure with no need to consider water content increase to explain the observed mobility.

**Keywords:** Rheology, undrained strength, yield strength, modeling, liquidity index, submarine slide
Seismic and multibeam data have shown the occurrence of Plesitocene large-scale Mass Transport Deposits (MTDs) and Holocene failure events in Ursa Basin at ~1000 m depth in the eastern levee of the Mississippi Canyon, northern Gulf of Mexico. During IODP Expedition 308 Sites U1322 and U1324 were drilled adjacent to the Recent failures and through several MTDs of Holocene and Pleistocene age. A complete suite of logging, sedimentological and geotechnical data were acquired to reveal the factors controlling initiation of past sediment failures and to characterize the hazard potential of future slope instabilities. Fluid overpressure estimated from a variety of direct and indirect methods indicates that the vertical effective stress is 50 to 70 % lower than if hydrostatic conditions existed. Overpressure in Ursa Basin most likely results from deposition of fine-grained sediments with rates at least 1 m ky\(^{-1}\) with peaks up to 25 m ky\(^{-1}\). The thickest and most widespread MTDs occur in periods of highest sedimentation rate. Considering the very low seismicity experienced by the margin it is most probable that the changes in sedimentation rate might be the primary driving force of slope failure. At Sites U1322 and U1324 a total of 14 MTDs were identified, which leads to a frequency of emplacement of 1 MTD / 4.5 ka. Considering only the thickest MTDs the recurrence interval reduces to 1 MTD / 10 ka.

**Keywords:** Mass Transport Deposits, Overpressure, Slope Stability, Gulf of Mexico
A portion of the Cap de Creus canyon, situated in the Gulf of Lion, has been selected for a detailed analysis of slope instability. This sector has been chosen because of morphological evidence for slide. Three piston cores have been taken at different water depths along an axis perpendicular to the thalweg and a box core has also been taken in the thalweg. At the top of the flank, the geotechnical signature suggests that clay sedimentation has been continuous. In contrast, overconsolidated silty clay has been observed in the core taken on the flank, about 60 m below a headwall escarpment, on a failure plane. The geotechnical profile of the core taken at the toe of the flank suggests that rapid depositional events, such as debris flows and turbidity currents, occur frequently. A series of triaxial tests have been performed, and provided input parameters for analyzing the initial stability of the flank with Slope/W. The impacts of several natural processes on failure development have been tested. Drained failures initiated by axial incisions seem to correspond to the main active process of the canyon, for small shallow failures. Large failure can occur under undrained conditions during earthquakes.
The rheological behavior of soils depends on many factors, including their mineralogy and grain size distribution. This work comprises an extensive search of data collected from the literature, an experimental work on about 17 samples. These results, along with a compilation of existing data, have been used to show that, as a first approximation, the yield strength/viscosity ratio is about 1000, 100 and less than 10 for clayey, silty and sandy fine-grained sediments mixtures, respectively. Our research results on the rheological properties of fine-grained sediments indicate that they are very sensitive to the variation in grain size, shear rate, and geometry of the system.

Keywords: Rheological properties, grain size, shear rate, Bingham yield stress, plastic viscosity
Pore pressure and shear strength are major controlling parameters for slope stability, which can be measured in situ using CPT (cone penetration testing) instruments. This paper presents results from initial tests with two free-fall CPT probes deployed in the neotectonically active submarine slope of northern Crete, Greece. Research expedition P336 investigated landslide-prone areas in the Cretan Sea using multibeam swath-mapping, seismic reflection profiling, in situ CPT measurements, and gravity coring. Several large landslide complexes at the NE Cretan Margin as well as a small, but steep landslide scarp structure further east were identified on the seismic profiles. CPT devices were deployed in undisturbed slope sediments, across the slide scar, and in the main body of the slide, and remained stuck in the sediment for ~10 minutes to monitor pore pressure dissipation upon insertion. Excess pore pressure after insertion is in a range around 60 kPa in background sediment, and exceeds 80 kPa in the slide deposits. Cone resistance of the slope sediment ranges between 300 and 500 kPa, corresponding to undrained shear strengths of up to 40 kPa. The slid sediments (specifically the headwall material with <10 kPa strength) show velocity-weakening behaviour during ring shear experiments, indicating that those sediments are unlikely to show stable creep and instead may fail catastrophically.

**Keywords:** CPT, landslide, shear strength, pore pressure
Section 5

Submarine slides in coastal areas, semienclosed seas (fjords, estuaries, gulfs) and lakes
SUBMARINE MASS MOVEMENTS IN THE BETSIAMITES AREA, LOWER ST. LAWRENCE ESTUARY, QUEBEC, CANADA

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A complex submarine geomorphology was revealed from multibeam bathymetry and seismic reflection surveys conducted between 2001 and 2006 in the Lower St. Lawrence Estuary offshore Betsiamites River, Quebec, Canada. In this paper, we describe the submarine morpho-sedimentology of an area of ~ 500 km² with focus on the consequences of three mass movement events. A chronology suggesting the ages for the failures is established. A major landslide scar is characterized by two large channels on the shelf and a sediments fan in the Laurentian Channel. This landslide is dated around 7.25 kyr cal BP. Morphological observations and sediment core analyses allow us to identify at least two different recent (i.e., less than 1 kyr BP) debris flow accumulations on the shelf and in the Laurentian Channel. Two different ²¹⁰Pb-dated debris flow deposits were identified and associated to two recent earthquake episodes: (1) the AD 1663 (M~7) earthquake and (2) AD 1860 (M~6) or AD 1870 (M~6.5) earthquakes. The 1663 debris flow deposit is associated with a subaerial landslide observed on shore.
The geomorphological interpretation of the high resolution bathymetry of the Albano lake (central Italy), together with conventional geological and geomorphological investigations for the subaerial slope, allowed us to identify several subaerial and submerged morphologies due to slope failures of different size and presumably age. Two main landslide categories will be described in this paper: totally submerged, combined subaerial-submerged landslides. Furthermore a detailed description of two past large slope failures (volume of $10^6$ m$^3$) and the 1997 subaerial and submerged debris flow are presented. The wave induced by the 1997 debris flow testifies also the tsunamigenic potential of these phenomena which is still more serious if the presence of coastal settlements is taken into account.

Keywords: Albano lake, bathymetry, submerged landslide, submerged slope failure, debris-flow, tsunami.
Section 5: Submarine slides in coastal areas, semienclosed seas (fjords, estuaries, gulfs) and lakes

**DYNAMICS OF THE DELTAIC CANYON AREA OF THE RV. CHOROKHI, GEORGIA**

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The Cape of Batumi belongs to accumulative morphological forms and mainly consists of terrigenous sediments of Rv.Chorokhi. It’s location in the central part of the City of Batumi stipulates an importance of intensive research of phenomena. The natural growth of the cape towards the sea was stopped in 30-40-ties of last century, when it’s frontal part closely approached the head of the Rv.Chorokhi submarine canyon. Investigation of the stability conditions of the bottom sedimentary layers deposited inside the canyon has been undertaken on the base of field observations, that repeatedly was held in 1960-2003. Sediment material from Rv.Chorokhi is a main component of the littoral cell of the Adjarian coastline of the Black Sea. The Chorokhi Canyon head locates at depth of 7-8 m at a distance of 70-140m from the river mouth and invades the area of sediment laden currents. Its frontal area spreads along the shore line for as much as 1,5 km. More, than 90% of the river’s load discharge were transported through the Chorokhi Canyon. The stability conditions of submarine sediments are disturbed by changes in the tangential reaction between soil particles or blocks, increased pore pressures, storms, instability of the underlying rocks, structural motions, tsunamis, earthquakes (e.g. stability conditions has been violated by strong earthquake occurred in Turkey on 14-th of January, 1999). Conducted research deals with the analytical considerations of dynamical processes occurring in the given area.

**Keywords:** Cape of Batumi, sedimentary layers, submarine canyon, earthquake, stability.
THE 1990 SUBMARINE SLIDE OUTSIDE THE NIDELV RIVER MOUTH, TRONDHEIM, NORWAY

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The Trondheim harbor has been the locus for many large flow slides during the last century. The most recent of these occurred in 1990 just outside the mouth of the Nidelv River and mobilized ca. 5x10⁶ m³ of sediments. The mass movement took place as a liquefaction-induced flow slide outside the river outlet and developed into a lateral spread. The sediment mass slid along a weak layer of loose silty sand recognized by a distinct seismic reflection interpreted from high resolution seismic data. A combination of static and dynamic loading probably triggered the slide.
SUBMARINE SLOPE FAILURES NEAR SEWARD, ALASKA, DURING THE M9.2 1964 EARTHQUAKE

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Following the 1964 M9.2 megathrust earthquake in southern Alaska, Seward was the only town hit by tsunamis generated from both submarine landslides and tectonic sources. Within 45 seconds of the start of the earthquake, a 1.2-km-long section of waterfront began sliding seaward, and soon after, ~6-8-m high waves inundated the town. Studies soon after the earthquake concluded that submarine landslides along the Seward waterfront generated the tsunamis that occurred immediately after the earthquake. We analyze pre- and post-earthquake bathymetry data to assess the location and extent of submarine mass failures and sediment transport. New NOAA multibeam bathymetry shows the morphology of the entire fjord at 15 m resolution. We also assembled all older soundings from smooth sheets for comparison to the multibeam dataset. We gridded the sounding data, applied corrections for coseismic subsidence, post-seismic rebound, unrecovered co-seismic subsidence, sea-level rise (vertical datum shift), and measurement errors. The difference grids show changes resulting from the 1964 earthquake. We estimate the total volume of slide material to be about 211 million m$^3$. Most of this material was transported to a deep, flat area, which we refer to as “the bathtub”, about 6 to 13 km south of Seward. Sub-bottom profiling of the bathtub shows an acoustically transparent unit, which we interpret as a sediment flow deposit resulting from the submarine landslides. The scale of the submarine landslides and the distance over which sediment was transported is much larger than previously appreciated.

Keywords: submarine landslides, 1964 earthquake, Alaska, multibeam bathymetry, tsunamis
ARCHITECTURE AND SLIDE DEVELOPMENT OF AN EARTHQUAKE INDUCED SUBAERIAL/SUBMARINE LANDSLIDE ON THE ELIKI FAN DELTA, GULF OF CORINTH, GREECE

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On June 15th, 1995, an earthquake of magnitude Ms 6.1R occurred offshore of the Aigion town in the Western Gulf of Corinth. An offshore survey using a 3.5kHz subbottom profiling system, which carried out fifteen days after the main shock has shown that the earthquake caused a small-size (6×10⁵ m²) subaerial to submarine landslide in the Eliki fan delta deposits. Further examination of the landslide, using a side scan sonar system and R.O.V for the visual inspection of the seafloor to map the complex seafloor morphology in and adjacent to the landslide, has shown that the Eliki submarine landslide is a complex low-angle translatory slide less than 5 m deep and that the sliding took place over a single basal glide plane dipping at about 1°. The slide has an almost amphitheatricall shape in plan view and extends parallel to the coastline. A distinctive difference in the deformation style was observed in the northern and southern part of the failure. The instability mechanism that triggered the landslide is liquefaction of a subsurface horizon at a depth of 5 m as suggested by the presence of sand and water injection features (sand boils) in the beach near the slide site and the conical depressions observed on the seafloor. Gas expulsions from the liquefied horizon perhaps enhanced the failure as suggested by the presence of gas charged sediments under the sliding plane and the rising of bubbles in the water column as observed by the fishermen.
THE AD 1881 EARTHQUAKE-TRIGGERED SLUMP AND LATE HOLOCENE FLOOD-INDUCED TURBIDITES FROM PROGLACIAL LAKE BRAMANT, WESTERN FRENCH ALPS

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High-resolution seismic analyses on the sedimentary subsurface of the deep basin of proglacial Lake Bramant (Grandes Rousses Massif, Western French Alps) allowed the detection of a large lens-shaped body with chaotic internal reflections corresponding to a mass wasting deposit (MWD) triggered by the nearby AD 1881 Allemond earthquake (MSK intensity VII). This MWD was only retrieved at the base of a short gravity core and the top of a piston core. Sediments associated with this MWD are remoulded and laminated. Locally, blocks of sediment have preserved the original stratification. This earthquake-induced mass movement is an example of a slide that evolved into a slump. In addition, several Late Holocene turbidite and hyperpycnal deposits related to exceptional flood events were identified using high-resolution sedimentological, physical and geochemical analyses. However, the identification of hyperpycnites is sometimes complicated as erosion of the basal sequence can occur during the rising limb of the flood. While the precise dating of the oldest flood event is still ongoing, two flood events are coeval with the St. Sorlin glacier retreat following the end of the “Little Ice Age”, suggesting outbursts of temporary ice contact lakes or subglacial lakes during warmer periods.

Keywords: slump, earthquake, hyperpycnites, turbidites, floods, proglacial lake, Western French Alps
Recent multibeam sonar and acoustic subbottom profiler surveys and sediment coring offshore the city of Sept-Îles (NW Gulf of St. Lawrence) reveal different types of submarine mass-movements and gravity flows in glaciomarine, paraglacial and postglacial deposits. These mass-movement and gravity flow features are slumps, gullies and channel-levee systems and fans. The key results of this study include: 1) slumps involve the entire deglacial and postglacial sequence, indicating their recent triggering; 2) identification of a 57-cm thick turbidite and several sand layers in sediment cores collected in a deep and isolated basin unaffected by fluvial inputs, along with $^{210}$Pb measurements, indicate the recent activity of mass wasting events derived from slope instabilities; 3) important volumes of sediments are being transported from the coastal to the deeper marine environment by gravity flows processes on the prodelta of the Moisie River. Hypotheses for explaining the widespread occurrence of recent mass-movements due to slope instabilities in the area possibly include their possible triggering by the AD 1663 (M~7) or another large earthquake.

Keywords: Submarine mass-movements, multibeam bathymetry, marine geomorphology, glaciated margin, Gulf of St. Lawrence.
SEDIMENT FAILURE PROCESSES IN ACTIVE GRABENS: THE WESTERN GULF OF CORINTH (GREECE)

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On steep (2-6°) offshore fan deltas of Western Gulf of Corinth medium to small scale ($10^6-10^7$ m$^3$) debris flows and avalanches are the prominent slope features. Loose sands, gravels and pebbles are observed in the lower fan while silty/sandy turbidites/tsunamites detected in cores, implying sediment dissociation during failure and downslope transport. These failures are associated with significant upslope retrogression that has caused coastal retreat with important human and economic impact. All the events were estimated to have occurred during the late 4-5 kyr after or during the deposition (progradation) of the HST fan delta. Recent (late 0.1-0.15 kyr) prodelta failures in the Gulf of Corinth are evidenced by the destruction of telecommunication cables, coastal collapse and the initiation of destructive tsunami waves (i.e. 1963AD). The frequency of major failure events in the Western Gulf of Corinth is estimated to 2-3 events/0.1 kyr, usually associated with strong earthquakes and tsunamis (i.e. 1817, 1861, 1917?, 1963 1995AD events)

Keywords: Offshore sediment failure, Fan delta, geotechnical properties, active graben, Gulf of Corinth, NE Mediterranean
COULD QUICK CLAY HAVE PLAYED A ROLE IN THE STOREGGA SLIDE? 3D SEISMIC EVIDENCE FOR THE DEVELOPMENT OF A SUBMARINE LANDSLIDE IN QUICK CLAY

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Exceptionally high quality 3D seismic reflection data have been used to image and describe an enigmatic seismic facies unit, interpreted for the first time as a submarine landslide developed in quick clay. The unit, covering an area of 850 km², is located on the composite northern margin of the giant Holocene age Storegga Slide, on a south-west dipping slope of 0.5° inclination. Characterised by numerous normal faults bounding rotated blocks, the unit exhibits a striking ‘crinkled’ appearance, which in planform, reveals an unusual morphology consisting of numerous ridges and isolated peaks, separated by an interconnected network of troughs. Calculation of an extension value of 4.5% based on maximum fault throws and dips reveals that limited lateral translation has taken place, a fact that cannot account for a 30% thinning of the unit.

Well documented onshore quick clay slides are characterised by their sudden occurrence, rapid flow velocity, and ability to translate over shallowly inclined surfaces for long distances. Onshore, quick clay slides often develop in young glacially derived clays, commonly overlain by a more competent crust. Such slides and are associated with flowbowls characterised by numerous pyramids and sharp-crested transverse ridges of collapsed and sometimes translated crust, with intervening collapse troughs aligned normal to the direction of slope. Following an initial slide downslope of the submarine quick clay landslide, removal of lateral confining pressure due to the newly formed downslope scarp initiated a backward propagating yield zone, within which the quick clay began to liquidise. As the quick clay was evacuated from beneath the overlying crust, tensional fracturing occurred as progressively more upslope sections of the crust subsided; eventually forming the highly faulted, extensional fabric observed from the data. Undeformed stratigraphy adjacent to the quick clay unit is thought to best represent the pre-failure stratigraphy of the Storegga slide. This suggests the possibility that quick clay may have played a role in the development of other large-scale slope failure events in and around the Storegga region.
ARE THERE DIAGNOSTIC FEATURES OF TURBIDITY CURRENTS GENERATED BY SLOPE FAILURE AND HYPERPYCNAL FLOOD DISCHARGE?

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Deposits of individual turbidity currents have been correlated over 120 x 30 km in the Miocene Marnoso Arenacea Formation of the Italian Apennines. Bed correlations between 109 sections document lateral evolution of individual sediment density flows. These ancient outcrops are an outstanding 'natural laboratory' for understanding submarine flow processes. This field data is compared to experimental and numerical models of turbidity currents. Previous modelling fails to reproduce a significant part of the observed deposit shape – suggesting we need to iterate our models of deposition from such flows. Most large-volume beds (0.7 to 7 km³) contain an internal erosion surface underlain by inversely-graded sandstone, recording waxing and waning flow. It has been inferred previously that these characteristics are diagnostic of turbidites generated by hyperpycnal flood discharge. These turbidites are too voluminous to have been formed by hyperpycnal flows, unless such flows are capable of eroding cubic kilometres of sea-floor sediment. It is more likely that the flows originated from submarine slope failure. Two beds comprise multiple sandstone intervals separated only by turbidite mudstone. Such multiple subunits are seen in other turbidites generated by submarine slope failure. These features suggest that submarine slope failure can occur as a waxing and waning event, or in a number of stages.

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Talling, P.J., et al. (2006). Shape of large volume turbidites, compared to previous modelling results, provides new insight into turbidity current evolution. Sedimentology, in press.
The Caspian Sea as the largest lake in the world has different characteristics considering geosciences. In fact tectonically movement, beach Geodynamic and sea level changing is the most important natural events in this region (Berberian, M, 1983, Khoshravan, H.1999) Historical record shows that these phenomena during the past time caused some hazardous statement in the coastal area like earthquake, sea level rising, beach erosion, huge sliding and scour (Mousavi, M.2001, Paluska, A and Degenz, E, 1992). In this paper we are trying to assess the measure of sea floor vulnerability and hazard statement from point of view sedimentary erosion and geotechnical properties. Also the most important hazardous agents have been introduced. In the sea survey stage with research diving direct observation on the sea floor along the 6 stations from shore line to deep water 60 sediment samples have been taken in the southern coasts of the Caspian Sea. Our data processing and GIS model results show that the value of sea floor vulnerability and hazardous statement is different in the several part of studied area. By the way the most important hazardous agents in the sea floor contain: Mud volcans, Diapiric Shale, loose sediments, sea steepness, hydrodynamic (wave and current), shallow gasses and this area of the Caspian Sea from tectonically activity and hydrodynamic influence point of view is the most hazardous region.

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Section 6

Submarine landslides in volcanic island settings
In the marine basin to the south-east of Santorini volcano, the uppermost sedimentary sequence includes a large number of blocks that range from 10 to 200 m in diameter and protrude about 20 to 40 m above the general surface of the sea floor. They occur in clusters, and the great majority are 10-m size hummocks. The massive and hummocky surface sequence extends more than 20 km from the volcano towards Anafi island, and seismic air-gun lines indicate a thickness of the order 50 m for much of this area. We consider the possibility that the hummocky deposit represents a debris avalanche, and that the source of these blocks may be found in the Profitis Ilias – Mesa Vuono crystalline metamorphic massif in south-eastern Santorini. This debris avalanche may have been contemporaneous with the Minoan eruption. Some geologic features on Santorini are important in this regard. Monolithos is an isolated 50 m long outcrop of marble and limestone that sticks out ca. 20 m above the surrounding Minoan ignimbrite plain at the east coast of Santorini, close to the island's airport runway. In the town of Kamari at the foot of the Profitis Ilias – Mesa Vuono massif in south-east Santorini, there occur two other isolated crystalline limestone or marble outcrops in the ignimbrite plain, ca. 15 m high and 30 to 50 m long. These isolated outcrops may be debris avalanche blocks on land, associated with the same event that produced the debris avalanche block field on the sea floor east of Santorini. The Profitis Ilias – Mesa Vuono metamorphic complex is up to 575 m in height and consists of crystalline limestones of Triassic age and low-grade metapelites of Paleocene-Eocene age. The eastern part of the massif is a very steep slope that forms an east-facing amphitheater-like feature, defined by the arcuate limestone ridge Exo Gonia-Pirgos-Profitis Ilias. In addition, a much smaller possible east-facing slide scar occurs between Mesa Vuono and Profitis Ilias. Finally, Seabeam bathymetric data show a possible remnant collapse scar on the eastern submarine platform of Santorini from 36° 21.73' N and 36° 23.53' N, in line with these features on land and at the landward end of the block-bearing submarine deposit. All of these features suggest that a partial collapse of the flank of Profitis Ilias has generated a major debris avalanche into the ocean to the east, and that this event may be linked to intense local earthquake activity during the Minoan eruption.
Seismic data have been used to evaluate the extent, characteristics and importance of the sediment failures in the Santorini basin. The failures are small but abundant, occupying almost half of the areal extent of the study area, and modify the relief of the basin and the surrounding slopes. The fact that surficial mass flow deposits are the source area of younger sediment failures is evident of the high intensity and frequency of the sediment instabilities. The major factors which are responsible for the observed instabilities are seismic activity and seismicity related to modern volcanic activity, steep slopes and the open sediment structure due to the specific texture of the volcanic material. Sediment failures are believed to compose a big part of the deeper sedimentary column.

Keywords: Santorini, sediment failures, seismic activity, volcanic activity, volcanic sediments
The Soufrière Hills volcano, Montserrat, West Indies, has undergone a series of andesite lava dome growth and collapse events since the eruption began in 1995. Over 90% of the pyroclastic material produced by these eruptions has been deposited into the surrounding ocean. The Soufrière Hills is an outstanding natural laboratory for understanding hazardous mass flows from island arc volcanoes. We present arguably the most complete data set for understanding what happens when pyroclastic flows enter the ocean (Trofimovs et al., 2006). The subaerial part of these flows was monitored in detail, whilst submarine deposits were cored during a cruise in 2005. One of these pyroclastic flows was generated in July 2003 by the largest historical volcanic dome collapse yet documented, which had a volume of ~0.2 km$^3$ and generated a tsunami.

However, seismic reflection profiles (Le Friant et al. 2004) and sea floor morphology record a number of much large debris avalanches whose volume greatly exceeds the entire volume erupted during all of the recent (1995-present) eruptions; ~0.7 km$^3$. The timing of these flank collapse events will be discussed in relation to the timing of eruptions using dated submarine cores. We will also discuss how turbidites record the dynamics of such events.


EVIDENCE OF LARGE-SCALE SECTOR COLLAPSE ON THE E FLANK OF STROMBOLI VOLCANO

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Stromboli is an island volcano, belonging of the Aeolian Volcanic Arc (Southern Thyrrenian Sea), characterised by persistent activity. The cone rises about 2500–3000 m from its submarine base with very steep slopes; its summit reaches 924 m above the sea level. The subaerial growth of Stromboli, occurred in the last 100 ka, has been marked by repeated episodes of large gravitational collapses especially affecting the NW flank of the island in the last 13 ka. The last one occurred less than 5000 years ago forming the deep depression on the NW seaward flank, named Sciara del Fuoco, that produced very likely large water wave according to the numerical simulation (Tinti et al, 1999).

The acquisition of new detailed multibeam bathymetry and geophysical data (high resolution, deep-tow 30kHz TOBI Side Scan Sonar) on Stromboli submerged flanks led to the identification of hummocky terrain and the occurrence of megablocks also at the base of the eastern slope, below -1250 and down to -1750 m, over 10 km far from the island. This witnesses that large-scale instability processes that occurred also on this flank of the island.

On land, an arcuate irregular embayment, open to E (Le Schicciole depression) was already interpreted by Pasquarè et al. (1993) as a scar, resulting from a lateral collapse occurred in the earlier stages of island evolution (some 34-26 ky old) and then partially filled by lavas and volcaniclastic sediments.

The scar prolonges below sea level down to -500 m and it is bounded by the submerged prosecution of the La Petrazza and P.ta dell’Omological high, with lateral scarps that are a few hundred meters high and gradually disappear at about 500-600 m of depth.

Reconstruction of the pre- and post- landslide morphology allowed an estimate of the area of the subaerial-submarine scar of approximately 1.77 km\(^2\) and a volume of 170-250 millions of m\(^3\).

This sector collapse is likely to have produced a large tsunami, that may have deeply affected the facing Calabrian and Sicilian coasts given the orientation of the scar, open towards these areas.

A morphological analysis of the scar-evacuation area and relatable debris avalanche deposits is presented, together with results from sampling of megablocks and discussed taking in account age constraints of the sector collapse and structural control leading to instability.
SEDIMENT STABILITY CONDITIONS WEST OF MILOS ISLAND, WEST HELLENIC VOLCANIC ARC

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Examination of seismic profiles west of Milos Island (Aegean Sea) show that the north Milos slope is affected by extensive mass movements, whereas the south slope is generally stable. Conditions that promote sediment failures include late Quaternary volcanic activity and related seismic activity, tectonically oversteepened slopes and possibly hydrothermal fluid escape. Big and small depressions indicative of phreatic explosions and hydrothermal venting, respectively, have been observed in Milos shelf. Sediment coring revealed that the surficial sediments are relatively soft and thus prone to failure. The lack or presence of sapropel layers is also indicative of unstable or stable slope conditions of the surficial sedimentary cover, respectively.

Keywords: Milos Island, mass movements, seismic activity, volcanic activity, hydrothermal venting, sediment stability
Section 7

Submarine mass movements and tsunamis
ROLE OF BASAL RESISTANCE ON THE INITIAL ACCELERATION OF TSUNAMIGENIC LANDSLIDES

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Most recent work by Grilli and Watts (2005) and Enet (2006) shows that one of the most important factors influencing the source characteristics of a landslide induced tsunami is the initial acceleration of the landslide itself. This finding is based on modeling a landslide as a rigid body moving down a plane slope and solving the equation of motion that balances forces due to inertia, gravity, buoyancy, basal resistance, and hydrodynamic drag. In these models, basal resistance is assumed to be perfectly plastic and frictional in nature. However, in real soils this may be an oversimplification because the shear resistance in soils is highly non-linear and is further complicated by the generation of excess pore pressures. As a result, the initial acceleration of the landslide may be very different than under the assumption of perfect plasticity. This paper presents a refined rigid body model that incorporates non-linear basal resistance developed from existing laboratory data on marine clays and sands. The equation of motion is solved using finite differences to predict landslide motion over the period of which tsunami wave generation typically occurs. The results indicate that initial acceleration would be highest in a stiff, overconsolidated or sensitive clay, possibly generating the largest tsunamis.
Earthquakes are a commonly cited mechanism for triggering submarine landslides that have the potential to generate locally damaging tsunamis. With measured runups of over 35 metres in northern Sumatra from the December 26th 2004 tsunami source, these runups might be expected to be due, in part, to local submarine landslides. Mapping of the convergent margin offshore of Sumatra using swath bathymetry, single channel seismic and seabed photography reveals that seabed failures are common, but mainly small-scale, and composed of blocky debris avalanches and sediment flows. These failures would have contributed little to local tsunami runups. Large landslides are usually formed where there is significant sediment input. In the instance of Sumatra, most sediment is derived from the oceanic plate, and there is little sediment entering the system from the adjacent land areas. Input from the oceanic source is limited because of the diversion of sediment entering the subduction system off of Sumatra, that is attributed to collision between the Ninetyeast ridge and the Sunda Trench at approximately 1.5 million years ago.

**Keywords:** Sumatra margin, tsunami, mass wasting, multibeam bathymetry, single channel seismic.
Section 7: Submarine mass movements and tsunamis

SLOPE FAILURES OF THE FLANKS OF THE SOUTHERN CAPE VERDE ISLANDS

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The flanks of the Cape Verde Islands Fogo, Brava and Santiago show extensive evidence of past and potential slope failure. Analyses of bathymetric and subaerial datasets show debris avalanches, turbidite pathways and debris flows, with the transportation of large volumes of rock and sediment. Similarities are seen with many of the processes operating on the flanks of the Canary Islands. In this paper we show the use of different multibeam bathymetry systems for geomorphological description and quantitative analysis. Slope maps, profiles and backscatter analysis can be used to classify the bathymetric characteristics. These derivative processes delineate the size and shape of the debris avalanches and flows and identify channel systems, as well as areas of recent seafloor volcanic activity. Two distinct debris fields covering at least 2000 km$^2$ sourced from the east coast of Fogo are thought to contain up to 250km$^3$ of material. Large slope failures, such as those from Fogo, may result in damage to seafloor installations such as submarine cables. However, greater hazards may be posed by the consequent generation of tsunamis.

Keywords: Slumping, debris flows, debris avalanches, Cape Verde, landslides, tsunamis
HAZARD SCENARIOS OF LANDSLIDE TSUNAMIS ALONG THE FRENCH MEDITERRANEAN MARGINS

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Submarine landslides may have a crucial role in tsunami generation. Landslide tsunami waves depend from the landslide size, motion and water depth. The evaluation of the hazard associated with landslide tsunamis is thus based on the ability to obtain quantitative information about past landslides identifiable at the seafloor and on the evaluation of seafloor instability through time.

An extensive multibeam bathymetric dataset off the French Mediterranean coastlines down to the continental slopes was analysed to produce a preliminary evaluation of zones that present a record of ancient submarine landslide deposits and a potential for future seafloor instabilities. The French Mediterranean seascape was subdivided in zones presenting homogeneous characters in terms of presence and dimensions of submarine slides and other parameters (seafloor slope, nature and thickness of marine sediment). For each zone, we propose two scenarios of landslide tsunami hazard. The first scenario considers the largest landslide recognised in the zone and ascribed to a single mass wasting event to estimate the maximum effect of an associated tsunami. The second scenario is based on the choice of the idealised most-frequent landslide for a given area in terms of size and recurrence.

For each zone, numerical modelling of tsunami wave generation, propagation and inundation shows the impact of a potential tsunami associated with a landslide of a given location and size. Here we present the modelling result in one selected zone. This study comes as a part of a larger programme funded by the French Ministry of the Environment and Sustainable Development (MEDD) to evaluate the tsunami hazard along French coastlines also linked to the direct effect of earthquakes and seismogenic faults at sea (Plan Séisme).
The main cause of tsunami generation in the Mediterranean Sea is tectonic activity associated with strong earthquakes. However, tsunami waves are also generated by landslides. From a compilation of 32 reliable cases of landslide tsunamis it comes out that most of them were caused by subaerial landslides or marine slides induced mainly by earthquakes and less frequently by volcanic eruptions. Others were caused by gravitative landslides or marine slides. The most frequent events were observed in the Corinth Gulf, Greece (11 out of 32 cases). In the volcanic Aeolian islands, Italy, 7 out of 32 cases were reported. In the Hellenic arc only 3 events are known, in contrast to the abundant, large-size tsunamis of seismotectonic origin historically documented. In Cyclades, South Aegean, only 2 but large landslide tsunamis were reported. Only few events have occurred in Marmara Sea, Cyprus, East Sicily, Liguria-Côte d’Azur and Algeria. Such a pattern of geographical distribution makes possible to assess the potential for landslide tsunami generation.

Keywords: landslide, tsunami generation, tsunami potential, Mediterranean Sea
**TSUNAMIGENIC LANDSLIDES IN THE WESTERN CORINTH GULF: NUMERICAL SCENARIOS**

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The western Corinth Gulf, central Greece, is characterized by steep slopes and large sediment river discharge, that are factors increasing the occurrence probability of underwater landslides. Thus the generation of tsunamis from submarine movements is expected to be frequent in this region, and this is confirmed in the historical tsunami catalogues, where reports of tsunamis related to landslides exist either triggered by earthquakes or by gravitational load. In this work we concentrate on the numerical simulation of submarine landslides and of the propagation of the ensuing tsunamis. We elaborate different scenarios basing on recent swath-bathymetry and seismic profiling surveys performed by the Hellenic Centre for Marine Research (HCMR). The most prominent potentially unstable bodies are found in three different regions: one is placed in the area off the city of Aigion, the second is located close to the Psathopyrgos fault, and the third occupies an elongated area off Eratini on the northern side of the gulf. All considered landslides are characterized by relatively small volumes (in the order ranging from $10^5$-10$^7$ m$^3$). For each scenario, the slide motion is simulated by means of a Lagrangian block model, implemented in the numerical code UBO-BLOCK1, developed by the Tsunami Research Team (TRT) of the University of Bologna, Italy. The tsunami generation and propagation modelling is carried out through the finite-element code UBO-TSUFE, developed by the same research team, solving the Navier-Stokes equation in the shallow water approximation on a triangular-element mesh. We will show how landslide-induced sunamis propagate inside the western Corinth Gulf, the amplitude and period of the tsunami waves at some selected coastal points, and the spatial distribution of the extreme wave heights along the coast.
TOWARDS THE MITIGATION OF THE TSUNAMI RISK BY SUBMARINE MASS FAILURES IN THE GULF OF CORINTH. THE XYLOCASTRO RESORT TOWN CASE STUDY

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Submarine-mass-failure-generated tsunamis pose a significant threat to the coastal communities around the Corinth Gulf. An effort was made towards the mitigation of a potential tsunami generated in the eastern part of the gulf, due to a submarine landslide. The impact of the tsunami was assessed along the coastal segment of the summer resort town of Xylocastro. The analysis (study) of the data within a Geographical Information System revealed that a 4 m tsunami run-up will flood 12% of the town’s district. One fifth of the permanent residents are expected to be affected, while one fourth of the infrastructure is likely to undergo damages. Although alarm and reaction times to a possible local tsunami are short, there is just enough time for evacuation. Therefore a more detailed hazard assessment and an emergency management plan should be undertaken, not only for Xylocastro, but also for other coastal regions in the Corinth Gulf, where extensive development is taking place.

Keywords: tsunami, run-up, inundation zone, submarine mass failures, natural hazard, GIS, Corinth Gulf, Greece.
A large-scale mass-transport deposit (MTD) called Sl6 was recognized on the upper slope of the western Nile margin, downslope from a 30 km-long scarp located along the outer shelf. Regional mapping indicated that this MTD extends on nearly 505 km$^2$ and involved about 14 km$^3$ of Pleistocene-Holocene sediment. Sl6 was triggered between 10 and 9 kyr BP, during the Holocene sea-level rise and coeval pluvial period (increased river flow). The consequent enhanced sediment supply on the upper slope and the outer shelf area caused local overburdening. This factor combined with the potential accumulation of gas in the sediment and earthquake activity is thought to have been the main factor triggering the Sl6 MTD. From the estimated volume of the MTD, a potential slide-generated tsunami was numerically simulated using the GEOWAVE software. The results indicate that the ~80 km wide Egyptian continental shelf protects the main part of the coastline from a slide-induced tsunami coming from the Rosetta area. An exception is the part of the coastline around Alexandria because focussing and shoaling processes can be simulated very close to the coast.

Keywords: submarine mass failure, triggering factors, tsunamogenic potential, numerical simulation
The level of tsunami hazard to the east coast of the United States is not well understood. This information is critical for the population, emergency services, and industry of the region. Assessing this hazard is particularly difficult because of the lack of tsunamis in the historical record and the uncertainty regarding the return periods of large-scale events that have been proposed, such as a large transoceanic tsunami possibly caused by a collapse of the Cumbre Vieja volcano in the Canary Islands, or a large co-seismic tsunami initiated in the Puerto Rican subduction zone. The most significant tsunami hazard in this region, however, may be due to local submarine mass failures (SMF), which could cause concentrated damage in coastal communities located near the failures. This paper presents results of a probabilistic analysis that estimates the hazard, expressed in terms of runup (at a given probability of occurrence), of SMF tsunamis triggered by earthquakes, on the upper northeast coast of the United States. A Monte Carlo approach is employed, in which distributions of relevant parameters (seismicity, sediment properties, type and location of slide, volume of slide, water depth, etc.) are used to perform large numbers of stochastic stability analyses of underwater slopes, based on standard geotechnical methods. When slope failure occurs, initial tsunami characteristic height and runup are estimated, based on earlier numerical work, for specified return periods of seismic events. The overall hazard associated with SMF tsunamis along the coast is found to be quite low at most locations as compared, e.g., to the typical 100 year hurricane storm surge in the region (5 m). Two sites, however, located off of Long Island, New York and Atlantic City, New Jersey, show an elevated risk of higher tsunami runup (5.0-7.5 m). These two sites should be the focus of more detailed studies.

**Keywords:** Submarine mass failures, tsunami triggering; probabilistic analysis; tsunami hazard; runup analysis.
Interest in the generation of tsunamis by submarine mass movements has warranted a reassessment of their distribution and the nature of submarine landslides offshore of the eastern U.S. The recent acquisition and analysis of multibeam bathymetric data over most of this continental slope and rise provides clearer view into the extent and style of mass movements on this margin. Debris flows appear to be the dominant type of mass movement, although some translational slides have also been identified. Areas affected by mass movements range in size from less than 9 km$^2$ to greater than 15,200 km$^2$ and reach measured thicknesses of up to 70 m. Failures are seen to originate on either the open-slope or in submarine canyons. Slope-sourced failures are larger than canyon-sourced failures, suggesting they have a higher potential for tsunami generation although the volume of material displaced during individual failure events still needs to be refined. The slope-sourced failures are most common offshore of the northern, glaciated part of the coast, but others are found downslope of shelf-edge deltas and near salt diapirs, suggesting that several geological conditions control their distribution.

Keywords: bathymetry, seismic reflection, side scan, sediments, Quaternary.
REASSESSMENT OF SEISMICALLY INDUCED, TSUNAMIGENIC SUBMARINE SLOPE FAILURES IN PORT VALDEZ, ALASKA, USA

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The M9.2 Alaska earthquake of 1964 caused major damage to the port facilities and town of Valdez, most of it the result of submarine landslide and the consequent tsunami. Recent bathymetric multibeam surveys, high-resolution subbottom profiles, and dated sediment cores in Port Valdez supply new information about the morphology and character of the landslide deposits. A comparison of pre- and post-earthquake bathymetry provides an estimate of the net volume of landslide debris deposited in the basin and the volume of sediment removed from the source region. Landslide features include (1) large blocks (up to 40-m high) near the location of the greatest tsunami-wave runup (~50 m), (2) two debris lobes associated with the blocks, (3) a series of gullies, channels and talus, near the fjord-head delta and badly damaged old town of Valdez, and (4) the front of a debris lobe that flowed half-way down the fjord from the east end. A transparent unit, with a maximum thickness of 10 m, above the debris flow deposits in the deepest part of the fjord, likely represents a lower density sediment flow related to the other failure deposits. Calculations from the bathymetric difference map suggest a total net volume of displaced sediment on the order of 0.4 km$^3$. However, an integration of the volume of debris flow deposits (mapped according to their acoustic signature) indicates a gross volume of about 1 km$^3$, showing that the landslides incorporated significant additional sediment from the fjord floor into the debris flow as it moved. Despite the large volume of sediment failures in the eastern part of the fjord, smaller, but more coherent block failures in the western part appear to be the primary cause of the largest tsunamis that impacted the shorelines.

Keywords: Submarine landslide, tsunami, Alaska, earthquake
On June 15th 1995 a strong earthquake of $M_s = 6.2$ magnitude struck the highly seismic area of the Gulf of Corinth Greece. Besides the extensive structural damage instigated to the city of Aigion (15km to the south of the epicenter), this earthquake was the cause of a number of ground failures at various locations along the coast of the Gulf. The most important of these ground failures were observed at Eratini, a small town located on the north coast of the Gulf, within the greater epicentral area of the earthquake. In particular, at four (4) sites, one within the fishing harbor of Eratini and three along the nearby 2km long beach, the coastline retreated 5 to 15m inland. In addition, water front barriers collapsed, paved park areas cracked and sunk into the sea, while the seaside retaining wall of a coastal road was threatened by scouring of the foundation soil. Submarine geophysical surveys (via O.R.E. 3.5-kHz subbottom profiler and EG&G 260 side scan sonar system) have shown that, in three of the above sites, the earthquake caused extensive slides accompanied by debris flows and block rotations. Reconstruction of the pre-earthquake topographic profiles along the main axis of the slides indicates that the failure zones extended to a maximum depth of 6 to 10m within the (up to 30m thick) loose alluvial deposits which cover the geological bedrock (mildly sloping flysch). Geotechnical exploration, based on CPT and DPHS measurements, revealed that the soil profile at the failure sites is characterized by a continuous interchange between (potentially) liquefiable silty sand and non-liquefiable clay layers. This profile favors the development of excess pore pressures which may remain trapped within the clay-sealed silty sand layers for a long time after the end of shaking and thus creating zones of reduced shear resistance that may lead to a static mass flow failure (after the earthquake), even for relatively small surface gradients. The geotechnical analyses consisted of liquefaction potential estimates at the locations of the in-situ tests and slope stability analyses of the pre-earthquake topography along the longitudinal axes of mass flows. From a practical point of view, the following points are worthy of attention:

(a) Post-earthquake landslides (under practically static conditions) occurred for ground slopes as low as 12.0%, corresponding to a pre-earthquake static factor of safety of about 2.0.

(b) In three of the four sites, ground failures were triggered by excess pore pressure build up in the thin silty sand layers, with average thickness between 0.25 and 0.35m. Such layers can be easily missed during a conventional geotechnical exploration or overlooked during the evaluation of the in-situ information on the grounds that they probably lack lateral continuity.

(c) Assuming complete liquefaction of the silty sand layers, the relevant analyses indicate that the horizontal peak ground acceleration in the area must have exceeded 0.29g. This is a relatively high value, but it is readily justified by the small epicentral distance of Eratini.
(d) The depth of minimum liquefaction resistance, ranging between 6.3 and 9.4m, compares well with the maximum depth of the failure surface estimated from the reconstruction of the pre-earthquake topography.
Seventy Tertiary age mass transport complexes, which range in area from 11.3 km\(^2\) to 2017 km\(^2\), have been identified in the continental margin of offshore Trinidad using a 10,000 km\(^2\) 3D seismic mega-merged. These submarine mass movements were of sufficient scale to produce tsunamigenic forces. The magnitude of the waves generated by a submarine slide will depend primarily upon the volume of material that is moved, the depth of submergence in which the failure occurs, and the speed of the landslide. These parameters can easily be calculated using direct input from the 3D volume, including thickness, length, width, area and general geometry of the deposits. Using 3D data offers a range of visualization and attribute analysis not afforded researchers working with 2D seismic or sea-floor imaging sonar.

Three different types of mass transport complexes were identified in offshore Trinidad based on the relationship between slope mass failures and the sourcing regions: 1) slope-attached systems, which occur when upper slope sediments catastrophically fail due to earthquakes and/or gas hydrate disruption, 2) shelf-attached systems that are fed by shelf edge deltas whose sediment input is controlled by sea-level fluctuations and sedimentation rates, and 3) locally detached systems, formed when local instabilities in the sea floor trigger relatively smaller collapses. Such classification enables a better understanding of the nature of initiation, length of development history and petrography of such mass transport complexes.

Maximum tsunami wave heights were estimated for the three types of mass transport complexes, the calculations were made assuming that the velocity of the slides was less than 50 m/s. Two key parameters were used as input; 1) the water depth in which the slides supposedly failed, and 2) the observed or reconstructed thicknesses of the slides. The results indicated that slope-attached systems, generated due to sudden sediment remobilizations, are more likely to disrupt the overlying water column. Slope-attached systems can generate maximum tsunami wave heights in offshore Trinidad that can reach 8 to 11 m high above the slide failure. Due to changes in water depth, and variations on the geometry of the coast line, the run-up heights of the tsunamis approaching the coast line are commonly greater than the heights of the tsunamis that were generated offshore by a factor of two or more times. In this case, slope-attached systems could easily generate tsunamis with run-up heights near the coast that can reach in between 16 to 21 m high. The same analysis indicated that shelf-attached systems could generate tsunamis with run-up heights approaching the coast in between 11 to 14 m high, whereas locally detached systems could generate tsunamis with run-up heights in between 8 to 11 m high.
Within the framework of an interdisciplinary study, we found sedimentary evidence of extreme events along the northwestern Greek coast between Lefkada and Preveza. Intense field survey, the analysis of remote sensing data, vibracorings and the sedimentological, microfaunal and geochemical analysis of sediment samples show that large parts of the coastal area have been affected by multiple tsunami washover, runup and runthrough effects.

Between the city of Lefkada and Aghios Nikolaos, five different types of deposits were distinguished: (i) washover fans (chevrons), (ii) dislocated mega-blocks, (iii) fields of scattered stones and blocks from the littoral zone, (iv) runup/backwash sediments, and (v) sediments of a breakthrough fan spreading into the near-coast environment of the Lake Voulkaria inducing (vi) tsunamigenic suspension deposits within the limnic sedimentary sequence. Age determination based on ceramic fragments and radiocarbon dates document at least four tsunami events around 1000 cal BC, 300 cal BC, 430 cal AD and 1000-1400 cal AD.

Vibracores from the Actio headland south of Preveza show high energy wave deposits immediately on top of bedrock units. These deposits are made up of fine gravel and coarse sand and include numerous fragments of marine shells. The transition towards the underlying bedrock is often marked by an erosional unconformity clearly documenting the event-like character of the unit. Ceramic findings both at the base and within the tsunamigenic deposits indicate a main event during Classical-Hellenistic times. At several sites, the ground surface is covered by another unit of coarse sediments possibly corresponding to a younger tsunami event of (sub-)recent age.

We assume that the tsunami events were triggered by seismic activities along the nearby Hellenic Arc and the Cefalonia Transform Fault and/or by submarine mass movements, e.g. from the north African shelf into the Ionian deep sea basin. The tsunamis between Lefkada and Preveza owed their extraordinary wave heights to the funnel-like coastal topography.
Submarine mass movements are well known to be one of the most frequent generating mechanisms for tsunamis. Although tsunami catalogues indicate that the largest percentage of worldwide tsunamis have tectonic origin, the hazard and risk related to landslide-generated tsunamis is not at all negligible and has received constantly increasing attention in the last two decades. Mass movements having tsunamigenic potential typically occur in volcanic environments or along steep ocean margins, and include rockfall avalanches, landslides, slumps, debris avalanches, sediment failures, etc. Only rare catastrophic collapses, like the Storegga complex landslide occurred about 8,000 years ago, the eruption and collapse of the Santorini volcanic edifice about 1500 years B.C., or the explosion of the Krakatau in 1883, are able to produce tsunamis having significant effects at ocean-wide scales. The tsunamis set in motion by moderate-size landslides tend to affect mainly the coastlines in a limited area close to the source, but these local effects can be devastating. This picture represents the common situation in the European seas, and especially in the Mediterranean where typical examples are provided by the Stromboli island in southern Tyrrhenian, by the Corinth Gulf (central Greece) and by the Marmara Sea. The hazard related to landslide generated tsunamis in the European seas will be one of the topics covered by the EU funded project TRANSFER (Tsunami Risk ANd Strategies For the European Region), which is coordinated by the University of Bologna, Italy, and involves 29 partners from several different European countries, and also Turkey and Israel. The project, started officially on 1st October 2006 and lasting 30 months, will tackle all the main topics related to tsunami research, ranging from the compilation of catalogues of historical and paleo-tsunamis, as well as of seismic and non-seismic sources, to the analysis of the present-day earth observing and monitoring (seismic, geodetic and marine) systems and data processing methods, from the improvement of existing numerical models for tsunami propagation and impact to the development and updating of statistical and probabilistic approaches for the computation of tsunami inundation maps, to the use of all the aforementioned results in the development of tsunami scenarios in seven different test-areas covering all the European seas. One of the tools that will be employed in the framework of TRANSFER as regards the numerical modelling of landslide dynamics is represented by the softwares UBO-BLOCK1 and UBO-BLOCK2, both developed by the Tsunami Research Team at the University of Bologna, Italy. The two softwares implement, in 1D and 2D respectively, a block-based Lagrangian model: at each time step the reference frame moves together with the moving mass, involving a clear distinction between it and the sliding surface. The mass is divided into blocks, and the motion equations are computed and solved on each block’s centre of mass (CoM), taking into account the gravity, the basal friction and the exposed surface stresses, the buoyancy effect and the block-block interaction forces. The volume is conserved, and the blocks are not allowed to separate from each other. At each time step $i$ the velocities and the positions of the CoMs and of the block extremes are computed from the $i-1$ acceleration: these allow to reconstruct the geometry and dynamics of the mass and to compute the acceleration at the $i$ time step, suitable for the subsequent $i+1$ step. The simulation is stopped when the velocity lowers a predefined value.
threshold, or when the mass exits the computational domain. The model is suitable to the simulation of landslide-generated tsunamis. We will present an application to a complex landslide sequence occurred at the island of Stromboli, southern Tyrrhenian, on 30th December 2002. Two main sliding episodes took place at a time distance of about seven minutes, both being tsunamigenic. The tsunamis were destructive in Stromboli and were clearly observed in the other islands of the Aeolian archipelago. In Stromboli, maximum tsunami run-ups of about 10 meters were measured.