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A data base on submarine landslides of the Mediterranean Sea

Roger Urgeles, Universitat de Barcelona (Spain)

Laura Fantoni, Università di Modena e Reggio Emilia (Italy)

Angelo Camerlenghi, Universitat de Barcelona (Spain)

Submarine landslides are an ubiquitous process along the continental margins of the Mediterranean Sea. A database, containing 232 occurrences of mass failure deposits and 211 occurrences of failure scars, has recently been compiled from publicly available literature indicating that submarine landslides in the Mediterranean occur on tectonically dominated margins as well as on passive margins and volcanic island flanks. The record is relatively rich in the European margins and relatively poor in the North-African margins indicating that further studies are necessary in the southern Mediterranean so as to obtain an inventory that might be useful for geohazard evaluation. Most landslides occur in the form of long distance travelling debris flows, but slumps and deep seated failures are also relatively common. On abyssal plains the distal product of massive failures is recorded as large megaturbidites, while on volcanic islands the dominant failure type are debris avalanches, owing to the rocky nature of their flanks. Submarine landslides, excluding megaturbidites, appear to occur on all water depth between the coastline and about 2000 m. No submarine landslides were recorded beyond that depth. Most landslides occupy areas ranging from a few squared km to about 600 km² and volumes up to 220 km³, but massive abyssal plain megaturbidites can attain 60,000 km² and 1000 km³. The headwalls are clustered around two modes: 0 to 40 m for relatively small landslides and 160 to 200 m for the largest ones. Most recorded submarine landslides are relatively young in age and several events appear to group near the Pleistocene to Holocene transition, indicating that a climatic control in triggering seems plausible. 50 events were reported to occur in areas where slope instability is a recurrent process, 20 events were reported as tsunami initiators. This study indicates that submarine slope instability is one of the most important processes operating on continental margins and poses a significant geohazard. Further studies are thus requested in order to characterize this process including drilling and monitoring of a few places where failure seems to be at an initial stage.

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Characterisation of landslide-prone slope sediments in the Cretan sea (eastern Mediterranean)

Annika Förster, RCOM (Germany)
Michael Strasser, RCOM (Germany)
Frank Strozyk, RCOM (Germany)
Giovanni Spagnoli, RCOM (Germany)
Sylvia Stegmann, RCOM (Germany)
Achim Kopf, RCOM (Germany)

Submarine slides have been mapped along continental margin throughout the world. Numerous slide events are described south of Crete. In opposite to this, our study focus at the Cretan Sea, a fore arc basin between the Hellenic trench and the volcanic arc north of Crete. We here present results from in situ and laboratory geotechnical experiments from the CRESTS (Cretan Sea Tectonics and Sedimentology) expedition P336, where landslide processes were studied in the neotectonically active submarine slope area. The main objective of this study is to characterise the physical behaviour and frictional stability of the sediments in order to relate the results to potential trigger mechanisms such as tectonic oversteepening, excess pore fluid pressure, weak clay horizons, or earthquake tremor.

Bathymetric and seismic reflection data show two distinctive slide complexes at the northern Cretan Margin with different geometries, thicknesses and internal deformations patterns. The continental slope differs in steepness from 8° (western Slide) to 1° (eastern Slide). The western complex, extended over 260 km, represents multiple slide events with clear headwalls. In contrast, the eastern complex extends over approximately 60 km and seems to be slid down as a more or less intact block. Bathymetric data suggest genesis of new headwalls in the slid sediments further downslope. Based on the geophysical observations, in situ CPT measurements and sampling for laboratory experiments were carried out. We here present the shipboard results which included core description, index properties, grain size analysis and various types of shear experiments.

All gravity cores show similar lithostratigraphic successions characterised by yellowish brown sandy to silty mud, light olive grey sandy to silty mud and olive black sapropels. Density values in the undisturbed sediments increase in both complexes more or less linearly downward. It is noticeable that the densities of the eastern complex are lower than those of the western complex. Also, densities near the scarp and the failed sediments of the eastern complex are similar to the undisturbed slope sediments. However, the farthest travelled deposits at the western slide complex show lower densities as the undisturbed deposits, suggesting homogenisation as a result of displacement. The undisturbed sediments are characterised by a linear downward increase in undrained shear strength in both slide complexes. Along the flow path of the slides, however, strength remains more or less constant.

Ongoing research aims to shed light on slope instability triggers including static ring shear tests, oedometer tests and dynamic triaxial shear tests to simulate high strains, seismic tremor and rate-dependent strength.



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Core-log-seismic integration of mass transport complexes in the shallow subsurface of the Ursa basin, northern Gulf of Mexico

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Seismic facies and material properties of mass transport complexes (MTCs) in the Ursa Basin are controlled by porosity, not lithology. Deformation is distributed throughout MTCs, but tends to be greatest towards the base. In seismic, MTCs are imaged as low-amplitude zones above a high-amplitude basal reflector. However, within the overall low-amplitude zones we identify two seismic facies:

1) locally high-amplitude chaotic, and 2) discontinuous/locally stratified. In seismic cross section the locally high-amplitude chaotic facies appears as high-amplitude discontinuous reflections. These reflections are sinuous in interval amplitude maps.

The basal reflector is high amplitude, continuous, and records grooves (~10 km long). The top reflector is lower amplitude than the basal reflector and is continuous. The discontinuous/locally stratified facies contains discontinuous reflectors that abut against pyramid-shaped islands ("pinnacles") of parallel stratified reflectors. Each pinnacle sticks above the surrounding material and each pinnacle is attached to the base of the MTC. The basal reflector has an interesting amplitude response: it is high-amplitude beneath the discontinuous reflectors but relatively dim beneath the pinnacles features. The locally high-amplitude chaotic facies has a pronounced increase in bulk density (lower porosity), shear strength, and resistivity relative to bounding undeformed sediment. Deformation in this facies appears as deformed mud with a homogeneous appearance, with occasional folds, and rare mud clasts. The discontinuous/locally stratified has only slightly increased bulk density (lower porosity), shear strength, and resistivity, relative to bounding undeformed sediment. Deformation is subtle in this facies and recorded as tilted bedding and small-offset faults.

The higher density MTCs creates a strong impedance contrast between bounding non-MTCs, and therefore a strong reflection at both the top and base. The density contrast is higher towards the base of MTCs and therefore creates a higher amplitude reflection relative to reflection at the top of the MTC. We interpret that the locally high-amplitude chaotic facies represents debris flows (relatively long run-out and greater deformation), and the discontinuous/locally stratified facies represents slumps (relatively short run-out distance, and minimal deformation). The relative positions of slumps and debris flows within the Ursa Basin provides insight into the controls on where each occurs. Debris flows occur where the highest overpressure ratio has been measured whereas slumps occur where the overpressure ratio is lower.



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Deposition rate and geochemical characters of sediments in Zhejiang offshore

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Based on the analysis of ²¹⁰Pb radioactivity, grain-size and element geochemical contents of 5 cores collected from shallow sea of Zhejiang offshore, we discussed the variation of deposition rates, the vertical distribution and change characters.

The results show that deposition rate is 1.19-0.91cm/a in Zhejiang offshore, with the tendency of lessening from north to south offshore, and influenced by local river. The content of element rises slightly in vertical from deep to shallow location, with circle variation of high-low-high-low or low-high-low-high. Of five key evaluation elements, i.e. As, Cd, Hg, Cr, Cu, Pb and Zn, the environment background value is high at large. The background value of Cr and Cu is close to top limited value of No. 1 grade according to standard of national marine sediment quality.

Key words: ²¹⁰Pb radioactivity; deposition rate; geochemistry; background value; Zhejiang offshore

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Geochemical evidence for groundwater-charging of slope sediments: The Nice airport 1979 landslide and tsunami revisited

Achim Kopf, RCOM (Germany)
Sabine Kasten, AWI (Germany)

In October 1979, a period of heavy rainfall along the French Riviera was followed by the collapse of the Ligurian continental slope adjacent to the international airport of Nice, France. A body of slope sediments, which was shortly beforehand affected by construction work south of the airport, was mobilized and traveled hundreds of kilometers downslope into the Var submarine canyon and, eventually, into the deep Ligurian basin. As a direct consequence, the construction was destroyed, seafloor cables were torn, and a small tsunami hit the Gulf of Antibes shortly after the failure.

Several hypotheses have been put forward to explain the trigger mechanism of the landslide. They include (i) construction of an embankment south of the airport added extra load on the slope sediments, (ii) failure of a layer of sensitive clays within the slope sequence, and (iii) excess pore fluid pressures from charged aquifers in the underground. Over the previous decades, both the sensitive clay layers and the coarse-grained sand and gravel layers of high permeability were sampled. One layer of gravel is particularly critical, since its pore water chemistry showed significant freshening.

During recent RV Meteor cruise M73-1 (summer 2007), the landslide scar and adjacent slopes were revisited for high-resolution mapping and sampling systematically. Results from half a dozen gravity and push cores in the shallow slope area reveal that the zone of freshening (i.e. groundwater influence) is very limited in extension. Along strike of the margin, an only 100-250 m wide zone shows pore waters with salinities of 5-50% SW concentration and depletion in other constituents (e.g. Cl, Fe, sulfate). Cores east or west of the landslide scar in the undisturbed slope show regular seawater (SW) profiles. Most interestingly, the three cores inside the landslide scar hint towards two potential source areas for the groundwater, because two cores show extremely high concentration of Cr (0.2-0.25 mg/l) whereas the third core shows SW Cr concentration. Ongoing analyses try to identify other elements that allow us to distinguish between the different sources of groundwater. The understanding of the aquifer system, possibly aided by water analyses from onshore wells, may help assess the risk of future slope failure in the Var estuary/Nice airport area.



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Mass movements on the inner slope of a wedge at the transition from frontal accretion to frontal erosion: Evidence from a fossil analogue in the northern Apennines of Italy

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Submarine mass movements are sedimentary phenomena abundant in both present-day seafloor setting and in the sedimentary record of ancient basins. For this reason they represent one of the most important processes in the destruction of submarine margins and sediment redistribution. The investigation of ancient mass movements in on-land examples recorded in former sedimentary basins is particularly important because it may provide insights into the features of their modern submarine correspondent. The study of fossil analogues offers, in fact, a more detailed source of information on internal structures, depositional processes and post-depositional deformation history than the present-day submarine examples.

In the Northern Apennines of Italy, both stratigraphic and structural data suggest a vast removal of the frontal part of the Ligurian accretionary prism through a large-scale process of tectonic erosion, in the early Miocene. This caused the destabilization of the forearc and the development of a distinct, large-scale mass-wasting event - the Canossa Event - which resulted in the collapse of the whole inner lower-slope of the foredeep. The slope failure is well recorded in the sedimentary infill of the external basins of the epi-Ligurian sequence, representing the lower portion of the original slope, where the sediments older than the Aquitanian are totally missing or represented by few scattered blocks ranging in size from several metres to several hundred metres (rarely few kilometres) and few hundred metres thick. As a consequence of this mass-wasting event, large submarine debris flow deposits, reworking material from the underlying accretionary Ligurian wedge, have been generated. They are now represented by the Aquitanian epi-Ligurian Val Tiepido-Canossa argillaceous breccias which in vast areas of the Northern Apennines are unconformably sealing the Ligurian substratum and few remnants of pre-Aquitania epi-Ligurian sediments.

The Val Tiepido-Canossa argillaceous breccias, extending for about 300 km along strike, ~10 km wide and ~300 m thick, provide a prominent fossil example of the sedimentary response to the destabilization of a slope apron in a convergent setting, as a consequence of the removal of a wedge toe through frontal tectonic erosion processes. This catastrophic mass-wasting event, implying a large tectonic reorganization of the outermost part of an accretionary prism, is one of the largest on-land examples of fossil submarine landslides and is comparable with present-day mass-wasting deposits in similar plate tectonic setting.



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Multi-parametric analysis and slope stability assessment of a submarine slide in the deep basin offshore Algiers (Western Mediterranean)

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Antonio Cattaneo, *Ifremer (France)*
Didier Leynaud, *Ifremer (France)*
Ricardo Silva Jacinto, *Ifremer (France)*
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Karim Yelles, *CRAAG (Algeria)*

Algeria has experienced several moderate to strong earthquakes during the last century in the coastal zone. The most violent instrumentally recorded earthquake occurred on October 10, 1980 in El Asnam (Chlef currently), and reached a magnitude of 7.3 (Ms). More recently, on May 21, 2003 an earthquake with a magnitude of 6.8 struck the city of Boumerdes, on the coast near Algiers, and generated significant gravity flows recognized by numerous submarine cable breaks. In order to investigate the offshore imprint of the earthquakes, we analysed a sector of the Algerian margin at the foot of the slope, and focused on an area located offshore Algeria about 50 km NE of Algiers. In this area, geophysical data acquired during the campaign MARADJA2 (2005) showed the presence of presumably recent slope instabilities and sediment deformations that could be responsible for the cables break-offs located a few kilometres downslope.

The present study summarizes data from three campaigns led from 2003 to 2007 in the area. The dataset includes multibeam bathymetry, high resolution reflection seismic, seafloor imagery, sediment samples and in situ measurements. On geophysical data, a submarine slide is particularly evident from side scan sonar (SAR) images. The echo-sounder profile associated with the SAR reveals the presence of a well-defined slide scar with associated deposits showing transparent echo-facies at the slope foot in about 2700 m water depth. These geophysical data have been complemented during the campaign PRISME in 2007 by sediments sampling and in-situ measurement (CPTU and piezometre). Five penetrometric measurements, supported by laboratory tests (triaxial and oedometric) on three piston cores, allows to constrain the mechanical properties of the sediment.

An assessment of the slope stability is being developed using numerical modelling software (PLAXIS 2D and SAMU 3D). Slope stability is assessed by integrating a soil model (based on sediment core and penetrometric data acquired upslope the headwall, in an undisturbed area), and triggering mechanisms such as high sedimentation rate and/or seismic loading. Finally, the movement of the slide is simulated based on the Smoothed Particles Hydrodynamics method considering the sediment character, the volume involved and the seafloor morphology downslope the slide. This approach allows to understand the rheological behaviour of the slide and its evolution towards gravity flow, including the erosive power of such sedimentary instabilities and the associate hazard for offshore infrastructures.



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Post-rift sedimentary processes on the Gebra Debris-Valley, central Bransfield Basin (Antarctic Peninsula)

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The Gebra valley (Gv) is located at the slope of the Central Bransfield Basin (CBB), a young and active rift basin in the Antarctic Peninsula. Later on it has been associated to a large slide system and recently the Gv has been included in the called "Gebra-Magia slide complex" which is defined as a major area of mass-wasting and includes two large debris valleys. This study is based on multibeam bathymetry and high and very high-resolution seismic profiles. The morpho-sedimentary and seismic stratigraphy analysis has allowed giving a new sedimentary and evolutive interpretation of the Gv.

This valley is situated on the lower slope and extends down to the CBB at 1930 mwd. It is divided into 2 morpho-sedimentary domains, the valley itself and adjacent open slope. The valley is about 31 km long and 7-10 km wide. It has a complex amphitheatre-shaped headwall constituted by two differentiated scar systems, an upper (1100 mwd) and a lower (1500 mwd) system. The headwall is affected by erosive features as gullies (< 350 m wide; 35 m of relief) and surficial slide-scars (up to 2800 m length; few meters of relief). Downslope the lower scar, the upper valley surface is highly irregular with chaotic geometry associated to mass-transport processes and downslope trending channels incising those deposits. This surface displays a general positive relief that becomes smoother downslope. The nearsurface sediments of this smoother surface comprise highly reflective stratified facies which could be associated to turbidity flows. The sidewalls (150 m of relief) of the Gv are steep and present secondary slide scars (about 50 m of relief) that configure a terrace-like shape. Both adjacent margins of Gv (the open slope) show an irregular surface overlying sediments associated to mass-transport and turbidity processes. Locally, a wavy seafloor area of about 10 km², shows discontinuous stratified facies that could be associated to a sediment waves field formed by unchanneled turbidity flows.

The stratigraphy reflects a buried depression limited by a steep scarp that represents the first and major slide scar of the Gv. The entire post-rift deposits fill this depression. Also the infilling of this major valley reflects a vertical succession of scars resembling ancient sidewalls of the valley. They indicate the occurrence of different cut and fill events and the dimensions of the valley have decreased with time. The infilling deposits are formed by a vertical stacking of chaotic levels/bodies in the proximal reaches of the valley that change downslope to subtabular units defined by a succession of acoustically transparent-chaotic packages, deposited from mass transport processes intercalated with stratified facies associated to turbidity flows.

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Seafloor stability monitoring by a 3-component servo-accelerometer system

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In order to monitor the seafloor stability during methane hydrate productions, it is required to measure seafloor displacement continuously. In the case of onshore landslide site, ground displacement monitoring of the landslide movement is usually done by such instruments as the slide sensors. These instruments measure the relative displacements between a fixed point and measuring points in the landslide mass. However, those can not be used for displacement monitoring at the seafloor where it is difficult to set a fixed reference point.

In this paper, we will first describe the outline of the prototype monitoring system. Next, the test results of servo-accelerometers and gimbaled mechanism will be explained. Then, we will introduce how to obtain displacement signals from the servo-accelerometer data, including data acquisition system and data processing algorithm. Then, we will demonstrate some results of performance tests for the servo-accelerometer in the laboratory. In addition, we will show a result of a shearing test for a soil sample in the laboratory and a monitored data at an onshore landslide site. Finally, we conclude the results and discuss about applicability of the system and future works.

This work was conducted by the Engineering Advancement Association of Japan (ENAA) under the contract of "the Research Consortium for Methane Hydrate Resources in Japan (also known as the MH21 Research Consortium)" supported by the Ministry of Economy, Trade and Industry. In this Consortium ENAA is doing research on Environment Impact (URL: <http://www.mh21japan.gr.jp>).



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Tsunami potential of the 25 ky BP Gondola Slide in the SW Adriatic margin

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The SW Adriatic margin provides evidences of numerous sites of slope instability from the shelf edge to the slope base and along a margin stretch of about 150 km. The upper slope displays multiple and steep headscarps in compacted sedimentary units deriving from a set of Pleistocene regressive sequences with a gentle basinward-dip. On the seafloor, Gondola Slide is the most evident mass wasting deposit with large blocks, a pronounced slide scar (10 km x 2.5 km) breaching the shelf edge (about 180 m deep today but at a paleodepth of about 50 m at the time of failure), and mobilizing about 4.5 cubic kilometers reaching a maximum runout of more than 50 km. Recent research provided data on the slide deposit morphology. It was found that the upper portion of the slide, which is exposed on the seafloor, extends about 23 km seaward of the slide scar and down to water depths of 800 m. Beyond this depth the distal part of the slide (buried by glacial-time and post glacial bottom current deposits) extends over 30 km. Gondola Slide failed during the last glacial (some 25 ky BP), but strong bottom currents active in the area swept the seafloor avoiding deposition and leaving most of the blocky slide exposed. Such a large mass failure might have generated a great tsunami, which is explored in this paper by means of numerical simulations that are based on reconstruction of the geometry of the water basin at the time of failure. The numerical model, that has been developed by the University of Bologna, Italy, consists of a series of modules: the first one computes the dynamics of the sliding mass through a Lagrangian approach where the mass is partitioned into interacting blocks, the third one computes the tsunami propagation on an unstructured Eulerian grid through the shallow-water approximation of the Navier-Stokes equations, while the second one is an interpolation interface module passing data from the slide grid to the tsunami grid. This model is an enhancement of the codes that were used to study tsunami generation by the Holocene flank collapses of Stromboli and of the mount Epomeo, Ischia in the southern Tyrrhenian sea. This paper aims also at triggering a debate on the present-day tsunamigenic potential of mass failures in southern Adriatic and on the related risk.



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3D slope stability : A probabilistic approach; Application to the Nice airport (France) slope

[Didier Leynaud, Ifremer \(France\)](#)

[Nabil Sultan, Ifremer \(France\)](#)

SAMU_3D, a three-dimensional slope stability software, was recently developed by Sultan et al. (2007) to account for complex geometry. The model estimates the factor of safety of a kinematically admissible failing mass using a 3-D analysis based on the upper bound theorem of plasticity developed by Chen and others. One of the main interest of this model is to propose complex critical failure surfaces, suitable for complex bathymetry (i.e. canyons) with a shape of failure surfaces defined using 8 parameters (ellipticity, curvature and size).

A probabilistic approach was recently added to the former deterministic model to consider the effect of soil parameters variability and uncertainties (undrained shear strength, unit weight) on the critical factor of safety. Such approach is often used to estimate the reliability of the results. The Monte Carlo simulation was used to represent the variability of the factor of safety given a specific number of trials. The search for the critical failure surface previously based on the deterministic safety factor is now performed in terms of probability of failure (or probability to have a factor of safety lower than an arbitrary constant). The probabilistic model was partially validated using the well known James Bay embankment case (2-D analysis) for which numerous probabilistic evaluations are available. The new model is applied to assess the present-day slope stability of the Nice airport area where a slide occurred on 1979 and for which a large uncertainty exists regarding the soil parameters distribution with depth.

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A positive interaction between slump-induced seafloor topography and deep-water coral growth (SW Adriatic sea)

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The SW Adriatic continental margin is characterized by intense slope instability from the shelf edge to the slope base over a margin sector ca. 150 km long. Failure of consolidated Pleistocene sedimentary units generates deposits ranging from blocky slides to fine-grained turbidites, impinging both the open slope and the steep walls of Bari canyon. The margin is also affected by the seasonal action of dense water cascading off shelf and reaching speeds exceeding 60 cm sec⁻¹ close to the seafloor. This combination of phenomena caused a variety of bedforms some of which (for instance hardened surfaces of slumped blocks) proves to have been propitious to the settlement of a variety of benthic hard-bottom organisms. The coupling of such slump-induced reliefs with the formation and cascading of cold and nutrient-rich water sustains a diverse deep-sea community of filter- and suspension-feeders dominated by frame-building scleractinian corals (*Lophelia pertusa*, *Madrepora oculata*, *Desmophyllum dianthus*, *Caryophyllia* spp., *Dendrophyllia* spp.), sponges, gorgonaceans, serpulid polychaetes and other benthic megafauna. In turn, these lush Adriatic ecosystems probably control dispersal and colonization patterns of far-distant deep-water coral growth in the Ionian Sea and have a role in contributing to a trophic web that includes fish and crustacean stocks of commercial value.

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Analysis of triggering mechanisms of the Ana Slide (Balearic margin of the Eivissa channel, western Mediterranean)

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The Ana slide is located in the low sediment rate carbonate continental slope of the Balearic margin of the Eivissa channel (western Mediterranean), where other slides are found with the same slip horizon, indicating a likely simultaneous occurrence under a common triggering mechanism. In the headwall area of the Ana slide, acoustic wipe-out identified from seismic reflection profiles masking the stratified facies beneath the slide could be indicative of the presence of gas. Moreover, the presence of pockmarks located at the headwall areas of the slides suggest that fluid escape processes in the upper Plio-Quaternary sedimentary sequence could be closely linked to its formation.

One of the objectives of the PRISME cruise (October-November 2007 - onboard R/V L'Atalante) was to characterize the physical, mechanical and sedimentological properties of the Ana slide. During the PRISME cruise, in situ measurements using the Penfeld penetrometer (CPTU- with a maximum depth of investigation of 30 mbsf) were carried out at ten different sites between the slide toe and the headwall. Three sediment cores were collected with Kullenberg corers at the slide toe, below and above the headwall, coinciding with CPTU locations. In order to characterize the hydraulic regime of the sliding area, piezometer measurements were run at four sites within and around the headwall scarp. Sedimentary and geotechnical analyses performed onboard and in the UB laboratory include: i) sediment core logging made with the Multi Sensor Core Logging and the Avaatech XRF Core Scanner onboard ii) classification tests (moisture contents, Atterberg limits and grain size analysis) obtained both onboard and in the UB laboratory iii) undrained shear strength acquired using a vane shear and fall-cone devices and iv) P-wave velocity measured with a celerimeter.

The data set gathered during the PRISME cruise and the preliminary results derived from laboratory analyses were used to conduct a slope stability analysis of the Ana slide by using the computer program SAMU3D (Sultan et al., 2007). The numerical analysis aims to identify the triggering mechanism(s) involved in the formation of the Ana slide by evaluating the Factor Of Safety (FOS) of the most critical failure surface under undrained and drained failure conditions.



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Anthropic amplification of small-scale, recurrent mass failure within submarine canyons along the Italian margins. The contribute of MaGIC project

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The Italian continental margins are part of the tectonically-active and complex Central Mediterranean area and are experiencing a very rapid geomorphic evolution. Geologic processes ranging from volcanic activity to active faulting and slope instability are frequent along the Italian margins and result in areas of potential geohazard relative to human settlements and activities. The exploitation of geohazard-related features that are detectable at the seafloor is therefore one of the main issues in the field of Marine Geology.

MaGIC project (Marine Geohazards along the Italian Coasts), a 5-year initiative funded by the National Civil Protection Department, is the most relevant contribute of the Italian Scientific Community in the field of marine geohazard mapping and monitoring. The project aims at producing a swath bathymetry database and compiling maps (scale 1:50.000) of geohazard-related features in the shelf and slope of most of the Italian margins.

In recent time, sea floor detection through extensive multibeam investigation has led to a growing attention on the role of small-scale but frequent instability. Data that are being collected within MaGIC indicate that small-scale slide scars and deposits are very frequent on the Italian margins and display two main distributional patterns: 1) one in which sediment failure is pervasive and affects the continental margin on a regional scale; 2) one in which failure concentrates within submarine canyon heads indenting the continental shelf. In this latter case, retrogressive erosion of the canyon head is enhanced and the process by which canyon erosion progressively cannibalizes the shelf results significantly accelerated. As a consequence, canyon heads are very close to the coastal area where anthropogenic infrastructures are present. The process may be particularly rapid in areas where the continental shelf rims steep/deep tectonically-controlled basins and is therefore very narrow. Phenomena from southern Italy (Calabria) will be presented, where the shelf margin is only few hundred metres from the coast and canyon heads deeply incise the slope, undermining harbours and other infrastructures. Here, small scale, periodic mass failure within the canyons has relevant impact for the coastal zones and for the risk related to human impact as a factor that may amplify or induce catastrophic phenomena.



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Effect of the displacement-rate of a compressional anticline on the slope stability in the deep-water Niger Delta

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A recent study conducted by Sultan et al (2007) in the detachment fold belt of the deep-water Niger delta reveals the occurrence of three submarine landslides expressed on the present day seafloor. These landslides lie on a mean slope angle of about 2° and are all located above the hinge of an anticline structure. Sultan et al (2007) used the cylindrical cavity expansion theory to simulate the compressional structure movements and to evaluate the strength generated within the upper sediment layers. Slope stability assessment conducted with the three dimensional slope stability model SAMU-3D has demonstrated that compressional deformation of the anticline could be a triggering mechanism for the observed slope failures in the area (Sultan et al., 2007).

These results leave an open question on how the displacement-rate of the compressional anticline affects the slope susceptibility to failure in the area. In an attempt to answer this question a further study is conducted using PLAXIS finite element code with two different constitutive models: Mohr-Coulomb and a more advanced constitutive model considering the Soft Soil Creep model which enables to account for stress-dependent stiffness and secondary (time-dependent) compression of the sediment. Different displacement-rates generated by the compressional structure movements are considered and applied at the base of the calculation domain in order to point out the importance of the time factor in terms of excess pore pressures, sediment deformations, and slope stabilities.



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Investigations on submarine mass movements along the Brazilian Coast: A review

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The Brazilian continental margin is approximately 7000 km long extending from the latitudes 31° S and 5°N. Its territorial sea, today under discussion at the United Nation, may be as large as 350 NM, resulting in an area of 4.5 million km², about the half of Brazil's inland territory. Despite this enormous area, very few have been done concerning research on seafloor stability. Today, the main projects are conducted by oil companies for their own specific exploration projects. Academic research on this topic is particularly limited by the elevated costs related to ship's rental. However, there are some important works on seafloor stability developed over the last 20 years along the Brazilian coast. These are most qualitative, are concentrated in the southeastern region and do not account for geotechnical evaluations.

At the Campos basin (CB), the most oil productive area in Brazil, several different instability features have been identified. They range from small scale creeps to large slumps, responsible for shaping the seafloor morphology. High-resolution seismic records show some periodicity with recent instability events overlaying older ones. At the southern portion of the CB multibeam bathymetry and high-resolution seismic survey identified a region with several small slumps, which were firstly mapped as a series of canyons. Up north, at the Espírito Santo basin, canyons and gullies have been identified as the result of instability processes associated to a shelf-margin delta during the Pleistocene. Studies conducted at the forests of the Amazon river delta observed presence of several geological factors that contribute to seafloor instability, like biogenic gas and high sedimentation rates. Preliminary studies at four offshore basins concluded that shelf-originating canyons are derived from catastrophic failure on the slope through gravity flows, creep, undercutting and turbidity currents. More recently, during the first cruise of the RETRO project, several kilometers of high-resolution seismic data have been acquired at the northern coast of Brazil. The data showed several mass movements features (recent and ancient), canyons and faults at the continental slope probably associated with neotectonic activity related to transform faults that reach the area.

However, the limited area of investigation in most seafloor instability research projects in Brazil, usually limited to the exploration blocks, restricts the overall understanding of the geological processes involved on these instability events not allowing the determination of the causes for the observed submarine mass movements. A large project for the research of seafloor stability is now being prepared to be submitted to Brazilian's science funding agencies.



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Large scale mass wasting at the NW-African Continental Margin: Some general implications for mass wasting at passive continental margins

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The continental margin off Northwest Africa is largely shaped by a complex interplay of sediment transport processes directed both downslope and along-slope. During several cruises sediment transport processes between 12° and 26° N off Senegal and Mauritania were investigated by means of geophysical, sedimentological, and geochemical methods. Bathymetric and high-resolution seismic data were used to study the areal extent and the internal structure of redeposited sediments. Based on these measurements sediment cores were taken for sedimentological and geochemical analyses. Sediment transport at the NW-African continental margin operates with different rates and styles including a significant transfer of land-derived terrigenous and hemipelagic sediments to the deep sea. Some sections show a large concentration of upper slope canyons but no indication for large scale mass wasting. Other sections are characterized by large scale mass wasting but no canyons and gullies were found. One example shows a large slide, which destroyed a major canyon, thereby leading to a reorganization of the sediment transport pattern as confined turbidity currents now spread over a much larger area.

Four mega-slides each affecting over 30,000 km² of seafloor were identified along the continental slope off NW-Africa. All slides are complex and show a stepped headwall pattern typical for retrogressive sliding. Several buried mass wasting events are found beneath the youngest slide complex for all slides, hence revealing that these sections of the continental margin have been unstable for a long period of time. Two of the mega-slides show headwalls at atypical large water depths deeper than 3000m. These observations allow to draw several conclusions for mass wasting off NW-Africa, which might be relevant for other passive margin settings as well. i) We speculate that the open slope areas without any major incisions allowed undisturbed rapid sediment build-up, which gave rise to sediment instabilities arising primarily from underconsolidation of the deposited sediments and widespread weak layers, while the canyons and gullies represent an effective pathway for 'semi-continuous' downslope sediment transport by turbidity currents. ii) Stacking of mass wasting events and the alignment of buried scarps with much younger headwalls suggest that sediments deposited above buried scarps are potentially unstable especially due to differential compaction and oversteepening, and therefore remain unstable after the initiation of land sliding. iii) The large size of the slides off NW-Africa is caused by high sedimentation rates but infrequent triggers. iv) Large scale mass wasting in water depths >3000m at the NW-African continental margin is more important than previously suggested.



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Modelling sediment-laden flows due to slope instabilities Application to the Nice (Var) slope

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Slope instabilities may be generated on open slopes or within canyons due to external mechanisms such as seismic acceleration, sediment overload or excess pore pressures. These instabilities can suddenly release great amounts of material and originate gravity driven slides or flows of different sorts. The way these sediment masses accelerate and move after a slope failure impacts differently the water column (tsunamogenesis) and the deposition geometry and architecture down slope. Some slides do not display enough energy to flow and may stop suddenly as they have been started. Other slides are drastically transformed while they accelerate and become gravity driven flows characterized by turbulence, mixing and sediment segregation. The aim of this work is to connect, in a modelling frame, the initial condition given by a 3D slope instability analysis (Samu 3D ; Sultan et al., 2007), providing the failure initiation, and the post-failure evolution till the final (de)position of the released material and its geometry. The depth integrated flow is simulated by a Smoothed Particle Hydrodynamics (SPH) deterministic model that solves in a Lagrangian approach the horizontal momentum equation and the sediment concentration transport for each class of grain sizes. The model accounts for non hydrostatic pressures, complex rheology, turbulence, entrainment of ambient water, particles settling, erosion and deposition. Being constitutively Lagrangian this approach provides a meshless solution. Hence, the computational effort is concentrated on the flow location and avoids computation elsewhere in the domain of interest. The model is applied to the Nice airport slope where well documented slide occurred in 1979. The 1979 event is used to constrain the model and provide confidence to simulate a flow originated from an area detached as potentially prone to failure thanks to in situ geotechnical measurements and 3D slope stability modelling (Leynaud et al., this conference). For each simulation the model provides flow velocities and acceleration and segregated deposition of the sediments.

Sultan, N., M. Gaudin, S. Berne, M. Canals, R. Urgeles, and S. Lafuerza (2007), Analysis of slope failures in submarine canyon heads: An example from the Gulf of Lions, *J. Geophys. Res.*, 112, F01009, doi: 10.1029/2005JF000408.



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On the dynamics of debris flows - the influence of the ambient fluid

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Anders Elverhoi, *University of Oslo (Norway)*

Fabio V. De Blasio, *University of Oslo (Norway)*

To elucidate fundamental parts in gravity mass flows, we have been focusing on how the ambient fluid influences the behaviour of debris flows. In order to achieve this we have performed a set of novel laboratory experiments consisting of a suite of tests varying the ambient environment from air to water, and the sediment composition from granular to viscoplastic material.

Field observations have shown that subaqueous mass flows seem more mobile than their subaerial counterparts, exemplified by the very long runout of subaqueous slides on slopes gentler than 1°. In our experiments we have been using a well equipped flume system at St. Anthony Falls Laboratory (U. of Minnesota), and in particular the use of high speed cameras and PIV techniques have made it possible to accurately study the internal flow characteristics of subaqueous as well as subaerial debris flows. The experiments document that subaerial flows behave according to well known principles, whilst subaqueous debris flows show a more complex behaviour. Low-clay content material demonstrates sediment break-up and turbidity current generation, while more clay-rich flows show a downslope acceleration of the frontal parts due to hydroplaning, leading to a stretching of the debris flow body.

The experiments also include detailed rheological measurements of the various slurry compositions, illustrating that the behaviour of subaerial debris flows are predictable based on their rheological properties. Due to the effect of the ambient fluid as explained, the behaviour of subaqueous mass flows seems less dependent on initial rheological properties.

We see this rather fundamental approach as an attempt to build a bridge between the traditionally separate fields within mass movements and to try to make it possible to transfer the right type of knowledge from subaerial deposits, flow observations and modelling to the subaqueous field and vice versa.



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Submarine mass movements in an active continental margin setting: First results from coring the Nankai Trough during IODP NanTroSEIZE stage 1 expeditions

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Achim J. Kopf, *University of Bremen (Germany)*

- IODP Exp314,315&316 scientists, - (NO COUNTRY SELECTED)

From late 2007 to early 2008 the 1st stage of the IODP Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) began drilling and coring along the Nankai Trough convergent margin. The NanTroSEIZE project is a multi-stage IODP drilling program focused on understanding the mechanics of seismogenesis, rupture propagation, and tsunamigenesis through direct sampling, in situ measurements, and long-term monitoring. Stage 1A included three coordinated riserless drilling expeditions to visit several sites across the continental slope and rise offshore the Kii Peninsula, SW Japan. Whereas the primary goals were to investigate the shallow portion of the plate boundary and splay fault, these drilling expeditions also provide valuable information to study submarine mass movements in an active continental setting.

First results reveal several lines of evidence for slope instability observed in five drill sites, both in the upper (site C0001), intermediate (site C0004) and lower slope region (sites C0006, -7), as well as within an intermediate slope basin seaward of a topographic rise that originates by fault movement and uplift along a prominent splay fault (site C0008). At all these drill sites, slumping, mass-flow deposits, syn-sedimentary breccias and mud-clast conglomerates occur at different stratigraphic levels. They record information about upper Pliocene-to-Recent sediment remobilization by past slope failures, which may be related to splay fault slip, tectonic uplift and oversteepening, or earthquake tremor. Most prominently, C0008C targeted coring a normal fault identified in 3D seismic site survey data along which surface material appears to have slid downward. A 5cm-thick, gently dipping shear zone within an interval characterized by high concentration of small core-scale normal faults was observed at ~40 mbsf. Shipboard initial data reveal lateral fluid flow from areas with thicker to thinner overburden along sand layers that are truncated by this slope collapse structure. This suggests that apart from seismicity and tectonic over-steepening also pore pressure may be an important mechanism for reducing slope stability in the study area. Also, sigmoidal fissures in the slope apron (e.g site C0001) sediments attest hydrofracturing, possibly coinciding with coseismic slip along an underlying fault.

All these lines of evidence document that the slope along this active continental margin is potentially unstable and easily collapses when triggered by tectonic movement or earthquakes. Depending on size and location, such slope failures may have a considerable tsunamigenic potential. Post-cruise examination of sedimentary structures, petrography and hydrological and geotechnical properties will help to reconstruct mass wasting history and to assess the interaction between fault movements, uplift, slope steepening, fluid flow and seismic shaking as well as its role in slope failure initiation and tsunamigenesis.



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Submarine slope failures on continental margins and their consequences

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Submarine slope failures occur when the downslope component of the of the submerged weight of the mass exceeds the shear resistance along the most critical slide base. The consequence of the failure event depends on the affected mass and area as well as the dynamics of the event and may range from nil to severe damage to subsea installations and infrastructure and to tsunami generation and widespread damage along surrounding coastlines.

Large slide events are seen as slide scars and extensive marine transport deposits on the continental slopes in the vicinity of river deltas and glacial fans. They take place at very low slope angles and may extend from large water depths up to and into the shelf edge. In these areas large and relative rapid accumulations of sediments have been generated at during the Pleistocene time, piling up on top of massive sediments from Pliocene and earlier periods. The major Pleistocene glaciations and the associated sea level variations shifted the position of beaches and river deltas in lower latitudes. Current erosion of the shelf generated density flows of resuspended material over the shelf edge in addition to the river transported sediments. At higher latitudes, glaciers transported eroded mass over the shelf edge causing a rapid progradation of the shelf and thick accumulations of glacial debris flows on the slope interbedded with marine hemipelagic clays from interglacial periods.

Rapid deposition of fine grained material leads to excess pore pressure (overpressure) in the whole sediment column. Increased deposition rates during sea level rise and fall periods may lead to rapid weight and pore pressure increase in the top sediments and a gradual and more slow increase in pore pressure level in the deeper sediments. Simulation of the deposition process applying compaction and permeability models derived from geotechnical site investigations, show that excess pore pressure may reach very high values resulting in low shear strengths relative to the weight of the overburden.

The strain softening behaviour of marine clays is another important contributor to slope instability and especially to the development of large scale slide events. When subjected to a changes in shear stress exceeding the strength of the material, these clays may typically loose 60 to 80% of the peak strength. The mobility of the slide material will thus increase considerably after failure initiation, and in areas with a low factor of safety against slope failure a local instability may spread progressively and retrogressively over large distances.

Geomechanical modelling of sedimentation processes, strain softening behaviour and retrogressive slide dynamics allows explanation of major slide events like the Storegga slide and extensive local instabilities in the upper strata observed in many delta areas. The methods are presently being applied in evaluation of slide risk for offshore petroleum development projects.



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Core-log-seismic integration of mass transport deposits in the shallow subsurface of the Ursa basin, northern Gulf of Mexico

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Seismic facies and material properties of mass transport deposits (MTDs) in the Ursa Basin are controlled by porosity, not lithology. Deformation is distributed throughout MTDs, but tends to be greatest towards the base. In seismic data, MTDs are imaged as low-amplitude zones above a high-amplitude basal reflector. Within these zones we identify two facies:

1) locally high-amplitude chaotic, and 2) discontinuous/locally stratified. In seismic cross section the locally high-amplitude chaotic facies appears as high-amplitude discontinuous reflections. These reflections are sinuous and channel-like in interval amplitude maps. The basal reflector beneath this facies is high amplitude, continuous, and contains grooves (~10 km long). The top reflector is lower amplitude than the basal reflector.

The locally stratified facies contains discontinuous reflectors that abut against pyramid-shaped islands ("pinnacles") of parallel stratified reflectors. Each pinnacle sticks above the surrounding material and is attached to the base of the MTD. The basal reflector is high-amplitude beneath the discontinuous reflectors but relatively dim beneath the pinnacles features. The locally high-amplitude chaotic facies is denser (i.e., lower porosity), has higher shear strength, and higher resistivity than bounding undeformed sediment. Deformation in this facies appears as a deformed mud package with a homogeneous appearance, occasional folds, and rare mud clasts. The locally stratified facies is only slightly denser (i.e., lower porosity), has slightly greater shear strength, and a slightly greater resistivity than bounding undeformed sediment. Deformation is subtle in this facies and is recorded as tilted bedding and small-offset faults. The higher density of MTDs of both facies creates a strong impedance contrast between bounding undeformed sediment, and thus a strong reflection at the top and base. However, the basal reflector is much higher amplitude because the density contrast is much higher at the base. We interpret that the locally high-amplitude chaotic facies records debris flows having a long runout; the locally stratified facies records slumps having only a short run-out, with minimal deformation.



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Factors leading to slope instability in the Ursa Basin, gulf of Mexico continental slope

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The Ursa Basin, at ~1000 m depth on the eastern levee of the Mississippi Canyon, Gulf of Mexico continental slope, is an extraordinary natural laboratory to investigate large-scale aseismic slope failure phenomena. Recent studies have suggested that seismic activity recorded in this area, is a result, at least in part, of shallow gravitational sliding rather than deep-seated tectonic processes. Extensive occurrence of Mass Transport Deposits (MTDs) in the Ursa Basin, both in time and space is also documented by multibeam and seismic reflection data. In June 2005, Integrated Ocean Drilling Program (IODP) Expedition 308 drilled three Sites adjacent to major Recent failures and mud-volcano type fluid escape structures, and through a series of MTDs of Pleistocene to Holocene age. Along these holes a complete suite of logs, sedimentological and geotechnical data were acquired, which illuminate factors that control failure initiation, provide insights into the failure mechanism itself and allow characterization of the hazard potential from future slope instabilities. On seismic data most MTDs appear as transparent bodies, and this appears to indicate some degree of remobilization of the failure mass, yet they do not appear to have moved far from the failure initiation area. Little overburden was removed because the failed masses did not evacuate the failing zone. MTDs that appear as seismic transparent bodies do not exceed 60 to 70 m in thickness. The first 60-70 m of overburden in Ursa Basin are characterized by very high porosity, decreasing down hole from 80 to 55%, and water content, rapidly decreasing from 100 to 40%, i.e. from values near the liquid limit to very close to the plastic limit. From measurements of porosity and stress state, we infer that fluid overpressure, derived from rapid sedimentation, is the most likely factor that initiated/controlled slope instability in the past. Fluid overpressures result in effective stresses that are 50 to 70% lower relative to hydrostatic conditions. Isotropically consolidated, undrained triaxial tests suggest low cohesion and a friction angle around 28° for fine-grained mudstones. This indicates that, given the slope geometry, nearly lithostatic overpressures were/will be needed to trigger slope failure. Profuse evidence of fluid escape structures, including large mud volcanoes, near failure scarps might indicate that such conditions existed in the past.



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Investigating submarine landslides and sediment failures through geotechnical instrumentation, in situ testing and numerical modelling

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During the last two decades, and thanks to combined efforts of research Institutes, Academia and Industry, great strides have been made in the area of marine geotechnics and submarine landslides. This advance was possible because of the substantial danger posed by submarine landslides to offshore structures, marine structures and coastal communities. Thanks to oil industry exploration, numerous studies and projects on submarine slope instability and its effect on offshore structures, pipelines and marine construction have been carried out on the Norwegian Margin, in the Gulf of Guinea and the Gulf of Mexico. It was often shown that conditions of seafloor instability are complex and result from interaction of many causal and triggering factors. It was also often demonstrated that an integration of geophysical, geological and geotechnical approaches are needed for a better assessment and understanding of submarine slide mechanisms.

The main objective of the present work is to report on integrated approaches used to improve submarine landslides and geohazards assessment by including multi-disciplinary study going from observation and description to more quantitative methods. Two different sites with evidence of sediment deformation and failures from the Gulf of Guinea and the Mediterranean Sea characterized, respectively, by the presence of gas hydrates and high seismicity will be presented and discussed. Developments are described in the following areas: i) field measurements and monitoring ii) causal factors and triggering mechanisms iii) advanced constitutive laws and numerical modelling and iv) uncertainties in data and knowledge.



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Logging, sampling and testing for submarine slope stability

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The shift of hydrocarbon field developments towards the continental slope has increased the assessment of submarine slope stability. Proper assessment requires a suite of complementary tools for in-situ sampling and testing. These tools are rapidly improving in terms of technology and robustness. The focus of this presentation is on improved tools for in-situ pore pressure dissipation tests. Excess pore pressure can induce slope failure. The Piezoprobe and Fugro Pore Water Sampler (FPWS) are downhole tools that have been routinely deployed in deepwater to determine the equilibrium pore pressure.

The FPWS is a sampler that includes optional add-ons for in-situ pore pressure and temperature measurements within a single deployment round. The water samples are kept pressurised to preserve the gas content and, hence, detect gas in soil.

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Multi-directional simple shear testing 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 characterization of soil behavior and relies on the selection of appropriate parameter 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 investigate the response of Gulf of Mexico marine deposits to different loading conditions. One-dimensional monotonic and cyclic shearing of K_0 consolidated specimens is used to simulate level ground conditions, whereas the effect of the slope was simulated using K_α consolidation for both monotonic and cyclic tests. The results of these tests are compared to the response of other marine clays, such as Boston Blue Clay and Young Bay Mud.



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Numerical simulations of the hinlopen-yermak landslide and possible tsunami, Arctic Ocean

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Swath bathymetry data from the glacier-fed, northern Svalbard margin reveal geomorphological details of a large, submarine landslide, the Hinlopen-Yermak Landslide. Multiple, planar escarpments have several hundreds meters of relief, with a maximum headwall height exceeding 1400 m at the mouth of the Hinlopen cross-shelf Trough. Beyond a pronounced constriction, the occurrence of semi-transparent acoustic units on seismic profiles indicates that the mass-transport deposits are likely the accumulation of remolded and/or fluidized debris flows that are in places hundreds of meters thick. At the outer rim of the extensive mass-transport deposits, numerous rafted blocks rise from the semitransparent sediment unit, and tower hundreds of meters to 450 m above the surrounding debris. The maximum remobilized volume from the slide scar area, estimated from pre-landslide bathymetric reconstruction, is in the order of 1350 km³. The headwall heights, the ratio of excavated volume and slide scar area, and the height of the rafted blocks are large compared to other landslides documented on siliciclastic margins.

The position, thickness, and shape of the mass-transport deposits illustrate the high mobility of sediments involved in submarine landsliding. Their dimensions require numerical modelling to understand landslide dynamics and the potential to generate tsunamis. In the simulations of the sediments dynamics, large blocks are rafted by a loose debris flow derived from the disintegrating landslide material in the headwall area. The main failure process completes after approximately 1 hour. The upper slide scar is probably not the source area for the large rafted blocks.

The mechanism of the failure is not yet fully understood, but the slide more than likely generated a tsunami that influenced the Polar Ocean. Steep waves implying dispersive and non-linear effects probably were more pronounced than for most other tsunamis induced by submarine landslides due to the combination of high speed and the substantial thickness of the mass transport. Generation, propagation and coastal impact of the tsunami are simulated by a weakly non-linear and dispersive Boussinesq model. Close to the landslide area, the simulations return sea-surface elevations exceeding 130 m, whereas sea-surface elevations along the coasts of Svalbard and Greenland are in the order of tens of meters. However, the Svalbard archipelago - and the 80 m lower sea-level at the time of slope failure which lead to part of the northwestern Barents margin to be subaerial - protects northern European and Scandinavian coastlines from the tsunami impact.



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Pore pressure penetrometers document high overpressure near the seafloor where multiple submarine landslides have occurred on the continental slope, offshore Louisiana, Gulf of Mexico

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Overpressures measured with pore pressure penetrometers during Integrated Ocean Drilling Program (IODP) Expedition 308 reach 70% and 60% of the hydrostatic effective stress ($\lambda^* = (u - u_h) / (\sigma'_{vh})$) in the first 200 meters below sea floor (mbsf) at Sites U1322 and U1324, respectively, in the deepwater Gulf of Mexico, offshore Louisiana. High overpressures are present within low permeability mudstones where there have been multiple, very large, submarine landslides during the Pleistocene. Beneath 200 mbsf at Site U1324, pore pressures drop significantly: there are no submarine landslides in this mixture of mudstone, siltstone and sandstone. We interpret that the high overpressures observed are driven by rapid sedimentation of low permeability material from the ancestral Mississippi River. The average sedimentation rate from the seafloor to the top of the Blue Unit is 12 mm/year at Site U1324 and 3.6 mm/yr at Site U1322. Ursa mudstones have hydraulic diffusivities of $2 \times 10^{-8} \text{ m}^2/\text{s}$ whereas siltstones have diffusivities greater than $2 \times 10^{-7} \text{ m}^2/\text{s}$. We interpret that at Site U1324, rapid deposition of fine grained low permeability mudstone in the upper 200 mbsf generated the high overpressures present. Reduced overpressure at depth at Site 1324 suggests suggest lateral flow (drainage) whereas high overpressure at Site 1322, where the sedimentation rate is low requires inflow from below: lateral flow in the underlying permeable aquifer provides one mechanism for these observations. High overpressure near the seafloor reduces slope stability and provides a mechanism for the large submarine landslides and low regional gradient (2 degrees) offshore from the Mississippi delta.

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Seafloor instabilities and sediment transport on the steep and seismically active Ligurian margin (North-Western Mediterranean)

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The Ligurian margin has a steep morphology showing complex inherited tectonic structures, variably incised canyons, and numerous submarine slides. The margin has been frequently affected by earthquakes (four historical earthquakes in 1564, 1644, 1817, 1887 AD), and tsunamis (1564, 1817, 1887, 1979 AD). The high anthropic pressure on this densely populated coastal zone was a further reason to investigate about the triggering mechanisms of sediment failures with two campaigns at sea (Malisar1 and Malisar2). The 2006 dataset consists of EM 300 multibeam bathymetry between Nice and Genova, from about 100 m to 2500 m water depth, 3-5 kHz profiles, and 24- or 72-multichannel seismic profiles. In 2007 followed the acquisition of sediment cores, side scan sonar (SAR) imagery, and very high resolution AUV multibeam bathymetry. The dataset reveals numerous fresh scarps and mass-transport deposits involving several cubic kilometres of sediment.

Offshore Nice (France), mass-wasting events mainly affect the upper part of the slope, near to the Var and Paillon river mouths, where sediment delivery is the highest. The most abundant failures are located near the shelf break; they are small-scale (< 100 m wide) and affect the uppermost sediment layers (up to 10 m). Larger-scale failures (up to 400 m wide) are located deeper on the slope and affect deposits over greater thickness (up to 40-50 m). Smaller failures mainly result from the under-consolidation state of slope sediment rapidly accumulated, while the triggering of larger failures probably requires an external forcing 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 could be related to active faults that remain to be detected precisely. Three impressive scarps are located in the epicentral area of the 1887 AD earthquake. One of them is clearly visible at the seafloor and could be related to the 1887 AD event. The two others are partly buried under hemipelagic deposits and could be related to the recurrent earthquakes in that area. Between Imperia and Genova (Italy), submarine slides are mainly restricted to the canyon flanks. A major scarp, 7 km long and 100 m height, is located in an interfluvial 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 hemipelagic deposits suggests that failure has been triggered recently. The timing of most of the slides is unknown, but ongoing research is aiming at: a) coupling the distribution of submarine slides with the location of epicentres of historical earthquakes, and b) establishing a chronological framework for the stratigraphic units involved in failure.



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Using seismic reflection data to investigate free gas in a landslide area: An example from Finneidfjord, Norway

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On the 20th of June, 1996, approximately 1 million cubic meters of soil failed retrogressively in Finneidfjord, Norway. The location provides numerous geological and environmental conditions relevant for offshore geohazards and large-scale submarine landslides. Examples are slide-prone layers, lateral and vertical lithological variability, the presence of slide blocks, gas-containing sediments, and migration pathways, which could well indicate excess pore pressure. The multi-phase, retrogressive landslide initiated underwater, and, within a few hours, undermined a highway and several houses, claiming the lives of 4 people.

Whereas several factors likely contributed to this slope failure, we focus on the role that free gas played in destabilizing the slope. In a core from near the slide area, gas bubbles appear in the X-ray as vesicular spots. High-resolution 2D seismic profiles reveal the presence of a pronounced gas front, topped by a distinct, polarity-reversed reflection that can be traced over an area of ~5 km². The top of the gassy zone lies a few meters below the seabed, and close to the suspected failure plane. After processing the seismic data to correct for spherical divergence and to remove multiples, the gas reflection can be characterized in more detail by its amplitude, phase and frequency content. Continuous wavelet and Gabor transformations determine values for these two parameters with minimal user input. We attempt to convert the lateral variations in amplitude and frequency content along the gas reflection to infer the degree of gas saturation and investigate whether or not it can be used to estimate pore pressure in the submarine sediments. Interpolation of the network of single-channel seismic data estimates a 3-D model of the present-day gas front beneath the fjord bed. Coupling this with information about the seabed sediments may indicate how free gas weakens submarine slopes and thus facilitates slope failure.