A geomorphological investigation of lateral spreading and translational sliding within the Storegga Slide.

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Lateral spreading and translational sliding are two of the most prevalent types of slope failures within the Storegga Slide. This has been concluded from a thorough analysis of three acoustic data sets from the Storegga Slide complex – high-resolution multi-beam bathymetry, TOBI sidescan sonar imagery and 3D seismic data. We have applied quantitative geomorphometric techniques to the bathymetry data set and analysed the texture of sidescan sonar images using Grey-Level Occurrence Matrices (GLCMs). Both techniques have been shown to improve the geological interpretation of submarine environments (e.g. Micallef et al., 2006), and allowed an objective characterisation of the slide surface to be carried out. These results were then combined with the interpretation of the seismic data set and all the geological information currently available for Storegga in the literature. In this way we were able to define the types and boundaries of the different styles of mass movements, and represent them on a geomorphological map. Further insight is provided into the origin and the mode of failure of lateral spreading and translational sliding. Finally we attempt to describe the characteristic morphology of lateral spreading and demonstrate that it is a very common slope failure process in the Norwegian margin.

On the Architecture and geological Development of the Mauritania Slide Complex: new Insights from acoustic and high-resolution seismic Imaging.

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Newly acquired Parasound sediment echosounder and high resolution multi-channel seismic reflection data have afforded a more detailed characterisation of the Mauritania Slide Complex than previously reported. The slide has affected an area in the order of 34,000 sq. km lying between the upper slope and the rise, and hence ranks as one of the major slides on the NE Atlantic margin.

The ovate-shaped slide displays a long run-out distance of more than 300 km as a result of higher sediment flow mobility induced in its northern parts by bounding canyon systems and the Cape Verde Rise. In addition, sediment deformation caused by underlying widespread diapiric growths appears to have enhanced quicker disintegration of overlying weaker contouritic deposits as well as pre-existing slide material, thus contributing to increased sediment flow mobility.

The headwall scars commonly occur as a series of steps in seafloor morphology ranging between 25 - 100 m high and within 600 - 2000 m water depths. The seismic data also reveal the presence of several vertically stacked debris flow deposits separated by well-layered sediment intervals within the internal structure of the slide hence suggesting that the stages of slide development have been characterised by multiple failure events. Major sediment failures were likely initiated in areas of low slope inclination, generally less than 2°, and propagated upslope as retrogressive modes of failure which were facilitated by widespread weak layers.

Excess pore pressures, resulting from decayed organic matter and/or sea level rise,
presumably constitute the most important trigger mechanism for slide formation. Slide
development following a major slide event may have been significantly modified by
later minor instability events which involved the remobilization of pre-existing debris
flows as well as translational sliding induced by underlying diapiric growths. The com-
bined activities of these destabilizing factors are the most likely cause of the complex
morphology of the Mauritania Slide Complex.
The Hinlopen Slide: A Giant, Submarine Slope Failure on the Northern Svalbard Continental Margin, Arctic Ocean

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Swath bathymetry data unveil a unique, giant, multi-phase and retrogressive submarine landslide on the passive northern Svalbard margin. The slide scar has a well developed amphitheatre-like outer escarpment, whereas the inner slide area reveals a multitude of impressive scarps and several fresh slip surfaces. The headwall heights range from a few hundreds of m to an unprecedented 1,400 m, thus more than 4 times higher than the Holocene Storegga Slide headwall heights off mid-Norway. The Hinlopen slide is a remarkable feature: from the relatively small 2,200 km² slide scar area, an estimated 1,350 km³ km of Plio-Pleistocene sediment has been evacuated to the deep Arctic Nansen Basin. Also the rafted blocks in the intermediate part of the slide downslope the pronounced bottleneck are enormous. They measure up to 450 m high, and comprise a volume of c. 1.89 km³, i.e. they are at least an order of magnitude bigger than rafted blocks observed in other mass wasting areas. These numbers make the Hinlopen Slide one of the few giant submarine landslides on continental margins worldwide, and understanding its development is a challenge. The slide has not been dated yet; however, the geophysical data suggest a relatively recent process, probably Late Weichselian or later. A slide of this size is clearly considered a tsunamigenic hazard, despite the fact that no tsunami deposits have been discovered so far. Similarities with the Storegga Slide and its settings suggest that changes in sedimentation related to glacial-interglacial cycles, e.g. glacial glacigenic debris flow deposits alternated with contouritic sediments with different physical and geotechnical properties, are the most likely processes contributing to slope failure.
Real time monitoring of slope conditions using the VENUS underwater cabled observatory

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Concerns by scientists, engineers and authorities for the stability of the Fraser Delta slope have resulted in a design for an array of instruments to monitor liquefaction and failure events, utilizing the Victoria Experimental Network Under the Sea (VENUS). The top of the Fraser Delta slope is an area of rapid deposition, oversteepening and consequential failure, in part due to fixing of the main river channel. It is known that the bed at shallow depth also fails periodically due to tidal drawdown resulting in excess pore pressures. Furthermore, measurement and modelling results show that the slopes in this area are significantly weakened by gas in the surface sediments, seismic events, erosion and undercutting by swiftly moving tidal currents, and perhaps even by ground water flow on the delta slope.

Piezometers capable of making seismic, ground water and deformation measurements will be deployed to measure water pressures, pore pressures, extent of gas, earthquakes, liquefaction, strain and flows over time scales ranging from milliseconds to years. The array will consist of six freefall seismic piezometers, ranging in water depths from 10m to 100m. An additional ‘sacrificial’ package will be placed in an area of known high activity in the hope of capturing events leading to failures. Deployment, power requirements and networking of the instruments will be facilitated by the VENUS Project, which will allow continuous, high bandwidth and real time observations so that the parameters described above can be studied in great detail. Eventually the instruments may be used as an early warning system to life-threatening failures and ensuing tsunamis, which are known to occur in this area. At the forefront of cabled underwater observatory technologies, VENUS will facilitate development of methods and geotechnical instruments for use in related fields. For example, a nearby instrument package will measure many aspects of sediment transport on the top of the
slope. There is also interest in using the VENUS array as a test ground for offshore
gas hydrate studies.
Effect of structural inheritance on the distribution and importance of slope instabilities along a passive transform margin. The example of the French Guyana margin.

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The French Guyana continental margin has been recently surveyed in the framework of the EXTRAPLAC French program (Guyaplac survey, Ifremer-IFP–SHOM-IPEV). During Guyaplac cruise (2003) EM12 bathymetry and backscatter imagery, seismic data and 3,5 kHz profiles have been collected.

The study area is characterized by different morphostructural domains: 1/ the western Guyana margin, including a part of the eastern Demerara rise, a large relief prolongating the continental platform. This domain is bounded by 1a/ the northern border of the Demerara rise – which appears quite sharp and corresponds to a transform segment, 1b/ the eastern border of the Demerara rise thought to be a divergent segment of the margin, 2/ the eastern Guyana margin, which corresponds again to an extremely gullied transform margin segment, 3/ the abyssal plain.

Analysis of surface data (bathymetry + acoustic imagery + 3,5 kHz echogramms) show a great variability of slope instabilities in these different domains:

- The northern Demerara rise shows a segmented morphology, low slope gradients, and a very rough surface (ripples perpendicular to the slope direction). Structural steps in early Cretaceous basement correspond in the more recent sedimentary cover to collapses of hecto-kilometric blocks towards northeast. Slumps initiate along these directions. The rough bathymetry seems in turn related to creeping processes. Numerous
debris flows have been observed in this area on seismic data and even at the foot of the main escarpment on 3,5 kHz profiles. At a regional scale, this part of the margin seem to be a collapsed part of the transform segment.

- The eastern Demerara rise is in turn characterized by numerous imbricated slumps. Some of these failures seem to be emplaced in the prolongation of the structural steps identified on the Demerara rise.

- finally, the eastern Guyana Margin slope is characterized by numerous imbricated debris flows (at least three generations on 3,5 khz profiles) and undulated masses, probably corresponding to creeping sediments or to older mass-wasting events. This transform margin segment is nearly entirely destabilized.

- The abyssal plain is characterized southwards by channels probably belonging to the distal tip of the Amazon fan and northwards, at the foot of Demerara rise by sediment waves.

All of these provinces are also characterized by numerous tracks of fluid ascents (seen on swath bathymetry and 3,5 kHz profiles), probably generating important overpressures and slope instabilities.

To conclude, this area appears as an opportunity to test the effect of structural control by the basement evolution on the initiation of slope instabilities.
Controls of the Behavior of Marine Turbidity Currents

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As the offshore industry continues to expand operations in deep water, on and below the continental slope, they are increasingly challenged to evaluate the risk associated with locating sea floor facilities in the path of potential turbidity currents. Fortunately, this growing need parallels the development of sophisticated surveying and sea floor sampling equipment that support detailed mapping of sea floor features and deposits shaped by historic turbidity current events. These data can be used with robust numerical models to recreate, or at least reasonably estimate the speed, width, heights, densities and other details of the past flows. If sufficient data are available, a population of events can be recreated so that a statistical parameterization can be made of this geohazard.

We have developed a robust three-dimensional numerical model that can reproduce many of the morphological features and sea floor deposits from sequences of turbidity current flow events. The model (a version of M3D) is an unsteady, process-based, three-dimensional model specifically designed for simulating gravity-driven sediment transport in deep water environments. It simulates sediment erosion, transport, deposition, and bed elevation changes for arbitrary initial bed profiles in response to gravity-driven flows due to sediment suspension (i.e. turbidity currents) or other gravity flows created by temperature and salinity variations. It includes representations of a) modification of flow turbulence by gradients in the vertical suspended sediment concentration, b) bed armoring, c) multiple grain sizes, d) both suspended and bed load sediment transport, and e) morphological change that is fully coupled with the forcing.

We have applied this model, and our experience with a number of detailed deep-water surveys, to systematically explore the role of major controlling parameters on the development and characteristics of turbidity current flows. Primary controls on the scale of the flow are created by the size of the bottom feature that contains the flow, the scale
and duration of the triggering event, and whether the flow is channelized or spreading. More immediate controls come from the slope of the bottom, the grain size distribution of the transported load and the underlying bed and the relative erodibility of the sea bed. A series of simplified modeling scenarios have been created to systematically explore the role of these parameters on the stability and growth of the flows, the maximum speed profile along the flow lengths and both the vertical and lateral spreading. The results are presented graphically so that they can be used to judge approximate flow characteristics in areas that have not been studied or modeled.
The central Nile deep-sea fan: an example of interaction between fluid ascents and slope instabilities

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Abundant slope failures and fluid seepages are often closely associated on the continental slope of the Nile deep-sea fan and particularly within its central province where superposed mass-wasting deposits are extending over more than 10 000 km². In this area fluid-related features characterize either as important gas chimneys (1 to 4 km in diameter), or numerous small carbonate mounds and pockmarks (25m to 900 m in diameter). We observe an evolution from upslope to downslope:

(1) Upslope (between 500 and 700 m water depth), gas chimneys are abundant and mostly emplaced along the shelf border on NW-SE and NE-SW fault trends. Many slides initiate from the vicinity of these chimneys, suggesting that they directly participate to the destabilization processes of the central Nile deep-sea fan.

(2) Midslope, (between 700 and 1500 m water depth), the sea bed morphology appears quite rough and slides initiating from the upper slope evolve to transparent superposed debris flows on 3,5 kHz data. In this area, high reflective patches are observed on the backscatter imagery and interpreted as pock-marks and/or mounds. Nautilis dives (Medinaut-Mediflux ESF program), carried out on one of these features, indicate that
the high reflectivity correspond to authigenic methane-related carbonate crusts.

(3) Downslope (between 1500 and 2000 m water depth), some debris-flows are draped by a gently folded hemipelagic cover, clearly undergoing creeping processes. Kullenberg cores reveal that the basal debris flow is highly compacted and that the deformed hemipelagic cover shows numerous fluid ascent related structures (fluidized sediments). Nautilide dives have been carried out in this area and demonstrate that reflective patches clearly correspond to carbonate crusts, either organized as important mounds (∼400 m long and 3 m high) or identified in the centre of circular depressions (∼3-20 m in diameter). Semi-quantitative measurements of methane concentrations in bottom-waters indicate that methane anomalies occur above the thinned areas of the creeping cover. These observations suggest that the sedimentary overloading of a fluid-rich debris flow has induced significant dewatering and that the top of this debris-flow may now acts as a gliding plane along which the sedimentary cover is slowly creeping. Recent debris-flows overlay partly this creeping sedimentary cover, suggesting on-going sedimentary processes in this area.

Our data set stresses clear relationships between fluid escape occurrences and gliding events. Upslope, gas chimneys seem to trigger important and repetitive slope instabilities, which generate debris-flows. Downslope, overloading, compaction and dewatering processes within debris-flow sediments initiate most likely fluid ascents and creeping within the sedimentary cover. In addition to those destabilization processes, the possible migration of gas-rich fluids from deeper sediment layers, may also contributes to overpressures in the sediments of the Central Nile province.
Evidence of a 10 - 20 years old mass wasting event off Mauretania proved by pore water chemistry analyses

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The Cap Timiris Channel system, discovered in 2003 during RV Meteor cruise M 58/1 off Mauretania, NW Africa, was subject of further studies on RV Meteor cruise M 65/2 in 2005. During this cruise the gravity core GeoB 9622-3, with a length of about 10 m, located in a bayou of this channel system, was recovered from 2881 m water depth. Pore waters were collected from the non opened core instantly after recovery by using rhizones as a fast, non-destructive and low maintenance sampling technique. The onboard analyses of ammonium, sulphate and alkalinity result in profiles, that indicate a very young mass wasting event with a thickness from the surface down to a sediment depth of about 4.5 m. At this depth a major shift in the concentration profiles of the measured parameters is detected. Above 4.5 m the pore water concentrations differ only little from the sea water concentration. Below this depth the profiles reveal a ‘normal’ steady state situation, in which the nearly linear gradients of both, alkalinity and ammonium, result in a change from a low seawater concentration in about 4.5 m to a high concentration in the deeper pore water. This is a characteristic pattern for a diffusive flux from deeper parts of the sediment to the sediment surface, or in this case to a former sediment surface. The sudden change in gradients from a zero gradient in the upper part of the sediment to a ‘normal’ gradient below 4.5 m depth, show a non steady state situation, indicating a very young slide event. The age of this young slide event was estimate to be of approximately 10 to 20 years, by geochemical modelling of the diffusion. If the event was older, the sharp kinks in the pore water profiles at 4.5 m sediment depth would have been smoothed much more. After opening the core onboard this geochemically detected slide event could not be found visually at the located depth of about 4.5 m. There was no obvious change in sediment material nor a visible glide plane, so that this mass wasting event would not have been
recognised. This shows that pore water analysis is a useful tool to detect especially young mass wasting events, defining the base of these events and estimating the age over geochemical modelling of the generated profiles.
Slope stability assessment on the Algiers area (Algerian margin) using a geotechnical approach and a 3D slope stability model.

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The northern African margin is a seismically active region. During the last century, several important earthquakes occurred offshore Algeria. After the Boumerdes earthquake (May 2003), important studies have been concentrated on the submarine tectonic structures and the consequences of these events.

The present study represents the first slope stability analysis realized on the Algiers area. The main objective of this work was to characterize the mechanical properties of the sediments and to realize the present-day slope stability assessment.

Data for the study have been acquired during three oceanographic campaigns. The Maradja (“MARge Active DJAzaïr”) campaign (August-September 2003), was aimed at identifying active faults and sedimentary instabilities offshore Algeria. Three giant cores have been also collected during the PRISMA campaign (May-June 2004). Coring operations and side-scan sonar high-resolution images have been conducted last November offshore Algiers (Maradja 2-2005).

This work is based on the geotechnical laboratory tests (cyclic triaxial cell tests, oedometric tests, shear vane test) carried out on the sediment cores. We present here the core MD04-2799 (PRISMA-2004), located at 32 Km from the coastline and 2295 mbsf, just upslope a slump scar, characterizing the undisturbed sediments.

A detailed analysis has been realized based on the results from the core analysis combined with different available data set (swath bathymetry, very-high resolution profiles). In this work, a new three-dimensional slope stability analysis model has been used in order to assess the slope stability. We present the impact of the earthquakes
loading on the sediment behaviour, the expected geometry of the failure and the critical failure surface. Results from our model illustrate that the slope located near the MD04-2799 core could be affected by new slides.

New in-situ monitoring, CPT measurements data, cores and high-resolution seismic profiles will be acquired (cruise planned in 2007) for a better and more exhaustive characterization of the slope stability along the entire Algerian margin.
Holocene Gravitative Mass Movements and Tsunami Hazards in a Highly Active Arc System: The Hellenic Arc.

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The Hellenic Arc system is located within one of the world’s most seismically active areas and has experienced extreme tectonism throughout the Quaternary. The object of the paper is to examine the various types of gravitative mass movements that have been detected and their causative factors. Furthermore the potential tsunamis which can be triggered by the mass movements are also discussed.

The areas examined are the North Aegean Trough and the Cretan Sea in the Aegean, the Gulf of Corinth and the Zante-Kefalinia slope in the Ionian Sea.

The various types of gravitative mass movements that have been documented include: (i) sliding of large masses with no or only slight internal deformation, (ii) sliding of masses with disintegration of sediment fabric to debris flows and (iii) slow downslope creep.

The mass movements are associated with fault escarpments, delta fronts and well stratified slopes with slope gradients ranging from 2° to 40°.

Earthquake seems to be the main mechanism initiating mass movement by either reducing the shear strength of the sediments or, causing liquefaction. Other mechanisms such as increasing topographic gradient through structural control, gas in sediment pores and heavy rain can also independently trigger and/or contribute to the initiation of mass movements.

The mass movements mentioned above can be considered responsible for the genera-
tion of tsunamis, as slide-induced tsunamis occurred in the Aegean Sea and the Gulf of Corinth during the 20th century. The first was in 1956 and the second in 1963 and both caused structural damage and loss of human life. Having in mind the latter, an analysis of two submarine landslides, which appear to have occurred about 1400 and 2800 years ago, respectively in the eastern part of the Gulf of Corinth, shows that the landslides were capable of generating tsunamis. The predicted tsunami wave heights over the landslides range from 1 to 4m with wavelengths of 3.6 to 6.2km.

These tsunami wave parameters can impose a threat to the low lying coastal communities, especially on the frontline.
Tectonics and large-scale mass wasting along the slope of the southern Adriatic basin

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The southern Adriatic basin is a sub-circular depression, more than 1000 m deep, located between the coasts of Puglia, to the west, and Albania, Montenegro and Croatia to the east. The W-verging Dinaride-Albanide fold-and-thrust belt runs along the eastern boundary of the Adriatic basin, and the intense seismic activity indicates that this fold-and-thrust belt is presently deforming. The basin is the current foredeep of the Albanide fold-and-thrust belt (De Alteriis, 1995; Argnani et al., 1996; Bertotti et al., 2001) and partly owes its remarkable water depth to the Mesozoic palaeogeography of the region (Argnani et al., 1996); in fact the southern Adriatic basin is superposed to a Mesozoic epicontinental basin which is bounded to the north and south by Mesozoic shallow-water carbonate platforms, the Dalmatian and Apulian platforms, respectively. The Mesozoic palaeogeography of the Adriatic region exerted a major control also on the geological evolution and current tectonic setting of the southern Adriatic basin, and several deformational features affecting the recentmost sediments can be related to the Mesozoic inherited palaeotopography. Regional high-resolution multi-channel seismic profiles acquired all across the southern Adriatic basin allow to outline the structural and sedimentary architecture of the basin slope. The eastern and western slope of the southern Adriatic basin present remarkable difference. The eastern slope is characterized by a thick stack of prograding units, fed by sediments coming from the adjacent fold-and-thrust belt (Roure et al., 2004), and presents extensive evidence of large-scale mass wasting throughout its Quaternary evolution. Because of the combined contribution of foredeep subsidence and Quaternary sea level fluctuation the shelf edge is relict, with sediments currently stored at the Albanian coastline. The eastern slope of the southern Adriatic basin, therefore, appears as a destructive slope system affected by progressive retreat which is mainly due to mass wasting processes.
The intense seismicity at the tectonically active front of the Albanide-Dinaride fold-and-thrust belt likely contributes to destabilize the basin slope. On the other hand, the western slope, which is adjacent to the low relief Apulian foreland, is characterised by a relatively reduced sediment supply. Tectonic and seismic activity are limited or absent over most of Puglia, with Gargano being the only exception (De Dominiciis and Mazzoldi, 1987; Argnani et al., 1993; De Alteriis and Aiello, 1993). Along the western slope of the southern Adriatic basin a key role in controlling the major Quaternary geomorphological features is played by the articulated and steep margin of the Mesozoic carbonate platform which represents a major mechanical discontinuity within the sedimentary succession. Creep and faulting driven by differential compaction tend to affect the sediments located above the carbonate platform margin. The ensuing mechanical weakening can led to focussing of mass wasting and erosion into specific places along the western slope of the basin.

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Stratigraphic prediction and impact of soft-sediment deformation phenomena in the southwest Karoo Basin, South Africa

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There are a wide range of soft-sediment deformation processes and products preserved in the geological record, but identifying the controls on their formation and distribution in space and time is problematic. Evidence from the Permian SW Karoo Basin indicates that the type of deformation phenomena is predictable in basin-floor and basin-margin stratigraphy, and controlled primarily by relative sea-level change.

Failure of the basin margin can set up a new slope profile, influences the routeing and storage of sediment from the shelf to the basin-floor, and forms the depositional template upon which the subsequent basin-floor fans evolve. A rare example of such a situation at outcrop is exposed in the Laingsburg Depocentre, SW Karoo Basin, South Africa. The Vischkuil Formation, which sits at the base of a 1.4 km-thick prograding basin margin succession, comprises at least three major phases of slide and slump emplacement. The slides and slumps were generated both from higher on the basin margin, and locally from the limbs of growth folds that deformed the seabed, and show proximal to distal changes in the character of deformation.

The adjacent Tanqua Depocentre began to accumulate deepwater siliciclastic sediment later and does not preserve a basal MTD complex. The preserved basin margin here evolved from a mixed bypass and depositional system (Unit 5, Skoorsteenberg Formation), to a largely accretion-dominated system defined by shelf edge deltas and slope lobes (Kookfontein Formation). The changes in slope morphology (an overall reduction in slope angle and increase in slope length) and usable accommodation through time is reflected by changes in the dominant deformation assemblages. The spatial and temporal distribution of the deformation facies suggests that different deformation as-
semblages occur in distinct palaeogeographical settings governed by a combination of profile position, depositional gradient, sediment flux, and position within the relative sea level cycle.

Integration of the sediment deformation data set with the sequence stratigraphic framework developed for the Karoo submarine slope successions demonstrates a predictable stratigraphic distribution. Emplacement of large-scale MTD’s occurred predominantly during the falling stage of 3\textsuperscript{rd} order sequences. Slope ‘creep’ bodies characterise deposits of lowstand systems tracts of 5\textsuperscript{th} order sequences. Within Cycles 2-5 of the Kookfontein Formation, falling stage systems tracts of 5\textsuperscript{th} order sequences are characterised by the occurrence of slumps/MTD’s, whereas foundered mouth bars are more typical of the lowstand systems tract. It is proposed that falls in relative sea level triggered the generation of slumps/MTD’s whereas rapid progradation and deposition onto a gradient over the shelf-edge led to gravitational instability, creep and failure of delta front mouth bars. This study contrasts with studies that emphasise seismicity as the trigger mechanism for sediment deformation.
3D sedimentary architecture of the Nidelva delta (Trondheim, Norway): Implications for regional slope instability assessment

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The city of Trondheim, Norway is built on a delta plain and urban development over the last hundred years has extended on the submarine part of the delta. A number of coastal flow slides are known, and some fairly well documented. The materials involved in the mass movement are thick deposits of loose fine sand and silt of Holocene age. These slides have resulted in damage to railways, roads, houses and industrial plants in addition to flood waves and loss of life.

This poster presents the preliminary results in assessing the regional stability along the coast of Trondheim and simulating future loading from new urban activities. The study includes the construction of a 3D geological model of the Nidelva delta based on a large data set comprising cone penetration tests (CPT), rotary pressure drilling tests, core sampling, detailed seismic profiles and swath bathymetry. The river dominated Nidelva delta is composed of many coarsening upwards sequences of soil ranging from silty clay to sandy gravel. It repose partly on bedrock, moraine material and on marine clays. The outskirts of the delta laps onto marine clays which form today’s land surface. The model shows that the delta has prograded in a direction NNE since the end of the last glaciation (ca. 10,000 years B.P.). An important aspect in the model is the fact that, the land has been rising 180 m relatively to sea level in the Trondheim area during the last 10,000 years. This has played an important role for in the delta development, erosion and sliding activities. Bathymetry reveals numerous slide scars on the delta front and seismic profiles show buried scars and slide masses. This emphasizes the fact that slope instability is a fundamental part of delta development.
and that it represents a hazard for urbanized areas situated on such coastal deposits. Coring and dating of organic material will help to estimate slide frequency.
In situ geotechnical measurements and slope stability analyses in Lake Lucerne: From understanding of past to predictions of future slides

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Lakes can be used as model basins to analyse subaqueous slope stability under static and dynamic loading conditions. Here we present results from detailed case studies in Lake Lucerne (Central Switzerland) derived from (i) in situ measurements of the geotechnical properties of the normally consolidated subaquatic slope sediment, (ii) lithologic and petrophysical description of the cored sediment cover, and (iii) limit equilibrium modeling of subaqueous slope stability under static and dynamic loading conditions. In Lake Lucerne the historic 1601 A.D. Mw ñ 6.2 earthquake triggered several translational slides on the sediment-covered slopes with inclination angles > 12 degree, as by numerous slide scars and by coeval debris flows deposits in the basin plains (Schnellmann et al., 2006). High-resolution seismic data and short cores from the failure surfaces indicate that slip planes developed in the Late Glacial deposits that underlie the 4-6 m of Holocene drape. Long piston cores, in situ vane shear and freefall CPT (FF-CPT) testing combined with in situ pore pressure measurements in undisturbed slope sections adjacent to failure scars reveal lithological and geotechnical characteristics of the slope-covering sedimentary section. Recovered lithologies indicate that the Late Glacial deposits consist of very fine clays with some angular gravel components and minor intercalated sand layers. This stratigraphic unit is characterized by low in situ shear strength values suggesting a potential zone of low stability conditions. Additionally, excess pore pressures in this interval, as measured using the CPT probe, suggest a potential for reducing effective shear strength when applying additional stresses (e.g. dynamic loading) to this material. Sedimentological
and geotechnical data were implemented into limit equilibrium slope stability models. Results indicate that the slopes are stable under static loading conditions with a factor of safety $FS > 2$. Pseudostatic back analyses reveal critical horizontal seismic accelerations of $\tilde{0.13} \text{ g}$ to trigger slope failures. This value is very similar to calculated peak ground accelerations at the study site during the 1601 A.D. Mw 6.2 event that had an epicentral distance of $\tilde{12} \text{ km}$ (deduced from predictive ground motion models; Bay et al, 2003). This study on subaqueous slope stability assessment in the lacustrine model basin provides promising insights into the stability of subaqueous slopes covered by normally consolidated sediments. Furthermore, when being analyzed on a GIS-based basinwide scale, this study will eventually identify sites of potential future slope instabilities in perialpine lakes of central Switzerland yielding the means to assess relative intensities of paleoseismic events and contributing to a general slide-related hazard assessment.
Modeling landslides in a submarine canyon within the upper plate of a subduction zone

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Active tectonic margins are often typical locations for the triggering of large landslides that can attain runouts of hundreds of kilometres and impact offshore activities over a considerable area. Although the great mobility of submarine landslides is not very well understood it is necessary to attempt to characterize the risk associated with these events for offshore human activities such as the development of natural resources and the positioning of submarine communication infrastructure. In this work we use a 2D model to simulate these phenomena in an active margin environment, and specifically in a submarine canyon where landslide runout effects can be amplified. The location chosen for the modelling is the San José Canyon along the Guatemala margin. The model is based on a code for incompressible Coulomb flow that is essentially a depth averaged shallow-water granular-flow model. The conservation equations for mass and momentum are solved with a Coulomb-type friction term at the basal interface. The governing equations are solved using a parallel, adaptive mesh, Godunov scheme. The code allows for computing on multiple processors, which increases computational power, decreases computing time, and allows the use of large data sets. Adaptive gridding allows for the concentration of computing power on regions of special interest (Sheridan et al, 2005). Of fundamental importance in these types of simulations is the existence of accurate bathymetric data, which in this case were acquired during Sonne cruise 173 within the SFB574 (Kiel University, Germany), using a Simrad EM120 Multibeam system. The area where the code is being tested is the San José Canyon, located on the Guatemala margin, an area surveyed since the 70s by deep sea drilling projects, and that lies offshore the city of San José (Guatemala) at about 13°N 91°W. The canyon is incised approx. 1.8 km into the edge of the shelf and has a length of ca. 100 km in the upper slope. Across the midslope terrace, normal faults give rise to a horst and graben structure, that causes the canyon to develop sub-parallelly to the
trench for several kilometres until it veers abruptly 90° and again heads towards SO, directly towards the trench, probably in correspondence of a major tectonic lineament. The canyon tapers out near the base of the lower slope. Core and log data from site 570 of DSDP Leg 84, located several tens of kilometres from the canyon, indicate the presence of a 15-m-thick hydrated zone containing a 4-m thick nearly pure hydrate section beneath over 200 m of hemipelagic sediment. Bottom Simulating Reflectors (BSR), negative polarity compressional (p)-wave reflections sub-parallel to the sea floor, also provide a tool for gas hydrate detection. The presence of BSRS within the seismic sections shows that gas hydrate layers in the area have a significant spatial extension, and likely reach the walls of the San Jose Canyon. Gas hydrate layers could provide both preferential slip planes and triggering factors for submarine landsliding and were therefore used as the lower boundary for the modelled events. The age of redeposited sediments indicates that the canyon already existed in the late Miocene. However, the lack of a fan and sediments in the trench are indication of an absence of recent sediment transport through the canyon. This can possibly be explained by a sporadic landslide activity and/or by the total subduction of the sediment accompanying the high rate of subduction (~7.8 cm/yr) of the Cocos plate beneath the Guatemala margin. Thus, another objective of the modelling is to understand the relationship between landslide volume and plate subduction rates.
Submarine mass movements on the eastern Algerian margin: preliminary results from the MARADJA 2 - Leg 2 cruise (2005)


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A geophysical survey conducted on the western margin offshore Algeria, southwestern Mediterranean, during the MARADJA cruise (2003) revealed the importance of gravity-dominated depositional processes (turbidity currents and mass wasting) in this seismically active area, located on the inner Europe-Africa convergent plate boundary. In order to extend toward the eastern Algerian margin the bathymetric and reflection-seismic survey, the MARADJA2/SAMRA - cruise, Leg 2 (21 November-12 December 2005, French R/V “Le Suroit”) was carried out between Delfys (4°E) and Annaba (8°E). We acquired multibeam bathymetry and backscatter imagery (Simrad EM300), high-resolution seismic-reflection profiles (2-5 kHz Chirp), 24- and 72-channel seismic profiles, and seven sediment cores. The purposes of this study are: (i) to identify and describe the recent eastern Algerian margin depositional systems with emphasis on mass wasting processes, and (ii) to evaluate the relationships between the sedimentary processes and the historical seismicity that affects this area. We present here for the first time a complete multibeam bathymetric map and illustrate the numerous mass movements (slumps and debris flows) identified at the foot of the continental slope, often associated with regional reverse faults developing over ramps discovered during the cruise.
Landslides and mass wasting offshore Sumatra – results from the HMS Scott and SEATOS surveys 2005.

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Earthquakes are commonly cited as a mechanism for triggering submarine landslides that have the potential to generate damaging tsunamis (e.g. Papua New Guinea 1998). Notwithstanding, based on the evidence now available, the Great Indian Ocean earthquake of December 26th 2005 is generally agreed to have been the only cause of both far field and local tsunami runups, with no contribution from submarine landslides. However, if earthquakes are such a common trigger for landslides then the magnitude 9.3 earthquake of December 26th might be expected to have caused numerous seabed failures within the area of rupture that may have contributed to local tsunami runup.

This contribution discusses the seabed and subseabed morphology and structure offshore of Sumatra acquired during the surveys carried out in 2005 by HMS Scott and the Sumatra Earthquake and Tsunami Offshore Survey (SEATOS). The Scott survey utilised high resolution 12 kHz, 361-beam hull-mounted Sass IV sonar, mapping over 40,000 square kilometres of seabed. During the SEATOS single channel seismic and seabed images from a Remotely Operated Vehicle were acquired over the area mapped by the Scott. One of the objectives of the surveys was to identify submarine slope failures that may have contributed to the tsunami. This paper reports on the results of this investigation.

The area mapped is an accretionary complex formed as the two plates (Indian and
Asian) have converged over the past 40 million years. Several seabed failure mechanisms of various ages have been identified. Along the plate margin in the west of the survey area the deformation front comprises a series of young thrust folds up to 1000 m in elevation and tens of kilometres in length. In places the seaward faces of these folds have failed cohesively and slumped blocks 100’s of metres high and up to several kilometres long have been displaced up to 13 kilometres onto the inner trench floor. At other locations older episodes of failure are identified by the presence of displaced slumped blocks located on the crests of the folds; the slumps thus predating uplift.

Where young thrust folds are absent, the outer margin of the accretionary prism is deeply dissected and comprises a steeply sloping seabed incised by numerous gullies and slide scars. Here, mechanisms of failure are incremental, and take place mainly through headwall erosion. There are small cohesive failures, although most sediment appears to be shed from the gullies into the inner trench through channels incised into the seabed. Sediment overflow from the channels has resulted in the construction of sediment fans upon which are located giant sediment waves. Along both the outer margin of the prism and within the forearc basin the Single Channel Seismic data shows that mass sediment flow is a common mechanism of failure.

Inboard of the deformation front, the accretionary prism the thrust folds are, deeply dissected and buried by hemipelagic sediment. There are no cross-cutting submarine canyons. The likeliest explanation for the lack of large failures and absence of cross-cutting canyons, seems to be that the region is sediment starved, with the main sediment input from offscraping along the plate boundary. There is little sediment input from Sumatra.
Dating submarine mass failures and relationships to tsunami generation: the use of multibeam bathymetry and seabed images, examples from the Pacific and Indian Oceans

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The potential tsunami threat from submarine mass failures (SMF) has been known since the late 19th century, but it was not until 1998 when a tsunami off the north coast of Papua New Guinea (PNG) killed over 2,000 people, that the real danger was at last fully recognised. The result was a wake up call to coastal communities worldwide. In December 2004 a Great earthquake in the East Indian Ocean resulted in a catastrophic tsunami that devastated adjacent shores. Whereas the earthquake was the primary cause of the tsunami, local runups of 30-35 m on Sumatra, in combination with the available maps of seabed morphology, was suggestive of an additional contribution from submarine landslides located off northern Sumatra.

In the instance of PNG the cause of the tsunami was initially controversial. This was because of a number of reasons: the tsunami threat from SMF was unrecognised; and the necessary mathematical models to reproduce the tsunami propagation from a submarine slump were not available. Another important aspect of the use of the acquired dataset in identification of the tsunami source mechanism was the application of the multibeam bathymetry in combination with seabed photographic images acquired from Remote and Manned submersible vehicles. The integration of these two technologies provided a powerful tool for mapping the seabed almost akin to mapping on land.
Identifying and mapping the seabed and sub-seabed is one aspect of the new methodologies that is utilised mainly by earth scientist for mapping form and structure. An additional and increasingly applicable tool is the utilisation of marine life to constrain the timing of events, based on knowledge of the growth of sessile megafauna. Growth rates of marine life are increasingly better understood and this, together with their relationships to seabed structures imaged both remotely using multibeam and directly with video and still photographs, is providing a powerful method of determining when events such as SMF take place.

This contribution, using examples from the research carried out on tsunamis in PNG in 1998 and the Indian Ocean in 2005, demonstrates how dating of seabed movement has contributed to a better understanding of tsunami generation in the instances quoted.
In situ - characterisation in marine slope sediments with lightweight CPT instruments

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Pore Pressure and shear strength are crucial geotechnical parameter for the stability of marine sediments. Their importance is reflected in natural processes like liquefaction, landslides, earthquakes as well as human impact in case of static loading by offshore constructions. Therefore Cone Penetration Testing (CPT) is an effective method for in situ measurements of these geotechnical parameters with one instrument. Based on the experience of earlier marine CPT devices since the 1970’s, we designed two different marine CPT probes for in situ measurement of strength (tip resistance, sleeve friction), pore pressure, tilt and acceleration. Both CPT systems rely on an industry 15 cm2 piezo-cone with the sensors at the tip and a pressure housing containing a microprocessor at the top. In addition, deceleration and tilt are monitored for vertical profiling of the penetrated sediment column. The lightweight (40-170 kg), shallow water (200 m depth) lance works completely autonomous with a volatile memory and battery package, and can be deployed from any platform, even without a winch. Length as well as weight of this system can be varied according to the sediment stiffness and allows variable penetration depth (usually less than 5 m). The design and the variable handling of the lance allow us to study the influence of the penetration velocity on the measured parameters. In consideration of pore pressure measurement the device is useful for longterm dissipation tests. Here, the lance can be left deployed over the desired period, e.g. connected to a buoy or other mooring. The sturdier, deeper water (currently 2500 m depth, anticipated 4000 m depth) system uses both power and telemetry for real-time data transmission from the research vessel, although spare batteries accommodate for limited use in autonomous mode. Initial use of the CPT systems attests their efficiency and reliability in the measurement of sediment physical properties. In a variety of estuarine and marine settings, our studies served objectives such as the
assessment of slope stability, navigability of harbours/estuaries, consultancy for cable laying and trenching, or ground-truthing of geophysical data.
Submarine morpho-sedimentology of the Betsiamites - Rimouski area, St. Lawrence estuary, Quebec, Canada

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A complex submarine geomorphology was revealed from multibeam bathymetric and seismic reflection surveys conducted between 2001 and 2005 in the Lower St. Lawrence Estuary between Betsiamites River and Rimouski, Quebec. Many erosional and depositional structures were observed on the Estuary shelf and the Laurentian Channel and are thought to be related to the major sub-aerial slides identified in the coastal quaternary deposits. This sub-aerial landslide is linked to a major earthquake that occurred in Eastern Quebec in 1663 and seems also to have a correlation with the submarine mass movements observed. However, more than one events of debris flow were identified on the seismic reflection surveys, which lead to the interpretation that the area has been unstable and active during the Holocene. Several regions on the shelf and on the Laurentian channel show evidences of gas pockmarks which could potentially influence submarine slope stability. Other structures such as buried channels and meanders could be linked to the deglaciation-related processes in the surrounding area. In this research we describe the overall geomorphology of an area of about 400 km2 and the morpho-sedimentology of the various submarine geomorphologic features observed. A depositional sequence and erosional history of the glaciomarine and post-glacial sediments of the area is also established. The linkage between the sub-aerial landslide and the submarine mass movement signatures is investigated in order to clearly define the correlation between these events. Studies of such mass movement deposits provide useful insight into submarine processes such as sediment instability in the St. Lawrence estuary.
The Eocene South-Pyrenean carbonate gravity flow deposits in the Jaca-Pamplona Basin: Internal structure variability and interpretation

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During Uppermost Ypresian and Lutetian times several catastrophic collapses happened in the foreland carbonate margin of the South Pyrenean Jaca - Pamplona Basin. These events originated up to eleven major carbonate sheet-like beds (megabeds) interlayered with siliciclastic turbidites in the basin trough. They were described as a carbonate resedimented deposits in the early sixties but their origin, internal structure variability and interpretation remain controversial. In this work we document the lateral variability of their internal structure (including all the existing sediment gravity flow types ranging from slices to turbidites) and discuss the triggering mechanisms for their deposition. These carbonate megabeds are build essentially by two parts. The lower one consists of a debris flow deposit ranging or including slices, slumps, clast supported and mud supported megabreccias. The upper one is made up of a huge turbidite sequence. The thickness of these carbonate megabeds reach up to 250 m and their lateral extension attain up to 140 km along the carbonate margin (E-W) and a minimum of 10 km basinward (S-N). These internal structure and bed geometry inform us about a complex depositional mechanism. It consists of a lineal source along the foreland carbonate margin due to their catastrophic collapse. The carbonate platform collapse was triggered by their flexural bending correlative to the orogenic wedge growth due to the thrust staking. The subsequent turbidite sequence could be related to the resedimentation of shallow water carbonate components as a consequence of a tsunami triggered by the margin collapse.
Assessing the stability conditions of the Cap de Creus Canyon, Gulf of Lions, using limit equilibrium methods.

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A portion of the Cap de Creus has been selected for a detailed analysis of slope instability. The selected area is located on the north side of the Canyon between water depth ranging between 280m and 750m. This sector presents evidences of landsliding which has led to the accumulation of debris at the toe of the slope. The headwall escarpment is about 30m high at a slope of 27° whereas the failure plane is inclined at about 20° and is about 450m wide. The slope of the debris where sample PCFL-665 was taken is at about 5° and reduces to about 1° near the thalweg. Results of various scenarios describing the canyon walls will be presented in order to assess the stability condition using limit equilibrium methods. A particular attention will be paid to conditions assuming that the factor of safety is close to 1 so that other parameters, such as excess pore pressure and erosion can be estimated. We will also consider the impact of sediment accumulation at the top as a result of sediment shelf transport. Finally, we are also considering the impact of a more or less cemented sandy hard layer on the top and its relation to slope angles and stability. The geotechnical parameters for the clayey sediments involved in the instability have been determined from laboratory testing obtained from samples taken in 2004.
New insights into turbidity current formation from submarine flowslides

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Submarine landslides and debris-flows are some of the most prominent and effective mechanisms of sediment transport from continental shelves to deep ocean basins. Recent seismic surveys of the seafloor near continental margins have revealed complex morphological features associated with mass flow deposits. In proximal zones, facies tracts tend to be characterised by poorly sorted, massive sands, interpreted as deposits of dense, inertial flows, which are replaced, in distal regions, by finer-grained laminae that have aggraded progressively beneath relatively dilute gravity currents. This stratigraphy is consistent with deposition from bipartite flows in which sediment, eroded from the leading edge of surge fronts as ambient fluid is deflected from their paths, is entrained into the overlying water column generating subsidiary turbidity currents. Although there appears to be a general consensus that many turbidites originate from the gradual transformation of sand-rich debris-flows into turbidity currents, very little research has been specifically directed at quantifying these processes in order to understand the basin-ward variation of deposit composition and architecture. Results from a series of highly instrumented flume tests are used to constrain the mechanics governing post-failure flow transformation in order to develop a quantitative framework in which to interpret process-oriented facies tracts. Flow processes are explored as functions of the original sediment composition and coherence of the dense parent phase. Through the simultaneous measurement of internal velocity and concentration gradients, both the volume fraction of sediment reworked into an overriding turbidity current and the degree to which the original dense flow is diluted through ingestion of ambient seawater are determined. This information is necessary input data for many theoretical models of seascape evolution and is, therefore, prerequisite for predicting the complex interactions and feedback mechanisms involved in current generation.
The 1783 Scilla tsunami: evidences of a submarine landslide as a possible (con?)cause

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On February 6th 1783, a span of coast of some 165,000 m$^2$ near the small town of Scilla (Tyrrhenian Calabria, Southern Italy) collapsed to the sea, following two main seismic events (estimated 7.3 and 5.8 Magnitudo). According to historical witnesses and tsunami catalogues, a huge amount of rock debris entered the sea producing a tsunami that killed some 1,500 inhabitants camped on the beach.

This event is, beside Vajont 1966, the only historic recent tsunami in Italy generated by a subaerial landslide entering in a water body. Two marine surveys have been carried out on December 2005 and January 2006 in the marine area immediately offshore the slide, by using shallow and deep water multibeam systems.

First results indicated a morphological continuum between the subaerial and submarine slope, the latter making up the right flank of the Scilla valley, a shore parallel feature that connects the Messina Strait with the Tyrrhenian abyssal plain. There strong currents are active, generated by the out-of-phase tidal movement on the Ionian and Tyrrhenian Seas. On this valley flank, dipping some 20-25°, a submarine steep slope approximately 1000x500 m in size is present, exactly offshore the subaerial one. The average depression respect to the surrounding seafloor is 10-20m and a rough estimation of the submarine lost volume is of some 3 Mm$^3$. Actually the scar is well-evident below 100-150m whilst it is almost undetectable in shallow water, either because of the primary geometry, and because of the presence of a stream deposit in the very neighbouring. Just at the foothill of the scar, a depositional bulge with hummocky morphology is present with an estimated thickness of max 10-12 m. Within the bulge large blocks are present, each one accounting for a volume between 100 and 200,000 m$^3$. The total volume of the deposit has been estimated something less than 2.8 Mm$^3$. The deposit shows clear evidence of reworking by bottom currents.
Preliminary results on the relationship between the subaerial and submarine scar, the lack of scar in shallow water and the difference in volume between scars and deposit will be discussed.