3D Seismic Analysis of Buried Slide Deposits in the SW Vøring Basin, Mid-Norwegian Margin

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Sediments on the Norwegian deep water margin have failed repeatedly during the last 2.5 Ma. This region has seen some of the largest submarine mass wasting events on continental margins worldwide. Considering the increased interest of the hydrocarbon industry in deep-water areas, there is a need to better understand slide deposits, slide development and areas prone to failure. The development of the Ormen Lange gas field in the Storegga Slide headwall area has been a showcase of assessing slope stability in hydrocarbon frontier areas. This integrated project led to a better comprehension of the Late Pliocene / Pleistocene evolution of the mid-Norwegian margin and its frequent slide activity. The slide mechanism is likely related to a distinct depositional environment of the glacial-interglacial cycles. Slide deposits may constitute a major geohazard for exploration and development of seafloor and sub-seafloor resources.

Two 3-D seismic data sets from the southwestern part of the Vøring Basin on the mid-Norwegian continental margin have been used to analyze the upper part of the Naust Formation (~ 0.5 to 0.2 ma) showing a number of chaotic units interpreted as slide deposits. A seismic stratigraphy with four main units has been established (unit 1-4). The two oldest units (unit 1 and 2) are dominated by glacial debris-flow deposits formed during glacial maxima when the Fennoscandian ice sheet reached the shelf edge. Parts of unit 2 are later deformed by younger slide events. The two youngest units (unit 3 and 4) are characterized as slide material and are related to the Vigrid Slide and the Sklinnadjupet Slide. Unit 3 shows compressional structures formed by well-consolidated deposits that have been broken up and pushed on top of rather undisturbed sediments. Less consolidated deposits are deformed by compression, which resulted in the formation of folded structures. Deposits in unit 4 show that the slide can be associated with a complex flow process and the development of general shear zones that separate zones of sediments with varying degrees of deformation. Slide deposits within the different zones may have been deposited at different times or may have moved at different velocities in one mega-event. The Sklinnadjupet Slide was probably triggered just after the Vigrid Slide. The Sklinnadjupet Slide has probably developed retrogressively and filled in the upper part of the Vigrid Slide.
Submarine landslides in the continental margins of the Mediterranean Sea: spatial distribution, major characteristics and implications for geohazard assessment

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Submarine landslides are ubiquitous on the Mediterranean continental margins and adjacent seas. Understanding the distribution of known submarine landslides is not straightforward because of incomplete coverage and lack of uniform studies in all areas. Nevertheless, during the last two decades, improvements in swath mapping and geophysical techniques, and growing interest of both academia and industry in these processes, have allowed to identify hundreds of submarine landslides. With the aim to understand the causes of the submarine landslides mapped in recent years in the continental margins of the Mediterranean Sea, we have undertaken a compilation of information from the scientific literature into a GIS-based framework. This work provides a first step towards understanding the role of geology in controlling the patterns, frequency and magnitude of submarine slope failures in the Mediterranean basin. Such analysis is an essential part in the assessment of submarine geohazards. Submarine landslides in the Mediterranean occur on tectonically dominated margins as well as on passive margins and volcanic island flanks. Large sedimentary wedges (Ebro, Nile, Rhone) appear to have a high density of large submarine slope failures. Tectonically active margins have numerous but relatively small failures. Most landslides in the Mediterranean originate in water depths exceeding 2000 m on slopes of 2° and most of them arrest only in slightly deeper water depths. This illustrates that a) most of the landslides in the database are relatively small, but also b) that the continental rise is a place of high slope instability compared to the continental slope and c) that limited energy is available for down-slope sediment transport, with most failures arresting shortly after triggering and/or producing little sediment transport. With regard to the age of the failure events little is known so far, stressing how little we know on the recurrence of these phenomena. Of the 524 submarine landslides events reported in the database, only 44 have somewhat accurate age determinations. The age of 128 events are simply reported in the literature with a geologic epoch, which induces a large error bar and makes almost impossible to establish a relationship with triggering mechanisms and environmental factors. Nevertheless, it is surprising the large amount of these 128 events that are reported as Holocene (68 events), which suggests that climate induced stress changes (sea level and bottom temperature changes and their effect on gas hydrate and gas systems, sedimentary load, ...) have had a major role in triggering slope failures.
Use of distal turbidites to decipher landslide records of frequency, volume and failure mechanism: case studies from the Moroccan Turbidite System

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Proximal debris aprons of volcanic islands and continental slopes have been studied in detail in the search of evidence for landslide activity. However, records of occurrence are difficult to calculate in these locations due often to substantial overprinting and geomorphic complexities. Furthermore, processes of failure are often obscured in these proximal areas of the landslide. However, submarine landslides commonly generate turbidites that are recorded in the quiescent basin plain. Along with archived pelagic sedimentation, the turbidite record linked to landslides can provide accurate reoccurrence intervals. In addition, adequate core coverage can provide better resolution on the volumes involved in specific landslide events. Studies of the turbidite facies can also provide valuable insight into the landslide mechanism that generated the turbidite. Wynn and Masson (2003) and ongoing work has attributed multiple-stacked repetitive upwards-fining sand and mud interval facies in the turbidite (subunit architecture) to representing a multistage failure at source. This is best exemplified by the 165 ka Icod turbidite from the Icod landslide from the northern flank of Tenerife. Furthermore, this facies is present in other major turbidite events generated from the most recent large volume volcanic landslides, including the El Golfo (15 ka) and Las Playas II (~125 ka). Of note these large volume turbidites from catastrophic failures have well developed bedforms that associate these flows with surge-like processes of Mulder and Alexander (2000). These bedforms range from massive sands (Ta), through parallel laminated sands (Tb), cross laminated sands (Tc), convolute laminated sands (Tc'), through laminated silts and muds (Td) and graded muds (Te). The volume, velocity profile, mud content and longevity of the flow have enabled the full sequence of bedforms observed to develop.

In addition smaller volume events are recorded in single and multiple fining-upwards packages. These are recorded in two facies: (1) a graded sand with parallel and cross laminations before a grain-size break and a limited mudcap, and (2) lower volume events with an ungraded structureless sand capped by a grain-size break and limited mud. Here the lower volume (2) facies is attributed to surge processes of Mulder and Alexander (2000) and the (1) facies mark a transition between the surge-like processes of the turbidites linked to catastrophic failures and the surge processes of the low volume events. The surge flows are attributed to small local failures of sediment accumulations on the volcanic island shelves. Here the sand fraction is stratified from the mud fraction during the flow and deposited rapidly, resulting in a lack of bedforms. The transitional surge to surge-like flows mark an increase in volume and mud content, where the flow is sustained for long enough for bedforms to develop. The implication is that turbidite processes can be inferred, where there is adequate core coverage for both volumetric calculations and facies analyses, and that this can provide insight into the landslide source.

This study presents a comprehensive appraisal of the provenance and recurrence of submarine volcanic island landslides in the Canary and Madeira archipelagos based on the distal turbidite record. This study also aims to show that the facies present in the turbidite record can enable insight into the failure source and mechanism. This is important in enabling appropriate geohazard assessment for a submarine area from a landslide and tsunami perspective.
Landslide and earthquake events recorded in distal turbidites in the deepwater basins of the Western European Margin

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Turbidites are of major economic importance in regards to sand distribution for hydrocarbon and aquifer reservoirs. However, more recently turbidite event histories have been studied in order to derive hazard assessments. Turbidite occurrences can be linked to earthquake and landslide activities, exemplified in the Horseshoe and Madeira Abyssal Plains respectively on the Western European Margin.

The Moroccan Turbidite System, which comprises the Agadir Basin, Seine Abyssal Plain and Madeira Abyssal Plain, records major landslide events from the Moroccan and West Saharan margin and island flank collapses from the Madeira and Canary archipelagos. ODP core from the Madeira Abyssal Plain and from the aprons of Gran Canaria can extend these records of major landslides back to 15 Ma. The events associated with continental shelf failures here can be correlated to points of sea level minima or maxima (Weaver & Kuijpers, 1987), whereas volcaniclastic events are associated with terminuses in volcanic island cycles. Piston coring has enabled recovery of high resolution records in these basins back to 200-500 ka and exceptional records to 1 Ma in the Madeira Abyssal Plain. The events recorded in the Madeira Abyssal Plain are related to the largest events capable of generating turbidites with large volume and runout. Piston coring around the Canary and Madeiran archipelagos have shown a great number of smaller events that are not recorded in the Madeira Abyssal Plain, thus providing a complete landslide archive of both major catastrophic and minor events.

Event histories in the Tagus and Horseshoe Abyssal Plains extend back to ∼130 ka. The most recent events in the last 20 ka have been linked to earthquake and tsunami records (Gracia et al., 2010). Indeed, this link between turbidites and seismology has been demonstrated on the modern Cascadia margin (Goldfinger et al., 2003). However, earthquakes generating large volume and margin-wide turbidites on each event is not true for Sumatra or indeed for the all events in the Tagus Abyssal Plain or Agadir Basin. Indeed, where significant sediment accumulations have not been generated between earthquakes, large earthquakes cannot necessarily produce failures and ensuing turbidite currents recorded in the basin.

Study of the turbidite internal architecture can demonstrate potential modes of generation and thus provide additional information regarding the hazards. Turbidites with multiple-stacked repeating sequences of sand and mud (subunits) can be linked to multistage landslide mechanisms. This is the case for the El Golfo, Icod and Las Playas II collapses in the Canary Archipelago. However, events in the Horseshoe Abyssal Plain and Sumatra trench also show these subunits but are thought to relate to earthquake triggers.

The present study shows the importance of using turbidites in deriving records of paleoseismicity and landslide activity. However, these records are often incomplete and knowledge of the sediment delivery and depositional processes of the turbidite are essential for critiquing the records. This is so that appropriate trends can be identified and future predictions better made.
Evidence of submarine landslide triggered by the 2009 Suruga Bay, Japan earthquake

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On 11 August, 2009, at 05:07 JST, a moderate-to-large earthquake (M6.5) took place in the Suruga Bay of central Japan. It struck two deep ocean water pipes, which reach 397 m and 687 m deep in the near source area. The temperature and the turbidity of deep ocean water became higher and larger, respectively than usual immediately after the earthquake. The temperature of 397 m deep ocean water have been recovered in one week later, however, the relatively high temperature of 687 m deep water has been continued. This implies that something to be damaged have happened on the 687 m water pipe due to the earthquake. In the meantime, three in-situ surveys to reveal damages of the 687 m water pipe and its cause could be carried out by using a research vessel and two vehicles of Japan Agency for Marine-Earth Science and Technology (JAMSTEC). The first survey was done by using ROV “Hyper-Dolphin”, which performed the visual surveys. As a result, the 687 m water pipe has been moved at least 2 kilometers downstream from the original laid position. Sediments and debris have been deposited somewhat in one side along the 687 m water pipe. And the 687 m water pipe has been buried into the sediment at water depth of 782 m. Thus the direct evidence of submarine landslide trace could be discovered during the first survey by ROV “Hyper-Dolphin”. The second survey by R/V “Natsushima” was to reproduce the bathymetry map in the source area after the earthquake. Comparing with the bathymetry map obtained before the earthquake by the same equipment on R/V “Natsushima”, a retrieved contour pattern, i.e. an erosion pattern could be found near the original 687 m water pipe location, whereas a sediment pattern has been reproduced in the downstream where the current 687 m water pipe disappears, which is possibly a submarine landslide trace caused by the earthquake. The last survey was done by AUV “Urashima” in order to obtain a high-resolution bathymetry map near the submarine landslide trace. AUV “Urashima” can dive close to the seafloor and obtain bathymetry map at a high resolution. A high-resolution 3D image of the seafloor clearly depicted a slump scarp of 450 meters wide and 10 to 15 meters deep near the original 687 m water pipe location. Dune structures, which seem to be generated by turbidity current, were found widely in the submarine slide area. Each dune has a wavelength of 20 to 30 meters and a height of about 1 meter. This submarine landslide might contribute to trigger the tsunami excitation, which still cannot be interpreted by the seismic faulting alone.
New data from the Sahara Slide complex off NW-African: timing, failure processes, and hazard potential

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The Sahara-Slide complex (NW-Africa) is a mega slide with a length of \( \sim 700\text{km} \) and an estimated volume of \( \sim 600\text{km}^3 \). The morphology and evolution of the headwall area of the Sahara-Slide complex was investigated during a Poseidon-Cruise in early 2010 by means of acoustic data and gravity coring. The bathymetric and sidescan data show a slab type failure with multiple headwalls and at least two glide planes. Some areas are characterized by elongated blocks, which have not moved far, while other areas are characterized by quickly disintegrating sediment masses. Seismic data show older mass transport deposits and giant elongated mound-like features, which are aligned with the sidewalls. We speculate that migrating fluids in the mound-like features control the location of the failure. Previous investigations of the distal deposits of the Sahara Slide yield an age of 50–60 ka for the main slide event, which is a period of global sea level rise. Major slides off NW-Africa are all dated at periods of global sea level rise. This observation is challenged by new observations made during the Poseidon-cruise in early 2010. Numerous cores taken beneath the upper headwall complex suggest an age of only 1 – 2 ka for this major failure. We are currently investigating whether this age represents a major re-activation of an existing headwall or a major failure of undisturbed slope sediments. The young age of this slide calls for a re-assessment of the risk potential of this margin.
Fluidization process in submarine landslides due to water infiltration caused the high mobility of debris flows

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In various environments, sudden variation in pore water pressure in the vicinity of shear surfaces can trigger a landslide. Landslides occurred in the subaqueous environments often involve huge amount of fine-grained sediments and cover large travelling distance, indicating that some are much bigger than any seen on-land. From the geotechnical and rheological points of view, this research would focus on the phase “transition from slide to flow”. The landslide fluidization due to water infiltration into the soil was studied by physical and numerical means. After the onset of slope failure, the failed mass might be experienced large deformation with ambient water – soil breaking into many pieces of soil blocks during shearing – and then turbidity current could be produced. During the transition phase, the interaction between sediments and water may thus play an important role in characterizing the mobility of debris flows and their deposition pattern. In fact, in slip surface, loss in shear strength in weakened slopes is related to the change in density and water content of landslide body. Mechanically, based on a strain softening behavior in clayey soils, shear strength suddenly decreases with increasing deformation or time, corresponding to increasing water content in slip surfaces. Preliminary findings have revealed that there is the strength evolution from intact through remoulded toward residual/yield strength of failed materials with the help of Cat-scanning image techniques and laboratory/hand-held vanes. Particularly for, under undrained condition, the case that fine-grained soils governed the landslide mobilization, the effect of water infiltration into soil is of great importance. In parallel with experimental evidence, the numerical simulation using dam-break concept were carried out in terms of landslide fluidization – dynamic interaction between soil particles and ambient water can lead soil fluidization. The model originally developed by Robert and Pagnacco in Laval University was used. This simple 2-D model included: continuity equation, Navier-Stokes equation, transport equation, and coupling equation between density of mud and water concentration. At the moment of failure, or just after, we look into the influence of the component of velocity and mud concentration on the acceleration of landslide motion. The acceleration of solid bodies may move inside the fluid domain and possibly generate landslide-induced water waves – sometimes called landslide tsunamis.
Comparative quantitative geomorphology of Holocene mass-transport deposits, St. Lawrence River Estuary, Canada.

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Recently acquired multibeam bathymetry data provide a unique opportunity to investigate seafloor instability features along a 310 km-long segment of the St. Lawrence River Estuary, one of the largest estuaries in the world and the most seismically active area in eastern Canada. The analysis of this dataset indicates that submarine slides occur over a much larger area than previously recognized and that Holocene sediments are reworked by mass-transport along significant portions of both the northwest and southeast margins of the lower and middle St. Lawrence River Estuary. In the surveyed area, 111 individual mass-transport complexes were identified representing 13 % of the seabed. In many cases, mass transport events appear to initiate in the vicinity of steep bedrock walls located along some segments of the estuary. The timing of mass-transport events was not constrained during this study. However, the observations that submarine slides have geomorphological signatures ranging from fresh to subdued, that failures occur at multiple stratigraphic levels in high resolution seismic data, and that a large portion of the seabed is reworked by mass wasting suggest the occurrence of multiple catastrophic events, several of them likely triggered by earthquakes.

Mass-transport deposits vary in area from less than 1 km² to more than 40 km². They exhibit various geomorphological signatures, including: 1) blocky morphology indicating significant internal disruption; 2) smooth morphology with less internal disruption except close to the headwall scar and in the frontal area; 3) morphology characterized by sub-parallel ridges formed by folding. For all mass-transport deposits, size, average slope and roughness, the variation of these parameters within the slide body as well as the height and geometry of the headwall scar were quantified. This quantitative analysis provides a unique opportunity to study these parameters in a statistically significant and homogeneous dataset located in a relatively small area that experienced a similar Quaternary history. The search for objective classification criteria using these parameters is in progress. Additionally, the derivation of relationships between the various parameters may offer valuable insight into fundamental dynamics of submarine landslides.
Mass transport complex in confined intra-slope basins: the case study of the Epiligurian Specchio unit (Northern Apennines, Italy)

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The tentative comparison of data coming from ancient and modern submarine landslides examples, as those provided by field-based surveys of exposed orogenic belts and geophysical studies of current continental margins, is not often a trivial task. This is mainly because of the resolution limits and scaling problems between these two approaches, and for the limited occurrences of comparable geodynamic contexts (i.e. collisional/convergent versus divergent margin settings). This is particularly evident for accretionary systems, where several controlling factors combine to produce “chaotic units” (i.e. rock assemblage characterized by different degrees of lithologic mixing and structural disorder) at the different scales.

This study has been carried out on an ancient mass transport complex (MTC), known as the Specchio Unit among the Apennine geologists, developed on the leading edge of a complex submarine accretionary prism. This unit occurs within the lower Rupelian turbidite-like deposits of the syn-orogenic Eocene-Oligocene Epiligurian succession, cropping out in the eastern side of the Northern Apennines (Italy) as isolated sedimentary remnants (i.e. outliers), representing the local syn-tectonic infill of intra-slope basins (i.e. piggy-back, wedge-top systems) developed on top of the translating Ligurian Nappe (i.e. proto-Apenninic accretionary wedge).

This MTC has been subdivided into five sub-units, representing at least two distinct MTDs: the lower ones, of local significance, derived from the southern sectors, and the upper ones, of basin-wide extent, derived from the northern sectors. The largest MTD reaches an inferred volume of involved dry material of about 150 km$^3$. The vertical stacking of these sub-units and the progressively “shallow-water” character of the internal components seems to represent the episodic deposition of closely spaced events, originated through a retrogressive failure process involving progressively more proximal areas (i.e. form relatively more open-marine to coastal environments).

Careful observations carried on the internal elements of these units (i.e. matrix and blocks), which include both slump- and debris flow-like facies (i.e. blocky-flow deposits), allow the interpretation of such sedimentary bodies as generated by catastrophic processes. The influence exerted by structural confinement on the slide emplacement is recognizable mainly in term of forced slide direction, localized over-thickening, substrate coupling (i.e. bed erosion in a sedimentological sense) and margin-induced strain partitioning. In particular, this study highlights the likely occurrence of a generalized lateral buckling (compression + transpression), almost perpendicular to the main sliding direction, and an overall unidirectional shearing in the longitudinal sense, giving important information on the slide kinematics.

This study also contributes to the understanding of the local intra-slope basin configuration, highlighting different depositional environments (in terms of facies associations and compositions) between the pre- and post-slide sedimentary successions, and the possible existence of an overall shallow level tectonism (gravity-related?) linked to a rearrangement of the regional tectonic framework (i.e. accretionary wedge frontal dynamics).
Down- and along-slope erosional and depositional processes on the NW Svalbard continental slope

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Swath-bathymetry and seismic data from the western Svalbard continental slope (between approx. 79°00'-79°45' N and 4°-9° E) reveal evidence of multiple mass movements, as well as the interaction of down- and along-slope sedimentary processes.

An ‘old’ slide scar in the northern parts of the study area is approx. 35 km long (in down-slope directions), at least 15 km wide and has a 30 to 60 m high headwall. It is located between about 1300 m and 3000 m water depth. The seafloor within this slide scar is irregular. However, some parts are smoothened by contouritic infill. The data indicate that slip planes were located at least at two levels, probably indicative of a multi-phase failure process.

A second, younger, slide scar is at least 35 km long, 6-8 km wide and located beyond 1400 m water depth. It merges with the older slide scar at a water depth of about 2700 m. The headwall is up to 30 m high and its morphology is relatively smooth. Also this slide scar is partly draped by contourites.

The youngest and southernmost feature related to down-slope erosion and sediment transport is the Kongsfjord Channel. Several channels/gullies start at the shelf break at approximately 250-300 m water depth and merge into the main channel at around 1400 m below sea level. The channel system can be traced over a distance of approximately 120 km, reaching maximum water depths of about 4000 m. The incision is maximum 400-500 m wide and 80 m deep. The data illustrate repeated interaction of the channel with contourite deposition. This includes relocation of the channel’s axis related to the northward migration of the contourites, as well as renewed incision of contourites by activity within the channel.
Drilling Quaternary submarine landslides on the Nankai accretionary wedge: Results from IODP Expedition 333

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We present results from Integrated Ocean Drilling (IODP) Expedition 333 on D/V Chikyu drilling and coring a Pleistocene-to-Holocene stratigraphic succession of a slope basin seaward of a margin-dominating out-of-sequence thrust (termed megasplay) in the Nankai accretionary wedge, offshore the Kii Peninsula, southwest Japan. The slope-basin represents the depocentre for downslope mass transport from various sources such as the hanging-wall block of the megasplay, anticline structures within the accretionary prism and the slope apron sedimentary cover. The stratigraphic succession is characterized by stacked mass-transport deposits (MTDs), including an exceptionally-large, up to 150 m thick MTD, the lateral extension of which is mapped in a 3D seismic reflection data set. Continuous coring over 315 meter at a location where the MTD bodies wedge-out and where basal erosion by mass-transport events is minimal, reveal a nearly complete stratigraphic succession recording more than 1 Million years of the submarine landslides history in this active tectonic setting.

We present D/V Chikyu shipboard results from IODP Site C0018, including litho- bio- magneto- and tephra-stratigraphy and physical property data. Six mass transport deposits of thickness ranging from 50 cm to 60 m at the drill site were identified from visual core description and X-ray CT-scans. The thick MTD lies at the base of the stack and coincides with a lithological transition between a sandy turbidite sequence below and ash bearing hemipelagites above. The thinnest MTD corresponds to a fluidized ash layer whereas the dominant lithology of the other MTDs is clay and ash bearing silty clay. The deformation style of these MTDs appeared heterogeneous, with intervals of chaotic or mixed sediments and intervals retaining coherent bedding. Shear zones and faults are often identified in the lower part of the MTDs and, in four occurrences the base of the MTD is defined by a shear zone within fine-grained sediments. However, a thick ash layer attributed to a cataclysmic eruption on Kyushu Island dated 1.05 Ma was found immediately below the thick MTD. Remarkably, no evidence for remobilization induced by fluidization was found in the underlying turbidite sequence. We hypothesize that the fluidization of ash layers during earthquakes is one mechanism by which exceptionally large submarine landslides could occur in subduction zones.
Large-Scale Submarine Mass-Masting offshore Uruguay

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New geophysical data acquired during cruise M78/3 with RV “Meteor” in 2009 reveal large-scale mass-wasting along the passive continental slope offshore Uruguay. The slope failure is hosted in contouritic deposits between 1800 and 3300 m water depth, affecting an area of at least 1200 km$^2$. Two escarpments up to 100 m high run along the slope. Echo-sounding data indicate that they are headwalls of individual failures with associated acoustically transparent sediment bodies. Sediment cores recovered from 3 transects across the failure complex confirm that the acoustic transparent units are debrites. Structure and geometry of the failure complex is indicative for a retrogressive submarine slide. Sedimentological evidence in accordance with hydro-acoustic data indicate that debrites deposited downslope of this failure complex are recent (Holocene) features on the slope. The morphology of the headwalls is underlain by a deeper reflector which we interpret as detachment. The detachment probably correlates with a regional BSR. Listric faults positioned upslope of the headwalls root into this detachment and are precursor of future failure at the location.
Slope failure and fluid flow in the northern margin of South China Sea

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The continental margin of the northern South China Sea and the area off SW Taiwan is considered as a potential area for gas-hydrate formation. The gas-hydrate signature is indicated by the abundant presence of BSR (Bottom-Simulating-Reflector). High methane concentration is also shown in the bottom water near the seafloor. We have conducted several geophysical surveys to understand the seafloor features associated with the gas hydrate. Pockmarks are found in several places and some are clearly related to gas seeping. Submarine landslides are found in several places and seem to be related to the occurrence of the pockmarks. By examining high-resolution subbottom profilers data, we can observe gas chimneys or gas seepage channels just beneath the sub-seafloor in the slope failure area. Structural faults could provide efficient conduits for fluid to migrate upward. We believe that the gas flow cause the instability of the continental slope and the slope failures. Because the gas seeps or chimneys are mostly found in the water depth less than 550 m, the gas(fluid) flow is inferred to be initiated from dissociation of gas-hydrate. The upward gas flow can even go into water column and create clear gas plume image in EK 500 data.
Assessing Arctic Submarine Slope Stability – Investigating the Glide Planes of the Hinlopen/Yermak Megaslide by Scientific Ocean Drilling

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The Arctic experiences the most drastic changes following global warming. Slope stability issues arise from the presence of large hydrate and permafrost provinces that are subject to future warming. Hence, understanding of the slope stability system (conditioning, triggering and consequences) within the slopes of the Arctic Ocean is a crucial condition for assessing the risks associated with submarine failures that will potentially be caused by rising temperatures.

The Hinlopen/Yermak Megaslide is the first and so far only large-scale slope failure of the Arctic Ocean proper. Its enormous headwalls document the translation of very thick sedimentary slabs reaching 1800 m. Yet, we lack understanding of the processes that allowed the development of glide planes at such deep levels inside the slope. Therefore, we propose to recover glide plane material through scientific ocean drilling and investigate its nature by state-of-the-art techniques. Further, we propose to monitor ongoing changes in the slope through in-hole observatories.
Debris Flow and Turbidity Current Interactions in a Large Submarine Axial Channel Belt, Upper Austrian Molasse Basin

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Deposits of subaqueous debris flows can build up substantial topography on the seafloor and the resulting seafloor morphology controls the pathway of turbidity currents. The detailed interaction of submarine debris flows and turbidity currents is still poorly understood. To investigate the interplay between these two end members of sediment gravity flows, the distribution of their deposits needs to be documented. Map views of seafloor morphology are available for parts of the modern seafloor and in high-resolution seismic-reflection data. However, these data sets usually lack lithologic information. In contrast, outcrops provide cross-sectional and lateral stratigraphic details of deep-water strata with superb lithologic control but provide little information on seafloor morphology. Here, we present a methodology that leverages fundamental lithologic information from sediment core and well logs with a novel calibration between core, well logs, and seismic attributes. Using this calibration, we created 3D lithofacies proportion volumes. These volumes enable the interpretation of the 3D distribution of the important lithofacies and thus the investigation of seafloor morphology produced by mass transport events and its impact on succeeding turbidite deposition.

The study area is located around the Puchkirchen sandstone, a depleted gas field in the Upper Austrian Molasse Basin. Sedimentation in the Molasse Basin during the late Oligocene to early Miocene was dominated by a large deep-marine axial channel belt, 3-5 km wide and over 100 km long, that served as a conduit for debris flows and turbidity currents. The data set includes a 3D seismic reflectivity volume, a pre-stack seismic inversion of this volume resulting in P-impedance, S-impedance and density volumes, and 40 wells with the basic suite of wireline log measurements, of which 13 are cored.

Core analysis reveals that the Puchkirchen sandstone consists of massive sandstone beds deposited directly from suspension through the collapse of high-density turbidity currents. The Puchkirchen sandstone is underlain by and laterally equivalent to thick debris flow deposits. Lithofacies proportion maps show that debris flows deposited a relatively regular distribution pattern of levees and lobes. When subsequent high-density turbidity currents encountered this mounded debris flow topography, they slowed and deposited a portion of their sandy high-density loads just upstream of the morphologic high. Understanding the depositional patterns of debris flows is key to understanding and predicting the location and character of associated sandstone accumulations. This detailed model of the filling style and the resulting stratigraphic architecture of a debris flow dominated deep-marine depositional system can be used as an analogue for similar modern and ancient systems.
Age constraints and sediment properties of Ana Slide (Balearic Sea, Western Mediterranean) and implications on age dating of submarine landslides

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The Eastern Ibiza Channel (Western Mediterranean) is an area of widespread seafloor instability as highlighted by recent multibeam and geophysical surveys. Ana Slide is the submarine landslide with the clearest morphological expression over an area of about 6 km², showing the headwall in 635 m water depth and the toe of the deposit in 790 m, with an average bathymetric slope of 1.6°. Seafloor morphology and direct observations of sediment cores support the interpretation of Ana Slide as resulting from limited displacement mass wasting: the upper part of the landslide deposit shows an intact stratigraphy and/or the presence of sediment blocks with intact stratigraphy. Recent results in geotechnics based on additional sediment cores and CPTU data allowed to identify a remoulded unit (landslide deposit) buried under about 2.5 m of undisturbed sediment, and to propose, based on numerical modeling, that the triggering mechanism could be linked to sediment strength degradation due to the presence of shallow gas. We propose here a re-evaluation of the available data from two campaigns to reconstruct the age of Ana Slide with AMS radiocarbon dating and planktonic foraminifer assemblages.

The evaluation of the age of the submarine landslide, also when the mass accumulation is evident in seafloor morphology, sediment cores and geotechnical tests, remains a delicate issue, because it requires to compare and summarize data of different types and to consider the extreme lateral and vertical variability of landslide deposits. Coupled sedimentological and micropaleontological evidences, supported by seismic reflection profiles, indicate that above the Ana Slide area there is a sediment drape of hemipelagic deposit at least 0.8 m thick and Holocene in age, based on AMS radiocarbon dates and faunal assemblages. This hemipelagic unit drapes also the landslide headwall and the surrounding seafloor unaffected by the landslide and it is correlatable by means of paleontological observations and magnetic susceptibility measurements. A sediment core reaching below the glide plain within the landslide headwall area sampled warm foraminifera fauna of MIS 5 that could be considered the lower boundary for the age of the landslide. Estimates of the age of landslide deposit and the underlying strata suggest that the mass wasting process did occur in the Late Pleistocene in times of MIS 2/3 or older. The largest uncertainty in age determination concerns the interpretation of the ‘post landslide’ unit, whose base could best approach the age of the sediment failure. This unit, interpreted from CPTU at 2.5 m, was correlated with regional oxygen isotopes curves thanks to measured XRF elemental profiles and suggests an age around 61.5 kyr BP. Alternatively, the undeformed section of the CPTU tests could include both a post landslide drape and a sedimentary unit carried for a limited distance during the failure without appreciable sediment deformation which would be thus older than the age of the landslide event.

An acoustically transparent body buried below Ana Slide demonstrates that recurrent mass wasting occurred in the area during the Pleistocene. Beside fluid expulsion supported by the presence of numerous pockmarks, sea level fluctuations and variations in sediment supply during the Middle and Late Pleistocene could have played an important role as predisposing factors for mass wasting in the Ibiza Channel. The case of Ana Slide represents an excellent example of how subtle can be the attribution of an accurate age to a sediment failure event, and suggests to proceed by multiple hypotheses supported by integrated datasets.
Modelling Submarine Turbidity Currents

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The collapse of continental shelves leads to the spreading of sediment across the deep ocean through particle laden flows known as turbidity currents. Turbidity currents are driven by gravitational forces associated with a density difference caused by the presence of suspended particles. This generates a flow which transports the suspended particles, but which progressively slows as they sediment to the underlying boundary. The surrounding fluid is also entrained into the current, further decelerating the flow by reducing the density difference between the current and the ambient fluid. The deposits from turbidity currents, known as turbidites, are of key importance to understanding sedimentary rock formations and present new opportunities for hydrocarbon reservoirs. Numerical modelling of the deposits from turbidity currents presents an opportunity for comparison with field data from turbidites, allowing the structure and size of the event that formed the deposit to be determined.

The distance travelled by a turbidity current over the ocean floor is much larger than the height of the flow and thus to model the motion we adopt a shallow layer model in which vertical accelerations are neglected. The model we employ is a three equation system that expresses the conservation of fluid and particulate and formulates a balance of momentum for a current flowing down an incline. Importantly we include the effects of surrounding fluid being engulfed into the flow in our expression for conservation of fluid through the entrainment law of Parker (1987). For sufficiently dilute flows a settling law is employed in which the settling velocity is determined through the balance of gravitational and drag forces on a single particle in the suspension. However for suspensions with higher particulate concentrations the settling velocity of a single particle will be reduced by the effect of an increased viscosity due to the presence of nearby particles and by the motion of interstitial fluid opposing the gravitational settling of the particle due to the motion of surrounding particles. Hence we employ a ‘hindered settling’ law for the rate at which particles sediment out of the current.

Through steady, time independent solutions to the governing equations we find that varying the initial conditions leads to two distinct regimes with two different shapes of deposit. Employing a hindered settling law we find that the steady solutions lead to deposits with interior maxima. Time dependent solutions are constructed using numerical means and they reveal the dynamical controls upon these flows.
The Submarine Hazards Off Southwestern Taiwan: from 2006 Pingtung Earthquake to 2009 Morakot Typhoon

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In the past several years, many international research teams pay close attention to the submarine hazards off southwestern Taiwan. The large earthquakes and stormy weathers, including Pingtung Earthquake (December 26th, 2006), Morakot Typhoon (August 7th-9th, 2009) and Jiashian Earthquake (March 4th, 2010), induced a series of submarine landslides and turbidity currents in this area and triggered over 30 submarine cables broke during or after the natural disasters invaded period.

The southwestern Taiwan offshore is mainly composed of a narrow Gaoping Shelf, broad Gaoping slope and connected to the northern South China Sea abyssal plain. Two major submarine canyons, the Gaoping Submarine Canyon (GPSC), and the Fangliao Submarine Canyon (FLSC), develop on the shelf and slope and influx into the northern termination of the Manila Trench. Owing to the GPSC directly connected to the Gaoping River and received large input of sediments from the river, traditionally was deemed as the major transport path for the sediments in southern Taiwan. Furthermore, the submarine cables broke after the Pingtung Earthquake and Morakot Typhoon were also following the major route of GPSC from the middle reach segment to the Gaoping deep-sea Fan and northern Manila Trench. All the evidences seem perfectly point out the GPSC should pay an important role on the forming and transportation of the turbidity currents or debris flows of submarine landslides which triggered the submarine cables break events in the study area.

The detailed offshore investigation was initiated after the Pingtung Earthquake. Integrated all the new evidences from core analysis results with geophysical explorations, the geological setting play an important role on producing the submarine landslides, slumping or debris flows. For the flooding event like Morakot Typhoon, besides the turbidity currents or hyperpycnal flows plunging from the river system may trigger the submarine cable break events, the instability of the seafloor which may caused by the faulting or liquefaction also can be an important element for the forming of submarine hazards. In this study, the submarine cable break events off the southwestern Taiwan can be divided into two types. One is located in the upper reach or the upper-middle reach of the GPSC which may relate to the seismic or flood events induced canyon wall failures or turbidity (hyperpycnal) currents from river. Another type of the cable failure events is located at the deep sea off southwestern Taiwan. The Gaoping Shelf and Slope which near the FLSC is the potential area where may triggered the submarine landslides and debris flows.
Unidirectional-migrating Slope Channel Systems in the Baiyun Depression, Pearl River Mouth Basin: morphology, architecture, and depositional processes

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A series of unidirectional-migrating slope channel systems are discovered in the Baiyun Depression, Pearl River Mouth Basin, northern South China Sea. The purpose of the paper is to document their morphology, internal architecture, and evolution using integrated 2D/3D seismic, well log, core, and biostratigraphy data and 3D visualization techniques.

Morphologically, each of the systems can be subdivided into a narrow “V”-shaped up dip segment, a broad “U”-shaped middle segment, and a down dip segment with low erosional relief. East flanks of the channels and channel complex sets within different channel systems are overall steeper than the west flanks.

An integrated seismic facies and well data analysis shows that: 1) internally, each of the channel systems consist of channel complex sets, which in turn are composed of stacked and nested channel complexes and channels; 2) vertically within each of the channel complex sets, sandy thalweg and channel fills in the lower part grades upward into debris flow/slump deposits, and finally into shale drapes in the upper part.

Depositional processes within the channel systems are controlled by a series of interacting factors, including seafloor morphology, relative sea-level change, sediment supply, and gravity flow and tidal bottom currents. During relative sea-level fall and lowstand, the paleoshoreline progrades to the shelf edge and quick sediment loading triggers significant sliding and sediment failure in the upper slope. When moving down slope, these lead to the development of large erosion scours, within which channel complex sets are developed. Meanwhile sandy sediments shed from the paleo Pearl River and its shelf edge deltas are delivered into and deposited within the complex sets. During relative sea-level rise, the paleoshoreline shifts landward and sandy sediment supply is largely shut down and debris flows and slumps are more common due to increased channel wall instability. The channel complex sets are eventually abandoned and draped with widespread shales. These processes are repeated during the ensuing relative sea-level cycles, resulting in vertically stacked and nested channel complex sets within each of the slope channel systems.
Sliding-surface-liquefaction of sand-dry ice mixture and long runout submarine landslides

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There are a lot of historical witnesses records about large-scale burning of flammable gas possibly ejected dissolved methane hydrates (MH) from sea floor. Since the vast distributions of the BSR in the continental margins, a lot of papers have been published which pointed out the possibilities of that gasification of those hydrates could have triggered gigantic submarine landslides. Recent triaxial compression tests on artificially prepared sand-MH-mixture samples revealed that they have slightly higher strength than the ones of only sands and MH’s endothermal characteristics may resist against accelerating shear and large-displacement landslides as well. While, the stress-controlled undrained ring shear apparatuses have been developed at Disaster Prevention Research Institute, Kyoto University to reproduce subaerial landslides induced by earthquakes and rainfalls. Using this apparatuses, Sassa and Fukuoka found localized liquefaction phenomenon along the deep saturated potential sliding surface due to excess pore pressure generation during the grain crushing induced bulk volume change. This phenomenon was named as “sliding surface liquefaction.” Similar sudden large pore pressure generation was observed in pore pressure control test simulating rain-induced landslides. In this paper, authors examined the shear behavior of the dry sand-dry ice mixture under constant normal stress and shear speed control tests using the latest ring shear apparatus. Sample was mixture of silica sands and dry-ice pellets (frozen carbon-dioxide). Those mixtures are often used for studying the mechanism of the methane hydrates in laboratories because no explosion protection facility is required. Applied total normal stress was 200 kPa and initial effective normal stress was maintained at about 70 kPa by slightly opening the drainage valve to vent CO2 gas. When the sample was sheared at 30 cm/s, the stress path reached failure line of friction angle of about 37 degrees immediately. However, excess pore air pressure increased soon after and the stress path moved toward the origin along the failure line. This means rapid shearing generates frictional heat and it accelerates the gasification of dry ice quickly. The obtained shear speed – excess-pore-pressure ratio relationship clearly shows speed dependency. When the speed is high, excess pore pressure ratio is high, which can contribute to high mobility of the landslide mass. Crushing of pellets may contribute to increase the total surface area of dry ice and to acceleration of gasification. Authors conducted high-velocity friction experiment of clayey silts samples from the core of the Integrated Ocean Drilling Program (IODP) Expedition 316 Sites C0006 obtained by the drilling vessel "CHIKYU". It showed certain rate velocity strengthening and weakening, however, the content was much smaller than that observed in this test series. This sliding-surface-liquefaction in the sand - dry ice mixture supports the possibility of similar accelerating displacement in the sand-MH mixture or boundaries between MH and sand layer induced by certain strong ground motion under sea floor. To simulate the earthquake-induced submarine landslides due to gasification of MH, authors applied the Kobe-quake wave form to the sample. The sliding surface liquefaction appeared when the initial stress condition is close to the failure line. Because MH has similar expansive gasification characteristics, MH still has high possibility to cause gigantic submarine landslides under certain strong earthquake condition.
Submarine slope stability at the Nankai Trough – dynamic triaxial testing of water-saturated sediment samples

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Submarine mass-movement phenomena are common along the tectonically and seismically active Nankai Trough accretionary prism. Earthquakes as well as other natural dynamic loading mechanisms pose time variant stresses on soils. Most soils show a different response to periodic loading than to static loading – making dynamic loading experiments and the study of the response of continental margins to time variant stresses a fundamental component in offshore natural hazard and risk assessment. Here we present results from dynamic triaxial shearing experiments using the new Marum Dynamic Triaxial Testing Device (DTTD). The experimental strategy is two-fold: (1) End-member tests on different artificial clay-to-quartz ratios were carried out to study the general behavior of different material to dynamic loading. The cohesive end member consists of natural clay (<2 µm) containing mainly montmorillonite and illite, while the granular end member is composed of an industrially produced quartz powder (<300 µm). Aliquots of each sample were tested under dynamic as well as static conditions. (2) Seven whole round samples from NanTroSEIZE sites C0004C, C0008A and C0008C (IODP Expedition 316) were exposed to dynamic loading in order to study the sediment’s strength to resist failure under dynamic loading. The generic end-member tests show typical failure behavior such as liquefaction for granular material as well as cyclic creep for cohesive material. Initial results indicate that under unimodal dynamic loading of the samples, granular end members fail at similar cyclic stress ratios as clayey, intrinsically weak end members. However, if we allow drainage of excess pore pressure between different dynamic loading steps, granular end members show significantly higher shear resistances than cohesive end members. To evaluate the failure potential of the in-situ samples from the Nankai Trough accretionary prism, the standard safety factor method is used. By means of geotechnical investigations on artificial sediments and natural samples from the Nankai Trough, we study the physical and geotechnical properties of sediments to infer failure processes. This study is motivated by the direct social relevance of understanding an earthquake’s potential to trigger submarine landslides that have had, and will have, great impact on nearby densely populated coastal areas.

Key words Nankai Trough • Dynamic and cyclic loading • liquefaction • creep in clays • submarine slope stability
Thin-skinned and giant submarine landslides on the southern Storfjorden Trough Mouth Fan (western Barents Sea)

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Several submarine landslides were identified on the Storfjorden Trough Mouth Fan (TMF) southwest of Svalbard archipelago during two recent research cruises carried out within the International Polar Year (IPY). The Spanish SVAIS and the Italian EGLACOM cruises, respectively in the summer of 2007 and of 2008, both contributed to IPY Activity 367 NICE-STREAMS (Neogene ice streams and sedimentary processes on high-latitude continental margins) aimed at understanding erosion and depositional systems associated with ice streams.

Thin-skinned, shallow (relatively recent) landslides, visible on both swath bathymetry data and on sub-bottom and multichannel seismic reflection profiles, are made up by elongated, more or less sharp-edged, depressions developed downslope of the head scars, which lie on the upper-middle continental slope. Giant paleo-landslides, detected only on multichannel seismic reflection profiles, are characterized by thick (up to over 200 ms thick) chaotic deposits on the lower part of the continental slope.

Both modern and paleo landslides are mainly found in the southern part of the Storfjorden TMF, towards the northern border of the Kveithola TMF. This area is characterized by the presence of the large INBIS deep-sea channel system. Channels are very rare along the Svalbard-Norwegian margin and limited to just two areas (INBIS and Lofoten Basin channels) within over 2,000 km of the margin’s length. In addition this area is located at the boundary between two adjacent paleo-ice-streams (Storfjorden and Kveithola). The coincident presence of landslides, channels and ice-stream boundary suggests to us a common controlling factor, which may be associated to the abundance of basal meltwater beneath the ice-sheet. This is also a known key factor that controls ice-streams flowing velocity and for the inception of mass-movements and/or genesis of landslides.
Small-scale mass wasting on the continental slope offshore Lofoten, northern Norway

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Swath bathymetry and side-scan sonar data, co-registered with high-resolution seismic records, from the continental slope off the Lofoten Islands, northern Norway, reveal evidence of repetitive small-scale mass wasting in water depths between 500 and 2500 m.

Based on a morphological analysis of the sediment evacuation area, various styles of failure have been identified: i) the first type forms an up to 4.7 km wide and 100 m deep slide scar, with relatively steep headwalls and sidewalls (up to 32 degrees). Run out distance is long and extends beyond the western limit of the surveyed area. This morphology is similar to other large slide scars along the Norwegian-Barents-Svalbard margin. ii) Stair-case pattern of secondary escarpments form a second type of morphology. These are found over a distance of up to 10 km from the headwall. Head scarps and secondary scarps have a height of up to 30 and 50 m, respectively, and are most likely indicative of a retrogressive landslide development. iii) A third type of mass movement processes is more subtle, as it is only identified from the side-scan sonar data, but cannot be discerned from the swath bathymetry data. This type is characterized by an along-slope fabric of smaller escarpments, delineating 10 – 15 m thick failing sediment blocks or slabs with variable dimensions. These zones with sediment slabs can be up to several hundreds of meters wide and are sharply delineated by shear margins or escarpments. There is evidence of different stages of development of the sediment slabs.

For all the instabilities identified, the basal zone of deformation runs parallel to the undisturbed sea floor nearby. This indicates the presence of a slip plane or “weak layer” which may have been the depth where the initial deformation and flow of sediments took place. In our study area, these “weak layers” occur at varying stratigraphic depths, the shallowest (type iii), only a few meters beneath the sea floor, the deepest (type i) approximately 100 m beneath the sea floor.

It is inferred that these different types of mass wasting originated from asynchronous slide events because of differences in the amount of draped/infilled sediments.