EUG XI

Symposium RCM4

Continental Slope Stability (COSTA) of Ocean Margins - Achievements and Challenges

Convenors

Juergen Mienert
Jacques Locat
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Sunday PO Session

RCM4 : SUpo01 : PO
Sediment and Rheological Character of Submarine Slides, Bear Island Fan

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Alternating mudflow and hemipelagic deposits form the structure of Bear Island submarine fan located along the Norwegian-Barents Sea continental margin. The two deposits are readily discernible in histograms depicting measurements of physical and acoustical properties. Prominent modes at 1490 m/sec and 1543 m/sec, for example, identify the silty-clay hemipelagics and sand-silt-clay mudflows, respectively. Physical properties measurements are, in general, remarkably uniform for the mudflows and variable for the hemipelagics. Low yield stresses (0.5 Pa to 3.5 Pa) indicate that the mudflows were emplaced as relatively low-density slurries. The low plasticity of the mudflows compares well with fine-grained glacial material, indicating a glacigenic origin. We suggest that during during mid/late Weichselian maximum ice advances, rapid sedimentation occurred in the proglacial environment along the shelf edge resulting in unstable, low yield-strength deposits. Low Bingham yield stresses (less than 12 Pa) indicate that the flow behavior cannot be described by a Bingham flow model.

RCM4 : SUpo02 : PO
Seafloor Classification of the Storegga Slide, Norwegian Sea, using Video and Photographs Acquired on US Navy Submarine NR-1

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The US Navy nuclear research/recovery submarine NR-1 was utilized to investigate the shelf break, headwall, and upper debris flow fields (to a depth of 850 meters) of the Storegga Slide deposit in the Norwegian Sea. The Storegga Slide is believed to have occurred approximately 8500 years ago in a series of three slides, and is by far the largest slide in the Norwegian Sea and one of the largest in the world ocean. Over 5,580 km^3 of sediment was displaced, some up to 800 kilometers from the known headwall. The objective of this investigation is to (1) characterize and map the seafloor morphology and sediment types on and adjacent to the headwall region, and (2) determine if the region is experiencing ongoing slope failure. NR-1 is a unique platform for seafloor investigations, for it permits the coupling of a wide variety of geophysical and environmental measurements as well as direct visual observation. We will present data from the interpretation of over 300 hours of videotape, 800 still camera frames, and 250 video-frame captures. Interpretation of the aforementioned data was complemented by the integration of 150 kHz sidescan sonograms, obstacle-avoidance sonar data, bathymetry and direct observations. The upper Storegga slide seafloor is very hummocky with relief on the order of 20-100 meters. Cobble-strewn slopes indicate post-slide current scour of finer materials. Between the steep-sided blocky regions are smooth, featureless sediment ponds that are on the order of a few meters thick and probably include material scoured from adjacent hummocks. Recent instability (post 8,500 years ago) of the headwall region is indicated by an escarpment devoid of sessile biota (such as sponges) on cobbles and a lack of fine-grained sediment. Conversely, a few regions which have not experienced recent activity were investigated and are characterized by deep-water, cold coral (Lophelia) reefs. We conclude that the coarse material was first brought to the shelf edge from Scandinavia by Pleistocene ice-sheet advances and subsequently redistributed by the Storegga slide, and finally exposed by the strong Norwegian-Atlantic Current during the Holocene.

RCM4 : SUpo03 : PO
US Navy Submarine NR-1 Dives in the Upper Storegga Slide Area, Norwegian Margin

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In 1999, the US Navy nuclear research submarine NR-1 dived along the Storegga slide area, Norwegian margin, one of the world's largest known submarine slides. The purpose was to characterize/map the slide headwall morphologies, and to examine crack and pockmark areas along the northern extension of headwall escarpment. The dive depth ranged from 200 m to 870 m, keeping the vehicle altitude 2 m to 50 m above bottom. The vehicle speed was less than 4 knots, with an average speed of about 1.5 knot throughout the 14-day long cruise. Collected data include total 590 km of NR-1 track with 25 kHz echo sounder, 290 km^2 side scan (150 kHz) at 10-50 m above bottom, 165 km of visual observation (2 - 10 m above bottom), 800 still camera frames, 300 hours video, 250 video frame captures, positional and environmental data (currents, CTD), and forward-looking obstacle-avoidance sonar image data.

Preliminary discoveries are (1) side scan imaging of deep/cold water coral reefs; (2) 'streaked' side scan images along the shelf edge, indicating sediment waves/channels; (3) bacteria mats and gas venting in the pockmark area north of Storegga; (4) no evidence for gas venting found in Storegga slide scar; (5) steep hills/ridges/escarpments, cobble-strewn sediment with interspersed soft sediment ponds in the upper slide scar; (6) local fresh-looking gravel/cobble exposures which suggest recent local sliding and very strong bottom-current winnowing at base of headwall escarpment; (7) numerous 10-60 cm long pelagic fish, mainly cod, along base of headwall escarpment.

RCM4 : SUpo04 : PO
3D Seismic Data Indicate Long-Term Instability Offshore Norway

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3D seismic data from the Storegga headwall area, offshore Norway indicate long-term instability, which is predating the known stages of this prominent slide event. 3D examples on geometry, morphology and development of continental slope failure will be presented. The sedimentary strata affected by slope failures have a thickness of approximately 800 m. 3D mapping and visualization of slope failures give insights in the internal structure of sediment instabilities, failure dynamics and resulting deposits. Our results show a high variability of external geometry and internal structure of slides and debris flows, their slip planes and run-out distances. There is an interrelation and a coupling of slope failures, which seems to trigger or activate further sliding. Other possible triggering and activation mechanisms comprise the occurrence of gas and possibly gas hydrates as well as earthquakes.

RCM4 : SUpo05 : PO
Giant Erosional Scours in Deep-Water Channel-Lobe Transition Zones

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Giant erosional scours formed by turbidity currents are a common feature of the channel-termination zone (CTZ), and are found in turbidite systems swept by large-scale, sand-rich flows with a high mud content. Scours are located immediately downslope of canyon/channel mouths, and are often associated with a break-in-slope. They occur in a variety of forms, from individual spoon-shaped scours, to large, irregular erosional scarps. Individual scours are 2-60 m deep, 50-2000 m wide, and 350-2000 m long. Smaller scours are probably widespread but are beyond the resolution of most seafloor imaging tools. In plan view scours are elongated parallel to flow direction, and become wider and shallower downcurrent. In profile, they are asymmetrical, with a steeper, higher upcurrent face. Large erosional scarps, up to 9 km wide and 6 km long, are formed of amalgamated individual scours and indicate more widespread seafloor erosion. The location, distribution and dimensions of erosional scours within the CTZ is controlled by turbidity current volume and composition, canyon/channel gradient, and the break-of-slope angle. Understanding these controls will help us to predict the occurrence of erosional scour zones, and reduce the potential hazard to deep-water exploration.

RCM4 : SUpo06 : PO
Transport Dynamics and Sediment Dispersal in the BIG-95 Debris Flow from Backscatter Imagery, Ebro Continental Margin, NW Mediterranean Sea

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In 1995, a 2,000 km^2, 26 km^3 recent debris flow, named BIG'95, was discovered in the Ebro slope and base-of-slope at depths ranging from 600 to 2000 m, by means of swath bathymetry and topographic parametric source (TOPAS) profiling (Canals et al., 2000; Lastras et al., 2000). Swath bathymetry data showed an area of uneven topography in the Ebro slope with several main and secondary scars identified between 600 and 1200 m deep. TOPAS records showed a large sediment body with transparent seismic facies covering the entire sea-floor, thus indicating the event's youth.

Backscatter data from the BIG'95 debris flow area have been processed using first-line software. The images obtained provide significant information on the dynamics of the debris flow and sediment dispersal paths. The debris flow area consists of a pattern of low-backscatter patches, representing large blocks of sediment which moved down-slope without loosing their internal coherence, separated by topographically-depressed lineations of high backscatter representative of coarse sediment pathways that buried at their terminus the uppermost course of the Valencia Channel. The large sediment blocks appear only between 1200 and 1550 m water deep, while coarse sediment paths are present all along the debris flow.

These features, together with the presence of multiple secondary scars, show up the complexity of the BIG'95 mass movement. The most probable sequence of events was (1) a major general destabilisation of the area, due to a variety of factors, led to the formation of the main scar at the base-of-slope (1000-1200 m) from which the large blocks of fine material were detached and moved down-slope without loosing their internal coherence; and (2) the formation of the main scar induced the destabilisation of the shallower slope areas and thus to the formation of multiple secondary scars, where coarser material began to flow down-slope following the depressed areas between the large blocks till reaching the Valencia Channel.

Seven piston cores up to 8.6 m long provide the groundtruth for the backscatter results. The BIG'95 layer, which is overlain only by a thin (up to 20 cm) hemipelagic drape, is mostly made of fine material contorted beds and clay chunks where backscatter is low, and unsorted chaotic sands along the elongated, high-backscatter pathways.

Canals M, Casamor JL, Urgeles R, Lastras G, Calafat AM, De Batist M, Masson DG, Berne S, Alonso B & Hughes Clarke JE, *GCSSEPM Foundation, 20th Annual Research Conference, Houston, Texas*, (2000).
Lastras G, Canals M & Urgeles R, *Geology and Petroleum Geology of Mediterranean Basins Conference, October 2000, Malta*, (2000).

RCM4 : SUpo07 : PO
Slope Failures on the Flanks of the Western Canary Islands

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Landslides are a key process in the evolution of the Canary Islands. The evidence includes landslide scars on the island flanks, debris deposits on submarine island slopes, and volcaniclastic turbidites in adjacent ocean basins. At least 14 large landslides are recognised on the younger and more volcanically active islands, El Hierro, La Palma and Tenerife. Most have occurred in the last 1 Ma, with the youngest as recent as 15Ka. Older landslides undoubtedly occurred, but are difficult to identify because they are buried beneath younger volcanic rocks and sediments. Canary Island landslides can be categorised as debris avalanches, slumps or debris flows. Debris avalanches, the commonest type of landslide identified, are catastrophic failures which affect only the superficial part of the volcanic sequence, up to a thickness of 1 to 2 km. Slumps are slow moving, deep-rooted landslides which may affect the entire thickness of the volcanic edifice. Debris flows affect only the sedimentary cover of the island flanks.

Individual debris avalanches range from 50-500 cubic km in volume, can cover several thousand cubic km of seafloor, and have runout distances up to 130 km. The morphological characteristics of debris avalanches include a narrow headwall and chute above 3 km waterdepth on the island flanks, broadening into a depositional lobe below 3 km. Avalanche deposits have a typically blocky morphology, with individual blocks up a kilometre or more in diameter. Considerable variation exists between the various avalanche deposits; e.g. the El Golfo debris avalanche on El Hierro has few large blocks scattered across the avalanche surface, while Icod on the north flank of Tenerife has much more numerous but smaller blocks over most of its surface, with a few large blocks confined to its margins. Icod also exhibits flow structures (longitundinal shears and pressure ridges) which are absent in El Golfo. The main control on block structure and distribution is the nature of the landslide material, particularly the greater proportion of fine grained pyroclastic material in the Icod landslide.

Landslide locations appear to be primarily controlled by the locations of volcanic rift zones on the islands, with landslides propagating perpendicular to rift orientation. The uneven distribution of landslides on some islands seems to indicate that unstable flanks are a 'weakness' which can be carried forward during island development. This may occur because certain island flanks are steeper, extend to greater water depths or are less buttressed by surrounding topography, and because post-landslide volcanic production may occur preferentially in the landslide scar, thus focussing subsequent landslide potential in this area. Although triggering factors are poorly understood, they may include dyke intrusion, pore pressure changes related to intrusion, seismicity or sealevel/climate changes.

RCM4 : SUpo08 : PO
Slope Failure Caused by Seamount Subduction on the Continental Margin of Costa Rica – Evidence from High-Resolution Sidescan Sonar Data

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At the Pacific margin of Costa Rica, the Cocos Plate is being subducted beneath the Caribbean Plate at about 9 cm y^{-1}. Seamounts subducted with the Cocos Plate are associated with widespread slope failure on the Costa Rica slope. Newly acquired TOBI sidescan sonar data show, in detail, the geological processes involved in creating these failures. Immediately ahead of the subducting seamount, compression and uplift results in intense faulting and fracturing of the overriding plate. The area affected by this deformation is relatively broad, up to twice the width of the seamount. Subsequently, as the seamount passes beneath the fractured area, slope failures occur above the steep trailing edge of the seamount, as the buttressing effect of the seamount is lost. In most cases failures are restricted to the immediate area of the seamount's trailing edge, resulting in long narrow 'scars' similar in width to the seamount. Failure scars can be traced up to 60 km landward of the trench. Debris from failures infills the adjacent trench in the early stages of seamount subduction, but is largely trapped within the scars as seamount subduction proceeds, and the resulting scar migrates upslope.

RCM4 : SUpo09 : PO
The COSTA Submarine Landslide Database

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The development of a submarine landslide database is one of the key issues of the Pan-European Continental Slope Stability Project (COSTA). It contains data from continental slopes in the North Atlantic as well as the Western Mediterranean Sea provided from project partners in France, Italy, Norway, Spain and the United Kingdom.

The database provides an overview of slope failures in the glacial-dominated regions in Northern Europe and the mostly river-dominated environments in the Mediterranean area. We compare parameters of the individual slides e.g. landslide origin and termination in relation to water depth and look for correlation of parameters or clusters of parameters related to the failure. It also incorporates parameters such as run-out distance, size, volume, slope angle and setting. The database also allows comparisons between different types of slides, their behaviour (disintegrative or non-disintegrative), frequency and possible causes or triggers that initiated them (e.g. seismic activity, high sedimentation rates etc.)

In addition to published and unpublished data used the web-based data collation will also include geotechnical information from areas of and around the slope failures.

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RCM4 : SUpo10 : PO
The Geotechnical Characterisation of Mass Movements as a Component of Submarine Landslides Risk Assessment: An Application to the New Jersey Margin

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As a contribution to the study of mass movements, Leroueil et al. (1996) proposed the geotechnical characterisation of slope movements as a framework enabling a rational analysis of landslides. It takes into account the following elements: (1) the material, (2) the slope movement, and (3) movement stage. With these elements, the slope movements are further analysed at various stages: (1) the pre-failure stage (i.e. when the sediment or rock is essentially in a state of equilibrium), (2) the failure stage, (3) the post-failure stage (describing the behaviour of the sliding mass until it essentially stops) and (4) re-activation. For each stage, we consider the following aspects: controlling laws and parameters, predisposition factors, triggering and aggravating factors, revealing factors and consequences. This approach can in fact be extended to the analysis of mass movements in general. An interesting aspect about this approach is that in can be incorporated into mass movement risk assessment in an area which has little indications of failures. We applied this framework to the case of the New Jersey Margin, near the Hudson Apron, where a particular slide area is under investigation (Desgagnés et al. 2000). Here, sediments (Wisconsinian in age) are involved in the shallow (50 m or so) mass movements. They are composed of silty clays which are mostly normally consolidated. For the pre-failure stage we considered that the revealing factors are the pre-existing slide of the area or signature of debris flow or turbidite deposits. Other revealing factors of potential instability could be the presence of pop marks (indication of potentially high pore pressure), or fissures near the slope. At the failure stage, it appears that failures were taking place in condition permitting debris flow generation, which is indicative that the failure took place quite rapidly so that undrained conditions can be postulated. Because of the nature of the sediments, we can consider that a Mohr-Coulomb failure criteria would be appropriate. The triggering factors can be associated to: gas hydrates, which are known to exist here, seepage force due to a regional groundwater flow, or a high sedimentation rate (as revealed by the presence of clinoforms). The post-failure stage is characterised by the development of debris flows and the assumed operating law would be that of a viscous mixture which could be well described by a bi-linear rheological model (Locat 1997). The consequences of these events would be significant if oil platform, communication cables or coastal structures were located along the path of the flow. Depending on the initial volume involved and its initial velocity, tsunamis could also be generated.

Desgagnés P, Locat J, Lee HJ, Leroueil S, Alexander C, Mountain G, & Pratson L, *Geotechnical properties of a mass flow deposit on the Hudson Apron, off New Jersey, U. S. A, Proc. 53rd Canadian Geotechnical Conf. Montreal*, **1**, 137-144, (2000).
Leroueil S, Locat J, Vaunat J, Picarelli L, Lee H & Faure R, *Geotechnical characterisation of slope movements,Proc. 7th Int. Symp. on Landslides, Trondheim, Norway*, **1**, 53-74, (1996).
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Locat J & Lee HJ, *Submarine landslides: advances and challenges. Keynote Lecture, 8th International Symposium on Landslides, Cardiff, U. K., submitted to the Canadian Geotechnical Journal*, (2000).

Monday PM Session

RCM4 : MOpm21 : F3
Landslide-Generated Tsunamis on the Pacific Coast of North America- Observation and Modeling

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The Pacific coasts of Alaska and British Columbia are characterized by a high risk of catastrophic tsunamis caused by underwater and subaerial landslides both on the continental margin and in coastal waters. Several such landslide-generated tsunamis have been documented. Some are clearly related to seismic events in southeast Alaska and near the Queen Charlotte Islands of British Columbia where local failures in fjords and coastal embayments have given rise to large tsunamis. Other failures have no relationship to seismic events but have created extremely damaging waves. For example, near Kitimat, British Columbia in 1975, a slope failure (debris flow) along the steep fjord resulted in an 8-m high wave. Similarly, in 1994, a catastrophic failure (primarily flow slide) took place in Skagway Harbor, Alaska resulting in a 5-6 m tsunami. Both the Kitimat and Skagway failure/tsunami events took place during extreme low tide and both appear to have been related to construction activities which placed increased loads on the steep underwater slopes.

The three-dimensional numerical model of Jiang and LeBlond (1994) for a viscous landslide with full slide-wave interaction was modified and improved to simulate tsunami wave generation in natural basins with complex geometry and seafloor morphology. The model was verified against the Skagway failure/tsunami event for which there were eye-witness accounts and a tide gauge record. Subsequently, the model was used to assess tsunami risk from postulated failures in the Strait of Georgia, in Malaspina Strait and on the subaqueous Fraser River delta of British Columbia. Both block slides and viscous flows were modelled.

Future development of the model will focus on four aspects: (1) advanced formulation of the initial few seconds of failure and the coupling to the sea surface; (2) evolution of failures in time and space and their implication for the resultant wave regime; (3) consequences of combined subaerial and submarine failures for wave generation and propagation; and (4) tsunami inundation and run-up in complex coastal areas.

Jiang, L & LeBlond, P.H., *J. Phys. Oceanogr.*, **24**, 559-572, (1994).

RCM4 : MOpm22 : F3
Slope Instability of Continental Margins

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Submarine landslides occur on almost every continental margin. Individual giant slides involve up to 20000 km^3 of slope material and cover an area of up to 80000 km^3. Their wide-spread distribution and their large dimensions make them important features, particularly as many of them are located within hydrocarbon deep-water exploration areas. The factors that are controlling slope stability are still poorly understood in spite of significant research efforts, and there are only a few landslides for which the trigger is known with certainty. It appears that ground motion due to earthquakes, rapid sedimentation, and slope destabilization by gas hydrates are among the most important factors. The factors will be presented and discussed using 3-D seismic and 2-D seismic examples.

RCM4 : MOpm23 : F3
Passage of Debris Flows and Turbidity Currents through a Topographic Constriction: Seafloor Erosion and Deflection of Pathways

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Previous studies have shown that some of the largest and most efficient submarine debris flows are to be found on the NW African margin. This margin has complex topography and is subject to continuing volcanic activity which has produced the Saharan Seamounts and the Cape Verde, Canary and Madeira Islands. The Saharan Seamounts and Canary Islands form a ~1000 km long volcanic ridge on the margin which form an effective barrier to sediments passing down the continental slope. The region directly SW of El Hierro Island is critical as it contains the only gap in this volcanic ridge for sediments to flow through. Recently, we obtained the first deep-towed sonar images, showing sedimentary processes operating within this topographic 'gap' or 'constriction'. These images show evidence for the passage of the Saharan debris flow and highly erosive turbidity currents, including the largest comet marks reported from the deep ocean. The Saharan debris flow appears to have been deflected by a low (~20 m) topographic ridge, while turbidity currents predating the debris flow appears to have overtopped the ridge. We suggest that as turbidity currents passed into the topographic constriction they experienced flow acceleration and as a result, became highly erosive. West of 19* the Saharan debris flow has a basal volcaniclastic sheared layer, although the recent sonar data do not suggest this layer was mobilised directly SW of El Hierro. A seismic reflection profile obtained 70 km to the east, upslope of the topographic constriction indicates that up to 30 m of the seafloor sediments have been eroded by the Saharan debris flow to form a basal volcaniclastic layer.

RCM4 : MOpm24 : F3
Continental Margin Slope Failure Related to Shallow Overpressures, Gas and Gas Hydrates: Observations and Processes

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Slope failures can be grouped into those triggerred by external forcing versus those that are internally driven. In this presentation we will focus on internally driven slope failure related to overpressuring. Internally driven slope failures are characterized by a distinct mophology of a flat base and a steep, amphitheatre-shaped headscarp. If overpressures persist (if the failure doesn't drain all excess pressure), then subsequent failure may occur within the original feature, leading to headward migration and a linear canyon morphology. By understanding the processes that lead to slope failure, we can model the fate of future failures (debris flow runout, turbidity currents). Within the oil industry we have used this approach to determine the origin of slope failure, evaluate the risk of future failure and quantify the hazard posed to facilities by such failures.

In this presentation we will focus on overpressuring related to hydrocarbon migration, shallow gas, and gas hydrates. On hydrocarbon prone continental margins we document numerous examples of internally driven slope failure, and demonstrate the link between hydrocarbon generation, gas migration, gas hydrate formation, and slope failure. At all of these locations seep-related phenomena have been documented, including water-column gas plumes, enhanced biological activity and/or the occurrence of precipitates such as gas hydrate nodules/pellets and carbonate crusts/nodules. We present a 'hydrologic model' of pressure transmittal from depth to the near-surface via conduits such as mud volcanoes or subsurface gas plumes. We will present examples from the Eel River Basin, the Gulf of Mexico, the Santa Barbara channel, the Storegga Slope Failure Complex, and the Cape Fear Slide.

RCM4 : MOpm25 : F3
Submarine Slope Failure Related to Fluid Migration Processes (Deep Offshore Gulf of Guinea)

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Many submarine slides occur on the continental slope at low declivities, which implies external triggering mechanisms. Several case studies show that the slope failure can be tentatively related to the mechanical behaviour of sediments in response to dynamic processes such as fluid migration. Therefore, the effect of this fluid flow isolated or combined to earthquake, shallow gas, gas hydrates, can act as triggering mechanisms. Different types of data (bathymetry and sonar imagery, cores and in situ experiment using a R.O.V.) were collected in the Gulf of Guinea off West Africa (in co-operation between Total Fina Elf and Ifremer). These data reveal numerous and different examples of seafloor instabilities often related to fluid escape features such as cold seeps, pockmarks, mud volcanoes, carbonate concretions in silty sediments etc.

One slide was identified on the upper slope of Gabon margin at water depths ranging from 200 to 2300 m. in regular slope of 3.5% (2°). Detailed interpretation of recent VHR seismic data shows that a main sliding area (max thickness: 60 m) is partly covered up by a smaller and thinner sliding unit (max thickness: 20 m). The slide clearly occurs downslope of a typical seepage area mapped on sonar imagery (high reflectivity patches: 100 m to several hundreds of meters wide). A characteristic feature of these spots is their close alignment along the direction N45, on a line located between 500 and 700 m water depth leading to the failure zone. Even though the rate of deformation is apparently low, the geotechnical analyses and the acoustic facies show that the mechanical process probably involves more than creeping and that the slide is disintegrative or possibly exhibits a limited liquefaction in places.

A slope stability analysis was undertaken for this slide, where seismic activity, faulting or high sedimentation rates are not likely to induce slope failure, but where seepage features occur in the failure zone. Several triggering factors related to fluid escape processes where quantitatively investigated to explain the failure: 1) small temperature variations which could have destabilised shallow gas hydrates in the zone of their upper limit of stability, 2) undissolved gas (bubbles) which may be responsible for undrained shear strength reduction, 3) seepage forces which may induce drained Coulomb failure in case of an excess pore pressure. A better understanding of the processes driving the Gabon continental slope obviously requires future in situ data acquisition concerning the nature, origin and behaviour of fluids. This will be conducted in December 2000 using the R.O.V. Victor.

RCM4 : MOpm26 : F3
An Alternative Mechanism for Slope Failure

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Various mechanisms have been proposed for slope failure. In the case of carbonate platforms the most frequently advocated hypothesis seems to be top failure reflecting the loss of buoyancy during subaerial exposure. In the case of siliciclastic shelfs the causal agent historically has been ascribed to the unproven incidence of earthquakes and more recently to gas hydrate destabilisations. The purpose of this contribution is to call attention to an alternative base failure mechanism as a more common method of slope failure.

An instructive analogy is increasing the height of a chimney to the point that it collapses due to the overlying weight by base failure. Naturally occurring slopes into deep water have neither vertical slopes, as in the chimney analogy, nor uniform strength of the constituent lithologies. Both factors contribute significantly to the incidence of naturally occurring slope base failure but they are variations on a theme that is fundamentally induced, as in the chimney analogy, by increasing load that is only water-column constrained.

Unlike the chimney analogy, however, the increase in load is largely a reflection of an up-dip increase in sedimentary load and consequent gravitational head.

Where salt is present the increase in gravitational head is relieved by mass movement of overlying sediment on the lubricating salt horizon, giving rise to the well-known salt raft tectonics of the West African Aptian Salt Basin. Where salt does not provide a short term time-release mechanism for increasing up-dip gravitational load, the accumulating stress produces massive recurrent slope failure as in Northwest Africa.

Factors such as coastal uplift and shelfal subaerial exposure also contribute to increasing up-dip gravitational load, but even without these events, recurrent slope failure into deep water would seem to be a normal consequence of continuing sediment aggradation on carbonate platforms and siliciclastic shelfs. The mechanism does not deny the importance of earthquake and gas hydrate destabilisations in continental slope failure, but relegates their frequency of occurrence to relatively minor significance.

RCM4 : MOpm27 : F3
Subsurface Physical Property Prediction from 3-D Seismic Data: The Challenge for Marine Geotechnical Studies

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Three-dimensional seismic data have revolutionized the petroleum industry by providing images of subsurface stratigraphy and structure that are much more accurate than could previously be mapped (1). Furthermore, new approaches to the analysis of 3-D seismic data aim at creating 3-D physical property volumes for intervals of interest. In this latter work, attributes (instantaneous frequency, reflection strength, etc.) are derived from the seismic traces. Empirical correlations are then sought between these attributes and physical properties (porosity, fluid saturation, etc.) derived from corresponding borehole logs. If statistically valid correlations can be established, and other parameters can be satisfied (2), they can be used to predict physical properties throughout the 3-D survey area, thus creating a 3-D physical property volume. Multivariate linear regression, neural networks and geostatistics are among the approaches being applied in these studies. Numerous case studies, often tested by the drilling of new wells, document the viability of this methodology.

We seek to adapt this approach to the study of underwater landslides. Seismic response is a function of density and velocity and these, in turn, are related to properties of interest in geotechnical studies. The work consists of collecting high-resolution 3-D seismic data over suitable areas, then correlating the seismic data with physical property information obtained from long cores. The result of the 3-D seismic attribute analyses can be one or more physical properties volumes that capture the extent, thickness, and 3-D geometry of 'geotechnical layers' (e.g., 'weak layers'). These results can then be integrated with the results of conventional seismic interpretations that address the 3-D geometry of the seafloor, slip surfaces, debris mounds, scarps, etc.

One of the major challenges in submarine slide risk assessment is to integrate all the uncertainties in a regional framework and it is believed that this will be eventually achieved by integrating the 3-D seismic and geotechnical properties (including variability and uncertainty). One way to approach this is to use a reliability method so as to: (1) provide a coherent approach to submarine risk assessment evaluation and (2) reduce the cost of site selection. This means that we will have to develop an approach which works at a regional scale and is flexible enough to enable zooming on particular site. Using existing and new data acquired as part of COSTA, we will work on modeling uncertainties and variability of the main parameters needed for slope stability evaluation (i.e., soil properties and slope geometry) and then integrate them with the 3-D seismic. This integration should provide a fundamentally new way of approaching this field.

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RCM4 : MOpm30 : F3
An Initial Assessment of the History of the Afen Slide, Faroe-Shetland Channel

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The Afen Slide is a small submarine slide of Holocene age on the UK continental slope in the Faroe - Shetland Channel. Its size (area: 3 km x 13 km, thickness 10-20 m) is small by global marine standards but provides a laboratory for understanding submarine downslope movements and their interaction with other seabed processes. Seabed imagery derived from sidescan sonar and 3D exploration data clearly shows that the slide is a multi-event feature. These can be interpreted as a retrogressive failure back upslope, however recently acquired high resolution records reveal repeated failure of side walls leading to the migration of the debris deposits further downslope onto the floor of the Faroe - Shetland Channel with each slide event.

Several factors have played their part in the generation of the slide. The slide is located close to the Victory transfer fault, and a seismogenic origin is suggested by the marked geometric similarity between the failure outline and fault patterns seen at depth beneath the slide. The detachment occurred within a poorly consolidated contouritic sand body that had achieved a local maximum thickness in the vicinity of the slide. Interpretations of complex seismic attributes derived from the 3D exploration data suggest that the displaced sediments have been subjected to reworking by the continuing action of contouritic currents, with sediment displacement to the southwest predominating. The Holocene movement of contouritic sands along the slope, their distribution pattern and response to horizontal ground acceleration suggests it is an important factor in the mechanism of slide failure. This allows assessments of other potential slide sites on the west of Shetland Slope.

RCM4 : MOpm31 : F3
Evaluation of the Risk of Marine Slope Instability using a Pseudo 3D Approach: Application to the Nice Slope

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In the last 4 decades an increased attention has been paid to submarine slope instability. Scientific and industrial concerns have instigated numerous studies regarding design of marine constructions and comprehension of continental slope failure and depositional processes (see for instance Mulder and Cochonat 1996). Instability of submarine slopes may vary significantly with the extent of the slope and the morphology. Furthermore, the heterogeneity of the hydro-mechanical characteristics of the sediment can greatly modify flow fields, effective-stress fields, and slope stability. Consequently, a new methodology, where the safety factor was considered as a spatially varying quantity, was developed for evaluating the risk of marine slope instability. Marine slope instability can be an important mechanism for sediment transport and deposition. Therefore, it was fundamental to identify the right geometry of the failure surface in order to simulate correctly the sediment transport and the turbidity currents. The extensive submarine zone makes it impossible to carry out a real 3D slope stability analysis. The General Formulation (Fredlund and Krahn 1977), which fully satisfies equilibrium conditions, was used to evaluate the safety factor of the marine slope in two-dimensional vertical cross-sections and it was interpolated to the three-dimensional area. Special attention was paid to 1) the complex morphology and the expanse of the slope, 2) the heterogeneity of the sediment and 3) the distribution of the pore pressure. The validation of this methodology was carried out by comparing the safety factor as well as the shape of the failure surface obtained from the developed method with the results obtained from the limit analysis method and the finite element method. The submarine slope failure, which occurred on October 16th 1979 near the nice new airport, was selected as a case study of slope instability. Geotechnical parameters were taken from experimental tests carried out by IFREMER on 19 cores sampled at different depths (from 27 m to 1300 m) (Cochonat et al. 1993). Several scenarios were proposed in order to explain the cause of the Nice slope failure (Habib 1994). In this paper, two of those scenarios were tested: 1) under static gravity loading and 2) under a lowering of 2.5 m of the sea level due to the collapse of a hundred million cubic meters of sediments far from the coast. Simulation results show that static stability of the area is satisfactory. On the other hand, the lowering of the sea level showed a decrease of the safety factor in the area surrounding the nice new airport. However, the safety factors were remained greater than 1 in the area where the failure occurred in 1979.

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RCM4 : MOpm32 : F3
The Role of Hydroplaning in Subaqueous Mass Transport as Ascertained by Integrating Field Data with Experimental and Theoretical Studies

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Sub-marine sediment transport is known to take place in several regions around the world. This represents a potential natural hazard (e.g. leading to tsunamis) and poses a threat to off-shore structures, e.g. platforms, cables and pipelines. The studies of sub-aqueous mass transport have revealed that although the sediment mass submerged in water has lower density (due to buoyancy) and higher resistance to flow (increased viscous drag) as compared to its subaerial counterpart, its mobility is much greater than the later. Sub-marine flows on very gentle slopes (slope angle <1o) often cover distances of hundreds of kilometres. The great run-out distances in the presence of extremely low gradients represent an enigma in the studies of sub-marine flows.

In the classical theory of sub-aqueous mass transport, the sediments are envisaged to start off as a high density, cohesive mass (debris flow) which, as it moves downslope, incorporates water and becomes more and more fluidal and lower density in nature (turbidity current) throwing the solid particles into suspension. As the mass comes to rest, the solid sediment particles settle down according to their densities forming a sedimentary deposit in which the diameter of the sediment grains progressively decreases towards the top. Such deposits in the geological records are known as turbidites.

Recent experimental studies have however shown that sediments can cover great distances on gentle slopes as high-density, cohesive flows (debris flows). This is especially true of clay-rich sediments. Hydroplaning of the moving mass facilitates this mode of transport. As the sediment mass begins to move down a slope in sub-aqueous environments, a thin layer of water is incorporated beneath the moving mass. This water layer acts as a lubricant by decreasing the friction between the overriding sediment mass and the underlying stationary ground allowing the mass to be transported to great distances with its density more or less unaffected.

This phenomenon which has been studied in detail in the laboratory, is supplemented by analytical techniques and has been shown to be true at natural scales. This integration of experimental and theoretical studies together with field data has opened up new and exciting avenues for investigating subaqueous sediment transport.

RCM4 : MOpm33 : F3
Simulating Submarine Slope Instability Initiation using Centrifuge Model Testing

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COSTA is addressing the questions of why seafloor slope failures occur where they do, and with what frequency they occur. This original program has been recently complemented by COSTA-Canada, (Université Laval, 2000) to include: 1. Assessment of historical records of slope instability, slope parameters, seismicity, and tectonic setting; 2. Understanding of seafloor failure dynamics through imaging of sediment architecture and geometry of slope failures; 3. Understanding of sediment properties of slip planes and areas prone to slope sliding; 4. Determination of presence of gas hydrate and its significance for slope stability; 5. Modelling of forces and mechanical processes that control the initiation of slope instabilities (release mechanisms), flow dynamics and initiation of tsunamis; and 6. Assessment of risk-fields related to slope stability.

The initiation of slope instability under task 5 will be addressed using numerical and centrifuge modelling. Centrifuge model testing is a physical modelling tool for geotechnical engineers. Analogues to this technique exist in other branches of civil engineering, such as wind tunnel testing in aeronautical engineering and flume testing in hydraulic engineering. To achieve mechanical similitude in geotechnical models it is necessary to reproduce the material behaviour both in terms of strength and deformability. This behaviour is primarily a function of the effective stress resulting from self-weight, pore pressure and external loads.

Centrifuge modelling is a technique for investigating gravity dependant phenomena, such as soil slope behaviour, using reduced-scale physical models. If the model is made at 1/100th scale and is accelerated in a centrifuge to 100 g, the stresses due to self-weight will be similar to the stresses in the prototype at homologous points. The model can then reproduce the phenomena of cracking, rupture or flow that would be observed in the prototype because the stress dependency of soil behaviour has been correctly simulated. Murff (1996) describes the principles, scaling laws and some offshore applications of centrifuge modelling.

The failure of a 16deg, 8.8 m high loose sand submerged slope was simulated by centrifuge modelling (Phillips and Byrne, 1995). Surcharging the slope crest caused the model slope to liquefy and flow with deep-seated lateral movements to an angle of 7deg. The initiation of submarine slope instability has been attributed to triggers such as earthquakes, erosion, oversteppening, wave loading, gassy soils and sedimentation. Centrifuge modelling has been used to simulate most of these loading conditions in similar boundary value problems. For examples, the VELACS (Verification of Earthquake Liquefaction Analysis by Centrifuge Studies) program included simulations of lateral spreading of submerged slopes due to earthquake effects (Popescu and Prevost, 1995). Wave loading has induced seafloor liquefaction and mobility (Phillips and Sekiguchi, 1992). Continuous rapid sedimentation induces persistently high pore pressures (McDermott et al, 1999) that may result in subsoil instability.

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RCM4 : MOpm34 : F3
Laboratory Investigation on the Effect of Fines on Cyclic Resistance

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The addition of fines to a sand (fine Ottawa) is investigated with respect to its cyclic resistance and post-liquefaction behaviour. Three sets of tests involve using the same sand with adding different percentage of a plastic type fine, a non-plastic type fine and a non-plastic type sand. The first two sets of tests involve materials of varying coefficient of uniformity (Cu) with fines below 74µm (#200 sieve) size being varied. The last set of tests involve a material of approximately equal Cu but with no change in the fines below 74µm.

For this research, the sand is a clean, uniform, sub-rounded quartz sand (Ottawa sand, C-109). The plastic-type fines are kaolinite and the non-plastic-type fines are crushed quartz sand. The non-plastic sand is a clean, sub-rounded quartz sand with gradation between 0.25 to 0.075 mm (#70 to #140 sieve sizes). To study the effect of adding fines and changing gradation, each of the three sets of tests involves adding 10, 20, 30, and 40% of kaolinite, crushed silica sand fines and 70-140 silica sand to Ottawa sand.

Undrained cyclic loading causes a progressive pore pressure increase that eventually may lead to the development of large shear strains. The strain can develop either due to liquefaction or limited liquefaction during cyclic loading or on account of the occurrence of cyclic mobility (Castro, 1969). The cyclic resistance in simple shear (tcy/s'vc) is regarded as the ratio between the applied cyclic shear stress amplitude (tcy) and the initial normal effective stress s'vc.

Liquefaction in cyclic simple shear can be defined as the development of single amplitude shear strain in excess of 3.75%. This corresponds to the common definition of liquefaction as 2.5% single amplitude axial strain in cyclic triaxial tests suggested by Silver and Park. Cyclic tests will be performed at different void ratios and confining stress levels. At each confining stress several cyclic resistance curves ec vs. cycles to liquefaction NL are developed at several cyclic stress ratios.

It is planned to extend the above findings to the effect of layering as it is the case in most of the field situations. Liquefiable soil deposits are often overlain by less permeable soils which can restrict the escape of pore water from the liquefiable layer. The less permeable layer could contain a parent sand with fines content of non-plastic to plastic. In the simple shear apparatus, the layering can be simulated having the known characterization of above investigation of parent sand and the less permeable layer either with a parent sand layer with fines contents (sandy silt) or a silty clay.

Tuesday AM Session

RCM4 : TUam01 : F3
Earthquake Response of Submarine Sediment

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In dealing with seismic stability of submarine slopes, we are concerned with the initial trigger mechanism as well as the resulting possible large movements leading to a flow slide.

The cyclic shearing induced by earthquake loading causes pore pressure rise which may directly induce a sufficient drop in strength and stiffness to trigger large movements, or the trigger may occur some time later, due to pore pressure build-up at strategic locations controlled by stratigraphy. This delayed trigger can occur because drainage is impeded by a barrier layer of low permeability causing the trigger and flow slide to occur, minutes, hours, days or, perhaps, years after the earthquake event. Once movement commences, the strength and stiffness may further reduce below the steady state strength due to mixing of soil layers.

These effects are illustrated using a coupled stress-flow dynamic time domain analysis procedure. A prescribed time history of acceleration is applied at the base and shear induced pore pressures are computed with time in all elements of the domain. The procedure is an effective stress one in which the rising pore pressures reduce the strength and stiffness of the elements. If the strength loss during the shaking is sufficient, a flow slide may be triggered during the earthquake. If not, pore pressure redistribution commences, and while excess pore pressures generally reduced with time, in some zones, pore pressures increase because flow is restricted by low permeability layers, and triggering can occur some time after the earthquake event. In addition, as movement commences, the strength may further reduce due to mixing effects. Example of the occurrence of such triggering and resulting flow slides will be presented.

RCM4 : TUam02 : F3
Failures on the Southeast Canadian Margin: The Canada-COSTA Focus

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The Canada-COSTA community has chosen two areas of seabed failure on the southeastern Canadian margin for detailed investigation of post-glacial sediment failures: (1) the central Scotian Slope and (2) the head of Laurentian Fan (the 1929 'Grand Banks' failure).

EM300 and EM1002 multibeam bathymetric imagery of over 30 000 square kilometres on the Scotian Slope shows that the eastern Scotian Slope is deeply incised by canyons in Pliocene-Quaternary shales. The canyons were cut, probably by subglacial meltwater, when glacial ice reached the outer shelf. No failures appear to postdate the last deposition of sand sheets on canyon floors, dated at about 12 ka. Sparse failures on intercanyon areas of the lower slope are draped with late Pleistocene sediment. The central Scotian Slope is less dissected. Smooth slopes of about 0.04 have widespread shallow rotational slumps with arcuate headscarps, retrogressive rotational slumps, bedding plane slides and debris flows. In addition, lateral spreading creep has occurred on decollement planes 50-500 m below seabed. Evidence of shallow gas, including pockmarks, is widespread. Piston cores from failed areas allow a 50 m thick composite stratigraphy to be established. Failures have been dated by radiocarbon methods, Heinrich events, and correlation with upper slope till deposition. Hypotheses for triggering of failure include: excess pore pressure due to ice loading, upper slope till deposition, or high rates of sedimentation; ice-load induced seismicity; and warming of bottom waters during deglaciation causing gas hydrate dissociation. The availability of large amounts of both industry and high-resolution seismic reflection profiles and piston cores have not yet resulted in discrimination of these hypotheses.

At the head of the Laurentian Fan, around the epicentre of the 1929 Grand Banks earthquake, a similar composite stratigraphy of the upper 50 m of fine-grained sediment has been developed and allows definition of the physical properties of layers that show different styles of failure in sidescan sonar imagery. Evaluation of the role of liquefaction in sands in upper slope channels must await future multibeam bathymetry and follow up studies. The turbidity current generated by the 1929 failure reworked late glacial sands from the valleys on Laurentian Fan and transported them to the Sohm Abyssal Plain. New seismic data from the eastern Canadian margin show that large, seismically-induced failures are very rare, with a recurrence interval of hundreds of thousands of years. The reduction in frequency of large deep-water debris-flow deposits after the cutting of the canyons on the eastern Scotian Slope in the middle Pleistocene suggests that excess pore-pressures, perhaps due to gas hydrates, play an important role in large failures.

RCM4 : TUam03 : F3

The Saguenay Fjord: Integrating Marine Geophysical and Geotechnical Data for Spatial Slope Stability Analysis

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In 1996 a major flood occurred in the Saguenay region, Québec, Canada, delivering several km^3 of sediment to the Saguenay Fjord (Brooks and Lawrence, 1999). Such sediments covered large extensions of the, until then, largely contaminated fjord bottom (e.g. Barbeau et al., 1981), thus providing a natural capping layer. Recent swath bathymetry data has also evidenced that sediment landslides are widely present in the Saguenay Fjord (Locat et al., 1999). It seems that, as indicated by the expanded seismic record of this region, the most probable cause of such landslides is seismic shaking. The occurrence of new seismic events could, in consequence, compromise the stability of the fjord bottom as well as the newly deposited sediment layer. Therefore, in this study, we try to characterise the critical accelerations induced by these earthquakes from which shallow sediment landslides could be triggered. The analysis is based on gradients obtained from multibeam data as well as sediment physical properties measured in box cores. Resolving the region of the 1988 Saguenay earthquake as the most likely source area of such earthquakes, we have analysed several magnitude and focal depth scenarios to deduce that sediment displacements will start from local magnitudes of 4.8. Major displacements, failure, and subsequent landslides will occur only from local earthquake magnitudes of 6.6.

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RCM4 : TUam04 : F3

Regional Variability of Factors that Influence Offshore Slope Stability, Synthesis within a GIS

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Submarine slope failures occur when the environmental forces that tend to move sediment downslope as a mass exceed the ability of the sediment to resist these forces. These forces are typically derived from earthquakes, waves, or gravity. Over the long term, both the environmental forces and the sediment resistance vary in a systematic regional way. As a result, the occurrence and character of mass movements vary regionally and reflect variations of sedimentological and environmental conditions. This situation lends itself well to the application of a Geographic Information System (GIS) toward predicting regional variations in slope failure susceptibility.

Regional studies were conducted in two areas off the coast of California: the Eel margin, near Eureka, and Santa Monica Bay, near Los Angeles. For each environment, detailed multibeam bathymetric maps were recently obtained, and extensive sediment coring programs were conducted. Each area represents a seismically active continental margin with significant sediment accumulation rates. The bathymetric maps show few obvious shallow-seated landslides with the exception of a steep slope south of the Palos Verdes Peninsula near Los Angeles. Extensive shallow-seated landslides and at least one deep-seated landslide cover most of the Palos Verdes slope. A simplified regional slope stability analysis was applied to both the Eel margin and Santa Monica Bay areas. The analysis uses an algorithm relating cyclic shear strength to surface sediment density that was derived from over 100 cyclic triaxial tests. Sediment strengths predicted using this algorithm were combined with slope steepness calculations from swath bathymetry and estimates of expected seismic shaking to calculate a measure of regional relative stability with respect to shallow-seated failure. All calculations and presentations were conducted within the structure of a geographic information system (GIS). Preliminary results show that the area of observed landslides on the Palos Verdes slope is associated with relatively low values of slope stability factors. Other, apparently more stable areas are associated with higher values of the stability factors.

RCM4 : TUam05 : F3

The Large Matakaoa Slide and its Impact on the Abyssal Plain, Near Hikurangi Margin, New Zealand

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The active convergent margin off the North Island of New Zealand is in a state of collapse. Seamounts, carried on the subducting Pacific Plate, have collided with the accretionary prism to generate several giant mass failure deposits with individual volumes reaching 3150 km^3. Even in the adjacent forearc basin, where the seamount-studded plate is too deep to disrupt the near-seafloor sediment cover, large-scale mass failure has occurred to generate the recently discovered Matakaoa slide.

Single channel airgun and 3.5 kHz seismic profiles show Matakaoa slide is a composite feature consisting of a debris avalanche that has deposited near the headwall on the continental slope, and a much larger debris flow that has advanced 190 km across the adjacent abyssal plain. The flow forms a 65 km-wide tongue whose western side is juxtaposed against a line of arc volcanoes extending from Kermadec Ridge. The eastern side, however, is unconfined and forms a scarp up to 68 m above the abyssal plain. The total slide volume is approximately 650 km^3.

Internally, the debris flow has an acoustically homogeneous signature with a few chaotically arranged internal reflectors. The flow surface is hummocky, but most is now blanketed by a turbidite cover up to 17 m thick that extends to within 5 km of the flow edge. Locally, the turbidite cover is disrupted by piercement structures that probably reflect expulsion of gaseous and fluidised sediment from the underlying debris flow. Tephra-dated cores from the slide and turbidite cover suggest that mass failure occurred about 35 ka or earlier.

Three factors conspired to form Matakaoa slide; (1) rapid deposition of muddy sediment that is estimated to have been 320 m thick before failing, (2) subsurface gas as indicated by bottom simulating reflectors and vent faunas near the headwall, and (3) frequent, large earthquakes as inferred from historical records which note at least 8 events of magnitude > 6 (Richter scale) over the past 36 years.

Matakaoa slide projects into the path of the northward flowing, Pacific Deep Western Boundary Current (DWBC). As a result, (1) the western boundary formed by the arc volcanoes has been modified by the slide which has partially blocked inter-volcano gaps thus reducing DWBC leakage into the South Fiji Basin, (2) the slide's relief has locally deflected and intensified the near-bottom DWBC, and (3) the terrigenous supply to the current has changed from an assumed regular flux of turbidites before the mass failure, to a sediment flush associated with slide emplacement, followed by a reduced supply as turbidity currents were captured on the hummocky slide surface.

RCM4 : TUam06 : F3

Large Slope Failure on the Northern Hikurangi Margin, New Zealand: Dynamics, Timing, and Mass Balance Calculations of the Ruatoria Debris Avalanche

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Despite convergent margins being unstable systems, most reports of huge submarine slope-failure have come from oceanic volcanoes and passive margins. Swath bathymetry and seismic profiles of the northern Hikurangi subduction system, New Zealand show a tapering 65-30 km wide by 65 km deep margin indentation, with a giant, 3150±630 km^3, blocky, debris-avalanche deposit projecting 40 km out across horizontal trench-fill, and a debris-flow deposit projecting over 100 km. Slide-blocks are well-bedded, up to 18 km across and 1.2 km high, the largest being at the deposit's leading edge. Samples dredged from them are mainly Miocene shelf calc-mudstones similar to those outcropping around the indentation. Cores from cover beds suggest failure occurred about 170 ±40 ka, at about the same time as a major rotational collapse in the upper indentation. However, the northern part of the indentation is much older. The steep, straight northern wall is close to the direction of plate convergence and probably formed 2.0-0.16 Ma as a large seamount subducted, leaving in its wake a deep groove obliquely across the margin and an unstable triangle of fractured rock in the 60° angle between groove and oversteepened margin front. The triangle collapsed as a blocky avalanche, leaving a scalloped southern wall and probably causing a large tsunami. Tentative calculations of compacted volumes suggest that the indentation is over 600 km^3 larger than the avalanche, supporting a two-stage origin that includes subduction erosion. Since failure, convergence has carried the deposits ~9 km back toward the margin causing internal compression. The eventual subduction/accretion of the Ruatoria avalanche explains the scarcity of such features on active margins, and perhaps the nature of olistostromes in fold belts.

RCM4 : TUam07 : F3

Sedimentation Patterns along the North-East Atlantic Continental Margin

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The north-east Atlantic continental margin displays a wide range of sediment transport systems with both alongslope and downslope processes. Off most of the north-west African margin, south of 26°N, upwelling produces elevated accumulation rates, though there is little fluvial input. This area is subject to infrequent but large-scale mass movements, giving rise to debris flows and turbidity currents. The latter traverse the slope and deposit thick layers on the abyssal plains, whilst debris flows deposit on the continental slope and rise. From the Atlas Mountains northwards to 56°N the margin is less prone to mass movements, but is cut by a large number of canyons which also funnel turbidity currents to the abyssal plains. The presence of a lithospheric plate boundary off SW Iberia is believed to have led to high rates of sediment transport to the deep sea. Even larger quantities of coarse sediments have fed the canyons and abyssal plains in the Bay of Biscay as a result of drainage from melting icecaps. Bottom currents have built sediment waves off the African and Iberian margins, and created erosional furrows south of the Canaries. The Mediterranean outflow is a particularly strong bottom current near the Straits of Gibraltar, depositing sand- and mudwaves in the Gulf of Cadiz. North of 56°N the margin is heavily influenced by glacial and glaciomarine processes active during glacial times, which built glacial trough-mouth fans such as the North Sea Fan, and left iceberg scour marks on the upper slope and shelf. Over a long period, especially during interglacials, this part of the margin has been greatly influenced by alongslope currents, with less influence by turbidity currents than on the lower latitude margins. Mass movements are again a prominent feature, particularly off Norway and the Faeroes. Some of these mass movements have occurred during the Holocene, though high glacial sedimentation rates may have contributed to the instability.

RCM4 : TUam10 : F3
The Traenadjupet Slide Offshore Norway – Age and Sediment Displacement

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^{14}C AMS dated gravity cores from the Traenajupet Slide scar area offshore Norway indicate that the slide occurred sometime during the mid-Holocene. The initial sediment disintegration produced detached sediment ridges, which moved through basal deformation or by backtilting. Disintegration of the sediment ridges and transition to sediment streams comprising more-or-less disintegrated sediments occurred over a distance of about one kilometre. The sediment streams consists of gravely sandy mud with scattered clay clasts of more consolidated sediments. A similar facies was also found in the distal lobes of slide deposits 200 km into the Lofoten Basin. This indicates sediment movement in the upper plug flow region of debris flows where no sediment deformation is expected during transport. The mass movement occurred above two glide planes. In the upper slide scar the glide plane is located 150 m below the sea floor, further downslope separated by a large escarpment it is at 250 m depth. On seismic data both glide planes are found within acoustic stratified units. Core data from the glide plane sediments display grey to dark grey sandy mud with scattered clasts. The origin of the glide plane sediments will be discussed. High sedimentation rates and low permeability of the glide plane sediments may have resulted in excess pore pressure at this depth. In situ methane formation due to decomposition of organic matter may also have resulted in excess pore pressure. As a result glide planes may have developed due to sediment underconsolidion within some intervals.

RCM4 : TUam11 : F3
The Storegga Slide; Chronology and Flow Mechanism

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The Storegga Slide scar on Mid-Norwegian margin represents one of the worlds largest exposed submarine slides. A volume of 5580 km^3 was mobilised and a total influenced area of 112.000 km^2 (Bugge 1983). The slide complex has been interpreted to be the product of three slide events whereas ranging in age from ca. 30 ka BP to 6 ka BP (Bugge et al. 1987, 1988; Jansen et al. 1987). During the last couple of years the Storegga Slide has been an area of extensive investigation focusing on margin stability and sedimentary processes. High resolution seismic data (e.g. airgun, deep-towed boomer, 3.7 kHz profiles), TOBI side-scan sonar imagery data (15.000 km^2) and cores (gravity, piston and shallow boreholes) have been collected. Core sites have been selected for dating based on a number of new high-resolution bathymetrical and imagery data. Also, cores have been collected especially to analyse some of the most pronounced glide planes identified in the slide area. With aid of the TOBI side scan sonar data the geometry of the flow pattern has been mapped in the upper slide area. The flow pattern and mechanism will be discussed. The preliminary chronological results have revealed that: The chronological investigations combined with the new TOBI side scan imagery and high-resolution seismic profiling in the upper Storegga Slide area strongly indicate that the previously defined slide events are erosions boundaries within the same slide failure event. They are therefore not representing any time as previously interpreted. Thus the Storegga Slide main events 1, 2 & 3 (as defined by Bugge, 1983) have been activated/ mobilised within the same age interval 7.300 - 7.350 radiocarbon age (^{14}C) BP or ca. 8150 cal. yrs BP.

RCM4 : TUam12 : F3
Large-Scale Continental Shelf Erosion as a Source for Megaturbidites in the Western Mediterranean Sea

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Slope failure and fluvial discharge along the shelf edge during low stands of the sea are common processes invoked for supplying sediment to gravity deposits such as debris flows and turbidites. We propose erosion of lowstand shorefaces as another process responsible for transfer of large amount of sandy sediments to the deep sea. This two-step process may be important in understanding timing and architecture of gravity deposits.

In the Balearic abyssal plain, a megaturbidite has been mapped and dated to ca 22,000 calendar years BP (Rothwell et al., 1998). The source and processes responsible for this large deposits were not clearly identified. Extensive mapping and sampling in the Gulf of Lion demonstrate that a large amount of sediment, mainly sandy, has been eroded from the outer continental shelf during or immediately after Last Glacial Maximum. The magnitude of erosion can be estimated in places where cemented sands, marking the position of paleoshoreline, are presently at an elevation reaching up to 22 m above the surrounding sea-floor. A massive sand sheet (more than 4 m in thickness) covers a large portion of the continental rise, to the West of the Rhone Deep Sea Fan. The southern extension of this sand body, first interpreted as a debris flow from its acoustic facies, is in the direction of the megaturbidite, suggesting a genetic relation between the two deposits. We believe that a large amount (if not all) of these deep-sea sands originate from shelf erosion, instead of being directly supplied by streams during lowstand, or slope-failure along the shelf edge or on the flanks of the Rhone deep-sea fan.

Rothwell, RG, Thomson, J, hler, G, *Nature*, **392**, 377-380, (1998).

RCM4 : TUam13 : F3
The Gebra Slide: A Late Quaternary Large-Scale Sliding Event along the Trinity Peninsula Margin, Antarctic Peninsula

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Numerous studies illustrate that high-latitude, ice-sheet-dominated, continental margins are more prone to large-scale mass-movements than lower-latitude margins. Major slope instabilities are well-documented along the northern hemisphere, glacial margins of the Norwegian Sea (e.g. Storegga Slide) and the Svalbard-Barents Sea and of Greenland and eastern Canada. However, similar slope-instabilities along the Antarctic Margins seem to be much more scarce. Here, we present the first detailed analysis of a Late Quaternary slide along an Antarctic margin.

The Gebra Slide is situated along the Trinity Peninsula margin in the Central Bransfield Basin, Antarctic Peninsula. The slide scarp, clearly revealed by multibeam bathymetric data, extends over a length of about 30 km, from 1500 to 2000 m of water depth on the lower slope, well below the slope break which is here at about 750 m. The head of the slide is formed by an amphitheatre-shaped set of scarps with an elevation of 100 m. Further upslope, but still detached from the slope break, a second less-developed set of scarps suggests a multi-stage retrogressive mass-wasting process. The slide scarp area covers about 230 km^2.

Seismic reflection (airgun) profiles show that the associated deposit covers about 315 km^2 of the western King George basin. Its typical acoustically transparent to chaotic seismic facies suggests it is essentially a debris flow deposit. The deposit is draped by the recentmost hemipelagic sedimentary unit. According to seismic-stratigraphic correlations, we put the age of the main sliding event at about 13.500 a B.P., around the last deglaciation in this part of the Antarctic (Banfield et al., 1995). The volume of this debris flow (21 km^3) agrees very well with the disappeared volume higher on the slope.

Although the Gebra Slide is positioned in front of a glacial trough with a higher sedimentary input, the sedimentation rates during both the present interglacial and the last glacial maximum - estimated as 0.24 cm/yr and 3.4 cm/yr, respectively, based on sediment cores and seismic stratigraphy - are too low for significant build-ups of excess pore pressure to develop in the sedimentary column. The position of the main scarp on water depths of 1500 m is far below the maximum grounding depth of the Antarctic Peninsula ice sheet (about 1000 m), excluding a possible triggering by loading/unloading of an advancing/retreating ice cap as a possible cause. No deep faulting in the underlying basement is observed on the seismic profiles, which also rules out a purely tectonic control. On the other hand, triggering by an earthquake in the volcanically and seismically active Bransfield Basin should not be excluded. Therefore, we propose that only an interaction between all above processes - in space and time - could have lead to the triggering of the Gebra Slide.

Banfield LA and Anderson JB, *Antarctic Research Series*, **68**, 123-140, (1995).