COSTA (COntinental Slope STAbility) EUROPE AND FUTURE MASS MOVEMENT STUDIES ON CONTINENTAL MARGINS FROM THE MEDITERRANEAN SEAS TO THE ARCTIC OCEAN

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ABSTRACT
Giant and medium size submarine landslides occur around Europe's margin. A giant Holocene landslide of approx. 90000 km^2 is found in high latitude margin settings while medium size landslides of several thousand square kilometres occur in both glacial-dominated margins of high latitudes and river-dominated settings of low latitudes. Submarine landslides are common and very effective mechanisms of sediment transfer from shelf and upper slope to deep-sea basins. During one single event enormous sediments can be transported on very gentle slopes over distances exceeding hundreds of kilometres. Individual mass movements involve simultaneous or successive material displacements including block detachment and translational sliding, block sliding, debris flow and mud flow. Although slide headwalls might present locally steep gradients (up to 23 degrees for the giant Storegga slide), the slope gradients of both the failed segment margins and the main slip planes are very low (2 degrees and usually < 1 degrees). The slip planes often correspond to mechanically distinct "weak layers" and also to climatically controlled changes in sedimentation rates and sediment types. Thus, we can state that a submarine landslide pre-conditioning is at least partially climate driven. In addition to the pre-conditioning factors, a final trigger is probably required for submarine landslides to take place. In high latitude margins, earthquake magnitude and frequency intensification due to post-glacial rebound has likely played a major role but gas hydrate destabilisation due to ocean warming may have significantly contributed. Future mass movement studies will investigate the role of sealevel changes in submarine slope failures and elaborate preconditioning factors that exist for submarine landslides from Mediterranean Seas to the Arctic Ocean, i.e river-dominated versus glaciated-margin dominated settings.

RÉSUMÉ
Des glissements de terrain sous-marins de tailles variées ont été répertoriés le long de la marge européenne. Un gigantesque glissement de terrain datant de l'Holocène (approx. 90000km^2) a été observé sur la marge continentale à haute latitude tandis que des glissements de terrain de taille moyenne (plusieurs milliers de km^2) se sont produits à la fois à hautes latitudes (marge continentale dominée par les glaciations) et à basses latitudes (dominées par l'apport des rivières). Les plans de glissement correspondent souvent à des couches de faibles résistances et aussi à des couches dont le taux de sédimentation et le type de sédiments déposés sont influencés par les conditions climatiques. Donc, nous pouvons établir que les conditions géotechniques in situ avant le glissement sont au moins partiellement contrôlées par le climat. Des études de mouvements des sols submergés analyseront le rôle exercé par les variations du niveau marin sur la rupture des pentes sous-marines et élaboreront les facteurs pré-conditionnants les glissements de terrain situés dans les eaux de la Méditerranée jusqu'à l'océan arctique afin de comparer l'influence des environnements glaciaires et non glaciaires.

1. INTRODUCTION

Increasing interests of the hydrocarbon industry to move from shallow to deeper water exploration areas took place in line with academia's interest to better understand slope failure processes on continental margins. A common interest in geohazards resulted in intensive efforts made in the last few years to improve acoustic imaging of slope failures and associated impact areas in European margin settings, which made it clear that submarine sliding is a widespread phenomenon on passive continental margins on both sides of the north Atlantic Ocean (e.g. McAdoo, 2000; Mienert et al., 2002; Piper et al., 2003, Mienert and Weaver; 2003; Locat and Mienert, 2003).

It is now well known that some of the submarine slope failures created destructive tsunami waves, which in turn can have devastating impacts on populations of coastal lowlands (Baptista et al., 1998, Bondevik et al., 1997). For example, the 1755 Lisbon event where an approximately 8.5 magnitude earthquake triggered a landslide and tsunami represents one of the largest natural catastrophes with approximately 60,000 casualties in Portugal alone (Gracia et al., 2003). The 8250 cal yrs. BP Storegga slide event caused a major tsunami with devastation along a several thousand km long coastline including Scotland and Norway. This major impact did not cause a high risk during that time because of the scarcely populated areas during the Stone Age. If such en event would happen today the risk (product of geohazard and destruction potential) would be very high. In this respect, one of the largest deep-water gas fields, the Ormen Lange gas field off the mid-Norwegian margin (e.g. Bryn et al., 2003) located in the Storegga slide scar, received very detailed seabed and sub-seabed mapping including geotechnical drilling to understand the Storegga slide development in detail (e.g. Bryn et al., 2003).

Six submarine slides located in Europe's margins have bee systematically studied and intensively investigated within the COSTA Europe project. These are from south to north the Central Adriatic deformation belt, the BIG95 slide from the W-Mediterranean Sea, Afen slide offshore United Kingdom, and Storegga, Traenadjupet and Finneidfjord slides of Norway (Figure 1). Two elected sites, Storegga and BIG 95 (Figure 2) are presented in terms of size, type of sediment down slope movement, age and potential trigger mechanism. Future mass movement studies in Europe are funded by individual National Science Foundations under the umbrella of the European Science Foundation in a project called EUROMARGINS. This program is aimed to gain a new understanding of margins from their rifting and tectonic phases to their interactions of sedimentary and fluid flow processes.

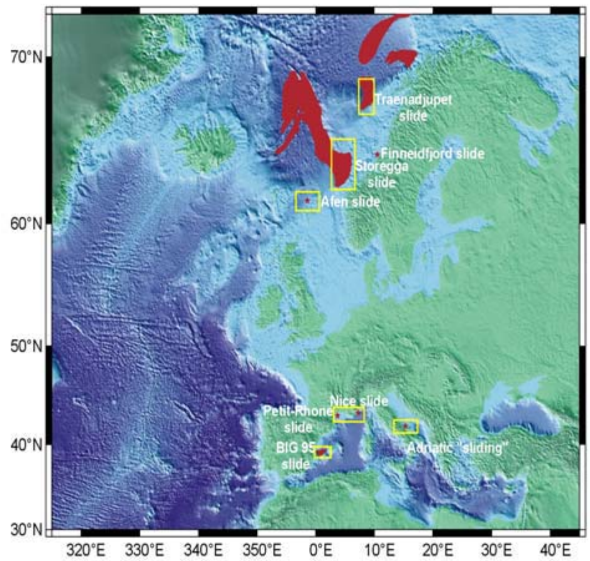

Figure 1: Locations of investigated submarine slope failures of Quaternary age in European Margin settings.

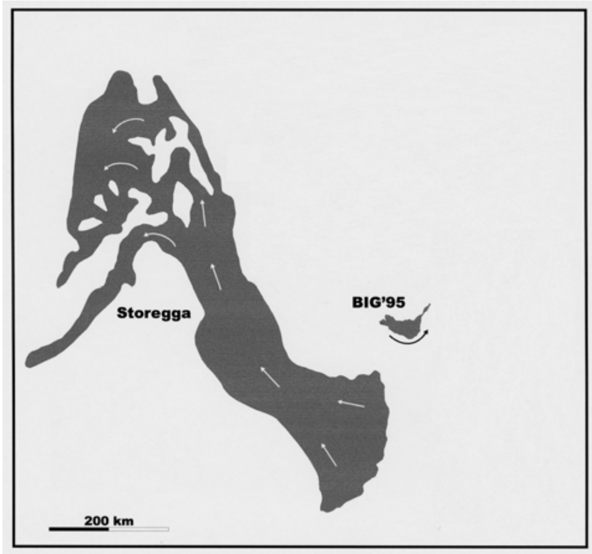

Figure 2: Size comparison between giant Storegga Slide and one of the largest W-Mediterranean slides (BIG 95).

2. GEOLOGICAL SETTING AND MORPHOLOGY OF A GIANT SLIDE (STOREGGA) AND A MEDIUM SIZE SLIDE (BIG 95)

Storegga offshore Norway: The location of the giant Storegga slide appears to be somewhat determined by the deeper margin structure. Here, where the Møre and Vøring marginal highs are formed from extrusive igneous rocks during volcanic activity prior to early Eocene seafloor spreading, the continental crust and the highs give more stable foundations than the thinner oceanic crust (Berndt, 2000) (Figure 3 and 4). The Storegga slide is located on the thinner oceanic crust; moreover, the Storegga slide depression is not only influenced by the deeper structural features but also by repeated slide activities taking place in this specific area of the mid Norwegian margin during the last 500 kyrs (Bryn et al. 2003, Nygaard et al., 2003).

The giant Storegga slide has developed as a retrogressive slide in a passive continental margin setting, where the shelf is approximately 100 km wide (Figure 1) (Haflidason et al., in press). It is located immediately south of the Vøring Plateau where it was discovered in 1979 (Bugge, 1983). The nearly 300 km long headwall is located in water depths from 150 to 400 m along the shelf break (Figure 4). The headwall reaches maximum heights of between 150 to 200 m. The maximum run out of slide material reached 400 - 800 km, and the final deposition occurred at 3800 m water depth. It is now well documented that the Storegga slide consists of lobes from more than 50 individual slide events ranging from the first phase of 2400 km^3 to minor slides of less than 1 km^3 at the headwall. The slope gradient along the failure planes is between 1 and 1.5^o but reaches 23 ^{o} or more at the head wall. The slides affected an area of approximately 95000 km^2 and they took place almost concurrent around

8250 cal. years BP (Haflidason et al., 2003a, b, c, in press). Therefore, it is appropriate referring to the “Storegga slides” of Holocene age.

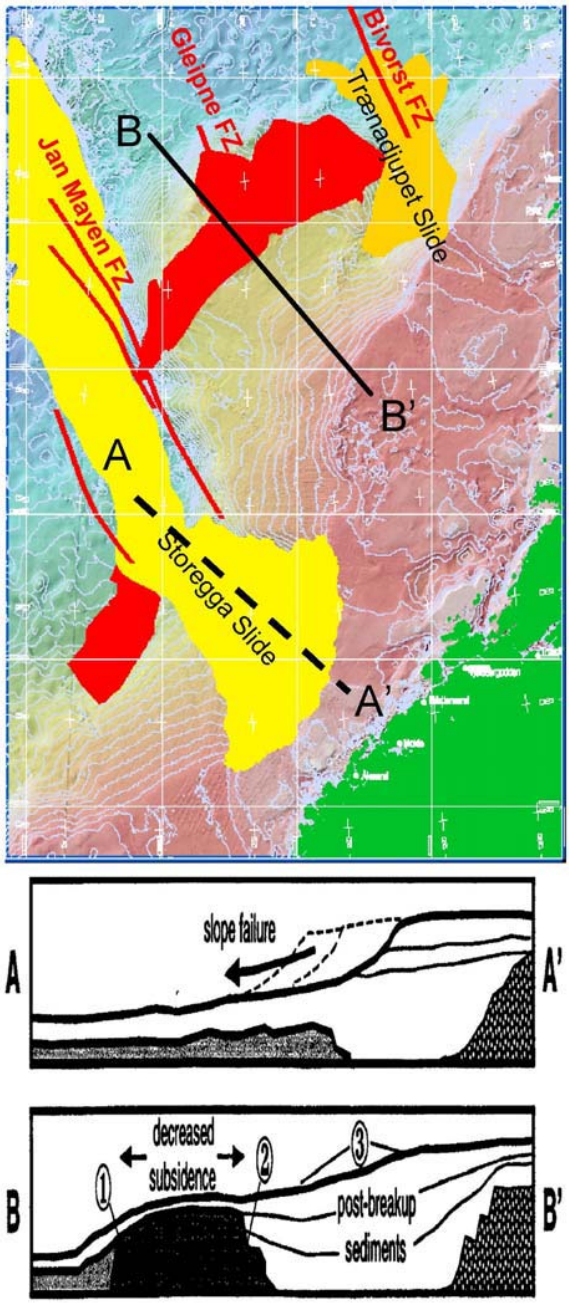

Figure 3: Volcanic formations may provide more stable foundations thus decreasing the potential for submarine slope failures. The continental crust and the highs (B-B’) give more stable foundation than the thinner oceanic crust (A-A’) (from Berndt, 2000).

The stratigraphy of the area prone to the Storegga slides is characterised by glacial-interglacial sedimentary cycles. During interglacials a hemipelagic contouritic depositional regime dominates, where the thickest accumulation of fine grained marine clayey sediments is found parallel to the warm northward directed Norwegian current, which produces a sediment drift with sorted marine clay layers (Haflidason et al., 2003b; Laberg et al., 2003). The glacial sedimentary units are composed of unsorted diamicton and /or ice proximal meltwater deposits on the upper slope. The glacial sediments were rapidly deposited on the interglacial sediments creating most likely an excess pore pressure (Bryn et al., 2003). However, layer-parallel slip surfaces and jumps between various stratigraphic levels have been observed (Bryn et al., 2003), for example, in the Storegga slide scar area (Figure 5). The identification of the nature of the slip planes is often hampered by the availability of long enough sediment cores. Fortunately, in Storegga slide areas, samples from bore holes and sediment cores are made available by the hydrocarbon industry. Slip planes in Storegga are developed in marine clays of contouritic origin, the youngest of Eemian age. Marine clays are weaker and have higher sensitivity than glacial clays, and show contractant behaviour upon loading (Laberg et al., 2003; Kvalstad et al., 2003).

Determinations of the morphology of the Storegga slides are based on joint academia- hydrocarbon industry research activities within and adjacent to the area of the Ormen Lange field (Bryn et al., 2003; www.offshore-technology.com/projects/ormen/). Morphological analysis is based on integrated multibeam/3-D bathymetry (Figure 4). and side-scan sonar datasets, which allowed systematic analysis of a system of lobe phases created during retrogressive slide failure events. The interpretations show various lobe terminations, pressure ridges, and orientation of material/fabric relative to the debris flow directions. It reflects the dynamics involved in this giant submarine slide from erosion with exposed failure plains and compression zones to depositional processes (Haflidason et al., in press). The failure plains (Bryn et al., 2003) indicate a slide failure process where the sediments laying on the youngest failure plane have failed first. After these sediments have been transported downslope, then the next stratigraphic deeper failure plane becomes active. Since the deeper units are much more lithified than the younger and shallower once, the failed deeper sediments are preferably transported as sediment blocks. The low slope angle is limiting a large run out of the blocks keeping the blocky material mainly on the deep seated failure plains.

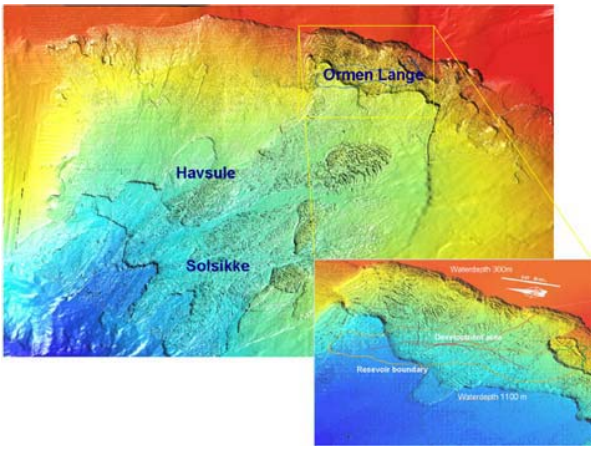

Figure 4: Seabed morphology of the Storegga slide scar (courtesy by P. Bryn of Norsk Hydro) indicating several backwalls..

The detailed mapping of five major lobes and numerous minor slide lobes resting on top of the major slide lobes allowed determining their stratigraphic evolution. The morphological character of these lobe phases differs because the source material (blocky, moulded etc.) and the length of transport pathways and thus the possibility of disintegration differ. The parameterisation of the lobes including their volume, run out and area provide an excellent approach to determine the general rheological parameters thus, improving flow models of submarine slide failures (Issler et al., 2003, Ilstad et al., in press).

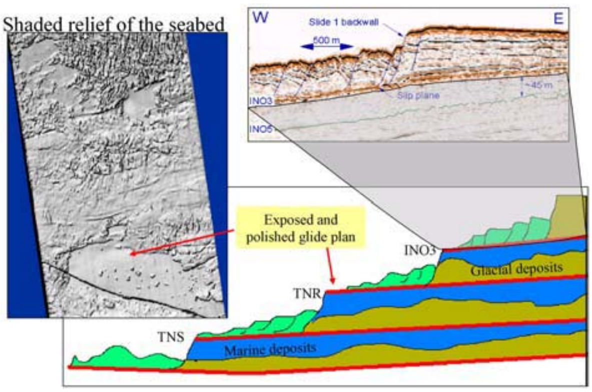

Figure 5: Seabed morphology of Storegga glide planes (Courtesy by P. Bryn of Norsk Hydro).

BIG95 offshore Spain: The Big 95 submarine slide is retrogressive and located on the river dominated Western Mediterranean passive margin where the shelf is 70 km wide (Lastras et al.,2002, 2003; Urgeles et al., 2003). It takes its name from the acronym of the cruises and year when it was first identified ("Biogeoquímica I Geologia", BIG95). The margin growth pattern is controlled by changes in fluvial sediment supply by the Ebro River, sealevel changes, and subsidence during Late Pleistocene and Quaternary times. There are several volcanic structures in the region including a volcanic archipelago in the Ebro margin outer shelf that is most likely a surface expression of buried volcanic fields (Maillard and Mauffret, 1993). The Ebro margin has a mean slope gradient of 4^o and the shelf break is at 130 m water depth. It is mainly fed by the Ebro River, which is discharging annually five to six million tons of sediment (Nelson, 1990). This volume is probably about three times larger during sealevel lowstands, when most of the margin progradation took place (Nelson, 1990).

The BIG 95 represents one of the largest submarine slope failures in the Western Mediterranean where it is overlying sediments of Pliocene-Quaternary age. It thus shows one of the youngest mass wasting events of the Ebro margin, where AMS 14C dating of the debris flow units revealed a minimum age of 11500 cal. years BP (Lastras et al., 2002). It is to note that the Storegga headwall area elongates within the outer shelf, while in contrast, the BIG 95 headwall is located on the upper slope between 600 to 1200 m water depths. Here, a main headwall and secondary scars can be identified (Figure 6). The main headwall has a total length of 20 km, a height of up to 200 m, and a mean slope gradient of 17^o. The headwall shows a staircase morphology which is somewhat similar to the northern sidewall of the Storegga slide (Figure 6). The higher the headwall the more height jumps occur as indicated by single steps of up to 10m. The maximum run out of slide material reached approximately 100km, and the final deposition occurred at 2000 m water depth thus affecting only the upper slope and the base of the slope (Figure 7). The debris flow shows varying sediment material with large sediment blocks concentrating between 1200 and 1550 m water depth and coarse sediments in between showing lineations. The coarse sediments occur all along its pathway terminating at the Valencia channel (Figure 7) (Canals et al., 2000; Lastras et al., 2002, Urgeles et al., 2003). The submarine landslide affected an area of 2200 km^2 (approx. 50 times smaller than Storegga) and has a volume of 26 km^3 (approx. 100 times smaller than Storegga).

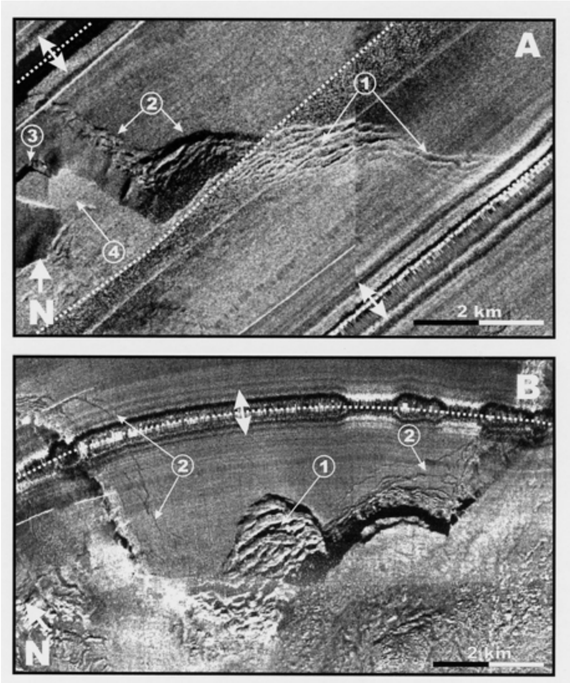

Figure 6: A) TOBi sonograph from the BIG95 headwall showing staircase morphology caused by creeping and retrogression; B) TOBI sonograph from the 90-100 m heigh northern sidewall of Storegga showing subparallel ridges probably due to creeping (from Haflidason et al., 2003, and Canals et al., submitted).

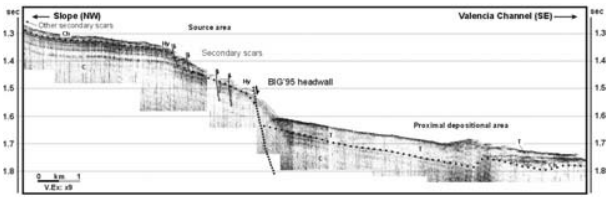

Figure 7: Seabed morphology of the BIG 95 debris flow.

Three sediment units are identified in the failed areas corresponding to post-, syn- and preslide material (Urgeles et al., 2003). The preslide material consists of grey massive sometimes laminated sills (Urgeles et al., 2003). The surface morphology has been mapped using swath bathymetry, side- scan sonar and very high resolution seismic profiling data. The presented submarine landslides of the COSTA project, either on a glaciated or a river dominated margin, involve blocks, which could present rather undisturbed material with a disturbed glide plane at its base. Big 95 is a COSTA slide where rafted blocks cover a large area of about 40% of the total affected slide area (Figure 7 and 8). Based on a morphological division of BIG 95 (Lastras et al., 2002), which is: source area, block-free proximal area below the main headwall, blocky zone in the intermediate area, and depositional distal area with mud flows, this classification may be of value to other submarine slides.

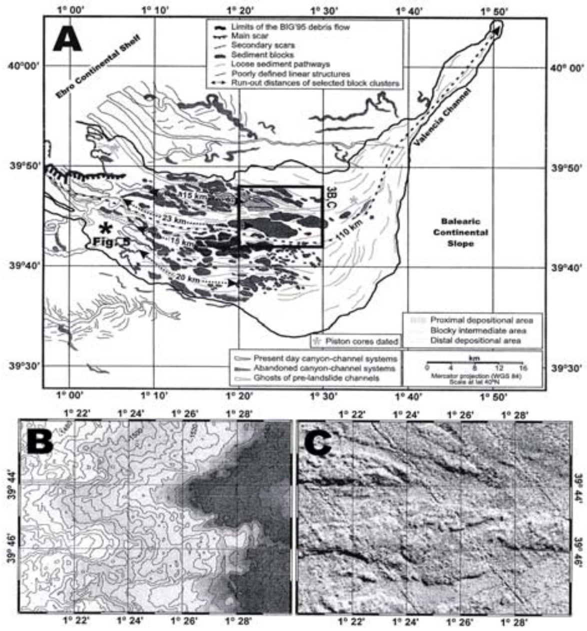

Figure 8: A) Interpretation map of the BIG'95 Slide. Box shows location of B and C: B) Multibeam map of blocky area; and C) Backcatter image of the blocky area .

Block material, such as observed in the Storegga slide scar, and in the BIG 95 area vary largely in size and shape. Long outrunner blocks (LOBs) may exists but they have not been imaged in detail enough. Run-out could be defined as the horizontal distance between the release area and the deposition area. Different slide phases usually involve different materials as seen in Storegga, and therefore have different run outs. Thus, identifying the run out from different events and discriminating the deposits resulting from different events is often more than difficult. There are, however, also debris flows where different elements have different run outs such as observed in BIG 95. Here, blocks released from the main scar and secondary scar moved a few tens of kilometres while a looser matrix reached more than 100km run out. Similar conditions existed in other COSTA slide areas and, with the exception of outrunners, large blocks derived from headwall and upper parts of failed seafloor areas tend to accumulate at short distances from source areas in comparison to the total sediment run-out. The largest total run out of the COSTA slides are in excess of 500 km and correspond to the Storegga slides, BIG 95, Traenadjupet, and Gebra slides from an intermediate group with total run outs between 200 and 50 kilometres, while the smaller Afen and Finneidfjord slides show run outs of less than 10 km.

3. WHAT TRIGGERED THE SLOPE FAILURES ON A GLACIATED- AND A RIVER-DOMINATED MARGIN?

Submarine landslides studied within the COSTA project provide excellent examples for passive margins how different pre-conditioning factors and triggers could interact to allow sediment failures during different times and at different sizes. The Storegga slides of Holocene age are the last events of a series of slides taking place in this area of the passive glaciated-dominated mid-Norwegian margin during the last 500 kyrs (Bryn et al., 2003). The precondition factors relate to repeated cycles of climatically controlled sedimentary processes, which are contourite drift sediment deposition at interglacials and rapid glacial debris flow deposition during glacials. Such a situation creates high loads of impermeable glacigenic debris flows on top of permeable marine contouritic sediments. It leads to excess pore pressure and reduced shear strength in the marine contour drift sediments. Ocean warming and gas hydrate melting may even further enhance the excess pore pressure build up in mid to upper slope settings (Mienert, 2004). Enhanced seismicity during deglaciation because of glacioeustatic rebound may be then the final trigger.

The best representative for a river-dominated margin within the COSTA project is the BIG95 slide. Her, past depocenters of the Ebro river mouth are located on the outer shelf and upper slope above the main scar. During sealevel low stands high loads of siliciclastic material spilled over the shelf edge. The presence of shallow gas in prodelta sequences has been observed and it is very likely that they also have existed in former slope sediments decreasing the shear strength of sediment layers. A volcanic dome beneath the main scar, may have contributed to differential compaction and oversteepening of these margin areas (e.g. Gruenthal et al., 1999). The preconditioning factors for a slide are therefore different from the glacial-interglacial pattern observed on the formerly glaciated mid-Norwegian margin. However, the final trigger of the BIG95 might have been an earthquake since instrumental records show frequent earthquakes of magnitude 4-5, but also larger earthquakes are known to occur. Based on seabed imaging, 3D seismic data and geotechnical coring studies a much better understanding of the different cumulative preconditioning factors have been reached which are partly climate driven, but our final trigger for slope failures to occur is still an earthquake.

In the future, we attempt to improve the dating of slides to better understand their relation to climate driven sediment flux as well as sea level changes. A better understanding of the pore pressure build up in different geological settings is to be achieved. This work is to be carried out in cooperation with the newly established International Centre of Geohazards in Norway (ICG) which is a partner in EUROMARGINS.

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