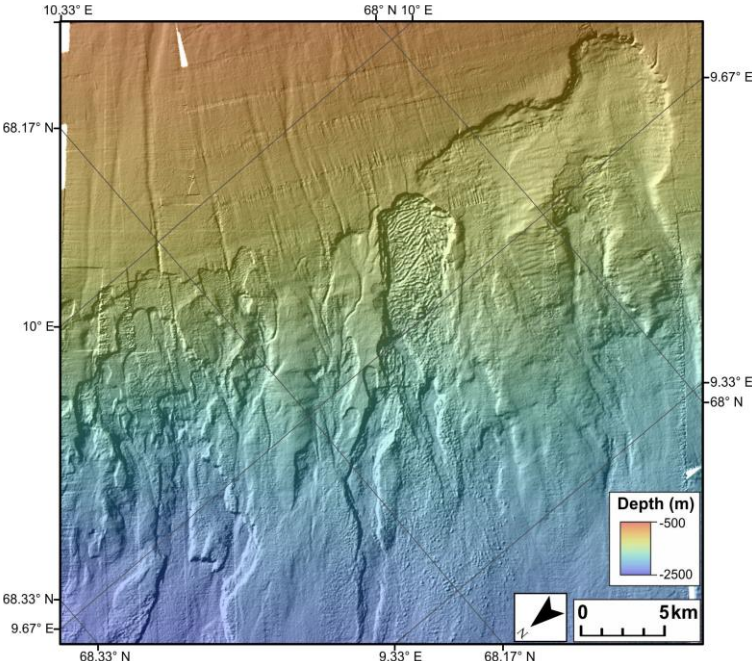
UNIVERSITY OF TROMSØ UIT

Faculty of Science
Department of Geology

Mass movements on the continental slope offshore Lofoten, Northern Norway



Nicole Jeanne Baeten

A dissertation for the degree of
Philosophiae Doctor

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Papers 1, 2 and 3

Preface

My PhD-thesis was carried out at the Department of Geology, Faculty of Science and Technology, at the University of Tromsø, Norway, from June 2009 until May 2013.

The study is a contribution to the project *Sea floor stability offshore Lofoten, Northern Norway* (LOSLOPE) and was primarily funded by the PETROMAKS program of the Research Council of Norway, with additional support from the UNESCO program Training Trough Research (TTR).

The LOSLOPE project itself is a collaboration project between the University of Tromsø and the Norwegian Geotechnical Institute (NGI) and Offshore Geohazards initiative of the International Centre for Geohazards (ICG) hosted at NGI in Oslo. The work was supervised by Jan Sverre Laberg, Tore O. Vorren, and Matthias Forwick at the University of Tromsø, as well as Maarten Vanneste, Carl Fredrik Forsberg, and Tore Kvalstad at NGI. While most of the work was carried out at the University of Tromsø, I visited ICG/NGI particularly for the integration of the geotechnical analyses and slope stability assessment with the sedimentological and geophysical data. Furthermore, I spent five months during the autumn of 2012 at the Geological Survey of Canada at the Bedford Institute of Oceanography (BIO) in Dartmouth, Nova Scotia, Canada, hosted by David Mosher, to analyze data for this thesis.

Parts of the data were collected during a cruise with RV *Professor Logachev* led by Michael Ivanov in 2008 and with RV *G.O. Sars* led by Haflidi Haflidason in 2010.

During the PhD, I participated in workshops and international conferences (e.g. Submarine Mass Movements and Their Consequences 2009 and 2011; EGU 2011) to present progress and results of the study, using posters and oral presentations.

This thesis consists of an introduction and three scientific papers, providing new information about the seafloor stability and the temporal and spatial occurrence of smaller-scale mass movements off Lofoten, northern Norway. These three papers are:

Baeten, N.J., Laberg, J.S., Forwick, M., Vorren, T.O., Vanneste M., Forsberg, C.F., Kvalstad, T.J., Ivanov, M**.,** 2013. *Morphology and origin of smaller- scale mass movements on the continental slope off northern Norway*. Geomorphology 187, 122-134.

Baeten, N.J., Laberg, J.S., Forwick, M., Vorren, T.O., Vanneste, M., Forsberg, C.F., Kvalstad, T.J., Haflidason, H., in prep. *Sedimentological and geotechnical analyses of shallow mass movements on the northern Norwegian continental slope*.

Baeten, N.J., Laberg, J.S., Forwick, M., Vorren, T.O., Vanneste, M., Forsberg, C.F., submitted to Marine geology. *Neogene – Quaternary contourite drift growth and mass-movement activity on the continental slope offshore Lofoten, northern Norway*.

Acknowledgements

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I am very grateful to my colleagues and friends at the University of Tromsø, for inspiring discussions but also for the social input: Kari, Juho, Andreia, Chiara, Steffen, Kasia, Diane, Sarah, Kjetil, Tom Arne, Andrea, Mariana, Julia, and especially Eythor, Noortje, Philipp and Marianne, for all the trips and for sharing everyday life at the institute.

I am grateful to the captains and crew and participants of scientific cruises on RV *Professor Logachev*, RV *Jan Mayen* (now *Helmer Hanssen*) and RV *G.O. Sars*, especially Steinar Iversen for essential support during the acquisition of data, to Trine Dahl, Edel Ellingsen and Kristine Hansen for their help in the lab, and to Jan P. Holm for help with some figures, and for always answering my questions.

I would like to thank all the people at the Bedford Institute of Oceanography in Halifax for my stay there, especially David Mosher and Calvin Campbell, for their help with the processing and interpretation of the seismic data, and for including me into the working group. I would also like to thank David Piper and Francky Saint-Ange, for fruitfull discussions and Kevin McKillop for his help with understanding the geotechnical results.

And a big thanks to the King family for including me into their family and making it such a fantastic stay!

I would like to thank some of my fellow marine geologists that I have met over the years at conferences, cruises and workshops. Anna Reusch for the great times at courses and conferences, Nicola Dakin for our fantastic trip in Japan. Elias Tahchi for his encouragement. Aggeliki Georgiopoulou for her help with my XRF data. Jean-Sebastien L'Heureux for his help with my geotechnical data. And a very special thanks to Aaron Micallef, for inspiring me and for his endless help and support on the other side of my skype-connection.

Finally I would like to thank Werner for his support and for giving me a reason to smile during the last months of writing, Fredrik for being my brother here in Tromsø when my own family was far away. My parents, brothers and sisters in the Netherlands for believing in me and for their support, Suus en Michelle for the great trips and Michelle for always being there for me.

1. Introduction

Submarine mass movements on continental margins are of interest, not only to understand the re-mobilization and deposition of large volumes of sediments from the upper slopes and outer shelves into the deep ocean basins, but also for estimating and ultimately properly assessing the risks related to mass-movement impact on offshore infrastructure and coastal communities (e.g., Locat and Lee, 2000; Canals et al., 2004; Zakeri, 2008; Leynaud et al., 2009; Yamada et al., 2012). Mass movements represent a major threat to exploration and exploitation of offshore natural resources including oil and gas, communication routes and seabed infrastructure, coastal developments (cities, harbours), and the marine environment in general. This necessitates the need for detailed investigations on submarine slope stabilities, to improve our understanding of their occurrence and frequency, to identify the geological and environmental factors contributing their origin and the processes involved in landslide dynamics and retrogression (e.g., Locat and Lee, 2000; Canals et al., 2004; Leynaud et al., 2009; Yamada et al., 2012).

1.1 Submarine mass movements on glaciated continental margins

1.1.1 Glaciated continental margins

The morphology of the shelves of previously glaciated continental margins has to a large extend been shaped by glacial processes during glacial-interglacial cycles (Fig. 1; e.g. Vorren, 2003). The ice sheets and ice streams have eroded the continental shelf forming glacial erosional features as large troughs, demonstrated to have been the drainage route for the paleo-ice streams. Glacial lineations are often developed within these troughs, showing the position and dynamics of paleo-ice streams draining the ice-sheet during glaciations. Iceberg plough marks or iceberg furrows form when keels of icebergs exceed the water depth and are therefore able to erode the seafloor sediments. Moraines or morainal banks are depositional features, often accumulating at the outermost edge of an ice-sheet or ice-stream. They can be used to document the outermost position or the retreat of the ice. Sediment supply from the ice-sheets were mainly delivered to the shelf break by ice-streams, and deposited onto trough-mouth fans on the continental slope. Trough-mouth fans are fans that build out at the mouths of transverse troughs on the shelf and are mainly composed of glacigenic debris flows (Vorren et al., 1989; Laberg and Vorren, 1995, 1996; King et al., 1996; Vorren and Laberg, 1997; Vorren et al., 1998). Other morphological elements on the continental slopes are cayons, gullies and channels, submarine slides and corresponding accumulations, and contourite drifts (Fig. 1; e.g. Vorren, 2003).

The glacial history in an area has had a distinct effect on the geotechnical properties of the sediments. On the shelf, the sediments are typically overconsolidated where they have been covered by sluggish ice. Sluggish ice occurs between the more active ice-streams. Ice-streams do not necessarily overconsolidate the sediments because the ice is carried by excess pore pressure taking most of the weight of the ice rather than transferring it to the soils (e.g. Bryn et al., 2005; Solheim et al. 2005).

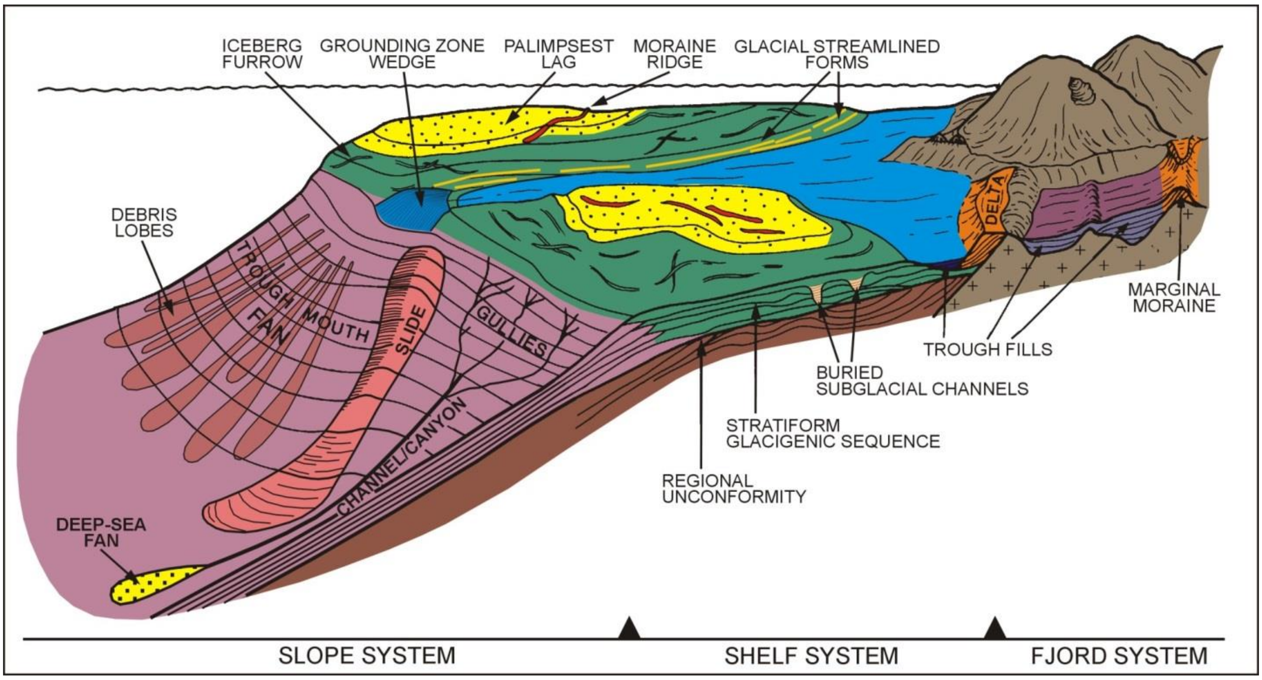

Fig. 1 Model showing the main glacigenic morphological elements and lithofacies of a passive glaciated continental margin. The figure was adapted from Vorren (2003).

1.1.2 Distribution of submarine mass movements

Mass movements are common phenomena on the North Atlantic, Arctic and Antarctic glaciated and formerly glaciated continental margins (e.g. Bugge, 1983; Kristoffersen et al., 1987; Bugge et al., 1987; Kenyon, 1987; Laberg and Vorren, 1993, 2000; Vorren et al., 1998; Elverhøi et al., 2002; Imbo et al., 2003; Laberg et al., 2003; Canals et al., 2004; Dowdeswell et al., 1996; Mosher et al., 2004, 2009; Haflidason et al., 2004; Piper and Campbell, 2005; Vanneste et al., 2006; Leynaud et al., 2009).

One of the best known examples is the Grand Banks event on the Canadian continental margin following a 7.2 magnitude earthquake in 1929 (e.g. Heezen & Ewing, 1952; Piper et al., 1999). This slope failure transformed into a debris flow, generating a turbidity current that cut off submarine telegraph cables. This event is perhaps the most famous historic submarine landslide because it led to the first formal recognition of turbidity currents and its damage to an engineering structure (e.g. Heezen et al. 1954).

Some of the largest submarine slides occur on the formerly glaciated Norwegian - Barents Sea - Svalbard margin (Fig. 2). Key examples are the Storegga Slide (Bugge et al., 1987; Evans et al., 1996, 2005; Haflidason et al., 2004; Bryn et al., 2005a; Forsberg and Locat, 2005; Kvalstad et al., 2005; Solheim et al., 2005), the Trænadjupet Slide (Laberg and Vorren 2000; Laberg et al., 2002, 2003, 2006; Laberg and Camerlenghi, 2008), the Bjørnøya Slide (Laberg and Vorren, 1993) and the Hinlopen-Yermak Slide (Vanneste et al., 2006; 2011; Winkelmann et al., 2006). Several of them developed off or at a short distance from the mouth of glacial troughs, occupied by fast moving ice streams during glacial times (Canals et al., 2004).

Smaller-scale slides dominate other parts of the Norwegian continental slope (Fig. 2), including the Storfjorden and Kveithola Through Mouth Fan (Pedrosa et al., 2011), the continental slope offshore Vesterålen (Rise et al., 2012) and Lofoten (Bugge, 1983; Kenyon, 1987; Yoon et al., 1991), and within some of the fjords in Norway and on Spitsbergen (e.g. Longva et al., 2003; Forwick et al., 2012; L’Heureux et al., 2012).

Large-scale submarine slides seem to be much scarcer on the Antarctic glacial margin than along the northern hemisphere glacial margins. It is however possible that this is due to the fact that there is far less data available from the Antarctic margins. One of these slides is the Gebra Slide, located on the northern tip of the Antarctic Peninsula (Imbo et al., 2003).

1.1.3 Size and sediment volume involved

The slide scar areas and displaced volumes on glaciated continental margins are typically much larger than slope failures occurring on river-fed or volcanic margins (Vanneste et al., 2006). However, their sizes differ greatly. They affect areas ranging between 95,000 km^2 for the Storegga Slide and 1 km^2 for Finneidfjorden, mobilizing volumes of 2400-3200 km^3 and 0.001 km^3 respectively (Longva et al., 2003; Canals et al., 2004; Haflidason et al., 2005).

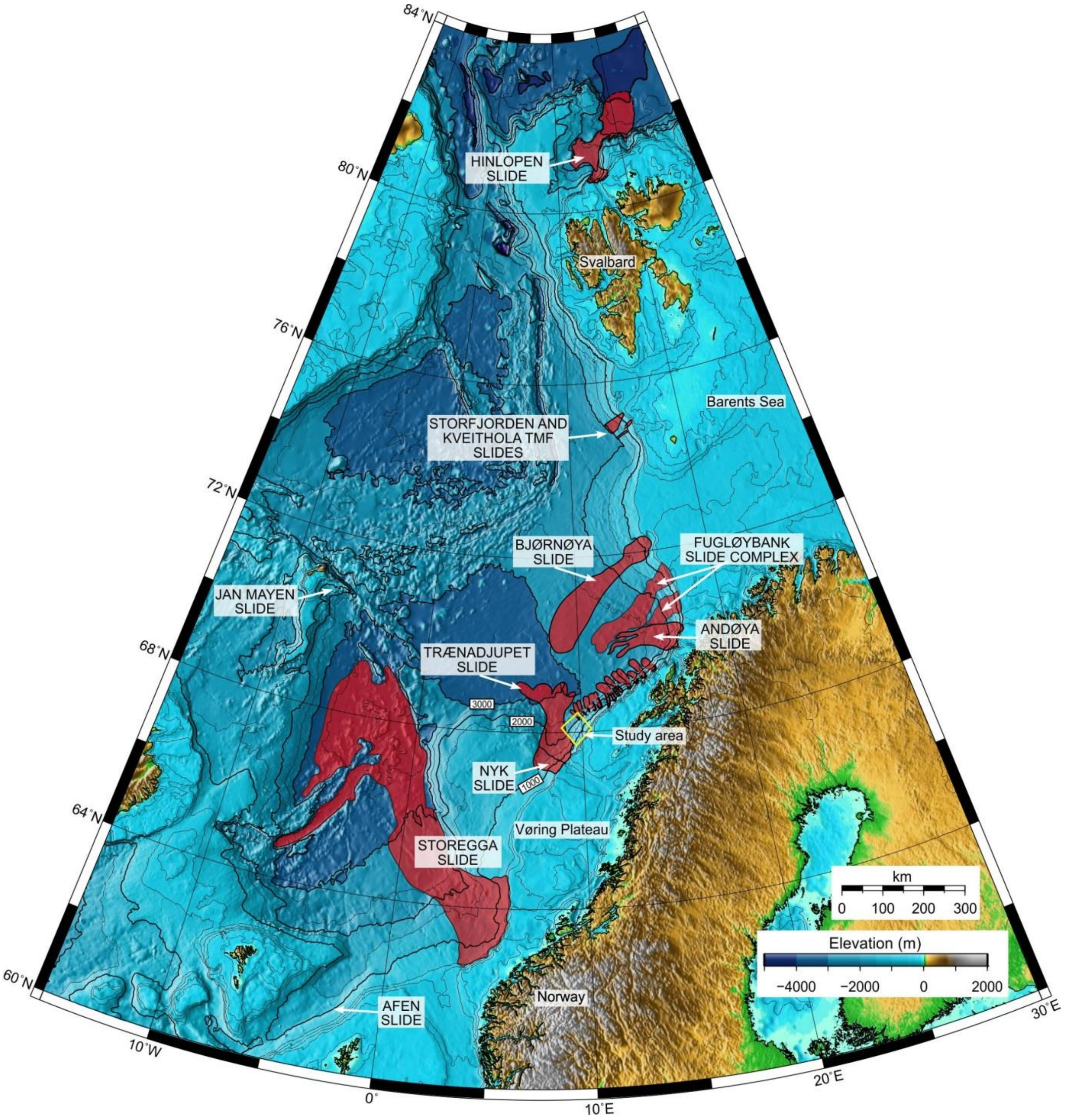

Fig. 2 Overview of the mass movements on Norwegian-Barents-Svalbard margin. The study area is indicated in yellow. The figure was summarized from e.g. Bygge (1983); Laberg and Vorren (1993, 2000); Laberg et al. (2000); Haflidason et al. (2004); Lindberg et al. (2004); Wilson et al. (2004); Vanneste et al. (2006); Pedrosa et al. (2011); Rise et al. (2012), and references therein.

The Trænadjupet Slide (Fig. 2) affected an area of about 14,000 km^2 and mobilized about 900 km^3 of sediments (Laberg et al., 2002). The Hinlopen-Yermak landslide (Fig. 2) has a headwall area of 2200 km^2, mobilized about 1350 km^3 of sediments, and is characterized by extreme headwall heights exceeding 1 km (Vanneste et al., 2006, 2011). The Bjørnøya Slide, the exposed part of the Bjørnøya Slide Complex (Fig. 2), was estimated to have mobilized 1100 km^3 of sediments (Laberg and Vorren, 1993). Older buried slides within the Bjørnøya

Slide Complex involved 25000 km^3 of sediments, thus containing an order of magnitude more sediment than the Storegga Slide, which is inferred to be the world's largest exposed slide (Hjelstuen et al., 2007). One of the smaller slides, the Afen Slide (Fig. 2 for location), has affected an area of 40 km^2 and mobilized about 0.2 km^3 of sediments (Wilson et al., 2004).

1.1.4 Timing and frequency

The frequency of large scale mass movements is lower on glaciated continental margins compared to non-glaciated margins. However, the total volume of remobilized sediments from mass wasting is much larger on the glaciated margins (Maslin et al., 2004; Leynaud et al., 2009). On the Norwegian margin, one mega-slide seems to have occurred approximately every 100 kyr (Fig. 3; Solheim et al., 2005; Leynaud et al., 2009).

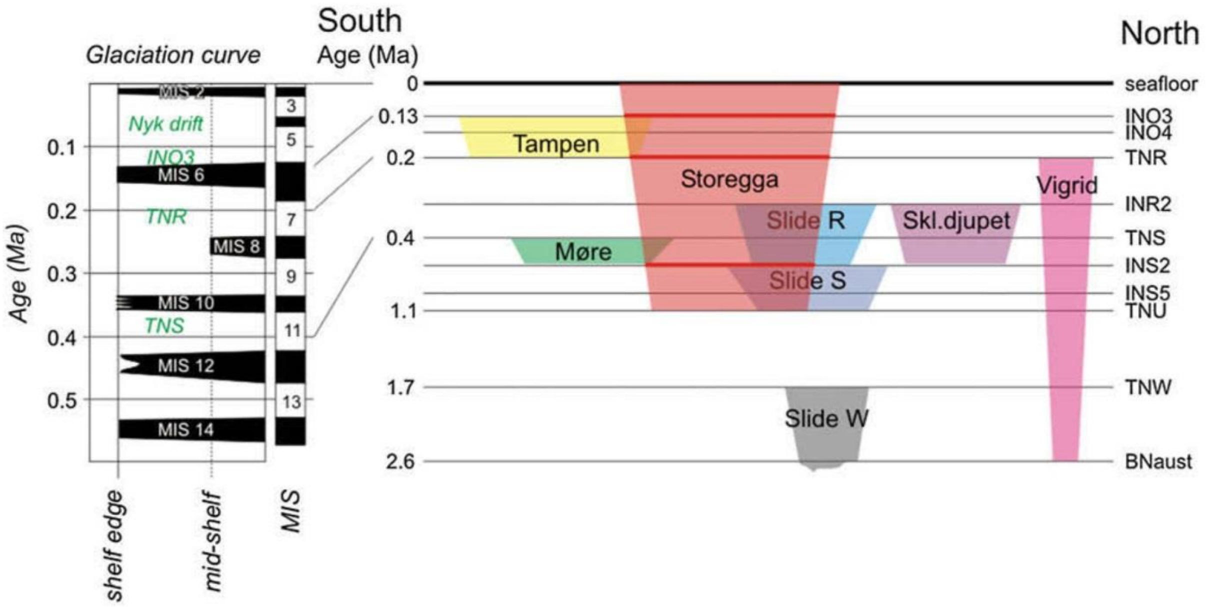

Fig. 3 Stratigraphy (after Solheim et al., 2005) of mid-Norwegian submarine slides showing 100 kyr cyclic instability during the last 500 ka. The names in right part of the sketch (INO3 etc.) refers to the seismic horizons corresponding to the repetitive glide planes in the area (bottom boundary) and are also used to define the timing of the slides (upper boundary). From Leynaud et al., 2009).

Many of the most recent mass movements on glaciated margins have occurred in a time frame between the last glacial maximum, until about five thousand years after the end of the glaciation (Lee et al., 2009). The Gebra Slide was initiated sometime during the transition from the Last Glacial Maximum to the current interglacial (13,500-6500 yr BP; e.g. Imbo et al., 2003). The Storegga region has been the site of a number of large-scale mass movements (Solheim et al., 2005), with the latest being the Storegga Slide dated at 8100 ± 250 cal. yr BP

(Haflidason et al., 2005). Also within Bjørnøya Fan Slide complex, three buried mega-slides were found to have occurred between1.0-0.2Ma (Hjelstuen et al., 2007).

The Trænadjupet landslide, dated at 4000 ^{14}C yr BP (Laberg and Vorren, 2000; Laberg et al., 2002, 2003), is one of the most recent mass movements on the Norwegian continental margin. The older Nyk landslide partly affecting the same area (Fig. 2), was dated to have occurred at about 16,000 ^{14}C yr BP (Lindberg et al., 2004).The Hinlopen-Yermak Slide, or at least its last phase, likely happened before Last Glacial Maximum (Vanneste et al., 2006).

The smaller-scale mass movements on the Vesterålen margin are thought to have middle-Weichselian to Holocene ages (Rise et al., 2012). Smaller mass movements within the fjords are most recent, as for example the 1996 Finneidfjorden landslide (e.g. L'Heureux et al., 2012).

1.2 Processes of sediment evacuation and flow

Submarine mass movements are initiated when the shear stress oriented downslope (driving shear stress) exceeds the shear strength (resisting stress) of the slope-forming material (Fig. 4; Hampton et al., 1996). In infinite slope equilibrium, the Factor of Safety (FoS) is defined as the shear strength divided by the shear stress. A slope is considered stable when FoS > 1 and unstable when FoS < 1.

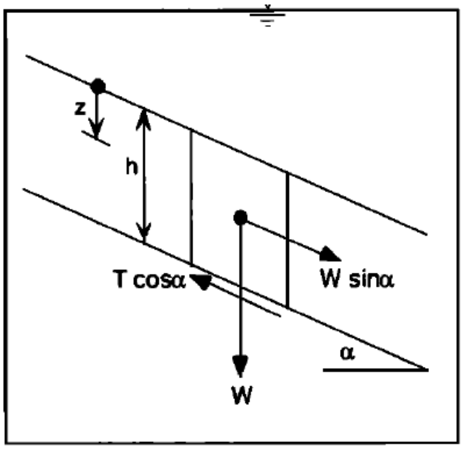

Fig. 4 Sketch illustrating the forces acting on a slice in a submarine infinite slope. Parameters are: T cos α = shear resistance of the sediments; W sin α = gravitational shear stress acting in the direction of potential movement; W, vertical component of body force of the slice; z, depth in sediment; h, height of slice; and α, slope angle. From Hampton et al., 1996.

Following initial failure, some mass movements may disintegrate and, depending on their rheology and external conditions, develop into a debris flow and also produce turbidity currents, whereas others can remain as slides and slumps with limited run-out or little internal deformation (Locat and Lee, 2000; Elverhøi et al., 2002).

Mass movements on formerly glaciated margins show clear resemblances in morphology and landslide development. The majority of mass movements on the Norwegian-Barents-Svalbard margin are translational in nature (Canals et al., 2004). In general, translational landslides have more or less planar failure surfaces, translational sediment displacement, and they commonly occur in sediment packages containing distinct bedding planes (Allen, 1985; Hampton et al., 1996).

Mass movements on glaciated continental margins are shaped by a number of different processes, two of these that have played a significant role in the development are spreading and retrogression.

1.2.1 Spreading

Spreading is a mass movement process in which a slab of sediment undergoes extension on a deforming soft layer. It is often characterized by a ridge-and-trough morphology at a variety of scales, oriented perpendicular to the direction of mass movement (Fig. 5; Haflidason et al., 2004; Micallef et al., 2007). It is a significant and widespread style of submarine mass movement worldwide that tends to occur over relatively large regions and on gently sloping terrain that superficially would appear stable (Micallef et al., 2007).

Spreading has been reported from the Trænadjupet Slide (Laberg and Vorren, 2000; Laberg et al., 2002), Storegga Slide (Fig. 5; Haflidason et al., 2004; Kvalstad et al., 2005; Micallef et al., 2007) and Hinlopen Slide (Vanneste et al., 2006). Within the Storegga Slide, the distal end of the spread generally collapses over the pre-existing downslope headwall created by the mass movement that triggered the spread, and the sediment either evolves into a debris flow or translates on a different slip surface, preserving the ridge and through morphology (Micallef et al., 2007).

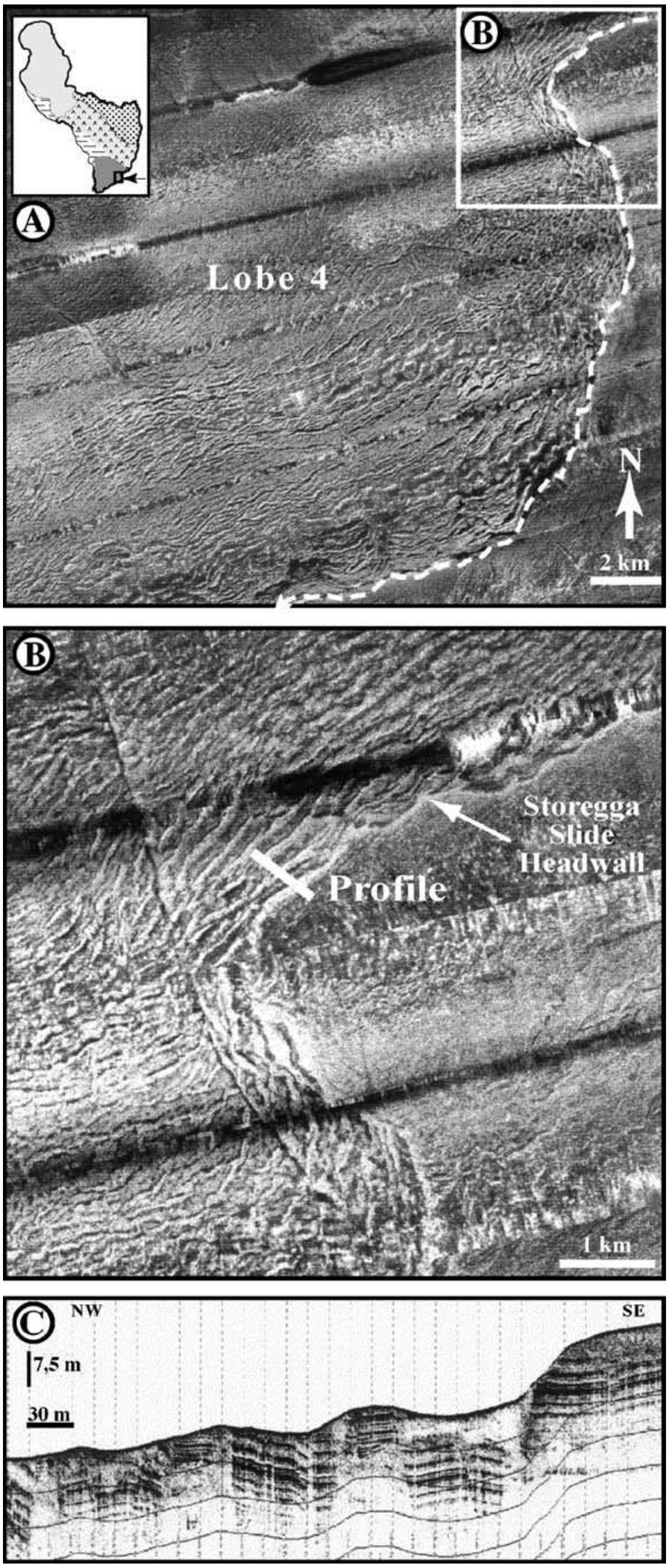

Fig. 5 A and B) TOBI backscatter imagery from the Storegga Slide, showing an example of spreading just below the headwall. The sediments inside the slide moved downslope along a failure plane forming semiconcentric subparallel ridges of a rather uniform size. **C)** The seismic signature on the pinger profile shows that the primary stratigraphy of the sub-seabed sediments is still preserved within these blocks/ridges after downslope movement. From Haflidason et al., 2004.

Besides spreading, localized events of compression also occur for example in the Storegga Slide (Haflidason et al., 2004; Micallef et al., 2007). Compression is suggested by the presence of groups of high convex-downslope ridges and troughs (e.g. Prior et al., 1982; Haflidason et al., 2004; Lindberg et al., 2004; Lastras et al., 2006; Micallef et al., 2007). Compression can be attributed to the several factors, as for example a decrease in the gradient of the slip surface. The morphological signature of compression is a series of ridges and troughs that tend to be longer and more pronounced than those formed by extension.

1.2.2 Retrogression

The majority of mass movements on the Norwegian-Barents-Svalbard margin have developed retrogressively in multiple phases (Canals et al., 2004; Leynaud et al., 2009). Several morphological features are indicative of retrogressive and multi-phase landslide development including spreading, the occurrence of detachment ridges and a staircase headwall configuration, which shows that slip planes at different levels within the stratigraphy are being utilized (Laberg and Vorren, 2000; Kvalstad et al., 2005; Vanneste et al., 2006; Micallef et al., 2007). The headwalls can be located hundreds of meters apart, and represent successions of major and minor events.

Strain softening is an important mechanism within retrogression, and is a typical behavior of marine clays on the Norwegian continental slope. When subjected to large strains, the marine clays show contractive behavior causing increased pore pressure and a reduction in strength. Sliding activity can generate progressive softening of sediments within a sensitive base layer as the slide retrogressively spreads upslope and also laterally. This process was used to model the retrogressive development within the Storegga Slide (Fig. 6; Kvalstad et al., 2005). Movement within the Storegga Slide is believed to have started on the mid to lower slope, and then developed retrogressively (Bryn et al., 2003).

The Afen Slide is less complex, but shows the same structure. Two or more main escarpments, as also observed for the Gebra Slide, could have been generated both from one single event, as interpreted for the Grand Banks Slide (Piper et al., 1999), or from a succession of upslope back stepping events as within the Trænadjupet Slide (Laberg & Vorren, 2000; Canals et al., 2004).

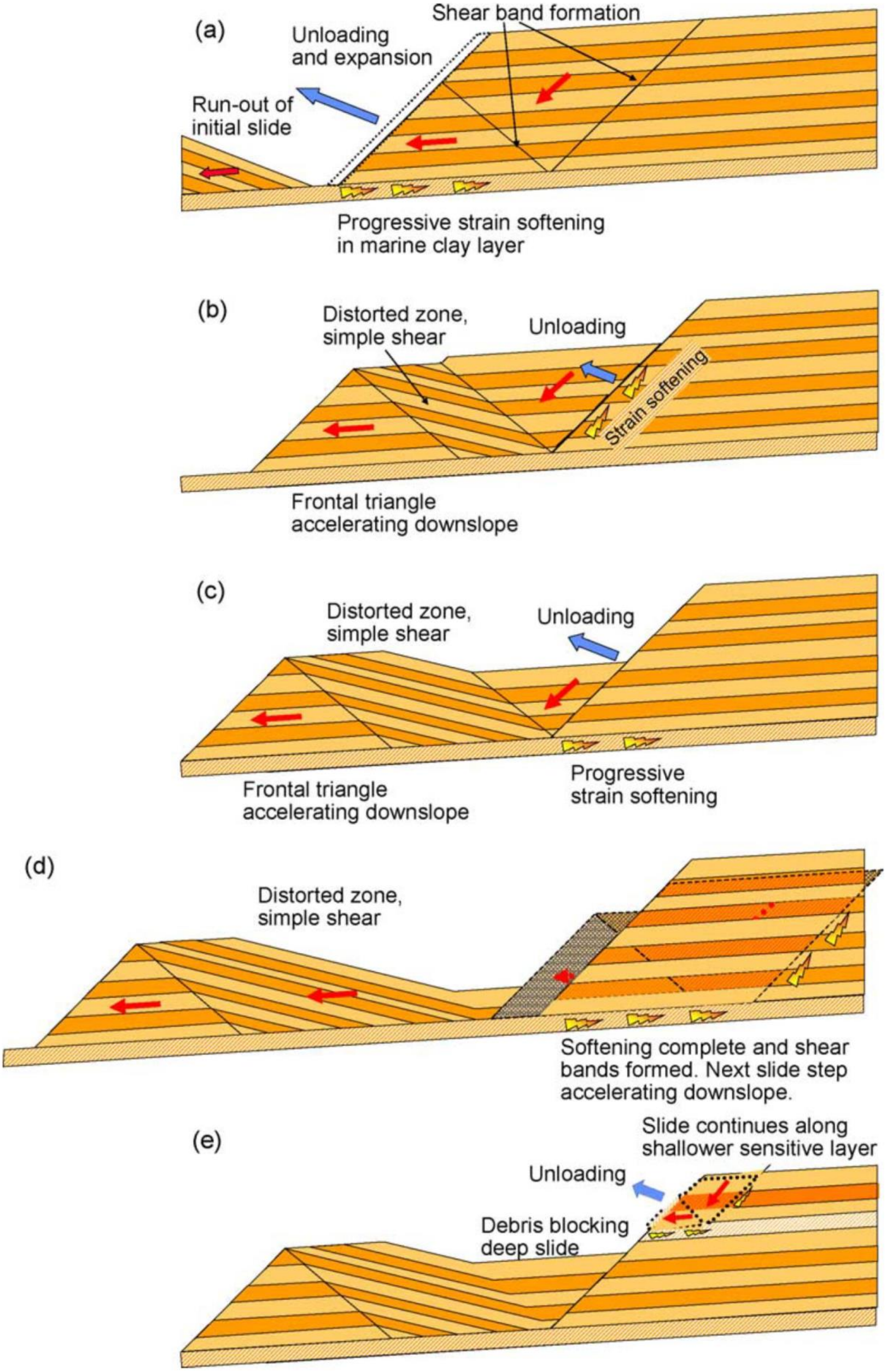
(a)
Shear band formation
Unloading
and expansion
Run-out of
initial slide
Progressive strain softening
in marine clay layer
(b)
Distorted zone,
simple shear
Unloading
Strain softening
Frontal triangle
accelerating downslope
(c)
Distorted zone,
simple shear
Unloading
Frontal triangle
accelerating downslope
Progressive
strain softening
(d)
Distorted zone,
simple shear
Softening complete and shear
bands formed. Next slide step
accelerating downslope.
(e)
Slide continues along
shallower sensitive layer
Unloading
Debris blocking
deep slide

Fig. 6 A retrogressive slide model showing, **a)** development of the initial slide in the lower part of the slope. The unloading of the headwall causes strain softening in the toe area of the headwall. **b)** The factor of safety decreases below unity and failing soil mass starts to accelerate downslope. **c)** A triangular front wedge is formed, being pushed along the slide base by a gradually distorted rhomb and triangular wedge creating a graben behind the front wedge, forming a new headwall. **d)** The released energy is partly consumed as friction along the base and circumference of the slide mass, and partly in remolding of the slide material along the slide base and internally in the distorted slide mass. Excess potential energy is transformed to kinetic energy accelerating the slide mass further downslope. The reduction in strength gives sufficient mobility to unload the next headwall and the process repeats itself until soil strength, layering or geometry change sufficiently to reduce mobility and decelerate the sliding process. **e)** If the mobility is too low, the slide mass will block further retrogression along the base layer and the process will, if possible, continue along shallower marine clay layers, creating steps in the slide base as observed in the Storegga Slide. From Kvalstad et al., 2005.

Within the Hinlopen Slide, the retrogressive nature is supported by the huge amount of sediments evacuated through the relative narrow bottle-neck, and the presence of detached sediment ridges adjacent to the headwall segments in the eastern part of the slide scar area, in addition to the multiple slip planes/escarpments and the cauliflower headwall morphology (Vanneste et al., 2006).

Most of the large mass movements on the Norwegian-Barents-Svalbard margin retrogress all the way up to the continental shelf break where they were halted when the flat lying, overconsolidated glacial deposits of the continental shelf provided sufficient support, and/or because of changes in the dip angle, as for example with the Storegga landslide and the Hinlopen-Yermak landslide (Bryn et al., 2003; Vanneste et al., 2006).

Exceptions are for example the Gebra Slide (Imbo et al., 2003) and the smaller-scale mass movements on the Vesterålen margin (Rise et al., 2012), where the scars do not reach the shelf edge.

1.2.3 Run-out

The run-out is defined as the horizontal distance between the upper edge of the slide headwall and the most distal point reached by the mobilized sediments during a slide event. Run-out tends to increase with retrogression in multi-staged slides because of continued transport and downslope extension of the released sediments (Canals et al., 2004). Different slide phases usually have different run-outs, with the largest failures in terms of volume having in general the largest run-outs. Run out distances vary from a few hundred meters - 1.5 km for the Finneidfjord and Vesterålen slides (Canals et al., 2004; L'Heureux et al., subm.) to 770 km for the Storegga Slide Slide (Canals et al., 2004). Rafted blocks varying in numbers from a few to hundreds have been identified within most of the mass movements on the Norwegian continental margin (e.g. Canals et al., 2004).

1.3 Preconditioning factors

Preconditioning factors are an important component in the risk assessment of continental slopes. Knowledge of preconditions of sediments that fail and their actual triggering mechanisms has improved following extensive studies throughout the last decade including Laberg et al. (2003), Canals et al. (2004), Bryn et al. (2005a and b), Kvalstad et al. (2005) and Leynaud et al. (2009). The preconditioning factors depend on the regional geological history and the local site conditions. The conditions leading to actual failure often form a complex pattern of interacting processes (Vanneste et al., 2006). There are, however, some factors identified that have played important roles in the majority of mass movements on glaciated continental margins:

(1) High sediment accumulation rates:

Glaciated continental margins have been greatly influenced by the deposition of large volumes of glacigenic sediments forming trough-mouth fans and prograding wedges, with sediment accumulations rates highest during peak glaciations (Fig. 7; e.g. Vorren & Laberg, 1997; Dahlgren et al., 2005; Nygård et al., 2007). Rapid loading of fine-grained sediments may well cause under-consolidation as excess pore pressure developing during sedimentation cannot easily dissipate (depending on the soil's permeability) (Fig. 7). The undrained shear strength of the sediments during the consolidation process depends on the excess pore pressure dissipation (e.g. Leynaud et al., 2009). Excess pore pressure generation due to high sedimentation during peak glacial has been suggested to be an important precondition to failure within the large submarine landslides on the Norwegian continental margin (Fig. 7; e.g. Bryn et al., 2005a, Kvalstad et al., 2005, Leynaud et al., 2007, 2009).

Most of the large landslides are situated close to glacial troughs characterized by high sediment delivery. The Trænadjupet and Storegga slide areas are characterized by modest sedimentation rates (less than 1 m/kyr) during interglacials alternated with significantly higher sedimentation rates (several tens of meters per kyr) at the end of each glacial period. At the Trænadjupet Slide, Laberg et al. (2003) estimated an average rate of 65 m/kyr for the glacigenic sediments (older than 15.5 ka) while for the Storegga Slide, Hjelstuen et al. (2004)

proposed a maximum of 36 m/ka (15.7-15.0 ka) at the northern boundary of the slide complex.

Significant sediment delivery (approximately 800 km^3 during the Late Weichselian; Taylor et al., 2002) onto the North Sea trough mouth fan is inferred to have caused sub-lateral migration of excess pore pressure towards the Storegga area. A similar setting may have existed Bjørnøya trough mouth fan (Hjelstuen et al., 2007).The modeling of excess pore pressure within the Storegga Slide illustrates how excess pore pressure generation could explain the development of layers of weakness, and cause instability on very gentle slopes in the deep subsurface (Leynaud et al., 2007). As such, the Storegga Slide does not coincide with the depocentre during the last peak glaciations, but is related to it (Bryn et al., 2003, 2005a; Kvalstad et al., 2005).

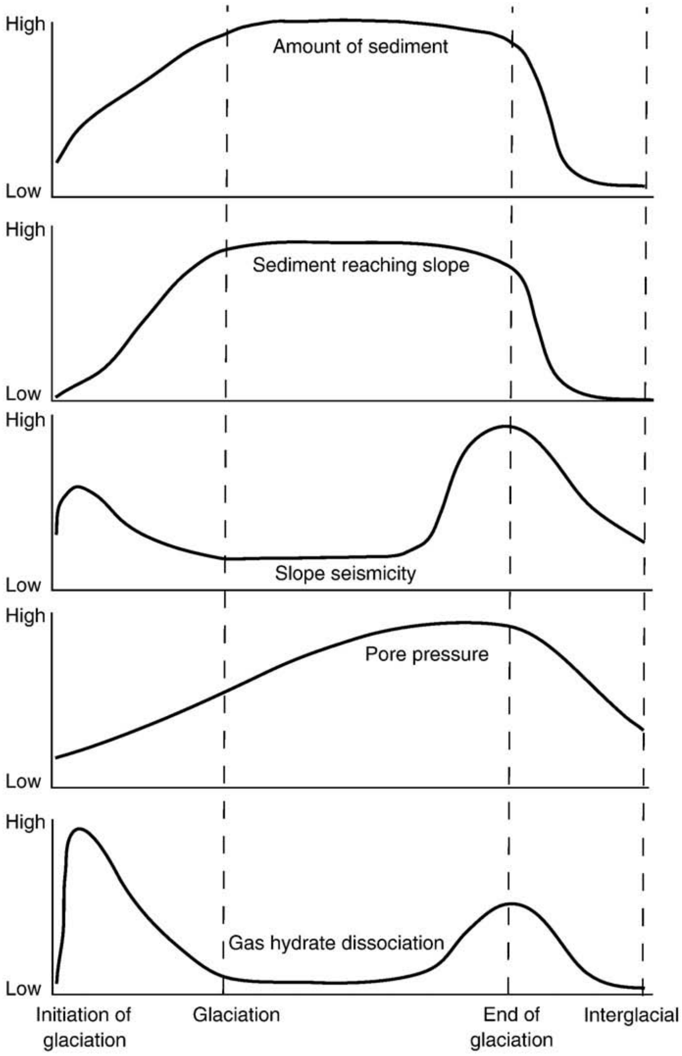

Fig. 7 Approximate impact of time on several factors that influence the stability of submarine slopes. From Lee et al., 2009.

Also in the Trænadjupet Slide area, the glacial and early deglacial high sedimentation rates probably prevented fluid escape from the relatively thin layers of interglacial and interstadial sediments due to the low permeability of glacigenic clays. This led to high pore-water pressure, producing relatively low shear strengths (Laberg et al., 2003).

On the northern Svalbard margin, high sedimentation rates have most likely promoted failure (Vanneste et al., 2006). Drainage trough the Hinlopen Trough is smaller compared to the drainage areas where large landslides have occurred off Norway, or other places along the northern margin of the Quaternary Eurasian ice sheet where major ice streams have fed the upper margin resulting in extensive trough mouth fan system without leading to massive failure. Considering this, the volume released by the Hinlopen Slide is surprisingly high (Vanneste et al., 2006).

(2) Properties of the sediments (contouritic versus glacigenic sediments):

An important parameter in slope stability is the nature or strength of the material making up the slope. The presence of ‘weaker’ sediment layers is often used to explain the failure of several of the large mass movements on the Norwegian - Barents-Svalbard margin. Within the Trænadjupet and Storegga Slide areas, two different types of sediments occur, with distinct geotechnical properties; geotechnically ‘strong’ glacigenic deposits, and geotechnically ‘weak’ marine contouritic sediments (Table 1; Tjelta et al., 2002; Bryn et al., 2003; Laberg et al., 2003; Leynaud et al., 2007, 2009). Contouritic sediments can act as weak layers considering their lower shear strength or higher sensitivity (Laberg et al., 2003), and their strain softening behavior, as discussed in chapter 1.2.2 (Kvalstad et al., 2005).
Contourites therefore provide potential glide planes (Forsberg and Locat 2005; Kvalstad et al., 2005; Laberg and Camerlenghi, 2008). On the Norwegian margin, the glide planes typically occur within hemipelagic/ contouritic sediments (Laberg et al., 2002; Haflidason et al., 2003; Lindberg et al., 2004; Bryn et al., 2003, 2005b). Also within the Afen slide offshore UK, the most likely ‘weak’ layer corresponds to a contourite layer (Wilson et al., 2003).

Table 1 Physical and geotechnical properties of glacigenic versus contouritic sediments within the Trænadjupet and Storegga Slide areas. From Laberg et al., 2003; Tjelta et al., 2002; Leynaud et al., 2007.

Sediment type	Water content (%)	Clay fraction	Sand fraction	Plasticity	Triaxial test behavior
Glacial deposits Trænadjupet Slide	20	25	30	Low to Medium	Dilative
Marine/contouritic deposits Trænadjupet Slide	40	50	10	High	Contractive
Glacial deposits Storegga Slide	< 20	28-35	5-15	Medium to low	Dilative
Marine/contouritic deposits Storegga Slide	>30	>45	Very little	Medium to high	Contractive

(3) Presence of fluids and gas hydrate dissociation:

The stability of gas hydrates depends highly on both temperature and pressure. Changes in these parameters between glacial and interglacial oceanographic conditions can cause dissociation of gas hydrates (Fig. 7; Mosher et al., 2004; Mienert et al., 2005). When gas hydrate is destabilized, it releases free gas and increases pore pressure, which reduces the strength of the sediments. As such, hydrate dissociation can affect the stability of the sediments (e.g. Lee et al., 2009).

Numerous seabed and subsurface fluid escape features exist on the southern Vøring Plateau and the northern Storegga Slide escarpment (e.g. Mienert and Posewang, 1999; Bouriak et al., 2000; Hovland et al., 2005; Reiche et al., 2011). These fluid escape features indicate overpressure and pressure release. A pronounced BSR, indicative for the presence of gas underneath presumably partially hydrate saturated sediments is present underneath the northern flank of the Storegga slide area, within contouritic sediments (e.g. Bünz et al., 2003). Gas hydrate dissociation and the initiation of submarine landslides could thus be connected (e.g. Maslin et al., 2004; Sultan et al., 2004b). There are, however, few studies that unambiguously show that this process indeed caused the submarine landslides (Lee et al., 2009), and several factors appear to contradict such a role (e.g., slip along specific stratigraphic layers). The Storegga Slide was thought to have been caused by gas hydrate dissociation, but more recent studies show that gas hydrates were not the major factor in causing the failure (Bryn et al., 2005a; Kvalstad et al., 2005).

(4) Slope angle:

In general, the stability of the slope also depends on the dip angle, as the downslope force increases with increasing dip (Fig. 4). However, submarine landslides occur on slopes of virtually every angle, although the majority occurs on slopes between 2º and 20º. It is, therefore, a poor indicator of susceptibility to mass movement (Hühnerback and Masson, 2004), and does not significantly influence the occurrence of mass movements on glaciated margins (Canals et al., 2004; Leynaud et al., 2009). However, when the slope does fail, it is typically initiated along its steepest part.

1.4 Triggering mechanisms

A triggering mechanism is an external stimulus that initiates the slope instability process (Sultan et al., 2004a). A trigger, or a combination of triggers, are often necessary to destabilize sedimentary packages already prone to failure because of a set of preconditioning factors as discussed in chapter 1.3 (e.g. Canals et al., 2004).

A number of factors may trigger mass movements along continental margins, including earthquakes, seismic loading, tsunamis, climatic changes, sea-level fluctuations, diapirism, fluid seepage, gas hydrate destabilization, oversteepening of the margin, loss of support at the base of the slope and human activity on or affecting the seafloor (Locat and Lee, 2002; Canals et al., 2004). In many cases, however, the actual triggers setting of the submarine landslides are poorly constrained. The most important mechanisms relevant for glaciated continental margins are discussed underneath.

(1) Seismic activity:

Earthquakes are among the most obvious and best known triggering mechanisms for submarine slides both on glaciated and non-glaciated margins (Leynaud et al., 2009). In many cases, an earthquake is the final external trigger required to initiate submarine mass movement (e.g. Canals et al., 2004). Earthquakes can result from tectonic movements and caused by glacio-isostratic readjustment during and following deglaciation when the ice sheet melts and sea level rises (Fig. 7; Bugge, 1983; Bugge et al., 1987; Gudmundsson, 1999; Bryn et al., 2003; Bungum et al., 2005; Lee et al., 2009). Seismicity due to glacio-isostacy is a more likely cause on formerly glaciated continental margins. Seismic activity offshore Fennoscandinavia was higher following isostatic rebound from 10 ka to the present (Fig. 7; Bryn et al., 2003; Bungum et al., 2005). Earthquakes can induce excess pore pressure generation, which can lead to the liquefaction of the sediments (Leynaud et al., 2009).

One of the most famous examples is probably the 7.2 magnitude Grand Banks earthquake (Piper et al., 1999). Also the Storegga Slide was probably triggered by an extremely strong earthquake with a very low probability of occurrence (Kvalstad et al., 2005) which altered a weak equilibrium between acting and resisting forces within fine-grained contouritic deposits. The Trænadjupet slide was most likely also triggered by one large or a series of smaller earthquakes possibly due to the postglacial crustal uplift of Fennoscandia (Laberg and Vorren, 2000).

The Gebra Slide on the Antarctic margin may be triggered an earthquake (Imbo et al., 2003). And also on the Canadian margin, many of the observed failures result from rare passive margin earthquakes (Piper et al., 2003).

(2) Loss of support:

A unit can lose its support due to a mass movement occurring further downslope. This is a common trigger mechanism for spreading within mass movements, or for retrogression of a mass movement further upslope. This process was suggested for the Storegga Slide (e.g. Kvalstad et al., 2005; Micallef et al., 2007). Similarly, within the Hinlopen Slide, the removal of support at the toe subsequently led to failure of the adjacent slopes in several phases (Vanneste et al., 2006).

(3) Changes in climate:

Climatic control on mass movements is exerted in various ways. An increase in bottom water temperature or lowering of sea level induces gas-hydrate dissociation, generation of free gas and pore pressure build up, therefore reducing the strength of the sediments (Lee, 2009).

Climatic variations control glacial advances and retreats, which as discussed above, can cause significant stress changes in the sediments because of high sediment accumulation rates, the deposition of sediment types with contrasting physical properties and permeability. They are also at the origin of isostatic adjustments causing seismicity (e.g. Yamada et al., 2012).

1.5 Tsunami potential

In general, factors including volume, velocity and initial acceleration of the moving mass are key parameters for the generation of tsunamis (Bondevik et al., 2005; Løvholt et al., 2005). The Storegga Slide produced a tsunami of which the deposits have been observed around the Norwegian Sea and the North Sea, and along the northeast coast of England (Bondevik et al., 2005). The deposits were found at onshore elevations of up to 10-12 m in Norway, 3-6 m in northeast Scotland and above 20 m on the Shetland Islands above the estimated sea level at the time of failure.

2. Study area and aims of the study:

2.1 Study area

The study area is located on the continental slope offshore the Lofoten Islands, northern Norway, between 300 and 2500 m water depth. It covers an area of about 2700 km^2 (Fig. 2 and 8). The continental slope generally dips up to 5^o, which is relatively steep compared to the rest of the Norwegian continental margin (Vorren et al., 1998). A marked reduction in slope angle to about 1° occurs at the base of the slope (at about 2800 m), leading to the Lofoten Basin that reaches a maximum depth of about 3200 m (Fig. 8).

Along-slope sediment transport has provided the main sediment supply to the study area (Laberg et al., 1999, 2002). Along-slope surface currents have caused erosion, sediment transport and deposition on the outer continental shelf and upper slope, whereas contourite drifts have developed further downslope. The Lofoten Drift is a contourite drift located on the continental slope north-east of the study area (Laberg et al., 1999, 2001; Laberg and Vorren, 2004). Recently acquired data indicate that the Lofoten Drift is larger than previously thought and that it extends into the study area (this study; Fig. 8). Part of the drift deposits have been affected by smaller-scale mass movements and the larger Trænadjupet and Nyk landslides have affected the continental slope immediately south of the study area (Laberg and Vorren 2004; Lindberg et al., 2004; Fig. 8).

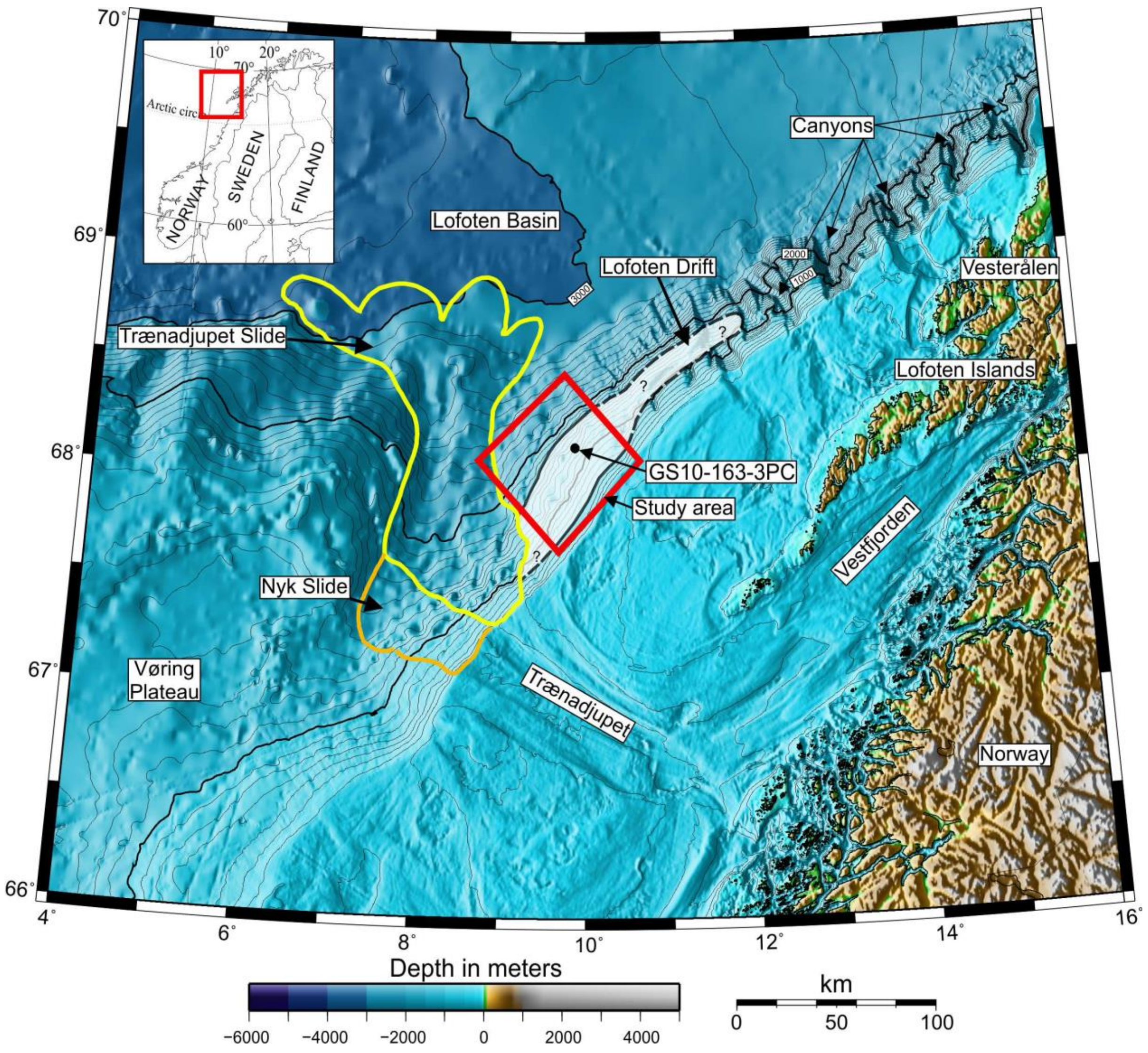

Fig. 8 Location map (inset) and bathymetric map of the continental slope off the Lofoten Islands, northern Norway, using IBCAO Version 3.0 (Jakobsson et al., 2012). The study area is outlined by the red polygon, and the location of cores GS10-163-3PC is indicated with a black dot. Location of the Nyk and Trænadjupet slide from Lindberg et al. (2004) and Laberg et al. (2002) and of the Lofoten drift from Laberg and Vorren (2004). The continuation of the drift within the study area is a result of this study.

2.2 Aims of the study

Whereas the larger-scale mass movements (as the Storegga Slide) have received considerable interest, little attention has been paid to the smaller-scale mass movements. Smaller-scale mass movements occur much more frequently than large-scale mass movements, and can – even though they are small – still have great consequences for submarine infrastructure.

The continental slope off the Lofoten Islands, north Norway, northeast of the Trænadjupet Landslide, was chosen as study area, because the seabed geomorphology is dominated by smaller-scale mass movements (Bugge, 1983; Kenyon, 1987; Yoon et al., 1991) (Fig. 2). This area has been the focus of research lately as it may be one of the next areas opened for hydrocarbon exploration in Norway (Bjordal et al., 2010; Rise et al., 2012).

The main objective of this study is to evaluate the present day seafloor stability of the continental slope offshore Lofoten, northern Norway, and understand the processes that caused the mass movements in this area.

To accomplish this, we combined morphological, sedimentological, geophysical and geotechnical data, complemented with slope stability modeling, in a multi-disciplinary approach. We believe that a single method would not have been sufficient, and that the integration of multiple methods and techniques allows for a better understanding of the processes affecting slope instability in the study area in particular, but it also applies to submarine mass movement studies on continental margins in general. Multi-disciplinary studies are important because mass movements are often very complex, and the exact processes, preconditioning factors and triggering mechanisms are in many cases still unresolved.

The main objective was achieved through three different studies.

1. *Morphology and heterogeneity of different mass-movement styles*

The first part of the study combines swath bathymetry, side-scan sonar, sub-bottom profiler, and seismic data, and focusses in particular on the morphology of smaller-scale mass movements. The integration of data explains the heterogeneity of three different styles of mass movements and sheds light on the different mass movement processes involved including their origin and dynamics.

2. *Sedimentology and geotechnical analyses of a shallow mass movement*

The second part of the study focuses on a shallow style of mass wasting where its glide plane only lies 12-13 m below the sea floor. The glide plane was sampled with a sediment core in order to:

a) Identify and characterize the glide plane and the so-called weaker sediments in which movement was initiated, and to link these to the sedimentary processes and paleoenvironments that prevailed during their formation;

b) To evaluate the present day stability of the continental slope, and to testify the possibility to numerically model the observed mass movements using parameters from the sediment core (Infinitive slope, BING and retrogressive slope models).

3. *Neogene – Quaternary evolution of the continental slope*

The third part of the study focuses on the interplay between contourite deposition, mass movement activity and canyon formation during Neogene-Quaternary times particularly based on the interpretation of 2D seismic data.

3. Data and methods

The swath bathymetry data was collected with RV *Jan Mayen* (now RV *Helmer Hanssen*) in June 2010 using a hull-mounted Kongsberg Simrad EM 300 multi-beam echo-sounder. Additional bathymetric data were provided by the Norwegian Deep-Water project SEABED. The side-scan sonar data were acquired by RV *Professor Logachev* in 2008 using a MAK-1M deep-towed hydroacoustic system operated at 30 kHz with a swath range of up to 2 km. Seismic data were acquired by RV *Jan Mayen* in 2010 using two GI air guns of 105 cubic inch each. They were towed at 4 m below the surface, 55 m behind the vessel and fired every 4 seconds. GMT, Fledermaus, Vista, Kingdom Suite and ArcGIS software were used to process, interpret and visualise the data.

The Calypso core (giant piston core) GS10-163-3PC (1178 m water depth) was retrieved with RV *G.O. Sars* in June 2010 (Fig. 8). In-depth analysis including measurements of the physical properties (bulk density, P-wave velocity and magnetic susceptibility), collection of CT scans and X-ray images, logging and grain-size analysis, dating (AMS on foraminifera and a shell fragment), and geotechnical analyses (water content, Atterberg limits, fall cone, direct simple shear, triaxial, and oedometer tests) were done both in Tromsø and at the Norwegian Geotechnical Institute. All tests were performed according to state-of-the-art practice.

More detailed descriptions of the data and methods used can be found within the three papers.

4. Summary of the papers/Synthesis

4.1 Paper 1:

In Paper1, swath bathymetry, side-scan sonar, sub-bottom profiler data and seismic records from the continental slope offshore the Lofoten Islands, northern Norway, reveal evidence of repetitive smaller-scale translational sliding, involving spreading and multi-phase retrogression, in water depths between 1100 and 2500 m. Three styles of failure have been identified, occurring in close proximity. Style 1 is characterized by an only partly evacuated 4.7 km wide and up to 100 m deep amphitheater shaped headwall, a relatively deep glide plane (± 130 mbsf), detached sediment ridges and a run-out area with rafted sediment blocks. Style 2 consists of a staircase pattern of escarpments, separated by glide planes within different levels of the stratigraphy between ± 110 and 30 mbsf. The slide scar is almost completely evacuated. Style 3 shows different phases of evolution, illustrating the gradual disintegration of a slab of sediments moving over a shallow glide plane at ± 12.5 mbsf. Zones with sediment slabs are up to several hundreds of meters wide and are sharply delineated by shear margins or escarpments. The spatial variations in the failure style is likely caused by the activation of different glide planes, which is probably a result of the thinning of contouritic sediments towards the south-west. In the north-east, the mounded contouritic sediments contain more potential glide planes and steeper slopes. The smaller-scale mass movements are suggested to have been triggered by undercutting and removal of support at the foot of the slope due to large-scale mass movements that have occurred immediately south of the study area, such as the Trænadjupet or Nyk slides.

4.2 Paper 2:

In paper 2, we use multi-proxy analyses of a sediment core penetrating a shallow, submarine mass movement, in combination with swath bathymetry, side-scan sonar and sub-bottom profiler data to characterize the basal glide plane and the so-called weaker sediments in which movement was initiated. The initial phase of shallow mass movement, consisting of a single fracture/crack formed due to movement of a mostly undisturbed slab of sediments, was targeted by a 16 m long Calypso core comprising mostly undisturbed massive and laminated, IRD-rich clays. The core penetrated a high-amplitude, semi-continuous reflection on the sub-bottom profiler data at about 12.5 m depth, consisting of a plumite interval acting as the basal glide plane. This plumite has dilative behaviour with pore pressure decrease with increasing shear strain and high undrained shear strength. Movement presumably started within contouritic sediments immediately above, characterized by higher sensitivities and higher water contents. The mass movements documented in this study area are likely affected by the presence of a larger submarine landslide complex directly downslope. The removal of sediments at the toe resulted in undercutting at the foot of the slope and a loss of support of the overlying sediments. This process triggered retrogressive movement further upslope and progressive spreading of strain softening along the slide base and in the slide mass. Numerical models (infinite slope, BING, and retrogressive slope models), using the geophysical and geotechnical data as input, illustrate that the present-day continental slope is essentially stable. The models furthermore allow reconstruction of the instability process initiated by an external trigger.

4.3 Paper 3:

In paper 3, we use a 2D network of seismic data to investigate the Neogene evolution of the continental slope offshore Lofoten, northern Norway. The presence of paleo-canyons shows that the area affected by canyon formation on the Lofoten-Vesterålen margin is more extensive than thought previously. The fact that they are not visible at the present seafloor shows they have not been active recently. The paleo-canyons are buried by extensive contourites, inferred to be a continuation of the Lofoten Drift, deposited from the mid-Miocene onwards. Changes in the distribution of contouritic deposits between the different units suggest that the paleo-current system has not been stable, and that there have been variations in both the strength and the depth of the paleo-currents. Contourites draping mass transport deposits suggest continuous deposition of contourites in the area. A glacigenic wedge consisting of stacked debris flows wedging out from the continental shelf edge, was most likely deposited during the Pleistocene, during shelf-wide glaciations. It appears that mass movements have occurred in this area since the onset of the Pleistocene. Likely reasons are the periodic higher sediment accumulation rates during glacial periods, alternated with extensive contourite deposits, and the triggering by the occurrence of larger slides within the Trænadjupet area.

5. Small- and large-scale mass movements on glaciated margins – a comparison

One of the reasons to study smaller-scale mass movements on the Norwegian continental slope was the lack of active research initiative dedicated to these features, compared to their larger-scale counterparts. However, in-depth investigation of such features is highly valuable for a number of reasons, as there are and remain many uncertainties and questions with respect to their origin, triggers and dynamics. It is thus important to compare the geological and environmental processes and trigger mechanisms for these instabilities with large mass movements, and find explanations why some mass movements are large whereas others are small. The results from this study are integrated with published data to discuss the similarities and differences of smaller- and larger-scale mass movements.

The morphologies of smaller-scale and larger-scale mass movements are often very similar. Both groups are considered the result of translational sliding and show signs of spreading and retrogression (e.g. Prior et al., 1982; Laberg & Vorren, 2000; Canals et al., 2004; Haflidason et al., 2004; Kvalstad et al., 2005; Vanneste et al., 2006; Micallef et al., 2007; Pedrosa et al., 2011; Lucchi et al., 2012; Rise et al., 2012). Glide planes are most often identified within laminated marine/contouritic sediments in both groups (Laberg et al., 2002; Haflidason et al., 2003; Wilson et al., 2003; Lindberg et al., 2004; Bryn et al., 2003, 2005b; L'Heureux et al., subm.). Furthermore, other pre-conditioning factors (e.g. high-sediment accumulation rates) and triggering mechanisms appear very similar (as e.g. earthquakes). These findings imply that one should not necessarily discriminate smaller- from larger-scale instabilities.

The most obvious difference is of course the difference in size, which is substantial when comparing the volume of the Storegga Slide of 2400-3200 km^3 and the smaller-scale mass movements on the Vesterålen margin of 0,0063-0,07 km^3 (L'Heureux et al., subm), and within this study (0.061-8.6 km^3).
Another difference is the upslope retrogression. Whereas the larger mass movements on the Norwegian continental slope cut back all the way up until the continental shelf break where they terminate at the flat lying, overconsolidated glacial deposits on the continental shelf (e.g. Storegga Slide and Hinlopen-Yermak Slide; Bryn et al., 2003; Vanneste et al., 2006), the retrogression of the smaller-scale mass movements on the Vesterålen margin (Rise et al., 2012) and in this study (Baeten et al., 2013), do not retrogress to the shelf edge. This is

presumably related to a change in sediment composition and/or decrease of slope angle (Baeten et al., 2013).
Furthermore, triggering mechanisms could well be different (despite the fact that actual triggering mechanisms are poorly documented). The smaller-scale mass movements investigated in this study area appear to be triggered by undercutting at the foot of the slope, resulting in a loss of support of the overlying sediments, thus, triggering retrogressive movement further upslope (Baeten et al., 2013; in prep.). Most of the larger mass movements on the Norwegian continental margin are inferred to have been triggered by earthquakes, often associated with glacio-isostatic readjustment during and following deglaciation (e.g. Bugge, 1983; Bugge et al., 1987; Gudmundsson, 1999; Bryn et al., 2003; Bungum et al., 2005; Lee et al., 2009).

One of the main factors causing the difference in size and area affected by mass wasting is the input of glacigenic sediments during glaciations, causing excess pore pressure development and a decrease in strength of the sediments. This could make the sediments more susceptible for lateral and upslope retrogression and greatly increase the area of the mass movement. The smaller scale mass movements on the Lofoten margin (Baeten et al., 2013, subm., in prep.) occurred in areas that received relatively little sediment input during glacial periods. During glacials, the Lofoten Islands acted as a sediment barrier guiding the large ice streams from central Fennoscandia - the main agents transferring large quantities of sediments to the shelf edge - to be routed south and north of the study area (Fig. 9; Laberg et al., 2002; Ottesen et al., 2005). Large-scale mass movements like the Trænadjupet Slide occurred immediately beyond the Vestfjorden-Trænadjupet Ice Stream which deposited substantial amounts of glacigenic material at the shelf break (Laberg and Vorren, 2000).

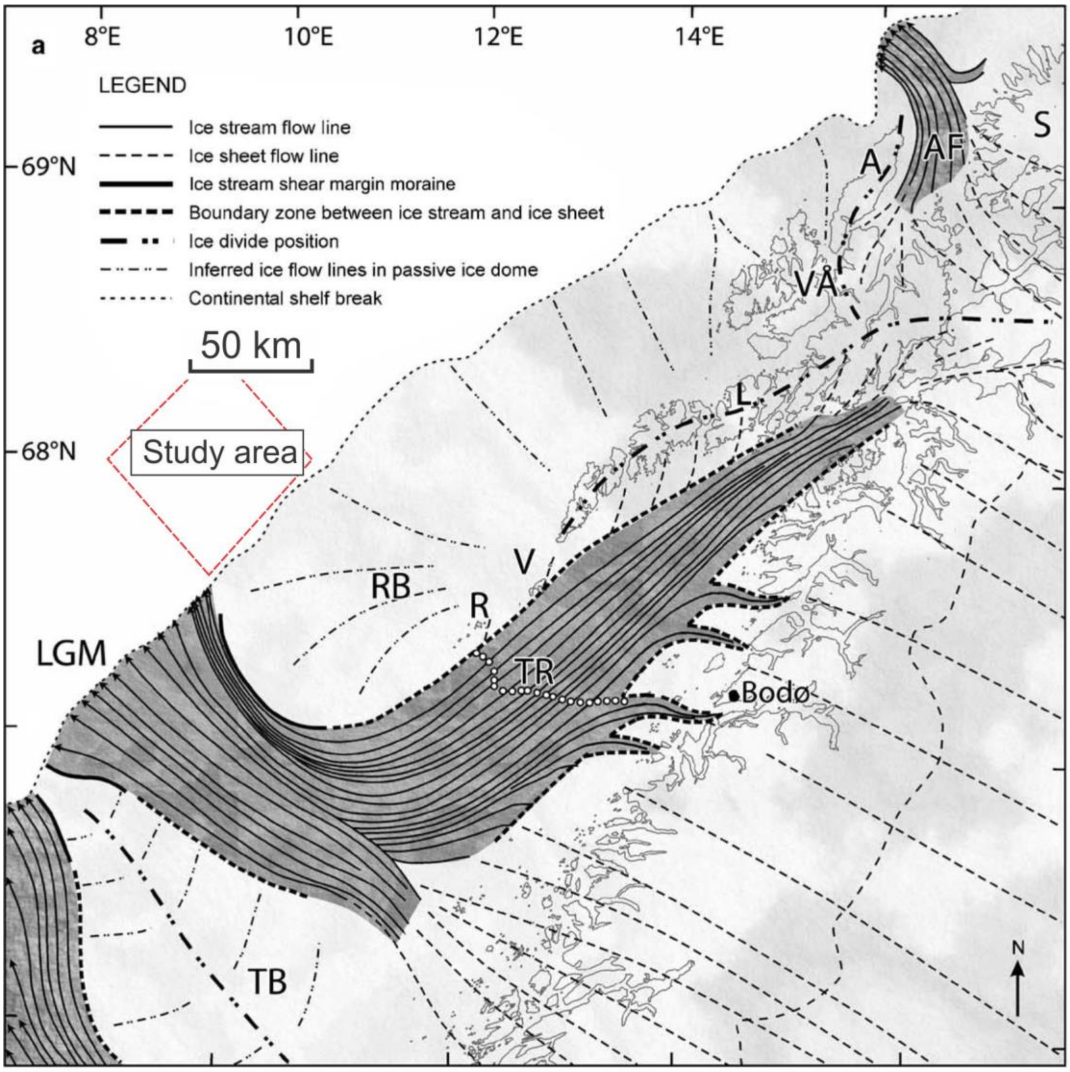

Fig. 9 Ice-sheet reconstruction for the Last Glacial Maximum. TB-Trænabanken, RB-Ræstbanken, L-Lofoten, R-Røst, VÅ-Vesterålen. The study area is indicated in red. From Ottesen et al., 2005.

6. Future work/research

6.1 Extension of swath-bathymetry and side-scan sonar datasets

As discussed above, the mass movements in this study are likely inferred to have been triggered by undercutting at the foot of the slope. Studying the area downslope of the dataset would allow further investigations in these mechanisms. As the actual preconditioning factors and triggering mechanisms in submarine landsliding are difficult to pinpoint, there could well have been other phenomena acting, like fluid migration. Investigating beyond the currently surveyed area would also allow us to study the morphology and length of the run-out area of the mass movements in more detail, and therefore shed further light on the dynamics of the landslides.

This dataset shows that, besides the well-known larger-scale mass movements, the Norwegian-Barents-Svalbard margin is also sculpted by numerous smaller-scale mass instabilities (e.g. Bugge, 1983; Pedrosa et al., 2011; Rise et al., 2012; this study). The ongoing mapping efforts of the continental margin and fjord areas (e.g. Mareano project; www.mareano.no) with increasing resolution is systematically revealing more of the morphology of smaller-scale type mass movements and thus the sedimentary processes involved. Studying other smaller-scale mass movements and comparing them to the model developed in this study (Baeten et al., 2013) will yield a better understanding of smaller-scale mass movements in general.

The shallowest style of mass wasting is only visible on the side-scan sonar data because of its higher resolution (Baeten et al., 2013). We therefore think that in addition to the extension of the swath bathymetry dataset, it is also important to collect more side-scan sonar data, or use higher-resolution swath bathymetry data (and the simultaneously recorded backscatter data). These shallow mass movements are visible on large parts of the side-scan sonar data within the study area. Collection of more side-scan sonar data will give the opportunity to check if it has a more widespread occurrence within the study area and on glaciated continental slopes in general.

6.2 Collection more sediment cores/wells

The modeling and geotechnical data in this study were obtained from a single sediment core. Geotechnical and sedimentological analyses on additional cores would be beneficial to check whether or not results from this study area are representative for larger parts of the continental slope offshore northern Norway, thus providing valuable data that can be used to more reliably evaluate the seafloor stability in the area. It is, however, a costly affair to collect seabed samples of high quality, and submarine landslide studies often suffer from undersampling, particularly with respect to geotechnical data (laboratory and in situ; e.g. Vanneste et al., 2013). A suggestion for placement of cores would be within different stages of mass movement development of the shallow mass movements discussed in Baeten et al. (in prep.), to analyze deformation within the glide planes and overlying sediment blocks, prior to, during and after disintegration.

So far, no wells have been drilled close to the study area. However, wells exceeding the recovery of gravity and piston coring would be very useful because:

1. They would allow obtaining physical properties of the entire sequences, including the deeper glide planes.
2. To establish a firmer chronology in the area based on ground-truthing the seismic data.

6.3 *In situ* sampling

The quality of the sediment samples from GS10-163-3PC used for geotechnical analyses is considered fairly poor. This is not uncommon for silty clays retrieved from shallow sub-surface depths (maximum 12.95 mbsf). Measurements on higher quality samples would be beneficial. Alternatively, *in situ* geotechnical measurements can be collected, for example CPTU data (cone penetration tests with pore pressure measurement). This is an efficient and widely used *in situ* measurement technique for geotechnical site investigations, both onshore and offshore (e.g. Lunne et al., 1997). It measures the cone resistance, sleeve friction and pore-water pressure (with possibility for dissipation tests). These parameters give important information regarding the lithology, stratification, and geotechnical properties of the sediments (e.g. Steiner et al., 2012). Long-term double-sensor *in situ* pore pressure measurements can show the pore pressure development over time (e.g. Vanneste et al., 2012).

In situ measurements across 'weaker' layers are important to improve our knowledge, since the presence of 'weak' layers has been recognized as an important factor for the initiation of submarine mass movements (e.g. Bryn et al., 2003; Haflidason et al., 2003; Longva et al., 2003; Laberg et al., 2003; Lindberg et al., 2004; Laberg and Camerlenghi, 2008; this study). However, high resolution is needed, and slip planes may not necessarily stand out on CPTU data (Vanneste et al., 2013). Therefore, an integrated approach is essential.

When integrated with other methods, like high-resolution seismic surveying, these *in situ* measurements could give good results regarding potential slope stabilization and location of the failure plane, and are considered well suited for exploring the shallow sub-surface of slide-prone areas (e.g. Steiner et al., 2012) The method is however only suitable for the top few meters of the succession, and will therefore be of no use when investigating larger mass movements.

6.4 Modelling

As discussed above, additional sediment cores and *in situ* measurements, will give more input data to reliably model the mass movements in the study area.

Other issues that could be approached with modeling are for example the reason why mass movements are smaller in some areas and larger in others, as discussed above. Models could maybe explain how much excess pore pressure is necessary to generate larger mass movements as the Trænadjupet Slide, and how much glacigenic sediment input is needed to generate these excess pore pressures.

Modelling is a tool that can be very useful in order to understand the various phenomena related to submarine mass wasting and slope stability, and can significantly improve our understanding of all stages of submarine mass movements, including mechanisms of failure and of the dynamics of the failed sediments (e.g. Yamada et al., 2012).

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Paper 1

Nicole J. Baeten, Jan Sverre Laberg, Matthias Forwick, Tore O. Vorren, Maarten Vanneste,
Carl Fredrik Forsberg, Tore J. Kvalstad, Michael Ivanov

Morphology and origin of smaller-scale mass movements on the continental slope off northern Norway

Geomorphology 187 (2013), 122-134

Paper 2

Nicole J. Baeten, Jan Sverre Laberg, Matthias Forwick, Tore O. Vorren, Maarten Vanneste,
Carl Fredrik Forsberg, Tore J. Kvalstad, Haflidi Haflidason

Origin of shallow submarine mass movements and their glide plane - sedimentological and geotechnical analyses from the continental slope off northern Norway

In preperation

Paper 3

Nicole J. Baeten, Jan Sverre Laberg, Matthias Forwick, Tore O. Vorren, Maarten Vanneste,
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