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

Nicole J. Baeten [a,*], Jan Sverre Laberg [a], Matthias Forwick [a], Tore O. Vorren [a], Maarten Vanneste [b], Carl Fredrik Forsberg [b], Tore J. Kvalstad [b], Michael Ivanov [c,1]

[a] Department of Geology, University of Tromsø, N-9037 Tromsø, Norway
[b] NGI & International Centre for Geohazards (ICG), 0806 Oslo, Norway
[c] UNESCO Centre of Marine Geology and Geophysics, Moscow State University, Moscow 119899, Russia

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ABSTRACT

Little attention has been paid to smaller-scale mass movements on continental slopes, even though they occur much more frequently than their large-scale counterparts. Swath bathymetry, side-scan sonar, sub-bottom profiler and seismic data 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 a 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 secondary escarpments, caused by the activation of several glide planes between ±30 and 110 mbsf. Headwalls and secondary escarpments have a height of up to 30 and 70 m, respectively. The run-out area shows an almost complete sediment evacuation. Style 3 is more subtle, as it is only identified on the side-scan sonar data due to its higher spatial resolution. This style shows different phases of on-going evolution, illustrating the gradual disintegration of a slab of sediments moving over a shallow glide plane at ±13 mbsf. Zones with sediment slabs are up to several hundreds of meters wide and are sharply delineated by shear margins or escarpments. The spatial variation in the failure style is inferred to have been 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 higher slope angles. 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. The geophysical data indicate that relatively recent mass movement processes have taken place in this area through the formation of shallow cracks and graben structures by the movement of ±13 m thick slabs of sediments (Style 3), which could have severe implications for offshore infrastructure.

1. Introduction

Submarine mass movements are common on continental slopes, in particular in environments where slide-prone sediments such as rapidly deposited, fine-grained sediments are subjected to strong environmental stresses such as earthquakes (Hampton et al., 1996). The potentially devastating consequence of submarine mass movements necessitate the need for detailed investigations of their occurrence, origin and dynamics, particularly in the light of continuing development of offshore natural resources such as oil and gas, the need for seafloor transport and communication routes or seabed infrastructure, the pressure of coastal development such as cities and harbors, and the protection of the marine environment (e.g., Locat and Lee, 2000).

Some of the largest submarine landslides have occurred along the continental slope off the Norwegian–Barents Sea–Svalbard margin, including the Storegga landslide (Bugge et al., 1987; Evans et al., 1996; Haflidason et al., 2004; Bryn et al., 2005a; Evans et al., 2005), the Trænadjupet landslide (Laberg and Vorren 2000; Laberg et al., 2002) and the Hinlopen-Yermak landslide (Vanneste et al., 2006, 2011). The Storegga and Trænadjupet landslides affected an area of about 95,000 and 14,100 km^2, respectively, and mobilized about 2400–3200 km^3 and 900 km^3 of sediments (Laberg et al., 2002; Haflidason et al., 2005). The Hinlopen-Yermak landslide 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).

Other parts of the Norwegian continental slope are dominated by smaller-scale landslides.

* Corresponding author. Tel.: +47 46245207.
E-mail address: Nicole.Baeten@uit.no (N.J. Baeten).
[1] Deceased.

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A total of eight smaller landslides were identified at water depths between 500 and 800 m on the continental slope offshore Vesterålen, North Norway (Rise et al., 2012). Several smaller-scale submarine landslides were recently identified on the Storfjorden and Kveithola Trough mouth fan on the western Barents Sea slope (Pedrosa et al., 2011). Smaller-scale mass movements also occur within Norwegian fjords such as the well-studied Finneidfjorden landslide (e.g. Longva et al., 2003; L'Heureux et al., 2012). The ongoing efforts of mapping the continental margin and fjord areas with systematically higher resolution are bound to reveal more of the smaller-scale mass movements.

Although the mass movements on the Norwegian continental slope contain similar morphological features, their overall morphologies are distinctly different. In addition to the understanding of the general mechanisms of single systems, similarities and differences between various systems need to be better known, in order to more reliably evaluate the slope stability as well as the formation mechanisms and processes of submarine landslides. This was demonstrated by detailed morphological studies e.g. those within the Storegga landslide complex, which led to the division of six distinctive morphological provinces, revealing detailed information about the initiation and the development of the landslide (Haflidason et al., 2004).

Whereas the large-scale mass movements have received considerable interest, little attention has been paid to the more frequently occurring smaller-scale mass movements. Whether or not the same preconditioning factors resulted in unstable sediments, and whether or not they originated in the same way or were triggered by similar mechanisms as the large scale events, remains uncertain. Smaller-scale mass movements occur much more frequently than large-scale mass movements, and can, even though they are small, have great consequences for submarine infrastructure.

One of the areas dominated by smaller-scale mass movements is the continental slope off the Lofoten Islands, north Norway, north-east of the Trænadjupet landslide (Bugge, 1983; Kenyon, 1987; Yoon et al., 1991) (Fig. 1). This area has recently received increased attention as it may be one of the next areas opened for hydrocarbon exploration in Norway (Rise et al., 2012). In this paper we present swath bathymetry, side-scan sonar, sub-bottom profiler, and airgun seismic data to explain the heterogeneity of smaller-scale mass movement along the north-Norwegian continental slope in terms of morphology, processes and preconditioning factors.

2. Physiographic setting

The study area is located on the continental slope offshore the Lofoten Islands, northern Norway, between 300 and 2500 m water depth. The shelf edge is located approximately 100 km from the Lofoten Islands (Fig. 1). The continental slope generally dips up to 5°, 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 a depth of about 2800 m, leading to the Lofoten Basin that reaches a depth of about 3200 m (Fig. 1).

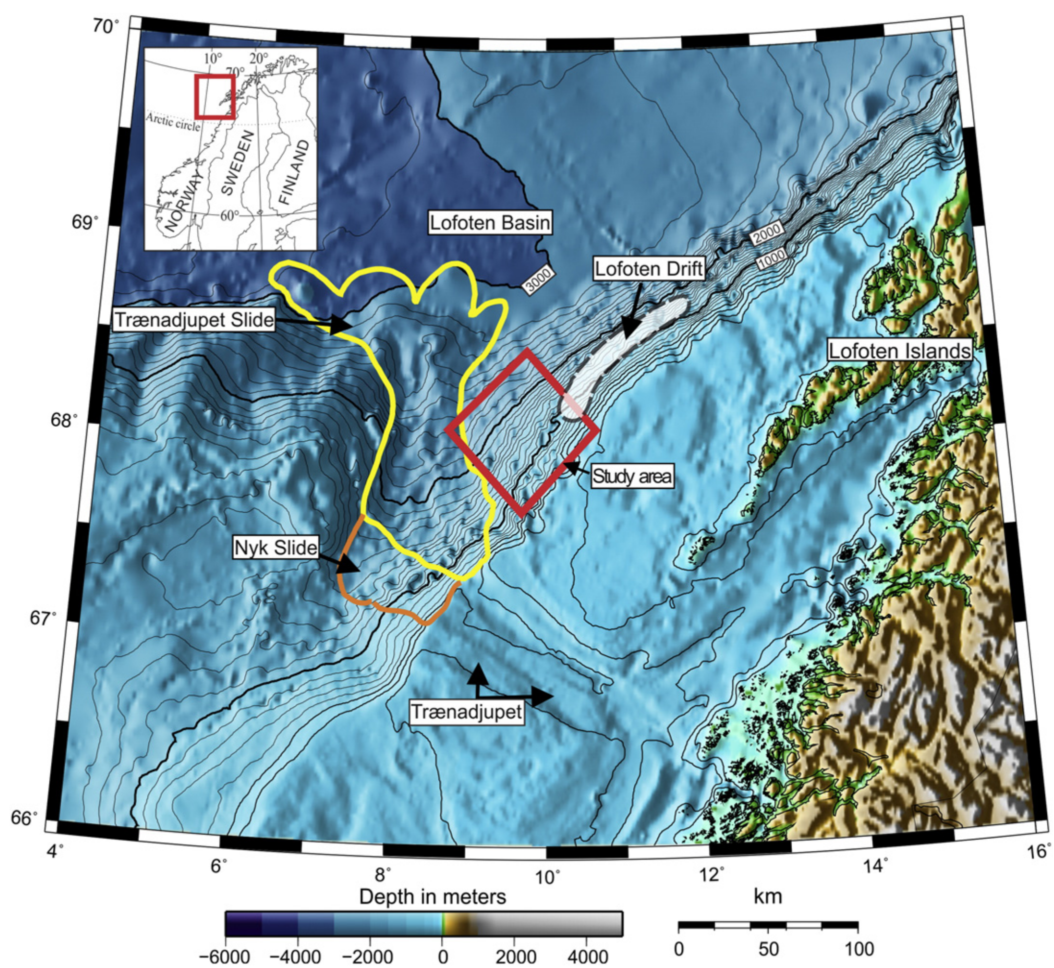

Fig. 1. Location map (inset) and bathymetric map of the continental slope off the Lofoten Islands, northern Norway. The study area is indicated by the red box. The Trænadjupet and Nyk Slides are outlined in yellow and orange. The approximate position of the Lofoten Drift is indicated (from Laberg et al., 1999, 2001; Laberg and Vorren, 2004).