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Formation of a large submarine crack during the final stage of retrogressive mass wasting on the continental slope offshore northern Norway

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ABSTRACT

High-resolution swath-bathymetry data integrated with sub-bottom profiles and single-channel seismics reveal an 18 km long, up to 1000 m wide and 10–15 m deep crack located approx. 4 km upslope from a slide scar on the continental slope off northern Norway. This crack is formed by subsidence of the sea-floor sediments to a depth of 120 m due to downslope movement of an ~80 km^2 large sediment slab that represents the final stage of retrogressive mass wasting in this area. From its morphological freshness, the crack this is inferred to have formed sometime during the last 13 cal. ka BP. These findings add to our understanding of the origin of sea floor cracks on passive continental margins where explanations as slip of normal faults or gas expulsion from the dissociation of gas hydrates previously have been suggested for the formation of cracks in similar settings.

1. Introduction

Slide scars in a variety of forms are well known characteristics of the continental slope. They owe their origin to the sudden release of sediments involving initial processes as liquefaction followed by sliding, slumping and/or spread, partly or completely developing into flows (e.g. Lee et al., 2007; Micallef et al., 2007). Cracks, also known as crown cracks have been reported from near the slide headwall (e.g. Mienert et al., 2010). However, the distribution and origin of cracks and their relation to the stability of the continental slope is less known, because of the limited availability of high-resolution multi-beam, side-scan sonar or high-resolution seismic data. Their proper identification and inference of origin are important because they may be the only morphological expression of an unstable sea floor, and their locations indicate areas of potential future slope failures. Factors such as the area of initiation and initial volume of the sediments released from submarine landslides are also of importance for the generation of tsunamis (Løvholt et al., 2005). As recently seen, submarine landslides that trigger tsunamis have a much wider and indirect impact on their surroundings including coastlines, their populations and infrastructure (e.g. Kawamura et al., 2012).

The continental slope off northern Norway (Fig. 1) has been modified by a number of slides. In contrast to other parts of the Norwegian continental slope, these events did not affect the uppermost part of the slope between ~300–1000 m water depth (Baeten et al., 2013). However, a depression oriented sub-parallel to the slope occurs between approx. 750–800 m water depth (Fig. 2). The aim of this study is to infer the origin of this depression and to discuss implications for the stability of the sediments on the upper part of the continental slope.

2. Geological setting

The study area is heavily influenced by erosional and depositional processes related to the northward-flowing Norwegian Current leading to the formation of the mounded and elongated Lofoten Contourite Drift (Laberg et al., 1999; Laberg and Vorren, 2004) (Fig. 3). Detailed studies have shown that the growth of the contourite drift was climatically controlled and that sedimentation rates were an order of magnitude higher during the last glacial compared to the present interglacial. The upper ~10 m of the drift were deposited over the last 20 ka (Laberg and Vorren, 2004; Rørvik et al., 2010). On the uppermost part of the continental slope, an upslope thickening wedge of sediments, partly interbedded with the contourite drift has been found. Based on analogy with similar deposits elsewhere on the Norwegian margin, the wedge-shaped intervals are inferred to be glacigenic sediments deposited during glacial maxima (e.g. Dahlgren et al., 2005) (Fig. 3).

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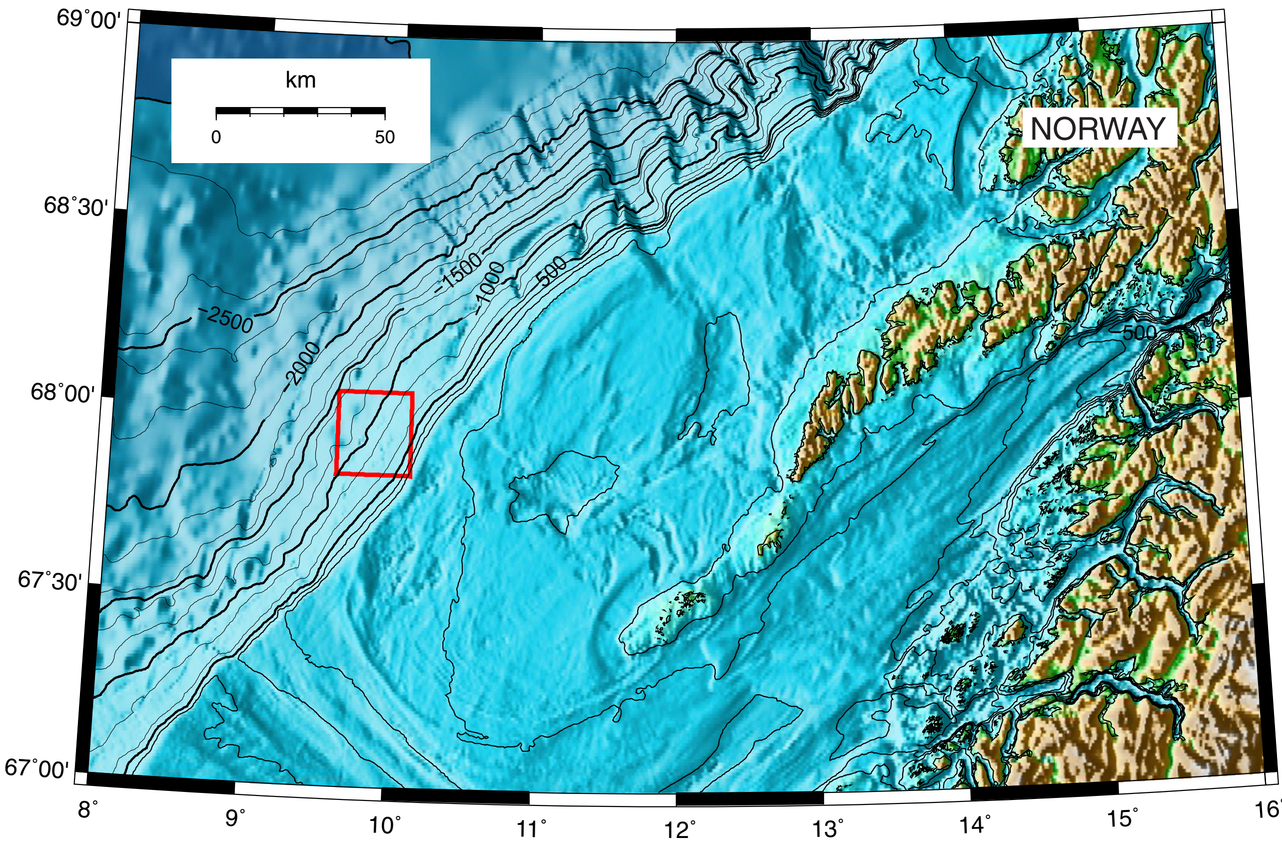

Fig. 1. Bathymetric map of the continental margin offshore northern Norway. The study area is located by the red frame. Contour interval is 100 m on the continental shelf and uppermost slope. The bathymetry is from Jakobsson et al. (2012).

3. Data

The study area was mapped during two cruises in 2010. During the first cruise on RV *Helmer Hanssen*, a Kongsberg Simrad EM 300 multi-beam echo sounder was used to collect a regional swath bathymetry data set. The data from this survey is displayed with a resolution of 50 × 50 m. Furthermore, sub-bottom profiles (Chirp) and single channel, high-resolution seismic data using two GI Guns (total volume of 210 in^3) and a Fjord Instruments streamer were acquired synchronously during the same cruise. During the second cruise on RV *H.U. Sverdrup II* a Kongsberg Simrad EM 710 multi-beam echo sounder was used to map the slope-parallel depression with a resolution of 25 × m. During this cruise, additional swath-bathymetry data from most of the depression was acquired with a Kongsberg Simrad EM2000 multi-beam echo sounder installed on the autonomous underwater vehicle *Hugin HUS* (Hagen et al., 2003). These data were gridded and visualized with a resolution of 5 × 5 m. Sub-bottom profiles, sidescan sonar data and optical photographs of the sea floor were also acquired during the *Hugin HUS* survey (not shown here).

4. Results

The study area includes an ~15 km wide slide scar terminating upslope in an ~50 m high headwall that is characterized by an amphitheater-shaped southern part at approx. 1000 m water depth and a slightly downslope-curved northern part between 1100 and 1200 m water depth (Fig. 2). The sea floor immediately upslope from the headwall is smooth, has a gradient of up to ~4° upslope to a water depth of about 750 m, and includes some gullies truncated by and thus pre-dating the slide. These gullies may have been formed during past glaciations as discussed by Gales et al. (in press). In this area, a NE–SW oriented and slope-parallel, slightly curved sea-floor depression, a crack, with well-defined lateral terminations has been identified (Fig. 2). The crack has a length of about 18 km (Fig. 4), i.e. it is close to the width of the slide scar. It is up to 10–15 m deep, and within the crack the sea-floor is slightly rotated and deepest in its upper part (Fig. 5A). Both the slide scar and the crack are located within the area of the Lofoten Drift.

The crack can be divided into a southern, middle and northern segment, respectively (Fig. 4). The southern and northern segments are mostly bounded by two parallel escarpments. Smaller, secondary escarpments delineating blocks of sediments are dipping into the crack, indicating that relatively stiff, consolidated sediments were involved (Fig. 4, indicated by the black arrows). The middle part is characterized by an en echelon set of smaller escarpments delineating sets of depressions of about the same widths and depths (Fig. 4).

A sub-bottom profile crossing the southern segment indicates that the uppermost, acoustically laminated unit of medium-high amplitude can be followed across the floor of the crack. We observe that there are no sediments covering the uppermost acoustically laminated unit within the crack detectable in sub-bottom profiles (Fig. 5A). The displaced sediments can be identified to approx. 120 m depth below the sea floor (using a p-wave velocity of 1600 m/s). There, the displacement terminates at the level of a pronounced reflection on the seismic data (Figs. 5B, C). This reflection is located at the same depth as the inferred slip plane of the nearby slide. Upslope from the depression, the reflection is irregular and discontinuous (Fig. 5B, C).

5. Discussion

The crack was most probably formed by subsidence related to mass wasting further downslope because i) it is located upslope from the