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 a ~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.

Keywords: crack, submarine landslide, retrogressive, contourites, Norway

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 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.

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; 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).

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 x 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 x 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 x 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).

Results

The study area includes a ~15 km wide slide scar terminating upslope in a ~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^o 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).

Discussion

The crack was most probably formed by subsidence related to mass wasting further downslope because i) it is located upslope from the headwall of a slide scar, ii) its length is nearly similar to the length of the slide scar, as well as its relatively uniform width (800 - 1000 m), iii) the architecture of the crack (extensional, en echelon geometry), and iv) no change in sediment thickness of the upper, acoustically laminated unit across the crack. Even though iceberg keels have reached water depths exceeding the water depths of the crack during past glaciations (e.g. Kuijpers et al., 2007), the architecture of the crack is distinctly different from that of iceberg plough marks (e.g. Bellec et al., 2008). Therefore, we regard iceberg scouring as unlikely for its formation. The occurrence of fluid-flow features (e.g. pockmarks, acoustic masking) in the area with cracks north of the Storegga Slide headwall has been used as an indicator by Mienert et al.

(2010) that crack formation in that area was related to the dissociation of gas hydrates. There “a relationship to deep seated faults is unlikely although it cannot be ruled out completely” (Mienert et al., 2010). Since fluid-flow features in our study area are absent, we also consider the formation of the crack in relation to fluid flow as unlikely.

The subsidence is inferred to have occurred following the downslope movement of a ~80 km^2 slab of sediments above a glide plane at about 120 m below the sea floor (Fig. 5C). This slab has nearly the same width as the nearby slide scar indicating that its movement was related to the evolution of the nearby slide, most likely as part of a retrogressive slide development, and that it was initiated from the downslope loss of support. According to this model, the slab movement causing the crack represents a temporarily final stage of mass wasting in this area. The presence of the crack indicates that also the sea floor shallower than 1000 m water depth, where no slide scars have been identified, may be unstable.

Crack formation due to movement of a large slab of sediments, as in our study, implies a different origin in comparison to up to tens of meters deep and ~1 km wide cracks reported from the upper slope of the US mid-Atlantic coast. There, a 50 m normal slip was found to have caused their formation and this was explained by “the existence of a normal fault with collapse and rollover of the hanging wall into the fault trace” (Driscoll et al., 2000). These differences show that cracks with morphological similarities can be formed by different processes. On active margins, smaller cracks have been reported to form due to earthquakes as for instance the March 2011 mega-earthquake offshore Japan (Kawamura et al., 2012).

Our results also imply a somewhat different evolution of the upper slide scar area when compared with the giant submarine landslides offshore Norway. Slope-parallel, elongated ridges, more than 1000 m long and several tens of meters high, characterize the uppermost part of both the Trænadjupet (Laberg et al., 2002), Nyk (Lindberg et al., 2004) and the Storegga Slide scars (Haflidason et al., 2004, 2005; Micallef et al., 2007). These ridges have been inferred to be released successively in a retrogressive behavior (Kvalstad et al., 2005a). Upslope from some of the areas of ridges, several hundred meters wide zones of cracks have been suggested to be part of this development (Micallef et al., 2007). Here, we show that the slope succession may also be remobilized as large slabs during an initial stage, prior to break up into elongated ridges.

The sharp terminations of the crack are most probably shear zones that act as the lateral boundaries of the slab. These zones have, however, not been identified on the swath-bathymetry and seismic data, most like because they do not cause well-defined morphological or acoustic contrasts, but their inferred location is tentatively given in Fig. 2C. From the available data, the gully formation does not seem to have influenced on the stability of the slope sediments including the crack development.

The fact that the sediments of the uppermost slope in the study area were not remobilized may be related to the slope morphology and/or the influence of glacigenic sediments in this area. The gradient in the area between the headwall and the crack is slightly higher compared to further upslope. This is due to the mounded geometry of the contourite drift deposits (Figs. 3, 5). Also, several studies have found the glacigenic sediments to be mechanically stronger and thus less prone to failure compared to the contouritic sediments (Kvalstad et al., 2005b; Laberg et al., 2003).

The age of the crack is probably late Weichselian or Holocene, as no sediments are infilling the crack. Results from nearby cores indicate very low sedimentation rates after c. 12,800 cal. ka BP, because the north-eastward flowing Atlantic water masses of the Norwegian Current are too strong for muddy sediments to be deposited at this water depth (Rørvik et al., 2010). From the data at hand we find no indications of recent activity of this crack.

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Figures

Figure 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).

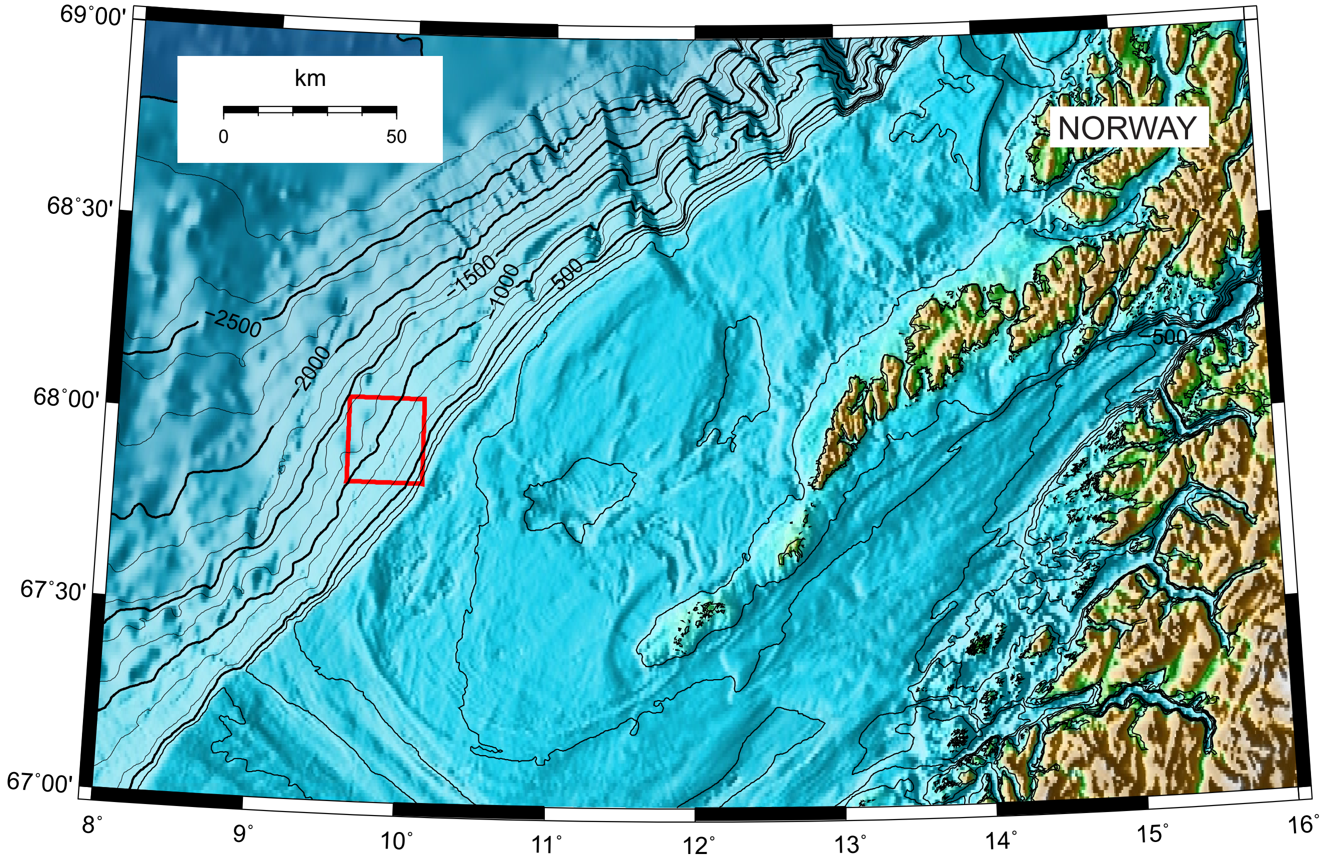
Figure 2: (A) Color-coded bathymetry; (B) bathymetry displayed in grey; (C) interpretative sketch of the main morphological features of the study area; the area dominated by glacigenic sediments is indicated by grey and the white area comprises mainly contouritic sediments. Whereas the dark blue area is the upper part of a slide scar, parts of another, smaller scar are indicated with blue area. The locations of gullies (see also Gales et al., in press) are shown by the stippled lines and the crack is framed and shown in more detail in Figure 3; (D) slope-gradient map. The hatched areas indicate the inferred location of shear zones, see text for further discussion. The location of Figure 3 and 5 is indicated by the black line in (A).

Figure 3: Schematic sketch showing the stratigraphic setting of the study area, the location of the crack and the landslide.

Figure 4: Detailed morphology (EM 700) (A) and EM2000 (B), and interpretation (inset) of the crack. The crack is subdivided into the segments (1), (2), and (3). Secondary escarpments

delineate blocks of sediments dipping into the crack (indicated by black arrows).The location of figure B is indicated by the frame in figure A.

Figure 5: a) Part of sub-bottom profile across the crack showing the vertical displacement of the uppermost part of the sub-sea floor succession. See Figure C for the location of the profile. B) Part of a single-channel seismic profile oriented across the crack and the uppermost slide scar. C) Outline of the sediment slab, the crack and the stratigraphic position of an underlying glide plane. See Figure 1A for the location of the profile.



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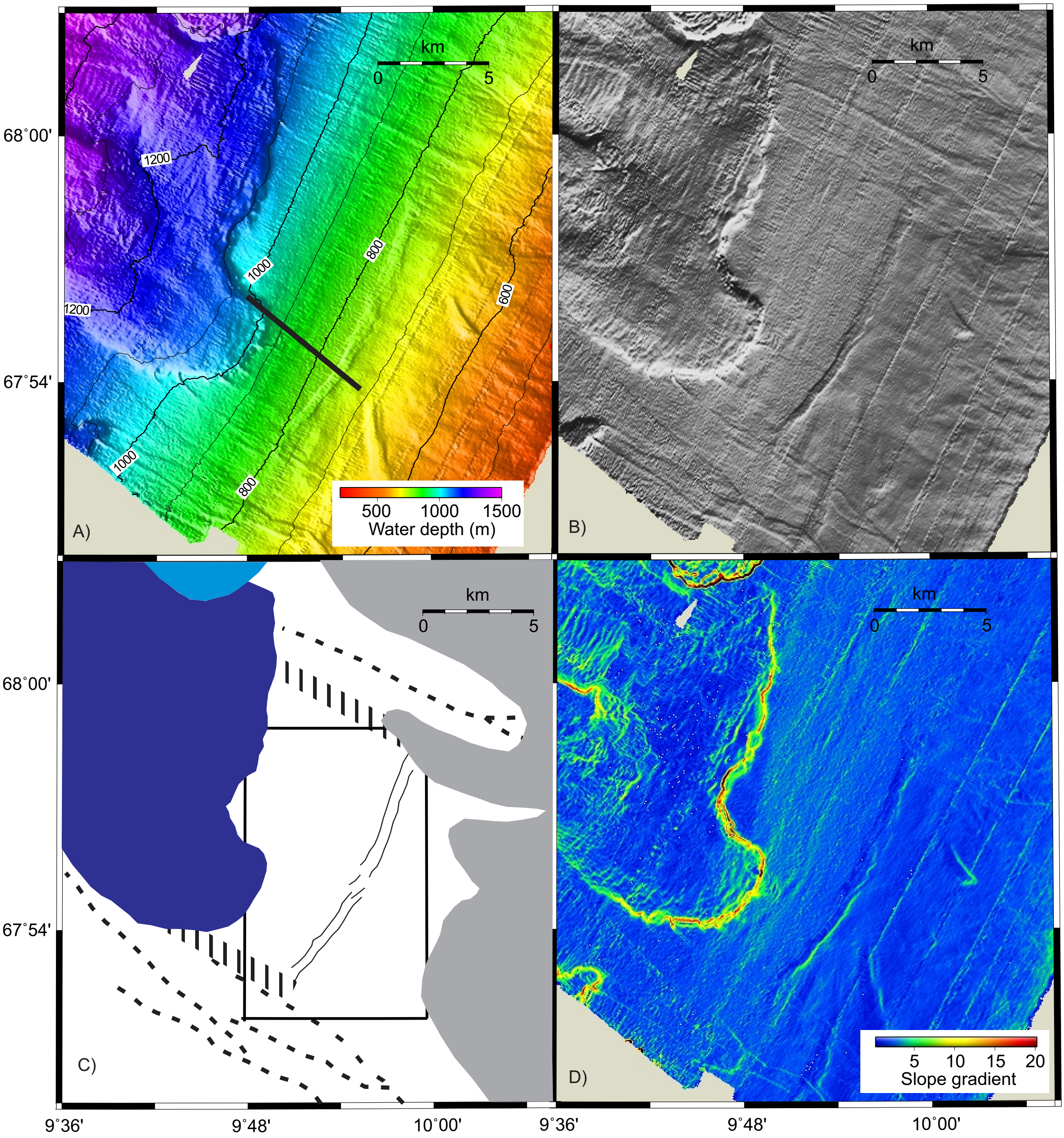
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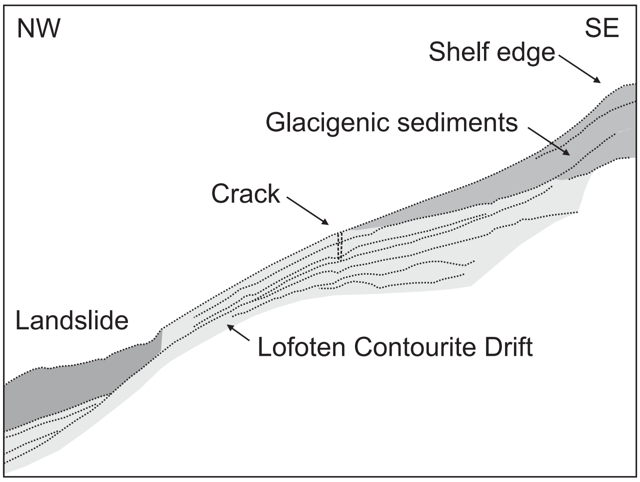
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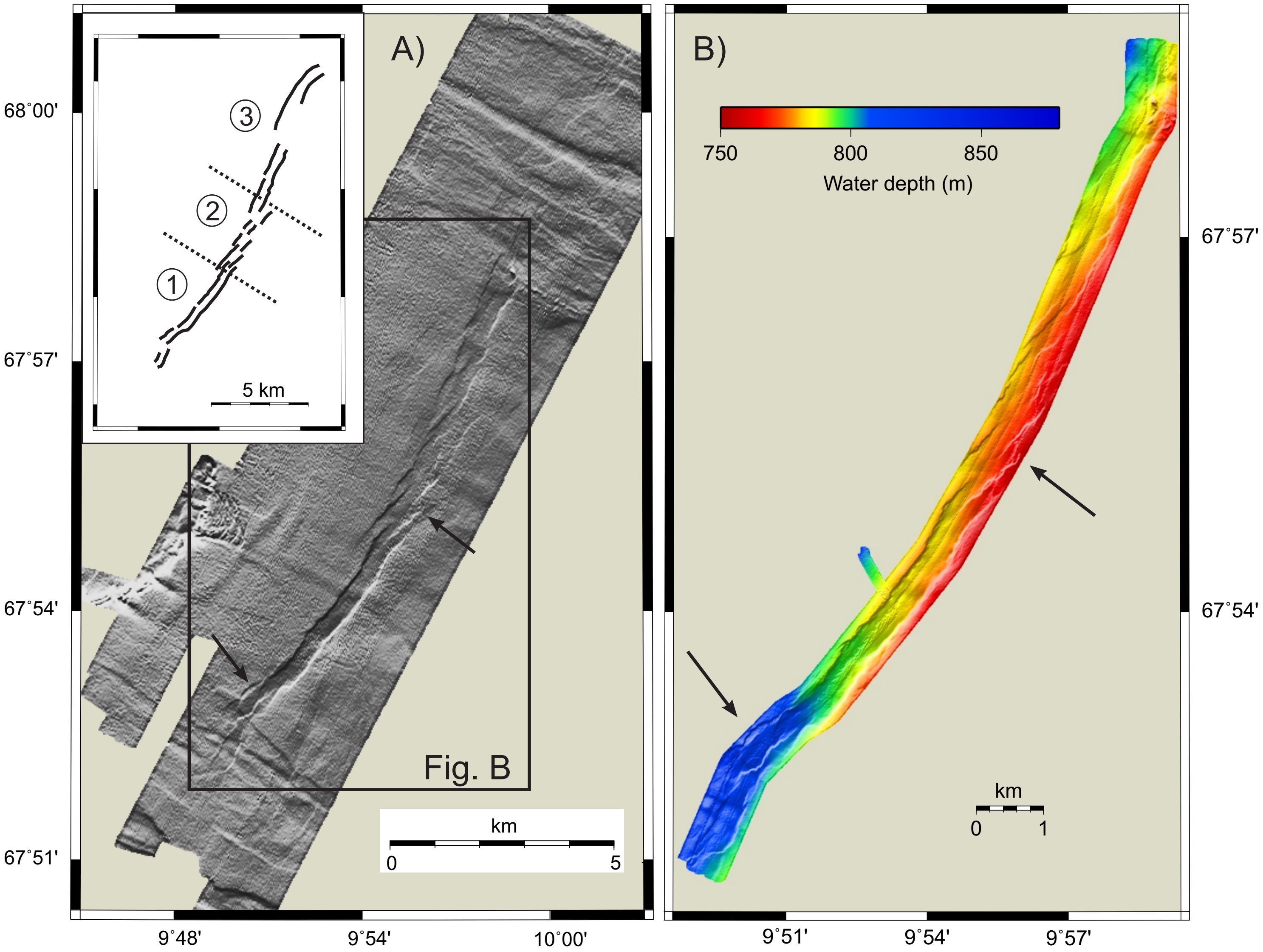
Lofoten Contourite Drift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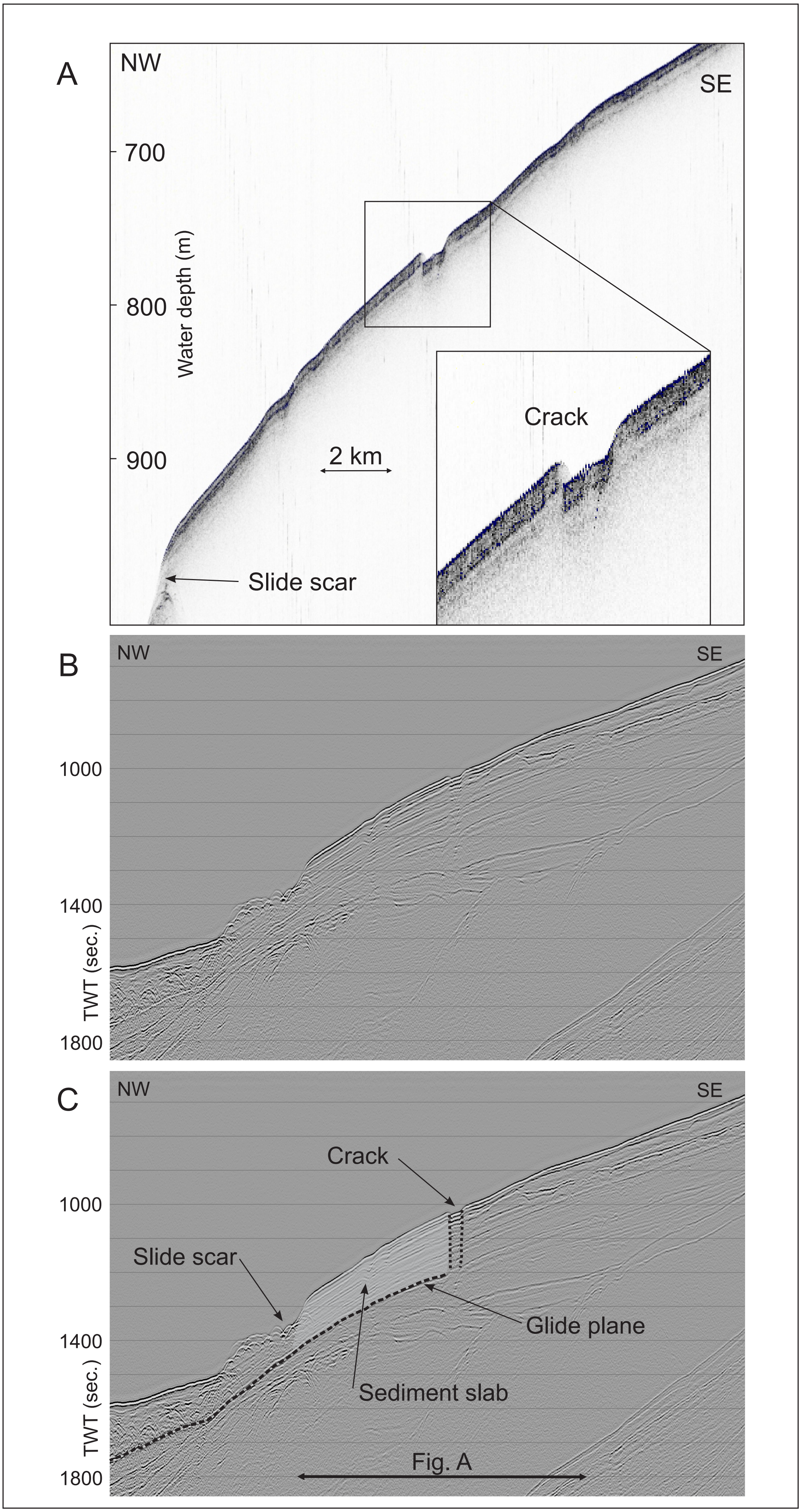
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Fig. A