SUBMARINE PALEO-FAILURE MORPHOLOGY ON A GLACIATED CONTINENTAL MARGIN FROM 3D SEISMIC DATA

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Abstract

The morphology of two lower – middle Pleistocene paleo-slope surfaces within a muddy glacigenic succession was studied on 3D seismic data. The lower surface is characterised by irregular relief. It terminates upslope by an escarpment that represents the upper part of a paleo-slide scar. The slide scar morphology is relatively similar to that of modern slide scars and failure is inferred to have occurred during or after a glacial maximum when the ice reached the paleo-shelf break. A large area immediately outside the paleo-slide scar was affected by sediment creep or sliding, thus the area of unstable sediments extends beyond the paleo-slide scar. The upper surface morphology is dominated by three straight to slightly meandering paleo-channels, at least one of them formed by mass wasting. Together, the two paleo-surfaces exemplify slope morphology that may result from sediment instability on glaciated margins.

Keywords: paleo-slide scar, paleo-channels, glaciated margin, Barents Sea

1. Introduction

Some of the largest submarine landslides have affected high-latitude glaciated continental margins, areas which now receive increased attention because of their hydrocarbon potential. On the Norwegian – Barents Sea – Svalbard margin submarine landslides have resulted in several slide scars including the Storegga (Bugge et al., 1987; Haflidason et al., 2004, 2005), Trænadjupet (Laberg and Vorren, 2000) and Hinlopen Slides (Vanneste et al., 2006; Winkelman et al., 2006). Paleo-slope records from these areas also reveal evidence of similar sized buried slide scars, indicating repeated large-scale sliding (Evans et al., 1996; Kuvaas & Kristoffersen, 1996; Laberg and Vorren, 1996; Solheim et al., 2005; Laberg et al., 2006). Another, less studied result of slope instability on glaciated margins is the development of large canyon – channel systems. Morphological studies of modern canyons have shown that sliding is an important process in their evolution and that they develop over a long period of time from the interaction of several processes which include repeated sliding (Laberg et al., in press).

In this study we have focused on the early – middle Pleistocene interval of a glacigenic depocentre in the south-western Barents Sea, the prograding wedge in front of the Bear Island Trough (Fig. 1). The objective of this study is to describe and discuss the morphology of two close-lying paleo-slope surfaces; the lower displays part of a paleo slide-scar, whilst the upper comprises several large paleo-channels, and to elucidate on the paleoenvironment during their formation.

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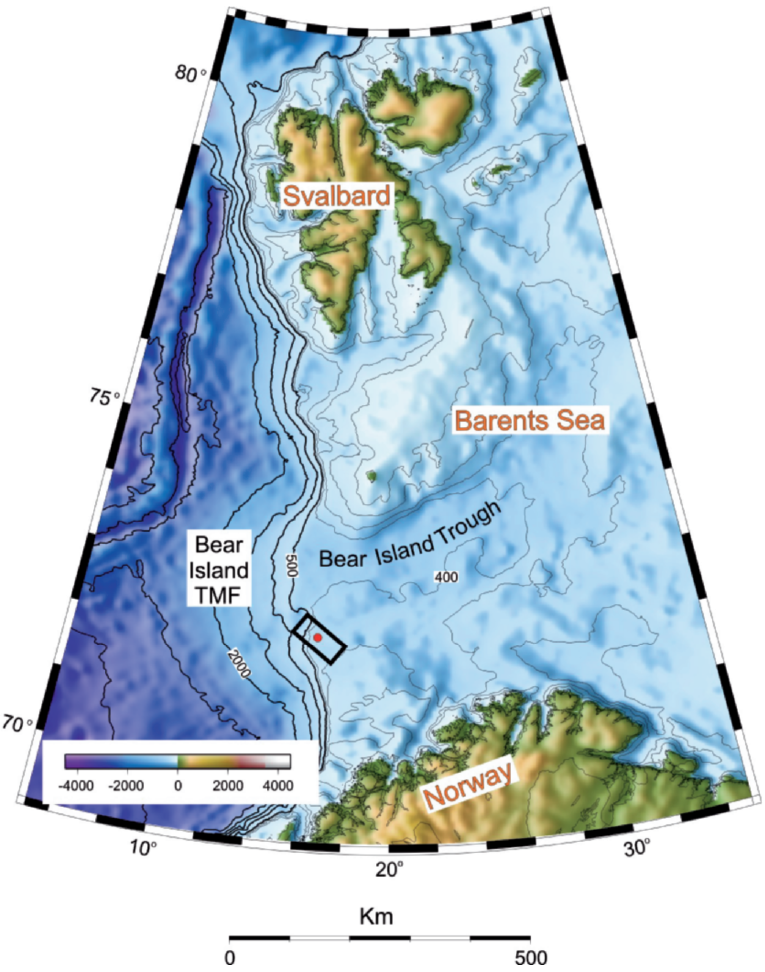

Fig. 1. Bathymetric map of the western Barents Sea continental margin. The box outlines the area of 3D seismic data and the red dot shows the location of well 7216/11-1. Contour interval is 100 m on the shelf and 500 m on the continental slope and in the deep sea.

2. Geological Setting

The Norwegian – Barents Sea – Svalbard continental shelf has a glacial morphology. Glacial erosion was most pronounced in the transverse troughs where ice streams were located during full glacial conditions when the Fennoscandian and the Barents Sea Ice Sheets extended to the shelf break along most of the Norwegian – Barents Sea shelf (e.g. Vorren, 2003). As a result of this spatially variable glacial erosion, some areas of the continental slope, i.e. the areas in front of the troughs received huge volumes of sediments. These depocenters have been called “Trough Mouth Fans” (Vorren et al., 1989). The largest trough mouth fan along the Norwegian – Barents Sea continental margin is the Bear Island Trough Mouth Fan (TMF) (Fig. 1) which developed due to deposition over repeated glacial episodes.

The onset of the Bear Island TMF development has been dated to about 2.75 - 2.3 Ma (Eidvin et al., 1993; Sættem et al., 1992; Mørk and Duncan, 1993). Based on shallow boreholes in the northern outer Bear Island Trough (c. 150 km north of our study area) Sættem et al. (1992) suggested that the lower part of the fan was deposited by "a high sediment input onto a shallow, sand-dominated continental shelf in front of a grounded ice margin". Where sampled during commercial drilling (mainly cuttings and small sidewall cores), the upper part of the fan comprises clast-bearing muddy sediments inferred to be glacimarine deposits which include Ice-Rafted Material (IRD). Data available from well 7216/11-1 located within the study area indicate that the paleo-slope surfaces studied in the present paper (Fig. 2) are located within muddy glacimarine sediments (Ryseth et al., 2003). Studies of 3D seismic data from the paleo-shelf indicated that grounded ice reached the shelf break from the level of the lower surface that is investigated here and upwards (Andreassen et al., 2004, 2007).

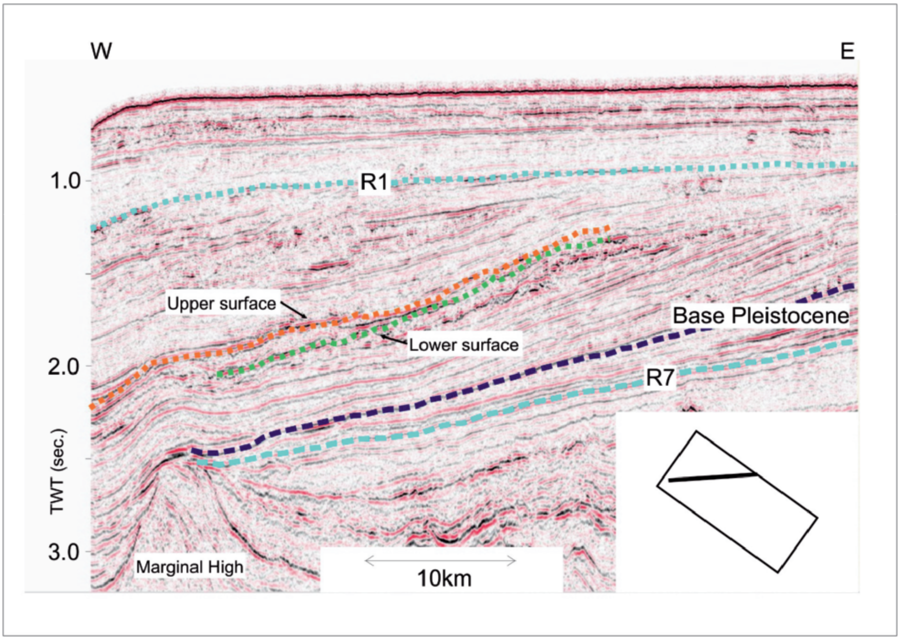

Fig. 2. Part of a seismic line showing the stratigraphic position of the lower and upper surface studied. Reflection R7 is the base of the late Pliocene – Pleistocene glacigenic sediments, Base Pleistocene the base of the Pleistocene sediments and R1 an upper regional unconformity of middle Pleistocene age.

3. Data Base

This study is based on a commercial 3D seismic data set covering an area of about 2900 km^2 (Fig. 1). The vertical resolution of the data is approximately 20-25 m. The theoretical limit for the horizontal resolution of 3D seismic data is ¼ of the seismic wavelet (Brown 2003), which here is ~ 20-30 m (using a seismic velocity of 2200 m/s). For the seismic interpretation the GeoFrame Charisma software was used.

4. Paleo-slope Morphology

4.1 THE LOWER SURFACE

The lower surface includes part of the upper paleoslope. It has been mapped from its upslope truncation by a semi-horizontal, slightly westward dipping "topset" reflection, downslope to the marginal high (Fig. 2). The central and northern part of this surface is dominated by irregular relief which terminates upslope by an escarpment (Fig. 3A). In some areas the escarpment is up to 50 ms (TWT) high and easily identified, in other areas it is more subdue probably because the height is below the vertical resolution of the seismic system. The area of irregular relief is separated into a northern and a southern part by a downslope oriented, steep-crested ridge which is up to 4 km wide and 100 ms (TWT) high (Figs. 3A-B). The ridge crest is irregular and dominated by amphitheatre-shaped depressions, except for in the lowermost part where a series of strait to curved lineations are seen (Fig. 3B). In an area north of the ridge a faint meandering pattern can be followed downslope from near the headwall (Fig. 3B).

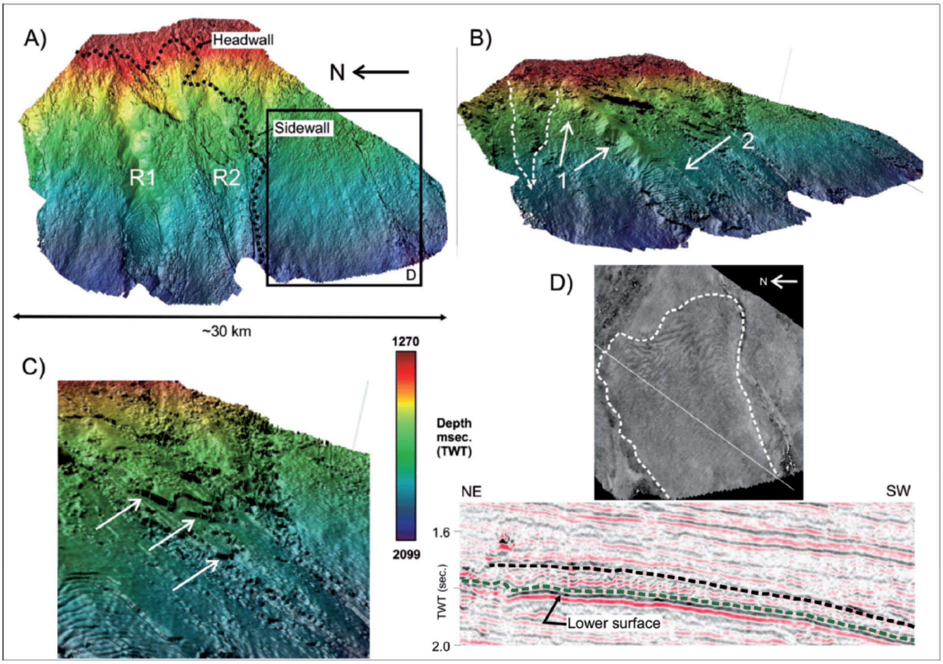

Fig. 3. A) Shaded relief time structure map of the lower surface with the vertical scale 2x exaggerated. Part of the headwall and sidewall is shown. R1 = downslope oriented, steep-crested ridge, R2 = a less-pronounced, downslope oriented ridge. Frame outlines Figure 3D. B) Three-dimensional perspective view from the north-western end of (A). (1) = small-scale irregularities, (2) = area of curved lineations. Stippled lines: areas which show a faint meandering pattern. C) Three-dimensional perspective view from the north-west showing secondary escarpments (arrows). D) Volume amplitude plot and corresponding seismic profile showing a large area of curved lineations immediately south of the slide scar. The area is outlined by the stippled line on the amplitude plot. On the corresponding seismic line it is located between the green (lower surface reflection) and the black stippled lines (see Fig A for location).

Small-scale irregularities are seen, most pronounced near the escarpment (Fig. 3B). Several secondary escarpments are seen within the upper, southern part of the irregular area (Fig. 3C). They occur within the upslope part of a less-pronounced, downslope oriented ridge (Fig. 3A). A small escarpment marks the southern limit of the irregular area. To the south of this escarpment the paleo-slope has a relatively smooth relief. Immediately above this surface the reflections are discontinuous and a volume amplitude plot shows a large area of curved lineations (Fig. 3D), similar to the lower part of the northern ridge (Fig. 3B).

The areas of irregular morphology are inferred to represent the upper part of a paleo-slide scar. The upper escarpment probably forms part of the paleo-headwall while the downslope oriented ridge is an erosional remnant. The amphitheatre-shaped depressions on this ridge are likely the result of smaller-scale mass wasting, whilst the curved lineations in the lowermost part are the result of sediment creep. South of the ridge secondary escarpments occur. Such features are not found north of the ridge, instead a faint meandering signature is seen, originating from near the headwall. This difference may be related to sediment physical properties variations, with the more consolidated sediments south of the ridge more difficult to mobilise into flows. A large area south of the slide scar was probably also affected by sediment creep or sliding, from the present data base it is not possible to discriminate between the two alternatives. This formed a pattern of curved fractures separating rafts or ridges of sediments and was possibly part of the same event that resulted in the formation of the slide scar.

4.2 THE UPPER SURFACE

Stratigrapically, the upper surface is located slightly above the lower in a similar physiographic setting (Fig. 2). Its morphology is dominated by three straight to slightly meandering channels (indicated 1, 2, 3 in Fig. 4A). The upslope part of the southern two channels (1-2) could not be mapped because this part of the paleo-slope has been removed by subsequent erosion. The southernmost channel (1) originates as two channels, then merges into one which keeps its identity as a straight channel downslope (Fig. 4B). The channel is V-shaped, 50 ms (TWT) deep and has a width of about 250 m. The channel is visible on the amplitude plot (Fig. 4D), showing an increased acoustic contrast downslope (Fig. 4D).

The middle channel (2) is slightly meandering (Fig. 4B), it has a depth and shoulder width of about 25 ms (TWT) and 250 m, respectively and has a U-shaped cross-section. It is also well displayed on the amplitude plot (Fig. 4D), indicating contrasting sediments at the bottom of the channel. This could be due to erosion and subsequent deposition of more coarse grained sediments brought downslope from the area of flow origin. The third channel (3), is U-shaped, c. 500 m wide and terminates upslope in a headwall area (Figs. 4A, C). The headwall is amphitheatre-shaped, about 3 km wide, and is incised by second-order channels (Fig. 4C). Downslope from the headwall channel 3 is seen on the amplitude plot, although the contrast is not as clear as for the other channels (Fig. 4D).

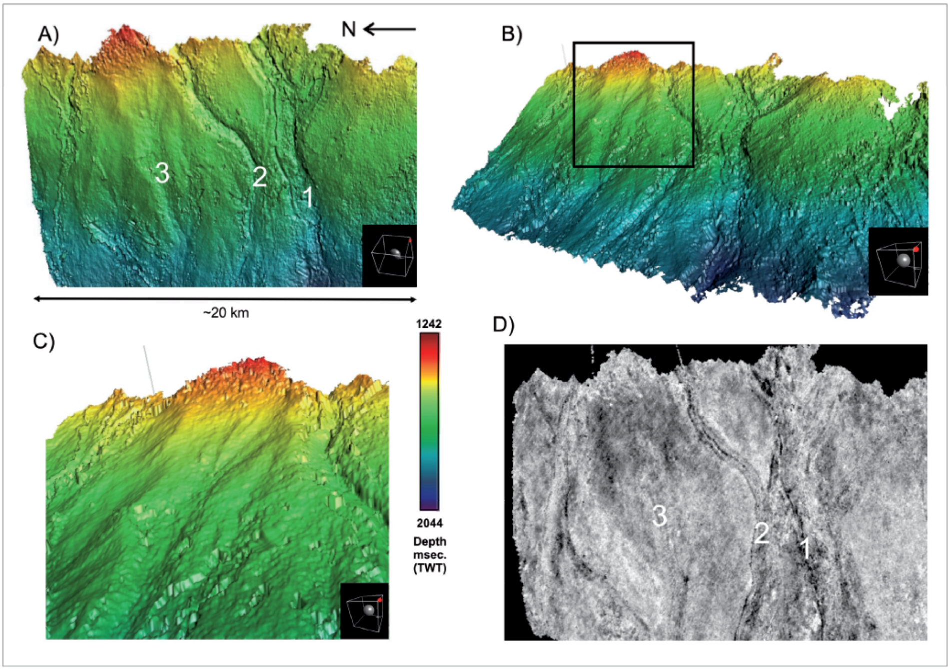

Fig. 4. A) Shaded relief time structure map of the upper surface with the vertical scale 2x exaggerated. Channels 1 – 3 are indicated. B) Three-dimensional perspective view from the south-west. Frame outlines Fig. 4C. C) Three-dimensional perspective view of the upper part of channel 3. D) Surface amplitude plot of area in (A). The location of channels 1 – 3 is indicated.

5. Discussion

5.1 PALEO-SLOPE PROCESSES

Although only part of the upper slide scar was identified on the lower surface, its morphology is relatively similar to that of modern slide scars. Secondary escarpments downslope of the headwall form the upper boundary of subparallel paleo-surfaces as seen for instance in the upper Trænadjupet (Laberg and Vorren, 2000) and Nyk (Lindberg et al., 2004) Slide scars. This indicates that sediments at different stratigraphic levels were affected by the failure, that the failure may have been initiated at specific stratigraphic levels forming layers of weakness, and that this may have occurred during one major event followed by smaller, secondary events.

The morphology of the upper surface differs from the lower surface, being dominated by paleo-channels of various sizes. One channel terminates upslope in a headwall area with second-order channels. Several second-order channels may indicate channel formation by sliding over a longer period, as seen in modern canyons (Laberg et al., in press).

5.2 FACTORS PROMOTING LARGE-SCALE SLIDING

Within the glacigenic sediments studied, the lower paleo-slope surface represents the oldest level of large-scale sliding. Below this surface, 2D seismic data display mainly acoustically laminated sediments where intervals of single channels, channel systems and small-scale sliding have been shown. So what caused large-scale sliding in this area at this time? Studies of the late Pleistocene succession on the Norwegian – Barents Sea continental margin have shown that sliding events tend to occur during, or immediately after, glacial maximum periods (e.g. Solheim et al., 2005; Laberg et al., 2006).

The advance of an ice sheet to the shelf break results in sediment erosion below the ice. This erosion is most intense beneath fast-flowing ice streams and large volumes of sediment will be deposited in front of these on the upper continental slope. This rapid sediment loading affects the physical properties of the underlying sediments, makes them more prone to failure (Bryn et al., 2005; Laberg et al., 2003; Kvalstad et al., 2005). We therefore suggest that the submarine landslide which resulted in the slide scar partly displayed on our lower surface was the result of increased sediment input to this part of the continental margin. This was probably due to the advance of an ice sheet to or near the shelf break, in accordance with Andreassen et al. (2004, 2007).

5.3 FACTORS PROMOTING CHANNEL DEVELOPMENT ON GLACIATED MARGINS

The upper surface morphology is also related to sediment reworking but why this resulted in channel features and not a slide scar morphology as the lower surface event is not known. The northern channel was probably formed by sliding over a longer period. However, the southern two may have been formed by a similar process as envisaged for the channels identified by Sættem et al. (1992) slightly north of our study area. These channels may have been formed at the margin of ice caps or ice sheets, possibly by meltwater erosion. This interpretation is supported by the fact that they have a more pronounced acoustic contrast (Fig. 4D) compared with the northern; i.e. that they were not formed by the reworking of slope sediments as the northern channel but related to large input of meltwater, introducing more coarse-grained sediments to the channels which caused the acoustic contrast. Thus the upper slope morphology was most likely a result of channel formation both by mass wasting and glacial meltwater erosion.

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