The Fram Slide off Svalbard: a submarine landslide on a low-sedimentation-rate glacial continental margin

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Submarine slope failures are a widespread, hazardous phenomenon on continental margins. The prevailing opinion links large submarine landslides along the glaciated NW European continental margins to overpressure generated by the alternation of rapidly deposited glacigenic and hemipelagic material. Here, we report a newly discovered large landslide complex off NW Svalbard. It differs from all known large slides off NW Europe, as the available data rule out that this slope failure resulted from rapid glacigenic deposition. This suggests that processes such as contour currents, tectonic faulting, and overpressure build-up related to the gas hydrate system must be considered for hazard assessment.

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Submarine slope failures occur all over the world and pose a significant natural hazard. They threaten offshore infrastructure in areas where hydrocarbon exploration is being carried out as well as underwater structures such as pipelines, rigs, and telecommunications cables. In addition, some landslides have caused destructive tsunamis endangering coastal communities.

Numerous large submarine landslides shaped the NE Atlantic glaciated margins during the Holocene and Pleistocene. The largest Holocene slide was the Storegga Slide, which initiated about 2400–2000 ka ago on the Fram Strait in 2012, we discovered the Fram Slide, a new large submarine slide complex (Fig. 1). The main objective of this paper is to document that this slide is not controlled by pressure build-up owing to quickly accumulated

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Glacial deposits. This means that other factors play an important role in slope failures; these factors will be discussed here using the Fram Slide as example.

Data. The basis of the study is a 58 km long 2D high-resolution seismic data profile (Fig. 1c) and about 750 km of Parasound and multibeam data that cover most of the slide over a depth range of 950–4200 m. Furthermore, we sampled near-surface sediments at three locations (Fig. 1c) using a gravity corer.

Results. The multibeam data reveal up to 250 m high breaks of slope extending 80 km along strike on the eastern side of the Fram Strait (dashed lines in Fig. 1c). These breaks of slope occur in water depths between 1260 and 3000 m, over a distance of more than 25 km in dip direction and in an amphitheatre shape. The bathymetry data gridded at 100 m show that the slope breaks have gradients of up to 30° whereas the sea floor further seaward dips at 1–6°. In the toe region in water depths between 2.5 and 3 km the sea floor shows a slope angle of 1–2°. Here slope breaks are absent. Several very steep breaks of slope striking in a NW–SE direction occur in a water depth greater than 3 km (Fig. 1c) at the northern edge of the trough of the Spitsbergen Fracture Zone (Fig. 1b).

The 2D high-resolution seismic data show a thick pile of parallel-stratified sediments in the shallow northeastern part of the profile (offset >30 km) (Fig. 2a). There is no seismic evidence for glacial debris-flow deposits, which are typically characterized by the absence of internal reflections and an overall wedge form (Bünz et al. 2003). Further downslope (offset 20–27.5 km), lateral thickness variations of single reflection packages indicate current-controlled deposition (Fig. 2c). A prominent 50 m high scarp at 30 km offset (Fig. 2d) truncates well-stratified sediments.

A very prominent series of seismic high-amplitude anomalies is aligned at 300 ms two-way travel time (TWTT) beneath the sea floor (assuming a sediment sound velocity of 1600 m s−1), shoaling to the east. They terminate at a line (Fig. 2b) that in some places (e.g. at offset 30–32 km) forms a continuous seismic reflector. We interpret these anomalies as gas hydrate-related bottom simulating reflectors (BSR), similar to those observed along the Svalbard and mid-Norwegian margin (Berndt et al. 2004). The presence of high-amplitude seismic anomalies beneath the BSR suggests the accumulation of free gas.

In addition, the seismic data show some vertical amplitude anomalies (Fig. 2e and f). We interpret them as pipe structures caused by upward migrating fluids. The low-amplitude anomalies indicate disruptions of the original layered sediment structure (Judd & Hovland 1992). The increased seismic amplitude anomalies within some of the pipes are possibly caused by free gas (Loseth et al. 2009).

Several steeply dipping low-amplitude anomalies interrupt the seismic reflections of the layered sediments between the offsets of 8 and 12 km (Fig. 2a). As they are associated with downward displacement of the seismic reflections, we interpret them as normal faults. They coincide with the breaks of slope in the bathymetry data.

Cores 605 and 606 were taken at locations with seismically transparent bodies shown by the Parasound data at a shallow depth below the sea floor (see Fig. 1c for location of cores), interpreted

Fig. 2. Line drawing of the 2D seismic profile showing the main features: a BSR (red) indicates free gas underneath; slide deposits are shown in dark grey; layered sediments in the shallow area with pipe structures indicate rising fluids (decreased or increased seismic amplitudes are shown in light and dark blue; respectively); location of core site 605; normal faults at about 10 km offset; the 0.78 Ma (green), 1.20 Ma (pink), 1.78 Ma (orange) and 2.58 Ma reflector (purple), implementing the seismic stratigraphy for ODP Site 912 from Mattingdal et al. (2014). The insets show representative seismic examples for the various features: (a) faults and offsets of the prominent reflectors in about 3 km depth; (b) high amplitudes of free gas underneath the BSR; (c) undulation of single reflection packages indicating contourite deposition within a sediment drift; (d) transparent slide deposits with a hummocky surface next to the headwall and evidence for fluid migration beneath; (e) and (f) fluid migration suggested by subdued and increased amplitude, respectively.
as slide deposits. This was confirmed by chaotic and sheared sediments at 270 and 210 cm depth in cores 605 and 606, respectively. Above these disturbed units, the cores consist of horizontal well-layered brownish and greyish sediments with few dropstones. Radiocarbon dating of core 606 yields calculated average sedimentation rates of 46 and 36 mm ka⁻¹, at 40–80 and 80–134 cm, respectively. Using these sedimentation rates we can estimate the onset of hemipelagic deposition following the slide event represented in the core to a minimum of c. 60 ka BP, assuming the higher sedimentation rate of 46 mm ka⁻¹ for the 76 cm below the oldest age and the top of the slide deposit.

Discussion. Along an area of at least 2200 km² of the continental margin NW of Svalbard, the multibeam data show numerous amphitheatre-shaped slope breaks (Fig. 1c). We interpret the downward stepping slope-parallel scarps as headwalls of a submarine landslide complex. Adjoining pairs of slope breaks with the down-thrown sides facing each other are interpreted as sidewalls. The seismic data support this interpretation. They show scarps with a truncation of the seismic reflectors upslope of the head wall, and hummocky sea-floor reflections with underlying chaotic seismic facies seaward of the headwall (Fig. 2). Furthermore, many of the observations point to the Fram Slide being a translational failure because it clearly cuts stratified sediments and the slide deposits are underlain by a planar surface interpreted as the glide plane (Fig. 2d). The limited amount of seismic data, however, does not rule out rotational movements in other parts of the slide. The multitude of nested headwalls suggests retrogressive sliding on multiple glide planes. The seismic data clearly show older buried slides (Fig. 2d), indicating a long history of slope failure in the region. Adopting the seismic stratigraphy from the study of Mattingsdal et al. (2014) for Ocean Drilling Program (ODP) Site 912, our data show that there have been slide events younger than 0.78 Ma and older than 2.58 Ma; the age model of core 606 suggests a minimum age of the latest slide event of c. 60 ka BP (Fig. 2d).

The Parasound data support this conclusion of different failure events. They show distinct morphological variation for different parts of the slide. No recent slide deposits are found downslope of some headwalls. The hummocky surface downslope of another scarp suggests that this feature was caused by a relatively recent slope failure; even the high resolution of the Parasound data does not show a drape.

The volume of mobilized slope material is between 65 and 220 km³ based on the area showing removal of sediments by the landslide and assuming a thickness of the removed sediments between 30 and 100 m, which is the height of the identified headwalls. This makes the Fram Slide smaller than most of the slides that affected the NE Atlantic margin (Hjelstuen et al. 2007) but this is a conservative estimate because of the incomplete data coverage.

With the large number of nested headwalls, translational sliding and an overall headwall length of several tens of kilometres the Fram Slide resembles other submarine landslides at glaciated margins (Laberg & Vorren 2000; Laberg et al. 2000). Therefore, similar geological processes may have controlled this slope failure. However, the continental shelf break is about 60 km SE of the slide (Ottesen & Dowdeswell 2009) and the closest observations of normal faults may be a rotational slump that developed on the steep part of the slope. Unfortunately, the data quality in this part of the profile is poor because the rough topography causes seismic artefacts. However, normal faulting offsets the sea floor and thus removes the buttress for the adjacent sea floor further upslope, which could be a reason for the observed slope failures.

The third possible mechanism for slope failure in the study area is overpressure build-up owing to permeability variations in the subsurface. The BSR is conclusive evidence for gas hydrate and gas accumulation within the main failure area (Fig. 2b). Gas hydrates cement the sediments and increases their shear strength (Sultan et al. 2004). This enhances the stability of the slope but also reduces the permeability (Berndt & Goswami 2007). Continuous accumulation of gas may increase pore pressure in the term long owing to buoyancy forces (Crutchley et al. 2010), which may destabilize the slope. In this scenario, pressure transfer may occur when the buoyancy force exceeds the fracture gradient of the sediments and gas blow-out pipes develop by hydro-fracturing (Bünz et al. 2003). Numerous examples of pipe structures in the seismic data (e.g. in Fig. 2e and f), in particular where the BSR appears brightest, imply that a large part of the slope has been affected by overpressures in the geological past. Overpressure development may have been the main destabilizing factor for the Fram Slide similar to the Ana Slide in the Western Mediterranean Sea (Berndt et al. 2012).

Mosher & Piper (2007) showed that some submarine slope failures on the Canadian glacial continental margins were caused by over-steepening owing to halokinesis. This process can be ruled out for the Fram Slide as evaporite deposits have not been reported for the Fram Strait.

Without a more robust understanding of the underlying mechanisms of the Fram Slide it is difficult to assess the associated compared with those of areas influenced by trough mouth fans (Laberg et al. 2000; Lindberg et al. 2004; Winkelmann & Stein 2007). The absence of rapidly deposited glacigenic material rules out interlayering of hemipelagic contourite deposits and over-consolidated glacial deposits as an explanation for the Fram Slide.

We conclude that other geological processes must be responsible for generating the Fram Slide. Three processes seem most plausible, considering the geological setting. The first possibility is contour currents, which have influenced the sedimentation in large parts of the Fram Strait since the Late Miocene (Eiken & Hinz 1993; Gebhardt et al. 2014). The contourite deposits are easily distinguished in the seismic data at 20–27.5 km offset (Fig. 2c). There is no evidence for submarine erosion close to the slide but bottom currents may have led to repeated failure owing to over-steepening of the slope and enhanced deposition (Biscara et al. 2012). Haflidason et al. (2004) and Bryn et al. (2005b) showed that current velocities peaked for water depths in which the Storegga Slide was probably initiated. However, contourite deposits are widespread also along the Fram Strait margin farther south and slope failures have not been observed at these locations, suggesting that contourite deposition might be only a minor control on the development of the Fram Slide.
hazard potential of slides in this area (Berndt et al. 2009), but it is likely that the combination of great water depth and multiple failures implies a low potential for destructive tsunamis (Nixon & Grozic 2006).

Conclusion

We report a new landslide complex that shapes the glacial continental margin NW of Svalbard. The Fram Slide affected the margin laterally for at least 2200 km² at 1.3–3 km water depth with maximum headwall heights of 250 m. The estimated volume of mobilized slope material (65–220 km³) suggests the Fram Slide to maximum headwall heights of 250 m. The estimated volume of a

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Ritzmann, O. & Jokat, W. 2003. Crustal structure of northwestern Svalbard and is therefore a very remarkable submarine landslide in the region. The characteristics of the Fram Slide do not follow the prevailing explanation for failure on glacial continental margins off NW Europe, as this slide does not show any evidence for a formation history linked to the deposition of glacial deposits or salt tectonics and is therefore a very remarkable submarine landslide in the region that requires further study. It is more likely that a combination of unstable sediments owing to contourite currents, tectonic movement and/or fluid migration has played a key role in this slope failure. The potential hazard for destructive tsunamis from the Fram Slide complex is difficult to assess because of the limited database but the combination of great water depth and multiple failures suggests it is not as high as for the other major slides on the NW European margins.

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