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Chronology of the Fram Slide Complex offshore NW Svalbard and its implications for local and regional slope stability

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ABSTRACT

The best known submarine landslides on the glaciated NW European continental margins are those at the front of cross-shelf troughs, where the alternation of rapidly deposited glycogenic and hemi pelagic material generates sedimentary overpressure. Here, we investigate landslides in two areas built of contourite drifts bounded seaward by a ridge-transform junction. Seismic and bathymetric data from the Fram Slide Complex are compared with the tectonically similar Vastness area ~120 km to the south, to analyze the influence of local and regional processes on slope stability. These processes include tectonic activity, changes of climate and oceanography, gas hydrates and fluid migration systems, slope gradient, toe erosion and style of contourite deposition. Two areas within the Fram Slide Complex underwent different phases of slope failures, whereas there is no evidence at all for major slope failures in the Vastness area. The comparison cannot reveal the distinct reason for slope failure but demonstrates the strong impact of variation in the local controls on slope stability. The different failure chronologies suggest that toe erosion, which is dependent on the throw of normal faults, and the different thickness and geometry of contourite deposits can result in a critical slope morphology and exert pronounced effects on slope stability. These results highlight the limitations of regional hazard assessments and the need for multidisciplinary investigations, as small differences in local controlling factors led to substantially different slope failure histories.

1. Introduction

Submarine slope failures are a worldwide phenomenon and represent a significant natural hazard. They can destroy offshore infrastructure and generate destructive tsunamis which endanger coastal communities. Numerous studies show that submarine landslides occurred in the Holocene and Pleistocene on the NE Atlantic glaciated margin (Fig. 1A) and concluded that the cyclic sedimentation pattern related to glacial/interglacial conditions critically influences slope stability (Laberg and Vorren, 2000; Haflidason et al., 2004; Lindberg et al., 2004; Hjelstuen et al., 2007; Winkelmann and Stein, 2007). This hypothesis fits well for slopes with failures at former maximum ice margins where the deposition of trough mouth fans led to very high sedimentation rates during glacial melting, presumed to lead to overpressure build-up in the sediment pore space. It does not explain the occurrence of submarine slope failures in other geological settings.

Future climate models predict that the Arctic will be mostly free of summer sea ice by the end of the 21st century (Stocker et al., 2013) and forecast a long-lasting bottom water warming. This trend may have an effect on gas hydrate stability while at the same time enhances the interest of the hydrocarbon industry to extend oil and gas exploration further north. Hence, it is necessary to improve our knowledge about the processes and settings that favor slope instability in order to assess hazards in the Arctic and to minimize the impact of seafloor stability on hydrocarbon exploitation.

There are not many submarine landslides known and studied in the European Arctic apart from the Hinlopen/Yermak slide complex (Winkelmann and Stein, 2007) and the Fram Slide (Elger et al., 2015). Elger et al. (2015) reported on the extent of the Fram Slide and compared it with the typical characteristics of slope failures on the NE Atlantic glaciated margin. That study confirmed that submarine slope failure in the NE Atlantic is not restricted to areas close to the maximum ice extent. Rather, the Fram Slide Complex (FSC) is developed in a contourite drift, near the tectonically active intersection of the Spitsbergen Transform Fault and the Molløy Ridge (Fig. 1B). An analogous tectonic setting is found 120 km southeast, in the Vestnesa area on the Svalbard continental margin, in contourite drifts near the intersection of the Knipovich Ridge and the

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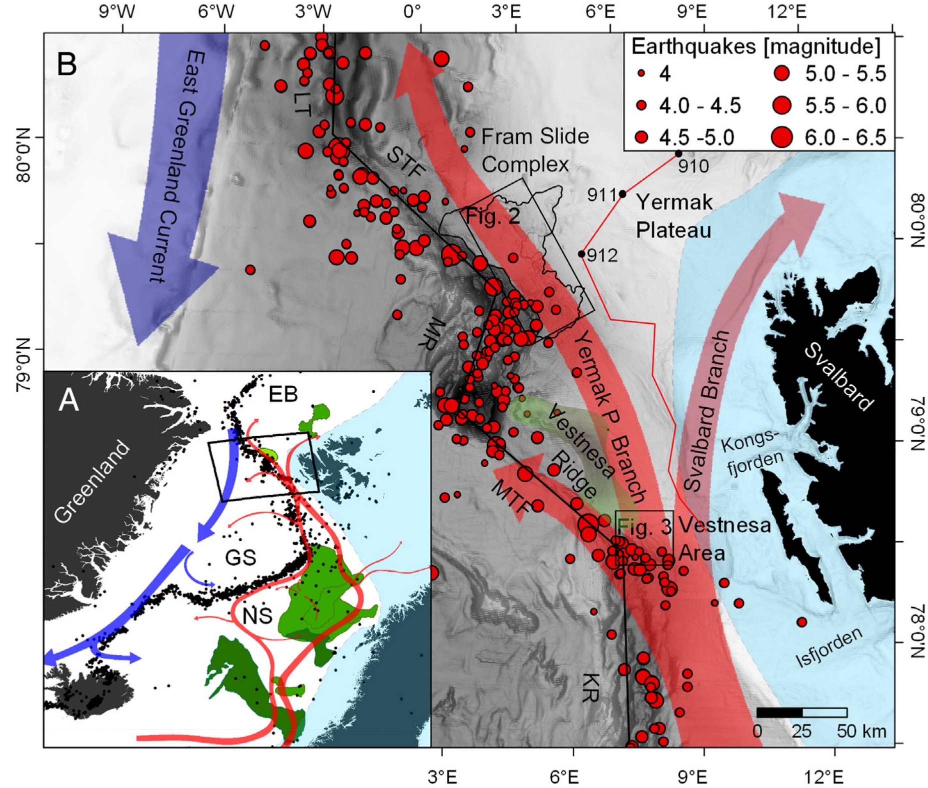

Fig. 1. Location of the Fram Slide Complex on the continental margin off Svalbard: (A) overview map with the location of the Norwegian and Greenland Sea (NS and GS), the Eurasian Basin (EB), the surface water circulation in the eastern North Atlantic including the East Greenland Current and the West Spitsbergen Current (red arrows) (adapted from Beszczynska-Möller et al., 2012), the sea floor affected by the Holocene Andøya, Trænadjupet and Storegga slides (light green, north to south), and by the Pleistocene Hinlopen–Yermak, Vigid, Sklinnadjupet, Bjørnøya Fan Slide Complex and Bjørnøya slides (dark green, north to south) (Haflidason et al., 2007; Winkelmann and Stein, 2007) and the location of the FSC (outlined in black) (map projection: azimuthal equidistant). (B) Regional bathymetry of the Fram Strait and Svalbard margin with the Lena Trough (LT), the Spitsbergen Transfer Fault (STF), Molløy Ridge (MR), Molløy Transfer Fault (MTF) and Knipovich Ridge (KR), the location of the ODP bore holes 910–912, the seismic profiles from which the stratigraphy of Mattingsdal et al. (2014) was extrapolated, the branches of the splitting West Spitsbergen Current, the northern and southern part of the FSC (NP and SP) and the location of Figs. 2 and 3 (map projection: WGS 1984 UTM Zone 32N). Both maps show the maximum ice extent during glacial periods since 100 ka (blue shapes) (adapted from Ingólfsson and Landvik, 2013) and seismicity in the area between 1973 and 2015 (M > 4) (black and red dots in (A) and (B), respectively; source: US Geological Survey). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Molløy Transform Fault. No submarine landslides have been reported there previously.

The purpose of this paper is to constrain the chronology of events that shaped the Fram Slide Complex (FSC) based on a new seismic and bathymetric data set. A second objective is to evaluate the role of regional and local geological processes that pre-condition and trigger submarine landslides, by comparing the internal variability in morphology and recurrence interval of landslides in the FSC and the Vestnesa area. Tectonic activity, influence of climate and oceanography, and contourite deposition are considered processes that shape the slope and can lead to toe erosion and over-steepening, whereas gas hydrates and basinal fluids are relevant for buoyancy-related overpressure. In addition, we assess the hazard of the FSC by comparing its features with other slope failures on the eastern glaciated North Atlantic continental margin and their estimated hazard.

2. Regional setting

The FSC is located at the intersection of the Spitsbergen Transform Fault and the Molløy Ridge in the Fram Strait that connects the Eurasian Basin with the Norwegian and Greenland Sea (Fig. 1A). When the Eurasian and North American plates separated in the earliest Eocene, the two basins were connected by a strike-slip fault. From the earliest Oligocene, motion between Greenland and Eurasia changed from transform to divergent and the sheared margin was rifted and broken into ridges connected by transform faults (Talwani and Eldholm, 1977). The Spitsbergen Transform Fault is the most prominent of several transform faults that connect the adjacent spreading ridges and move in a dextral shear sense (Engen et al., 2003) (Fig. 1B). It forms a narrow northwest–southeast oriented valley with a length of ~150 km connecting the southern Lena Trough in the north with the 60-km-long Molløy Ridge in the south. The Molløy Ridge is bounded to the southeast by the Molløy Transform Fault, which intersects with the Knipovich Ridge in the Vestnesa area.

Present day oceanographic conditions are characterized by the northward inflow of the West Spitsbergen Current carrying warm Atlantic Water into the Arctic Ocean (Manley, 1995) (Fig. 1A). At ~79.0°N the West Spitsbergen Current splits into three branches (Quadfasel et al., 1987) (Fig. 1B). The Svalbard Branch turns eastward directly north of the Svalbard archipelago and flows across the shallow southern Yermak Plateau (Schauer et al., 2004). The west branch flows southwards and joins the East Greenland Current (Bourke et al., 1988) and the Yermak Plateau Branch transports water northwards along the western Yermak Plateau where it enters the Arctic Ocean (Rudels et al., 2002).

An initial oceanic channel connected the Eurasian Basin with the Norwegian-Greenland Sea since earliest Miocene (Thiede et al., 1995) but the present day mode of seafloor spreading was probably delayed until late Miocene (Engen et al., 2008). A major provenance change of sediments at 11.2 Ma documented in sediment cores of ODP Leg 151 (Winkler et al., 2002) supports this tectonic change. The connection of the two basins led to gradual cooling of the northern hemisphere, as evidenced by ice-rafting activity from 5.7 to 3.2 Ma (Wolf and Thiede, 1991). Long-lasting moderate glacial conditions from 2.6 to 1.0 Ma were followed by increased glacial/interglacial environmental conditions until 0.6 Ma. These

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