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Analyses of past and present rock slope instabilities in a fjord valley: Implications for hazard estimations

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ABSTRACT

For quantitative hazard assessment it is necessary to define the magnitude–frequency distribution and a temporal model of the landslide frequency. This is often complicated for large rock slope failures due to the lack of significant numbers of large rock slope failures in inventories of a given homogeneous region or sparse information about the timing. An inventory of 108 rock slope failure deposits within the fjords of the Storfjord region including a relative rockslide chronostratigraphy was available for this study. The temporal distribution of rock slope failures is characterized by a rapid response with a high frequency of failures directly after deglaciation followed by a lower constant frequency since 9,000 years BP for the entire Storfjord region. The largest recorded volumes failed directly after deglaciation. Volumes larger than 5×10^6 m^3 have not been recorded within the last 9,000 years.

In addition, 17 rockslide scars and on the other hand 17 potential rock slope instabilities have been mapped at the northeastern flank of Tafjord, which is a branch of the Storfjord. Volume–frequency relations have been developed for the three inventories from Tafjord, comprising (i) fjord deposits, (ii) rockslide scars and (iii) potential instabilities. They result in very similar distributions over the entire volume range. All three inventories are underlying the same processes that lead to destabilisation and finally failure. Additionally, the compilation of the three inventories is independent and based on different methodologies. The similarity of the volume–frequency distributions is thus verifying the different inventories. Hence the obtained volume–frequency relation can be used to assess the rockslide hazard for the study area. Present day annual expectable frequencies for different volume classes have been assessed based on the obtained volume–frequency relation of the fjord deposits. For example, the average annual frequency for rock slope failures of $V \geq 1 \times 10^6$ m^3 originating from the northeastern flank of Tafjord is 1/1670 based on a lognormal distribution. This regional hazard can be used to improve previously existing qualitative susceptibility rankings for potential unstable rock slopes within the Tafjord region. The resulting probabilities are very low. However, the uncertainties of all hazard estimates are very high.

1. Introduction

Quantitative hazard estimations for large rock slope instabilities are difficult to obtain because of the lack of significant numbers of events with large volumes in inventories for a given homogeneous region. Magnitude–frequency distributions for past rock slope failures have been analysed over several orders of magnitudes, but always with very limited numbers of large events (e.g., Whalley, 1984; Hungr et al., 1999; Dussauge-Peisser et al., 2002; Dussauge et al., 2003; Guzzetti et al., 2003; Hantz et al., 2003; Malamud, 2004; Brunetti et al., 2009; Santana et al., 2012). This is mainly because historical inventories cover too short time to adequately capture low frequency–high magnitude events. Pre-historic rock slope failures need to be included to cover the entire volume spectra of potential rock slope failures. However, for those, information about the timing is sparse.

Many mountainous regions that were glaciated during the last glaciation, are characterized by large-scale post-glacial rock slope failures (e.g., Korup et al., 2007; Ballantyne and Stone, 2013; Ballantyne et al., 2014). It is well accepted that rock slope failures decrease in number and size with the time elapsed since deglaciation (e.g., Terzaghi, 1950; Abele, 1974; Cruden and Hu, 1993; Ballantyne, 2002a,b; Soldati et al., 2004; Hermanns and Longva, 2012; McColl, 2012), but the exact temporal pattern has only been constructed for few inventories and is still debated (e.g., Cruden and Hu, 1993; Ballantyne and Stone, 2013; Ballantyne et al., 2014). However, in order to assess the present day

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landslide hazard of a certain region, it is necessary to develop a temporal model of the landslide frequency and magnitude distribution, since these vary non-linearly with time.

During the last century Norway has suffered several natural disasters with large losses of life due to rockslides and related tsunamis (Bjerrum and Jørstad, 1968; Furseth, 2006). Glacially oversteepened slopes in combination with unfavourable climatic conditions, like heavy seasonal precipitation, intense snowmelt in spring and long frost periods, increase the vulnerability for rock slope failures. In addition, geological studies show a high concentration of present rock slope instabilities in western Norway (Blikra et al., 2006; Böhme et al., 2011, 2012; Henderson and Saintot, 2011; Saintot et al., 2011). This is why special attention is paid to the Åknes rockslide in western Norway (Fig. 1), currently assumed to be the most hazardous rockslide in Norway (Ganerød et al., 2008). The Åknes rockslide is a large rockslide with an estimated maximum volume of 40×10^6 m^3, showing velocities of 3 to 10 cm per year. A large international project focusing on the investigation, monitoring, and early warning of the Åknes rockslide and other large unstable rock slopes in the inner Storfjord region started in 2005 (Blikra, 2008). This project resulted in a large amount of data as an outcome of numerous site specific investigations (e.g., Ganerød et al., 2008; Lacasse et al., 2008; Oppikofer et al., 2009; Eidsvig et al., 2011; Jaboyedoff et al., 2011). In addition, more regional investigations considering the entire fjord system have been undertaken within the Åknes/Tafjord project. These comprise systematic studies of post-glacial rock slope failures including their deposits on the fjord bottom (Longva et al., 2009) and potential unstable rock slopes (Henderson and Saintot, 2011; Saintot et al., 2011). Oppikofer (2009) analysed rockslide scars and potential instabilities in detail for a smaller part of the study area, namely the northeastern flank of Tafjord between the villages Fjøra and Tafjord (Fig. 2a).

These regional investigations resulted in a unique dataset with three independent types of inventories for Tafjord including (i) fjord deposits, (ii) rockslide scars and (iii) potential instabilities. The fjord deposits cover the entire post-glacial period and yield a complete inventory of post-glacial rock slope failures within the entire fjord system, including relative ages and volumes. Analysed rockslide scars are the equivalents on the slopes of the fjord deposits, whereas their detection and their volume calculations depend on completely different methods. Both fjord deposits and scars represent and characterize the past rock slope failure activity. Failure of potential instabilities instead represents the future thread. The aim is to quantify the potential hazard of the instabilities. Detailed analysis of the temporal distribution of the fjord deposits allows the development of a model for present rock slope failure frequency. Volume–frequency relations of the three inventories were analysed and a possible link between them may help to characterize and quantify hazard within the Tafjord region.

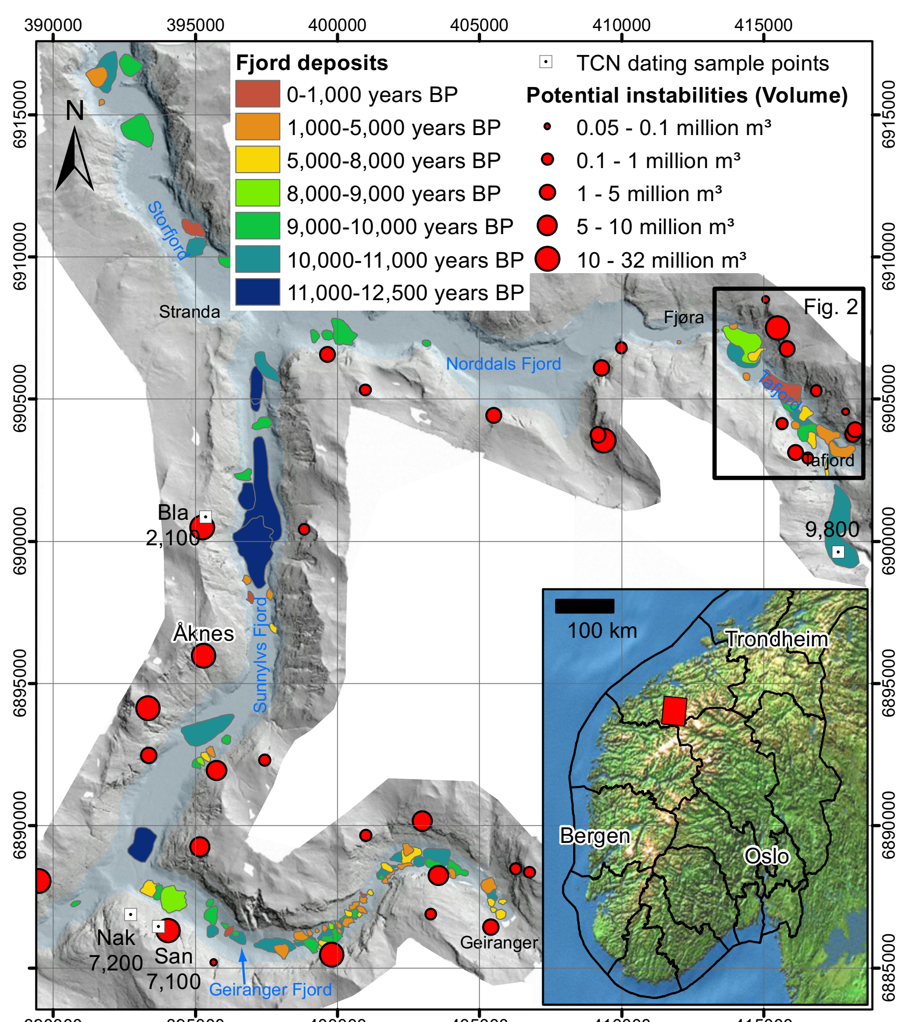

Fig. 1. Overview of the study area. Fjord deposits are adapted from Longva et al. (2009) and potential instabilities from Henderson and Saintot (2011). The location of the Åknes rockslide above Sunnylvs Fjorden is displayed. Relative deposit ages are given in calibrated ^{14}C years BP (Longva et al., 2009) and average TCN ages in years BP. TCN sample locations: Nak—Nakkeneset, San—Nokkenibba, Bla—Blåhornet. The inset shows the location of the study area in southern Norway.