From incipient slope instability through slope deformation to catastrophic failure — Different stages of failure development on the Ivasnasen and Vollan rock slopes (western Norway)

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A B S T R A C T

The long-term evolution of rock slope failures involves different stages, from incipience of slope instability to catastrophic failure, through a more or less long-lasting slope deformation phase that also involves creeping or sliding. Topography, lithology, and structural inheritance are the main intrinsic factors that influence this evolution. Here, we investigate the role of these intrinsic factors on the rock slope failure development of the Ivasnasen and Vollan rock slopes (Sunndal Valley, western Norway) using a multitechnique approach that includes geomorphic and structural field mapping, kinematic analysis, terrestrial cosmogenic nuclide exposure dating, topographic reconstruction, and deformation quantification. Ivasnasen is a rock slope failure complex with several past rock slope failures and a present unstable rock slope, located on a cataclinal NW-facing slope and developed in augen gneiss. Vollan on the opposite valley side is a deep-seated gravitational slope deformation (DSGSD) affecting the whole mountainside, developed in quartzite in the upper part and micaschist in the lower part. These different lithologies belong to different nappe complexes that were emplaced and folded into a series of syn- and anticlines during the Caledonian orogeny. These folds lead to different lithologies being exposed in different structural orientations on the opposite valley flanks, which in turn leads to different types and evolution of rock slope failures. At Ivasnasen the 45°–55° NW-dipping ductile foliation allowed for a fairly simple planar sliding mechanism for the 1.2 million m³ post-glacial rock slope failure. Failure occurred ca. 3.3 ka ago after a short period of prefailure deformation. For the present 2.2 million m³ unstable rock slope at Ivasnasen, a steepening of the foliation at the toe impedes such a mechanism and up to 10 m of displacement has not lead to a catastrophic failure yet. The Vollan DSGSD is characterized by a steep major back scarp with its up to 130-m-wide graben, which opened along the subvertical foliation in the quartzite, and a conspicuous array of counter-scarps in the micaschist. The morphologic features are explained by a flexural toppling mechanism in the micaschist, which likely initiated in the lower slope section and propagated retrogressively until reaching the massive quartzite at the back scarp. Flexural toppling cannot solely explain the total along-slope displacement of up to 200 m, i.e., an elongation of 28%. Creep along a basal shear zone, which may have developed in the hinge zone of the flexural toppling, combined with shallow valley-dipping joints, likely accounts for the large elongation. Implications of this study for the hazard assessment of unstable rock slopes in Norway include the relatively rapid development of instabilities in cataclinal slopes and the important insights on long-term displacement rates gained from cosmogenic nuclide dating for a better understanding of the evolution of unstable rock slopes.

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1. Introduction

The valleys and fjords of western Norway were carved by Cenozoic rivers and glaciers, leading to an extreme Alpine relief with steep-walled, over-deepened glacial valleys (Etzelmüller et al., 2007). Sudden unloading of the steep slopes caused by glacial erosion and rapid glacier retreat, in combination with regional isostatic adjustments and possibly
large-magnitude earthquakes (Olesen, 2004), generated a large number of rock slope failures and gravitational deformation structures shortly (i.e., 1000 to 3000 years) after deglaciation (Blikra et al., 2006; Böhme et al., 2015). The Alpine relief, combined with the abundance of brittle and ductile bedrock structures, seasonal heavy precipitation, snow melting, frost cracking periods, and freeze-thaw cycles make many fjords and valleys of western Norway particularly prone to rock slope failures (Blikra et al., 2006).

Large rock slope failures involving $>10^5$ m$^3$ of fragmented rock have caused rock avalanches, typically characterized by high velocities and a significantly longer runout distance than rockfalls (e.g., Crosta et al., 2004; Hermanns and Longva, 2012). They have also generated severe secondary effects such as displacement waves in fjords and lakes (e.g., Hermanns et al., 2013a; Harbitz et al., 2014) or damming of rivers leading to upstream flooding and possible downstream flooding in case of dam breach (e.g., Costa and Schuster, 1988; Hermanns, 2013). According to $>400$ years of historical records, approximately two to four rock avalanches occur each century in Norway (Blikra et al., 2006; Hermanns et al., 2013b). Nearly all of these events followed active rock slope deformation, either shortly before or long in advance of the failure (Hermanns et al., 2013c). Mapping and monitoring of rock slopes with gravitational deformation is thus a promising mitigation measure to prevent loss of life during future events (Hermanns et al., 2014). Over 250 unstable rock slopes have been detected in Norway in recent decades (Oppikofer et al., 2015). This large number requires prioritization of follow-up activities (periodic or continuous monitoring, early-warning systems, and other mitigation measures) through a hazard and risk classification (Hermanns et al., 2012a, 2013c). While numerous studies have focused on mass wasting hazards in active orogens such as the Himalayas, Andes, Alps, and North American Cordillera, challenges to the hazard assessment are different in less tectonically active regions where fjord-relief is developed in Palaeozoic mountain ranges, such as in eastern Canada, Scotland, and Scandinavia. Here we present new results with innovative methods that reveal the complexities in assessing rock slope failure potential at two adjacent locations with different lithological and structural characteristics. In the upper Sunndal Valley, western Norway (Fig. 1), several rock slope failures occurred from Ivasnasen, and an unstable rock slope is evident on the same slope.

![Location map of the Ivasnasen and Vollan rock slope failure complexes in the upper Sunndal Valley in western Norway. The extent of the Ivasnasen rock slope failures is shown with (1) syn-glacial failure and (2) post-glacial failure. Different areas of the Vollan DSGSD are also shown (coordinates in UTM zone 32N).](image-url)