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Diagnostic characteristics and paleodynamics of supraglacial rock avalanches, Innerdalen, Western Norway

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ABSTRACT

Misinterpretation of rock-avalanche deposits in mountain environments is not uncommon because of the complex interactions between rock avalanches and glaciers. This paper for the first time presents a detailed description of suspicious rock-boulder deposits, which are remnants of a rock avalanche onto a Late Pleistocene glacier. The boulder deposits cover around 1.1 km^2 and are distributed over an area of around 7.5 km^2 and a variety of landforms: three closely nested distinct terminal moraines (0.45 km^2) and dislocated terminal moraines (0.34 km^2) entirely built up of large boulders, lateral moraines that decrease in elevation over a short distance and connect to the terminal moraines, small patches (0.02 km^2) of boulders that occur in islands on a peat-dominated valley floor, and large patches of boulder fields (0.25 km^2 in size) hanging 350 m above the valley floor. The latter are disconnected from any potential source area. ^{10}Be cosmogenic nuclide ages of the three terminal moraines give an indistinguishable Late Pleistocene age of 13.6 ± 1.4 ka, whereas the largest boulder field that is located on the opposite side of the valley from the failed mountain yields a ^{10}Be age of 14.1 ± 0.4 ka, which is slightly older but indistinguishable from the moraine deposits within uncertainty margins. All boulder deposits add up to a volume of 31 × 10^6 m^3. The interpretation of a single rock-avalanche source for those landforms is further confirmed by numerical runout modeling using DAN3D. A failure of the entire volume from Skarfjellet Mountain would result in a runout pattern that is identical to that of the distributed boulder fields when considering that the valley was filled with a glacier around 350 m thick. The rock avalanche would not reach the position of the terminal moraines; however, a glacial re-advance could have transported the boulders to that position. The Late Pleistocene rock avalanche was followed by a Holocene rock avalanche with a volume of 23 × 10^6 m^3 and a typical lobate deposit damming the Innerdalen Valley and creating a lake. ^{10}Be ages indicate that this event occurred 7.97 ± 0.94 ka ago. Structural measurements performed on high-resolution LiDAR scans show a strongly jointed source rock with three joint sets with dip/dip direction 81/034, 86/331, and 77/354 and a foliation with 22/003. The kinematic of the failures can thus be a combination of small-scale wedge failures and planar sliding on shallow dipping foliation. Our detailed description can enable a better identification and interpretation of similar deposits in other mountain areas.

1. Introduction

Rock avalanches, that is, large volumes of fragmented rock mass propagating as highly mobile flows (Heim, 1932; Hutchinson, 1988; Hungr et al., 2001), have on a interglacial time scale first-order controls on landscape evolution in fluvial and alpine glacier environments. They are among the most destructive types of landslides because of the high release of energy, an excessive runout length, and secondary effects such as displacement waves and damming (Heim, 1932; Crosta et al., 2004; Evans et al., 2006, 2009a,b, 2011; Hermanns & Longva, 2012). In steep terrain, rock avalanches may generate a significant fraction of sediment delivered through stream systems (Burbank et al., 1996; Antinao & Gosse, 2009; Korup et al., 2010). Rock avalanches control valley evolution by creating dammed lakes that reduce stream incision and increase sediment storage, and in the common case of supraglacial deposition, they alter the mass balance and dynamics of glaciers (Hewitt et al., 2008, 2011; Hewitt, 2009a).

In high-latitude glacially oversteepened regions such as Western Norway, such rock failures and subsequent displacement waves are widespread hazardous processes that generate significant risk in populated fjords (Braathen et al., 2004; Blikra et al., 2005, 2006; Longva et al., 2009; Böhme et al., 2011). Recent improvement in our understanding of the complex relations between melting glaciers or thawing permafrost and rock-slope failure (Fischer et al., 2013; Krautblatter et al., 2013;

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Ballantyne et al., 2014; Blikra & Christiansen, 2014) has further illustrated the difficulties in assessing future risk associated with rock avalanches. This has led to increased systematic mapping activities in Norway (Hermanns et al., 2011a, 2012a) to establish the spatial and temporal variabilities in rates, recurrence intervals, style of rock avalanches, and factors that control them.

However, the recognition of the co-influence of glaciers and slope failures in the Quaternary and Holocene geological record is complicated. Rock-avalanche dynamics are increased by propagation over low-friction glacial surfaces (Pirulli, 2009; Sosio et al., 2012; De Blasio, 2014; Delaney & Evans, 2014). Glacial dynamics are affected by rock-avalanche debris cover because it reduces melting and induces glacial advance (Deline, 2009; Reznichenko et al., 2011). Glacial and landslide deposits are often diamictons, which makes them difficult to distinguish in many alpine environments, particularly if a landslide fell onto a glacier (Evenson et al., 2009). This has led to misinterpretations of landforms associated with rock-slope failures as moraine deposits (Hewitt et al., 2011; Ostermann et al., 2012). It is even more difficult when a rock avalanche runs over a glacier but continues into an ice-free terrain and entrains moraine material (Gosse & Evenson, 1994; Hermanns et al., 2014). The sedimentology of rock avalanches can be modified during the winnowing of fine sediment by supraglacial meltwater, leading to avalanches with coarser grain-size distributions and boulder lags (Hewitt, 2009b; Shulmeister et al., 2009; Shugar & Clague, 2011). Glacial deformation of rock-avalanche sediment can cause not only geometric disturbance but also sediment compaction, mixing with glacigenic sediment, or mixing of previous rock-avalanche deposits, which is potentially increasing the uncertainty on volume estimates and rates (e.g., Cook et al., 2013). Such a complex situation was found in the Innerdalen Valley, Western Norway (Schleier et al., 2013).

In this contribution, we present a detailed description of the landforms in Innerdalen Valley, together with cosmogenic ^{10}Be exposure ages of the deposits. We conduct runout modeling of two rock avalanches from the same source area, one that fell onto ice and another that ran into an ice-free valley. The study contributes a new dataset of surface-exposure ages of multiple rock avalanches in Western Norway and provides insights for assessing landslide risk from rock-avalanche deposits associated with deglaciation.

2. Regional setting

The Innerdalen Valley (62.72° N, 8.73° E) is located in Sunndal Commune, Møre og Romsdal County, Western Norway (Fig. 1a). It is part of the Trollheimen mountain area, with a relief extending from hundreds of meters below modern sea level to mountain peaks over 1600 masl. It is situated in the cold temperate (boreal) climate zone. Like most of Fennoscandia, the regional geomorphology was affected strongly by multiple Quaternary glaciations. This is expressed by oversteepened valleys, rock slopes, and fjords up to 1000 m deep. The extent of penultimate and earlier Quaternary glaciations is not yet well defined, in contrast to our growing knowledge of the dynamics, chronology, and extent of glaciations in Norway during the Last Glacial Maximum (LGM) and the Younger Dryas (YD) (Olsen et al., 2013a; Sollid & Sørbel, 1979) (Fig. 1).

The LGM and YD events left strong evidence for the impact of glaciation on landscape evolution and sediment storage (Blikra et al., 2006). In contrast to the long-lasting ($<1 \times 10^4$ yr) LGM glaciation, the YD was a very short-lived (~12.8–11.5 kyr) cooling event preceded and followed by rapid warming (Andersen & Mangerud, 1989; Wanner et al., 2008; Shakun & Carlson, 2010). In Western Norway, the YD chron is characterized by a cooler and drier climate. Most glaciers rapidly re-advanced, because conditions deteriorated toward the full ice-age climate of the LGM in less than a century. Then, rapid warming and concomitant rapid rise in sea level following the YD triggered an accelerated decay of the glaciers and the accompanying thawing of permafrost. This rapid change in ice volume contributed to faster rates of lithospheric unloading and post-glacial isostatic uplift (Nesje & Dahl, 1993; Olsen et al., 2013b).

The LGM and YD glacial geology and oversteepened valley walls are particularly evident in the valley of Innerdalen. Prominent terminal-moraine ridges are well preserved and interpreted to define the YD ice extent. Although the valley was completely covered by glacial ice during the LGM, the YD limit was farther upstream (Sollid & Sørbel, 1979; Wasrud, 2010). Today, the study area shows high topographic relief and stretches between elevations of 200 masl in the NW part and 1770 masl at the highest peak of Skarfjellet Mountain at the southern border (Fig. 2). A landslide-dammed lake, the Innerdalsvatna (spanning around 557×10^3 m^2), is located in the center of the valley with a mean water level of 396 masl.

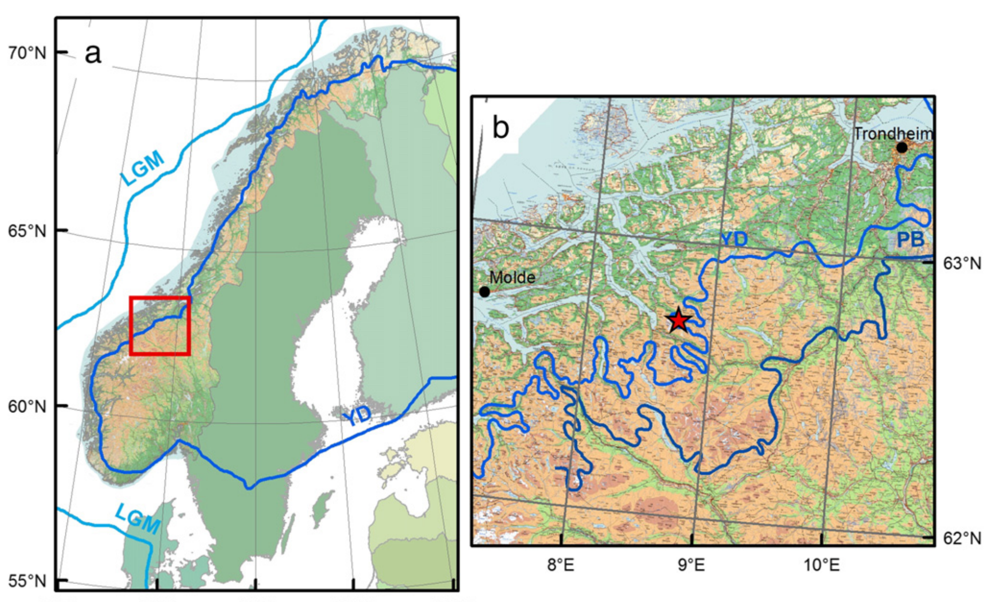

Fig. 1. Overview map of Norway. (a) Ice extent of the Last Glacial Maximum (LGM) and Younger Dryas (YD) glaciations. The rectangle delimits area of (b). (b) Location of Innerdalen Valley (star) and local glacial-ice extent of YD and Preboreal (PB) times.
(a) Ice margins are adapted from Olsen et al. (2013a). (b) Ice margins are adapted from Sollid and Sørbel (1979).