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Terrestrial slopes in northern high latitudes: A paradigm shift regarding sediment origin, composition, and dynamic evolution

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ABSTRACT

High-Arctic terrestrial slopes have received limited systematic research interest, but increased vulnerability related to regional warming has driven the call for better knowledge of the dynamics of these systems. Studies of sediment transport from a plateau area in Adventdalen, Svalbard, and associated slopes extending to sea level demonstrate that glacial processes play a more prominent role than earlier anticipated, — especially the impact of glacial meltwater. Traces of drainage at the plateau and the dissection of the plateau edge and upper slope were clearly initiated during various stages of Late Glacial runoff. Further, there is a close association between the sediment distribution and composition at the plateau and the evolution of various types of slopes. The reconstructed sedimentation history shows that the landscape will undergo four stages with contrasting modes of sediment transport: 1) subglacial processes related to active ice, 2) processes related to the margin of active ice, 3) processes related to the melting of inactive ice, and 4) nonglacial processes. These stages form four successions, referred to as *supply regimes A–D*, which control the supply of water and sediments to a given slope segment. In this landscape, traces of glacial meltwater occur at most altitudes, in "odd" positions and in slope segments "without" catchments. The associated depocenters (isolated, composite or coalescing into aprons), are often outsized compared to the apparent slope catchment. Reworked glacial sediments form a significant part of the slope-debris but are covered partly or entirely by products of physical weathering. Colluvium, *senso stricto*, thus masks a distinct system shift related to the local termination of glacial meltwater. Consequently, the weathering part of the slope sediment budget in this region is considerably overestimated.

1. Introduction

Steep debris-covered slopes form a conspicuous geomorphic element in the nearly vegetation-free landscape of Svalbard. The glacially shaped terrain has a relief of 2000 m (Fig. 1) with glaciers and ice-cored moraines covering 60% of the area.[1] The ice-free slope surfaces show numerous small depocenters, isolated, composite or coalescing into aprons. Similar clastic slope-waste debris referred to as colluvium (Holmes, 1965), talus or scree (Luckman, 2013) are found in most climatic zones with physical weathering. Colluvial debris is mountain slope systems dominated by poorly sorted avalanches, including rockfalls, debrisflows, and snowflows, with minor waterflows (Blikra and Nemec, 1998; Luckman, 2013; Millar, 2015), in contrast to alluvium that occupies the mountain footplain and comprises debrisflows and waterflows (Harvey, 2012). Alluvial systems were first described in the Indus River valley in Himalaya (Drew, 1873) but the best-known systems are from mid-latitude arid settings (Bull, 1977; Rachocki and Church, 1990; Thomas, 2011). Colluvial systems are less known.

Slope deposits at high latitudes attracted interest quite early (De Geer, 1896), and sediment thicknesses formed the basis for the general understanding that the denudation rate here is larger than elsewhere. The size and thickness of slope debris were attributed to the high rate of frost weathering due to low temperatures and a lack of coherent vegetation (Högbom, 1914), a finding later supported by Büdel (1948) and Dege (1949). In a classical study from Tempelfjorden (Rapp, 1960), one of the key questions is why the frost processes are so active in this region. The early slope studies in Svalbard (Jahn, 1947; Rapp, 1957; Jahn, 1960, 1961, 1967; Brenner, 1971; Åkerman, 1984; André, 1986; Rapp, 1986; Rudberg, 1988) were initiated at a time when most researchers inferred a limited ice-sheet during the Late Glacial Maximum (LGM) (Hughes et al., 1977; Boulton, 1979). A scenario with large ice-free areas on the west coast, dominated by frost processes, must have influenced their approach, and the extent of physical weathering has remained undisputed for more than a century of slope research.

Today we know that a dynamically active ice sheet reached the western shelf break during the LGM (Mangerud et al., 1998; Landvik et al., 2005; Ingólfsson and Landvik, 2013). Raised marine beach terraces support this notion and show a glacioisostatic rebound that increases from 65 to 90 m from the mouth to the head of Isfjorden, the largest

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[1] http://toposvalbard.npolar.no/.

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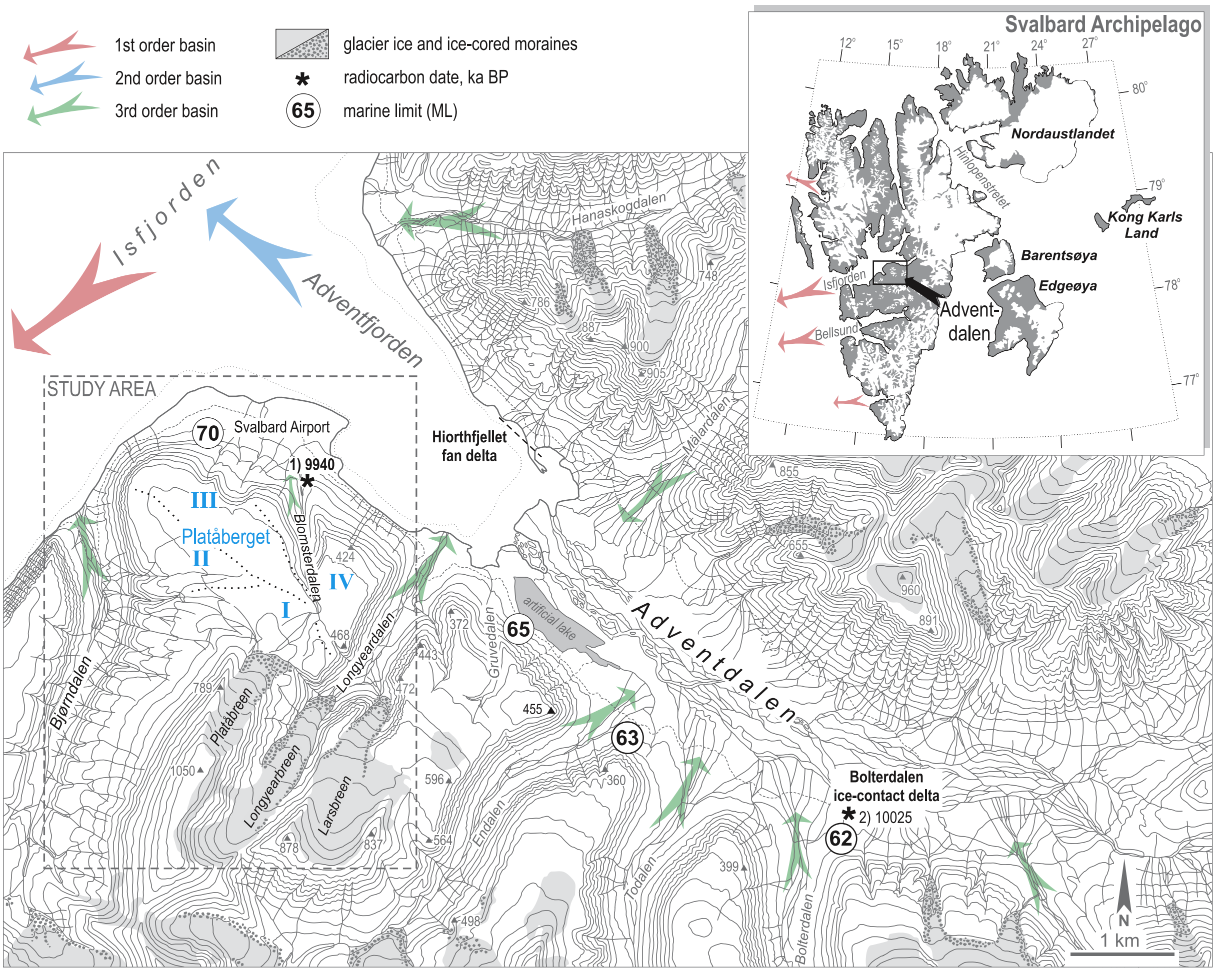

Fig. 1. Platåberget study area in Adventdalen. Svalbard Airport has been the official meteorological station in Svalbard since 1912. Location of radiocarbon dates 1) 9040 ± 115 yrs. BP (Lønne and Nemec, 2004), 2) 10,025 ± 160 yrs. BP (Lønne, 2005).

fjord basin on the west coast (Forman et al., 2004). This glaciohistorical scenario has important implications for the approach to the dynamic processes operating in the region.

Steep terrestrial slopes have received limited sedimentological attention (Harvey et al., 2005; Blair and McPherson, 2009; Harvey, 2011), and in Svalbard, most studies have a morphological approach. There is, however, growing recognition that slope debris may represent archives of environmental and climatic responses (Hétu and Gray, 2000; Hales and Roering, 2005; Decaulne et al., 2009; Dorn, 2009; Sanders and Ostermann, 2011), but the key to unlocking such information has not been captured. There is also an awareness that there could be a continuum of systems, from small debris cones to large waterflow-dominated fans, that may appear in most climatic settings (Harvey et al., 2005; Saito and Oguchi, 2005) but are not controlled by the same key factors. If this is correct, the terminology and classification in use may not necessarily serve our present needs.

In Svalbard, the first investigations combining sedimentology, geomorphology, and modern glaciation history demonstrate that novel glacial historic information can be retrieved from terrestrial slope successions (Lønne and Nemec, 2004; Lønne, 2005; Lønne and Lysså, 2005). The studies also demonstrate that such information is a valuable supplement to the classic marine sediment archives below and above sea level.

The study area in Adventdalen is underlain by Mesozoic strata, chiefly shallow marine sandstones and shales with a low regional dip towards the south (Major et al., 2000). The landscape shows large plateaus separated by fjords and valleys. Deltaic depocenters occupie the mouth of the larger basins (Johansen et al., 2003), whereas fans and cones occur along the shorter dissections. Platåberget, a 13-km^2 plateau at 500 m, provides the opportunity to study three important aspects: the supply of debris to the slopes, the sediment transport mechanisms along various slope segments, and the chronology of key episodes of sedimentation.

A significant volume of ice, active or inactive, is still present in the Svalbard landscape, and it is difficult to imagine a surface above the marine limit (ML) that is unaffected by glacial processes in one way or another. This interaction of glacial- and slope processes challenges our approach to sediment facies and calls for new methods for investigating the sediment composition and transport mechanisms. To understand the contemporaneous processes, we discuss some selected ice margins. The paper comprises three parts; 1) processes along present ice margins, 2) the sediment distribution at Platåberget, reconstruction of deglaciation dynamics and the evolution of associated slopes, and 3) implications for landscape evolution.

2. Setting

An ice sheet covered the Svalbard archipelago during the LGM, and the large, western fjord systems acted as pathways for fast-flowing ice streams that reached the continental edge (Landvik et al., 2005; Landvik et al., 2014). The 100 km long, east — west-oriented Isfjorden (Fig. 1), is the largest of the westward draining basins and was deglaciated in the course of a few thousand years (Forwick and Vorren, 2009). Isfjorden can thus be considered a 1st order basin. Adventdalen (with