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Early and late Holocene sediment yield of Austdalsbreen glacier, southwest Norway

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ABSTRACT

Early and late Holocene sediment yield of Austdalsbreen glacier, an eastern outlet glacier of Jostedalsbreen ice cap in southwest Norway, was investigated by studies of sedimentation rates in the proglacial lakes Austdalsvatn and Styggevatn, along with subglacial topography radar survey and seismic surveys of the lake bed sediment. Sediment cores were taken from both lakes. Annual sedimentation throughout the cores was identified from high resolution photographs and X-ray scan analyses. Three accelerator mass spectrometry (AMS) ^{14}C datings were carried out to assist dating of sedimentation during different periods. The seismic survey profiles revealed the distribution of these sediments. The impact of the subglacial topography on the sediment delivery from upstream, along with grain-size distribution and organic content analyses, were also taken into account in the interpretation of sediment cores. Possible impact of climate change on sediment delivery from the glacier was discussed by comparison of the average lake sedimentation rates during two periods of postglacial time. Around calibrated years 9000–8870 BP, Austdalsbreen glacier was subject to rapid retreat and calving. It was found that the glacier retreated rapidly from its maximum extension, which had totally covered the two lakes, in the 130 years in the early Holocene. About 1.4 million tonnes suspended load was delivered from the glacier during this short period, giving an average sediment yield of 400 t/y/km^2. Such a high sediment yield is hypothesised to be caused by rapid calving, fast ice motion, abundance of meltwater, and larger areal extension and volume of the glacier at that time. The glacier probably disappeared from the catchment around 6000 BP. The glacier advanced after the 1100s, reaching its Little Ice Age maximum before retreating to its present position. About 3.5 million tonnes suspended load was delivered from the glacier during the 800 years from A.D. 1186 to 1986, corresponding to an average sediment yield of 290 t/y/km^2, 30% lower than that of the early Holocene retreat. This difference is probably mostly caused by the smaller area of the modern glacier.

1. Introduction

Global warming has a number of implications for fluvial geomorphology because of changes in precipitation, vegetation, glacier and permafrost melting, and geomorphological reactions to these environmental changes, including rates of soil erosion (Goudie, 2006). More than 2600 km^2 of Norway is covered by about 1600 glaciers. Landscape development in this country during the Quaternary to a large extent reflects erosion and sediment transport by glaciers. According to the RegClim (2005) scenario and predictions of future firn-line altitudes (Nesje et al., 2008), a general recession will occur and the volume of most glaciers in Norway may decrease by 70% by 2100 as a result of the continued rise in temperatures (Jóhannesson et al., 2010). Over a short term, more sediment transport in glacier-fed rivers is expected as a result of the anticipated increase in summer temperatures (Bogen, 2008), and an increase in the frequency of outbursts from glacier-dammed lakes may also be expected (Xu et al., 2014). However, over the long term, ice recession is likely to lead to lower sediment yield.

Comparing historical data of long-term sediment delivery in glacier catchments during the different periods with full, partial, and no glacier cover is essential in order to understand the impact of climate change on sediment transport in glacier-fed rivers and to assess the implications for river management. Information on modern sediment yields of glaciers has been obtained by direct measurement of sediment transport in their meltwater rivers (Bogen and Olsen, 1986; Hallet et al., 1996; Bogen and Bønsnes, 2003; Riihimaki et al., 2005; Geilhausen et al., 2013; Hinderer et al., 2013). These measurements record short-term sediment yields. At Nigardsbreen, an eastern outlet of the Jostedalsbreen ice cap in west-central Norway (Fig. 1), measurements have been taken for over four decades and indicate that allowing for

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year-to-year fluctuations caused by variations in weather conditions, the sediment yield of Nigardsbreen glacier was found to be constant from one decade to another (Bogen et al., 2012). The current study investigates the Austdalsbreen Glacier, another outlet of the ice cap about 15 km northeast of Nigardsbreen (Fig. 1).

Studying sedimentation rates in proglacial lakes is a way to obtain long-term sediment yields of catchment areas. Schiefer et al. (2000, 2010) used lake sediment records to investigate historical changes in sediment yields. Larsen and Mangerud (1981) and Larsen and Stalsberg (2004) studied the glaciolacustrine rhythmites and determined erosion rates of a Younger Dryas cirque glacier at Kråkenes in western Norway from analyses of bed sediments of a former proglacial lake. O'Hara et al. (1993) proposed a method for estimating long-term (since 4000 BP) sediment yield by combining volume estimates from individual core sedimentation rates and the surrounding area of the core location in a proglacial lake, taking into account the density difference between sediment and bedrock. Then the average sediment yield is generally determined by dividing the mass of sediment delivered to the lake per unit time by the contributing basin area. This method has been applied in this study, supplemented with seismic surveys of sediment deposits.

An important knowledge base for interpretation of lacustrine sedimentary records from proglacial lakes has been provided by previous studies. In a proximal basin, rhythmites are irregular and contain many coarser, commonly graded layers, which have been interpreted as turbidity flow deposit (Leonard, 1981). In a distal basin, where deposition is almost exclusively from interflows and overflows (Smith, 1978), such coarse layers are much less common, and the rhythmites are more regular, with a classical varve development (Leonard, 1986). At very long distances from the river mouth, only fine fractions remain in suspension and varves become less distinct and finally disappear (Bogen, 1987). Where a sufficient number of cores are available to characterise spatial patterns, one method of indexing the volume of sediment contained within a single varve is by measurements of varve thickness and the area of the lake-bed with the same varve thickness (Leemann and Niessen, 1994; Wohlfarth et al., 1998). Kennie et al. (2010) found by studying varves in the proglacial lake Nigardsvatn that the volume deposited during the years 1979 to 2006 corresponded to the sediment transport measured in the meltwater river that feeds the lake.

In this study, the proglacial lake sedimentation of a large glacial catchment Austdalsbreen (>10 km^2) was studied to interpret the local Holocene climate and its impact on glacial activity and sediment delivery and to determine long-term sediment yields. The project involved a combination of lake-sediment coring, sediment analyses, seismic surveys of the lake bed, and subglacial topography surveys. The impact of climate changes on glacial sediment yield throughout the Holocene is studied through the geomorphological responses revealed by deposition in proglacial lakes that formed downstream from retreating glacier fronts, acting as sedimentation basins for the large quantities of sediment supplied from the glaciers.

2. Study area and methods

2.1. Study area and sampling sites

As shown in Fig. 1A, Austdalsbreen is an eastern outlet glacier of the northern part of Jostedalsbreen ice cap, the largest ice cap in Norway. In contrast to other outlets of the ice-cap (e.g., Østrem and Olsen, 1987; Nesje et al., 2008; Liermann et al., 2012), Austdalsbreen has received

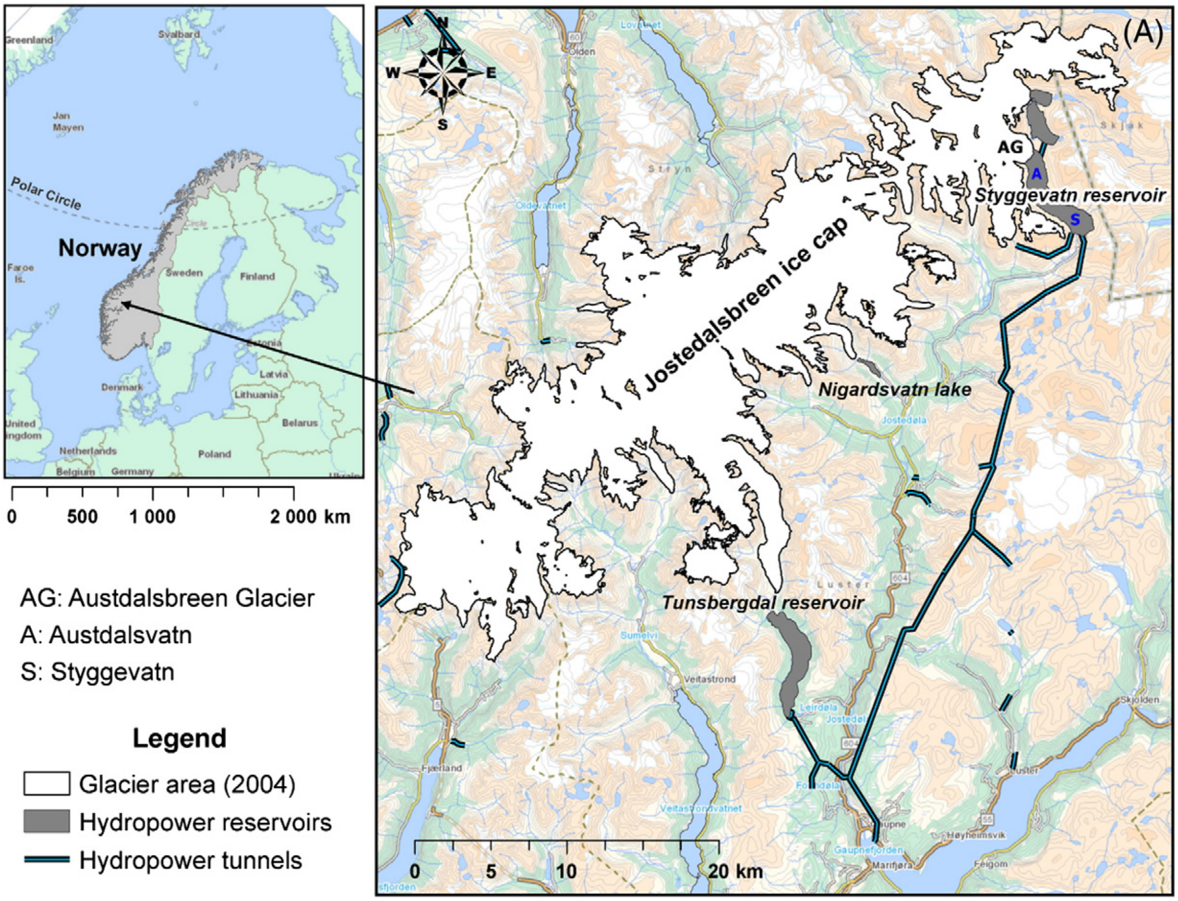

Fig. 1. (A) Study area: Austdalsbreen Glacier (AG) and its proglacial lakes Austdalsvatn (A) and Styggevatn (S); (B) The longitudinal line of subglacial topography profile (Flowlines_Steg_Aust), lake bed contours of Austdalsvatn and Styggevatn, glacier contours and ice thickness of Austdalsbreen; (C) Sampling sites of sediment cores (A1–A5, S11–S16, SN, SU1) and selected refraction seismic survey profiles (P22/85, P10/85) in Austdalsvatn and Styggevatn.