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Geomorphological consequences of a glacier advance across a paraglacial rock avalanche deposit

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ABSTRACT

Glacial reworking of paraglacial rock slope sediment has been inferred from long-deglaciated terrains to contribute significantly to glacial sediment transfer. At Feegletscher, Switzerland, we provide the first description of the geomorphological consequences of glacier advance across paraglacial rock avalanche sediment. This produced a small arcuate end moraine that encloses a zone of hummocky debris. The sedimentology of these landforms is conditioned by rock avalanche sediment and can be differentiated from purely glacial sediments, indicating that the contribution of glacially reworked rock avalanche debris may be recognisable in deglaciated terrain. Remarkably, much of the overridden rock avalanche debris has maintained its angularity and delicate brecciation features, despite up to 40 years of glacial action. We suggest that the surface 'carapace facies' of the rock avalanche deposit, comprising large openwork blocks, limited the effectiveness of glacial erosion processes. The carapace facies will have resisted significant erosion by the relatively thin glacier because of its high shear strength and because it was able to transmit subglacial meltwater efficiently. Thus, enhanced debris transfer associated with reworking of paraglacial rock avalanche sediment should not necessarily be expected during the initial stages of glacier advance.

1. Introduction

Recognition is growing that glacial sediment budgets and the evolution of mountain landscapes are influenced by the enhanced operation of geomorphological processes following deglaciation (e.g., Benn, 1989; Evans, 1999; Ballantyne, 2002; Curry et al., 2006; Burki et al., 2009; Curry et al., 2009a; McColl, 2012). Such geomorphological activity is termed 'paraglacial' (Church and Ryder, 1972; Ballantyne, 2002). Reworking and redistribution of sediments associated with paraglacial activity add complexity to the sedimentological and geomorphological record, and hence detailed studies are needed of paraglacial activity in contemporary deglaciating environments. Such studies are required in order to correctly quantify bedrock erosion by glaciers, the evaluation of which has typically ignored any component of glacially reworked paraglacial sediment (Hallet et al., 1996; Burki et al., 2009).

Rock slope failures, including rock avalanches, are common during and after deglaciation and are mainly attributed to the debuttressing of valley walls following glacier thinning and recession. Glacial sediment transfer has been suggested to be enhanced where a glacier advances across and reworks such rock slope failure debris (Ballantyne, 2002). Furthermore, a number of studies have suggested that moraines may be especially large where they have been built by a glacier that has advanced across and reworked paraglacial slope deposits (e.g., Matthews and Petch, 1982; Benn, 1989; Evans, 1999; Ballantyne, 2002; Burki et al., 2009). Nonetheless, Burki et al. (2009) envisaged situations where the reworking of paraglacial sediment may have been underestimated or indeed not recognised because of subsequent glacial reworking of the sediment. Hence, an evaluation of the geomorphology and sedimentology of such polygenetic deposits is needed so that sedimentary criteria can be developed to recognise the influence and relative importance of glacial and paraglacial processes in mountain landscape development (e.g., Curry et al., 2009a). Currently, the identification of diagnostic sedimentary signatures for paraglacially reworked deposits is in its infancy (Curry et al., 2009a).

Despite the potential significance of glacial reworking of paraglacially modified sediments, Ballantyne (2002) noted the absence of modern analogue studies of landform development by glacial reworking of paraglacial rock avalanche debris that can be used for comparison against suspected examples from deglaciated terrains (e.g., Matthews and Petch, 1982; Benn, 1989; Shakesby and Matthews, 1996; Ballantyne, 2002; Burki et al., 2009). This is probably a consequence of a general global trend of glacier recession, meaning that opportunities to study moraine formation at modern glaciers are rare (Winkler and Nesje, 1999; Winkler and Matthews, 2010). Furthermore, the only detailed study of glacially reworked landslide debris in the palaeoglacial record is that of Shakesby and Matthews (1996) who examined landforms and sediments of Loch Lomond Stadial (Younger Dryas) age within Craig

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Cerrig-gleisad cirque, in the Brecon Beacons of south Wales. Notably, this included a raised area (up to 20 m above the surrounding valley floor) of subparallel ridges containing angular sediment with some evidence of glacial striations. Whilst this represents an isolated palaeo-glacial case study with relatively little known about the nature of the glacier that occupied the cirque, it is nonetheless a useful reference study to aid formulation of testable predictions for the geomorphological consequence of glacier advance across paraglacial rock slope debris.

In this study, we assess the sedimentological and geomorphological consequences of a relatively recent (late twentieth century) advance of the Feegletscher Nord, Switzerland, across a rock avalanche deposit thought to be associated with deglaciation. Critically, documentary information exists on glacier length change and rock avalanche occurrence at Feegletscher, and as such, the geomorphological history of the area is reasonably well constrained. Our objectives are (i) to describe the landform–sediment assemblage produced by glacial reworking of paraglacial rock avalanche debris; and (ii) to assess the extent to which the sedimentology and geomorphology of the assumed paraglacial rock avalanche deposit has been altered by a glacier having advanced across it.

Hewitt (1999, 2009) and Shulmeister et al. (2009) have suggested a range of sedimentological criteria by which to recognise the influence of rock avalanches in the landscape record. We adopt these criteria and previous descriptions of glacially reworked rock slope debris (i.e. Shakesby and Matthews, 1996) to predict that moraines produced by glacial reworking of rock avalanche debris will (i) be composed of a single or dominant lithology inherited from the parent rock wall; (ii) contain dominantly angular and very angular clasts; (iii) have a similar particle size distribution to unmodified rock avalanche sediment that is expected to be diamictic in nature but with a high proportion of fine-grained sediment caused by crushing during rock avalanche emplacement; and (iv) contain some clasts with evidence of subglacial wear (i.e. facets and striations), although fewer such features than purely glacial sediments. Additionally, several studies have indicated that the particle size distribution of rock avalanches is invariably self-similar, with fractal dimensions commonly exceeding 2.58 (e.g., Dunning, 2006; Crosta et al., 2007; Davies and McSaveney, 2009; see Methodology section for more details). By testing these predictions, our study contributes to an understanding of how significant glacial reworking of paraglacial sediment might be in the formation of landforms and to what extent these processes can be recognised in the landscape record. Our overarching hypothesis is that the glacier will have reworked the rock avalanche deposit significantly to produce a sediment–landform assemblage that is strongly conditioned by rock avalanche material.

2. Study site

This study describes the geomorphology of the proglacial zone of Feegletscher Nord (46° 06′ N., 7° 54′ E.), Saaser Valley, Switzerland (Fig. 1). The proglacial zone is bounded by an ~60 to 120-m-high Little Ice Age (LIA) moraine. Feegletscher Nord has receded by ~1100 m from its A.D. 1818 LIA maximum position (Bircher, 1982; SAS/VAW, 2009), although this general trend of recession has been punctuated by periods of advance. Feegletscher Nord receded rapidly by 520 m between 1953 and 1956 to a position similar to its current extent (SAS/VAW, 2009). It had already been experiencing recession from 1923 of between 2 and 60 m a^{-1}. The glacier then advanced at a rate of between 6 and 87 m a^{-1} to a maximum position in 1988, marked in the proglacial zone by the end moraine marked 'B' in Fig. 1 (see also Fig. 2A for 1985 terminus position, and Fig. 3 for terminus positions since 1969). Many other Alpine glaciers advanced in the 1970s and 1980s following climate cooling from the 1950s to late-1970s (e.g., Beniston et al., 1994). Since 1988, Feegletscher has receded by around 800 m to its current position (Figs. 2C, D and 3). This latest phase of recession has followed a similar pattern to the 1923 to 1956 recession, with steady initial recession until 1997 at a rate of between 5 and 55 m a^{-1}, followed by periods of very rapid recession, most notably by 111 m in 1997–1998 and by 209 m in 2000–2001 (SAS/VAW, 2009). The main trunk of the glacier now appears to be separating progressively from the main ice field at a short icefall and looks to be almost stagnant downvalley from the icefall.

The geomorphology of the proglacial area is strongly conditioned by paraglacial slope activity. Paraglacial reworking of the steep sediment-mantled slopes of the LIA moraine has already been investigated by Curry et al. (2006, 2009b). The bedrock valley walls are also subject to regular minor rock falls. Of particular significance to this study is a large rockfall, named the 'Guglen' event, which was reported in local chronicles to have taken place on 28 July 1954 and to have involved $>1\times10^6$ m^3 of rock (Ruppen et al., 1988). The magnitude of the event dictates that it be classified as a rock avalanche according to the scheme of Hsü (1975). The Guglen rock avalanche scar remains clearly visible on the valley wall (Fig. 2). As shown in Figs. 2A and 3, the glacier overrode much of the rock avalanche deposit, as is reported by Whalley and Krinsley (1974); and a small proportion of the rock avalanche was left untouched by the glacier. This eastern end of the rock avalanche runout is labelled 'A' in Fig. 1. Fig. 2A also shows that, before overriding by the glacier, the surface of the rock avalanche deposit comprised an openwork mass of large (metre-scale) blocks. Recent descriptions of rock avalanche deposits refer to this as a 'carapace facies' (e.g., Dunning, 2006; Hewitt, 2009). Some of the rock avalanche sediment was also deposited on the glacier surface (Whalley, 1979; Schnyder, Pers. Comm., 2010; Fig. 2B).

Consideration of the bedrock geology is pertinent to this study, and it can be split into three lithological suites (Fig. 5) based on the mapping of Bearth (1964, 1968). Bedrock outcrops in a number of locations in the proglacial area where surficial sediment is thin or absent (Fig. 1). Most of the catchment is underlain by Palaeozoic mica-schist, and this lithology dominates the northern side of the valley. Weathering of the schist gives it a distinctive red colour, and the rock is known locally as Mischabel Crystal (Bearth, 1968). Much of the southern downvalley bedrock outcrops are Mesozoic metasedimentary rocks composed mainly of quartzite. The southern upvalley area is underlain by an ophiolite sequence comprising serpentinite, amphibolite, and albite-schist.

3. Methodology

Geomorphological mapping was achieved through a combination of aerial photograph interpretation and field mapping following standard techniques (e.g., Hubbard and Glasser, 2005). The aerial imagery was used to map large-scale features such as the rock avalanche scar and LIA moraine. Field mapping onto the aerial imagery identified more subtle features such as the end moraine and zones of hummocky debris.

A number of techniques were used to characterise the sedimentology of glacially reworked rock avalanche debris as well as other reference glacial sediments (LIA moraine, upper hummocky debris) and modern rockfall debris (see Fig. 1 for locations), which provide context to the nature of glacially reworked debris. Samples of 50 clasts were analysed from the different sediment types for clast shape (by measurement of orthogonal *a*-, *b*- and *c*-axes) and roundness using the Powers (1953) roundness scale, following techniques described by Benn (2004), as well as for lithology. The maximum *a*-axis length was 12 cm, and the minimum *c*-axis length was 1 cm. Clasts were selected at each location from the dominant lithology within the sediment. Clast shape measurements were used to derive C_{40} values for each sample (i.e. the proportion of clasts with a $c{:}a$ axial ratio ≤ 0.4). For each clast sample, the proportion of angular and very angular clasts was combined to give a value for relative angularity (RA). Clast impact structures, such as brecciation, are often highlighted as evidence for pulverisation of rock during rock avalanches (e.g., Hewitt, 1999, 2009) and so were photographed and their location recorded using a hand-held GPS.

Sediment particle size analysis has been described by some (e.g., Owen, 1991; Hewitt, 1999) as being unreliable for distinguishing