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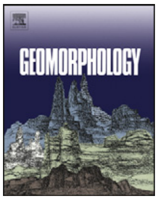

Identifying palaeo-ice-stream tributaries on hard beds: Mapping glacial bedforms and erosion zones in NW Scotland

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ABSTRACT

Ice streams are fed by tributaries that can extend deep into the heart of ice sheets. These tributaries are born at onset zones — the abrupt transitions from slow sheet flow to fast streaming flow that often occur at significant topographic steps on hard beds (bedrock-dominated beds). For this reason, tributary onset zones leave only a subtle erosional geomorphic signature in the landscape record that is rarely studied. This paper examines, in detail, the geomorphic signature of ice-sheet flow on a hard bed at the head of a palaeo-ice stream. We use field survey techniques to map glacial bedforms within an ~200-km^2 area of hard crystalline bedrock in a landscape of 'areal scour' around Loch Laxford in NW Scotland. The bedrock bedforms range from plastically moulded (p-forms) and wholly abraded forms, to stoss–lee forms and plucked surfaces all on an outcrop scale (1–100 m). We devise a five-zone classification system to map (in a GIS) the presence, absence, and abundance of glacial erosional forms within 619 (500-m square) grid cells. We go on to use these erosional bedform zones, along with known glaciological relationships to interpret the spatial and altitudinal pattern of palaeo-ice sheet processes and glacier dynamics in this part of NW Scotland. Our interpretation highlights the strong vertical thermal zonation on mountains, and the spatial variations in ice rheology (softness), ice temperature and, by inference, ice velocity in troughs — intimately associated with the onset of ice streaming in tributaries. Consequently, we define the *Laxfjord palaeo-ice-stream tributary* — a feeder to the Minch palaeo-ice stream in NW Scotland. Finally, we suggest that this new mapping approach could be performed in other deglaciated hard-bed terrain to examine, more widely, the subtle erosional signatures preserved in areas traditionally thought to represent ice sheet 'areal scour'.

1. Introduction

Ice streams and their tributaries are the major conveyors of mass within ice sheets (Bentley, 1987; Bamber et al., 2000), with the transition from slow sheet flow to fast streaming flow occurring at the *onset zone* (Bindschadler et al., 2000; Whillans et al., 2001). Radar-derived ice velocity maps from Antarctica and Greenland show that these tributaries can extend into the heart of ice sheets, with the downstream velocity transition involving an order of magnitude or more increase (from <10 to >400 m/a) over a relatively short distance (approximately tens of kilometres) (Joughin et al., 2002, 2010; Rignot et al., 2011). Joughin et al. (2002) defined two types of onset zone: an upper one where inland flow velocities increase rapidly at the head of ice stream tributaries (typically to 50–150 m/a); and another further downstream where these tributaries converge and accelerate to full ice stream velocities (>400 m/a). The upper, *tributary onsets*, are normally associated with abrupt increases in basal-shear stress related to changes in subglacial topography such as flow into troughs; whereas the lower, *ice stream onsets*, normally occur in low basal shear stress regions where ice emerges from confining subglacial valleys and ice stream tributaries increase rapidly in width (e.g. Paterson, 1994; Bindschadler et al., 2000; Whillans et al., 2001; Joughin et al., 2002, 2010). By definition, tributary onset marks a thermal transition from ice frozen to its bed to warm-based ice lubricated at its bed; whereas ice stream onset may be a complex function of decreased lateral drag and decreased bed resistance (Bindschadler et al., 2000; Whillans et al., 2001; Joughin et al., 2002).

Ice sheet flow around high relief topography and into subglacial troughs has long been suggested as a mechanism for perturbing the temperature and stress field of ice sheets, causing fast flow onset and organization into streams of differing erosional capability (Sugden, 1968, 1974, 1977; McIntyre, 1985). More recently, numerical modelling experiments have emphasized the importance of topographic focusing and strain heating on the flow dynamics of ice sheets (Payne and Dongelmans, 1997; Hindmarsh, 2001; Boulton and Hagdorn, 2006). Flow focusing, or channelling, concentrates strain heating in areas of low elevation, increasing ice temperature and leading to increased ice deformation rates and increased rheological softness (Nye, 1957; Paterson, 1994; Hindmarsh, 2001). Much of this ice deformation is concentrated in the basal layers but can involve large components of both vertical and lateral shear (Truffer and Echelmeyer, 2003; Clarke, 2005). Deep mountain passes and narrow topographic cols aligned with ice flow are therefore ideal places to see evidence of ice softening (i.e. higher plasticity) owing to increased basal shear stresses and strain

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heating, possibly augmented by enhanced creep and increased liquid water content (Clarke et al., 1977; Duval, 1977; Echelmeyer et al., 1994). Unsurprisingly, topographic steps have also been associated with the onset of palaeo-ice streams in formerly glaciated settings (Stokes and Clark, 2001; Briner et al., 2006; Kleman and Glasser, 2007; Bradwell et al., 2008a; Briner et al., 2008; Winsborrow et al., 2010), yet little detailed work has been done to characterise the glacial geomorphology in these settings.

From a palaeo-glaciological perspective, identification and examination of palaeo-onset zones in the landscape record allow glaciological inferences to be made regarding former ice sheet dynamics, thermal regimes, and flow characteristics. Unfortunately for geomorphologists, onset zones typically occur in bedrock-dominated (hard-bed) areas, with only thin or very limited sediment cover; hence their geomorphic signature is largely reflected in the erosion record (Stokes and Clark, 2001; Briner et al., 2008; De Angelis and Kleman, 2008; Winsborrow et al., 2010; Ross et al., 2011). Bedrock (hard-bed) landforms produced by glacial erosion are an important tool for understanding glacial processes but have received relatively little attention compared to their soft-bed counterparts (cf. Piotrowski et al., 2004; Menzies and Brand, 2007; Clark et al., 2009; Stokes et al., 2011). Although subtle differences in bedrock bedform morphology have long been regarded as valuable indicators of former subglacial processes (e.g. MacClintock, 1953; Sugden, 1978; Evans, 1996; Glasser and Bennett, 2004; Roberts and Long, 2005), few have analysed these morphological variations on hard beds over large areas in detail. Recently, however, Trommelen et al. (2012) outlined a new and promising spatio-temporal *glacial terrain zone* approach, using remote sensing data in combination with fieldwork, to map bedrock and sedimentary bedforms and establish a relative chronology across a large area of complex subglacial terrain (8100 km^2) within the core of the former Laurentide ice sheet.

Landscapes of glacial erosion versus no-glacial erosion have been used effectively by numerous workers examining the thermal regime and (minimum) thickness of former ice masses (e.g., Sugden, 1977; Kleman, 1994; Kleman et al., 1999; Briner et al., 2006; De Angelis and Kleman, 2008; Fabel et al., 2012; Trommelen et al., 2012). However, reconstructions of former ice dynamics (i.e., velocity, ice rheology, and flow mechanics) from erosional landform evidence are far less common (Gordon, 1979; Hall and Glasser, 2003; Roberts and Long, 2005; Bradwell et al., 2008a; Eyles, 2012). The relative paucity of research in this field probably stems from four main reasons: (i) it is still unclear how some glaciological processes are reflected in the erosional landform record; (ii) bedrock properties can mask or influence landform evolution, especially in areas of strong structural control; (iii) glacio-erosional evidence is sometimes difficult to discern in remotely sensed imagery; and (iv) complex glacio-erosional forms can relate to more than one erosional event.

In this paper we examine, in detail, the geomorphic signature of ice-sheet flow on a hard bed with major topographic obstacles — the dissected mountain range of the NW Scottish Highlands. We use a geomorphological approach to classify and map erosional bedrock bedforms, on the outcrop scale (1–100 m) chiefly on a single rock type, across a large study area in NW Scotland. The field area includes ca. 200 km^2 of glaciated Precambrian shield rock terrain. This rugged *cnoc and lochan* topography (Linton, 1963) is often taken to be a classic landscape of ‘areal scour’ — thought to be the result of widespread and laterally unconfined ice-sheet erosion over several glacial cycles (Sugden and John, 1976; Haynes, 1977; Sugden, 1978; Rea and Evans, 1996; Benn and Evans, 2010). However, this idea has not been rigorously tested. Crucially, our new approach takes outcrop-scale bedforms, which yield point information about the basal processes operating at the *local* scale, and synthesises this data over a wider area in an attempt to understand ice-sheet processes and patterns on a broader *landscape* scale (cf. Sugden, 1978; Trommelen et al., 2012). This empirical field-based approach, examining relatively small features (~10^1 m^2) over wide spatial scales (~10^8 m^2), is rarely practised in palaeoglaciology.

2. Study area

2.1. Physiography, geology, and palaeoglaciology

The study area is defined by a rectangular box, 13 km north-south by 22 km east-west, centred on the head of Loch Laxford in NW Scotland (Figs. 1, 2) and includes part of the ancient dissected mountain range of the NW Highlands [Laxford = *laxfjord*: from the norse for *salmon inlet*]. The field area stretches from Badcall Bay in the south to Loch Inchard in the north, and east almost as far as the geographical watershed — a total land area (including inshore water bodies) of ca. 200 km^2 (Fig. 2). The influence of bedrock geology and structure on the large-scale landscape of this part of NW Scotland is strong and well established (Peach et al., 1907; Krabbendam and Bradwell, 2010). The landscape can be divided into two physiographic types: (i) the *cnoc-and-lochan terrain* of the Lewisian gneiss complex, comprising around 80% of the study area; and (ii) the *quartzite-capped mountains* (inselbergs), comprising around 20%. The cnoc-and-lochan terrain is a low-lying, extremely rugged, undulating landscape of rock basins (lochans) and rock hills (cnocs) rarely exceeding 200 m in elevation with relief typically around 100 m (Fig. 3). The inselberg of Ben Stack (721 m) and the broad hills Ben Dreavie (501 m) and Ben Auskaird (387 m) are the only notable high points within the Lewisian gneiss terrain. The quartzite-capped mountains are the two (conjoined) massifs of Arkle and Foinaven, the latter reaching 915 m in elevation. The mountains are ancient upstanding masses of Lewisian gneiss unconformably capped by gently dipping, tectonically thickened strata of Cambrian quartzite. Ben Stack also has a very small residual cap of Cambrian quartzite at summit level (>700 m asl). The island of Handa is geologically distinct from the mainland and comprises a generally featureless gently dipping slab of Torridon sandstone, with 100-m high vertical cliffs along its western coast.

The cnoc and lochan terrain of NW Scotland is an example of a deglaciated, rough, hard ice-sheet bed. The roughness of a glacier's bed can be determined by the number, size, and spacing of bedrock bumps and irregularities — although no standardised definition exists. Topographic profiles, drawn parallel to and perpendicular to former ice flow, show typical bed roughness within the study area (Fig. 3). For simplicity these were calculated using the NEXTMap Britain digital elevation model (DEM) and are expressed as the total length of the surface profile divided by the planar or ‘map’ distance. Values for both transects are between 1.02 and 1.03. These bed-roughness profiles underline the rugged, highly undulating nature of the Lewisian gneiss shield rock terrain in NW Scotland (Fig. 3).

The bedrock geology of the study area can be simply classified into two main units. *The Lewisian Gneiss Complex*, a residual fragment of the Laurentian Shield, comprises felsic to intermediate orthogneiss (coarse-grained, crystalline, meta-igneous rock) with occasional lenses of mafic orthogneiss (typically finer grained), all of Archaean age. The gneisses are characterised by mineral layering (felsic and mafic), typically on a centimetre-scale. The gneisses are cross-cut by dolerite dykes with a strong WNW-ESE trend, part of the Scourie Dyke Swarm (Fig. 2). In the vicinity of Loch Laxford, a marked WNW-ESE trending, 2–3 km wide, ductile shear zone occurs. This shear zone includes a number of thin granite sheets; together with the Scourie dykes these give the appearance of a strong structural ‘grain’ in this part of NW Scotland. Several sets of large-scale brittle structures occur (faults and joints), which are now associated with zones of locally intense fracturing (Beacom et al., 2001). In addition, NNE-SSW and NNW-SSE trending conjugate fracture sets cut the gneisses on a range of scales (typically from 10^2 to 10^3 m).

The Cambrian Strata comprise generally medium- to coarse-grained, cross-bedded, almost pure quartzite (metamorphosed sandstone). The rock contains <10% feldspar grains and is tightly packed with very little matrix. The Cambrian quartzite has been thickened considerably (up to 500 m) to form the upper parts of the mountains of Arkle and Foinaven.