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Quaternary evolution of glaciated gneiss terrains: pre-glacial weathering vs. glacial erosion

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ABSTRACT

Vast areas previously covered by Pleistocene ice sheets consist of rugged bedrock-dominated terrain of innumerable knolls and lake-filled rock basins – the 'cnoc-and-lochan' landscape or 'landscape of areal scour'. These landscapes typically form on gneissose or granitic lithologies and are interpreted (1) either to be the result of strong and widespread glacial erosion over numerous glacial cycles; or (2) formed by stripping of a saprolitic weathering mantle from an older, deeply weathered landscape.

We analyse bedrock structure, erosional landforms and weathering remnants and within the 'cnoc-and-lochan' gneiss terrain of a rough peneplain in NW Scotland and compare this with a geomorphologically similar gneiss terrain in a non-glacial, arid setting (Namaqualand, South Africa). We find that the topography of the gneiss landscapes in NW Scotland and Namaqualand closely follows the old bedrock—saprolite contact (weathering front). The roughness of the weathering front is caused by deep fracture zones providing a highly irregular surface area for weathering to proceed. The weathering front represents a significant change in bedrock physical properties. Glacial erosion (and aeolian erosion in Namaqualand) is an efficient way of stripping saprolite, but is far less effective in eroding hard, unweathered bedrock. Significant glacial erosion of hard gneiss probably only occurs beneath palaeo-ice streams.

We conclude that the rough topography of glaciated 'cnoc-and-lochan' gneiss terrains is formed by a multistage process:

1) Long-term, pre-glacial chemical weathering, forming deep saprolite with an irregular weathering front;

2) Stripping of weak saprolite by glacial erosion during the first glaciation(s), resulting in a rough land surface, broadly conforming to the pre-existing weathering front ('etch surface');

3) Further modification of exposed hard bedrock by glacial erosion. In most areas, glacial erosion is limited, but can be significant beneath palaeo-ice stream. The roughness of glaciated gneiss terrains is crucial for modelling of the glacial dynamics of present-day ice sheets. This roughness is shown here to depend on the intensity of pre-glacial weathering as well as glacial erosion during successive glaciations.

1. Introduction

In the Northern hemisphere, Pleistocene ice sheets covered large flat-lying shield areas, now typically characterised by an exposed bedrock landscape of numerous knolls or ridges and a multitude of lake-filled basins. Although the large-scale relief of this landscape is limited, such landscapes commonly show a rugged undulating hilly relief, narrow linear valleys and an abundance of closed rock basins. Roughness wavelength typically ranges from 10 to 1000 m and amplitudes up to 100 m. Such landscapes cover much of eastern Canada, Finland, Sweden, West Greenland and NW Scotland (e.g. Sugden, 1978; Rastas and Seppälä, 1981; Rea and Evans, 1996; Roberts and Long, 2005). The landscape is commonly referred to as a 'landscape of areal scour' (Sugden and John, 1976; Rea and Evans, 1996; Benn and Evans, 2011). In Scotland, the more descriptive term 'cnoc-and-lochan' terrain, often written as the Anglizised version 'knock-and-lochan' (from Gaelic; cnoc = knoll; lochan = small lake) is commonly used (Linton, 1963). Although these landscapes differ regionally in relative relief, they are significantly rougher than till-covered plains as found for instance in Saskatchewan and in northern Germany or Poland.

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Cnoc-and-lochan terrains are typically underlain by crystalline basement 'shield' rocks such as gneisses and granitic rocks, and it is clear that the characteristics of these rocks are important in the development of these landscapes.

The geomorphology and landscape evolution of deglaciated gneiss terrains is important for a number of reasons:

1) Basement gneiss, together with similar granitic rocks, cover significant areas previously occupied by Pleistocene Northern Hemisphere ice sheets, and thus form much of the former bed of these globally important former ice masses. Around 80% of the onshore Fennoscandian Ice Sheet and about half of the Laurentide Ice Sheet rested on basement gneiss at their maximum extent (Fig. 1). Gneiss lithologies also comprise around 90% of the bed of the present-day Greenland Ice Sheet (Henriksen et al., 2000) and a considerable but unquantified part of the East Antarctic Ice Sheet bed (Tingey, 1991; Boger, 2011).
2) Bed topography and roughness have a strong effect on and basal sliding and ice flow near the base of ice sheets and are thus important, but currently poorly constrained, parameters in dynamic ice sheet modelling (Weertman, 1957; Schoof, 2005; Gagliardini et al., 2007; Petra et al., 2012). A better knowledge of subglacial bed roughness, combined with a better understanding of the mechanism(s) of glacier sliding, could therefore significantly reduce uncertainties in future dynamic ice sheet models (e.g. Patterson, 1994). There is increasing evidence for palaeo-ice streams on hard bedrock beds (e.g. Stokes and Clark, 2003; Roberts and Long, 2005; Bradwell et al., 2008a; Eyles, 2012; Bradwell, 2013), which cannot be explained by the 'deforming-bed model', which requires a deforming layer of till

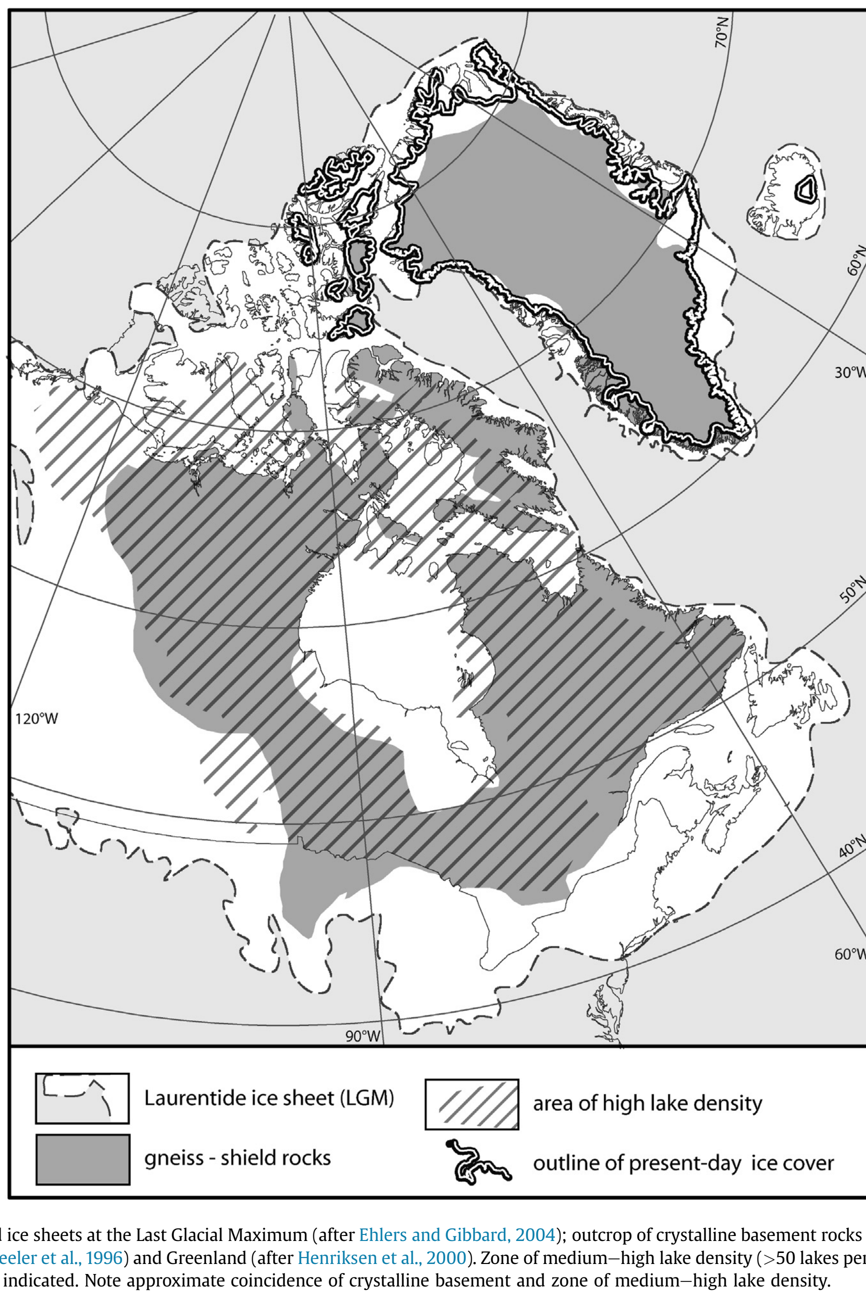

Fig. 1. Laurentide and Greenland ice sheets at the Last Glacial Maximum (after Ehlers and Gibbard, 2004); outcrop of crystalline basement rocks (gneiss and granitic igneous rocks) of the Canadian Shield (after Wheeler et al., 1996) and Greenland (after Henriksen et al., 2000). Zone of medium–high lake density (>50 lakes per 400 km^2) after Sugden (1978) and outline of present-day ice cover indicated. Note approximate coincidence of crystalline basement and zone of medium–high lake density.