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Late Cenozoic deep weathering patterns on the Fennoscandian shield in northern Finland: A window on ice sheet bed conditions at the onset of Northern Hemisphere glaciation

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ABSTRACT

The nature of the regolith that existed on the shields of the Northern Hemisphere at the onset of ice sheet glaciation is poorly constrained. In this paper, we provide the first detailed account of an exceptionally preserved, deeply weathered late Neogene landscape in the ice sheet divide zone in northern Finland. We mine data sets of drilling and pitting records gathered by the Geological Survey of Finland to reconstruct regional preglacial deep weathering patterns within a GIS framework. Using a large geochemical data set, we give standardised descriptions of saprolite geochemistry using a variant of the Weathering Index of Parker (WIP) as a proxy to assess the intensity of weathering. We also focus on mineral prospects and mines with dense pit and borehole data coverage in order to identify links between geology, topography, and weathering.

Geology is closely linked to topography on the preglacial shield landscape of northern Finland and both factors influence weathering patterns. Upstanding, resistant granulite, granite, gabbro, metabasalt, and quartzite rocks were associated with fresh rock outcrops, including tors, or with thin (<5 m) grusses. Plains developed across less resistant biotite gneisses, greenstones, and belts of alternating rock types were mainly weathered to thick (10–20 m) grusses with $\mathrm{WIP_{fines}}$ values above 3000 and 4000. Beneath valley floors developed along mineralised shear and fracture zones, weathering penetrated locally to depths of >50 m and included intensely weathered kaolinitic clays with $\mathrm{WIP_{fines}}$ values below 1000.

Late Neogene weathering profiles were varied in character. Tripartite clay–gruss–saprock profiles occur only in limited areas. Bipartite gruss–saprock profiles were widespread, with saprock thicknesses of >10 m. Weathering profiles included two discontinuities in texture, materials and resistance to erosion, between saprolite and saprock and between saprock and rock. Limited core recovery when drilling below the soil base in mixed rocks of the Tana Belt indicates that weathering locally penetrated deep below upper fresh rock layers. Such deep-seated weathered bands in rock represent a third set of discontinuities. Incipient weathering and supergene mineralisation also extended to depths of >100 m in mineralised fracture zones. The thin weathering crusts found extensively beneath till may represent types of early or middle Pleistocene palaeosols.

We confirm that glacial erosion has been very limited (<20 m) in northern Finland and has been widely restricted to the partial stripping of saprolith. The Fennoscandian Ice Sheet in this ice-divide zone remained cold-based and unerosive throughout the Pleistocene. The large-scale shield geomorphology developed before glaciation and is a product of differential weathering and erosion acting on diverse rock types and structures through the Neogene. The first ice sheets did not advance across planar, uniformly soft, deeply kaolinised beds as proposed in recent models of the Laurentide ice sheet. Instead, in northern Finland, the shield topography comprised broad plains and valleys with isolated hills and hill masses, with a relative relief of several hundred metres. Weathered rock was restricted in its distribution and thickness and provided diverse bed materials for ice sheets, including rock, broken saprock, permeable gruss, and linear zones of impermeable clay, with multiple discontinuities. Glacial erosion and local glacial transport led to widespread incorporation of this saprolith material into tills.

1. Introduction

Global cooling in the Late Cenozoic led at 3.2–2.6 Ma to the first of many advances by large ice sheets onto the shield lowlands of the Northern Hemisphere (Gao et al., 2012; Bailey et al., 2013). Erosion by

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ice sheets progressively removed thick, deformable, and permeable preglacial regolith from shield surfaces to expose rigid and impermeable rock beds (Chalmers, 1898; Roy et al., 2004a; Refsnider and Miller, 2013). This fundamental change in substrate has been linked to marked changes in ice sheet dynamics and extent through the late Pliocene and Pleistocene (Clark and Pollard, 1998; Clark et al., 2006). In this hypothesis, regolith composed mainly of weathered bedrock formed the interface between the Laurentide Ice Sheet (LIS) and its bed until ~1.25 Ma. This deformable, wet substrate with a supposed original thickness of 50 m (Clark et al., 2006) allowed the development of thin but extensive ice sheets. By the time of the middle Pleistocene transition at 1.25–0.7 Ma, more of the LIS flowed over rigid crystalline bedrock, resulting in higher basal shear stresses, lower flow velocities, and greater ice thicknesses. This regolith hypothesis receives support from studies of till stratigraphy in North America that show that Pliocene and early Pleistocene tills have geochemical and cosmogenic isotope signals consistent with stripping of old soils and weathered regolith (Roy et al., 2004a; Refsnider and Miller, 2013). Yet the initial distribution, thickness, and weathering characteristics of the regolith that existed on the shields of the Northern Hemisphere at the onset of ice sheet glaciation in the late Neogene all remain poorly constrained owing to the general removal of loose regolith from shield surfaces by glacial erosion.

Preservation of delicate landforms and regolith on shields requires covers of unerosive, cold-based ice (Kleman, 1994). Numerous studies have shown that the impact of Pleistocene glacial erosion in lowland shield landscapes was limited across wide areas because of the prevalence of frozen bed conditions (Sugden, 1974, 1978; Hall and Sugden, 1987; Lidmar-Bergström, 1997; Hättestrand and Stroeven, 2002). In most cases, however, there is evidence for slight glacial erosion through the removal of regolith and from recognition of rock landforms representative of the first stages in the development of erosional glacier bedforms (Ebert et al., 2012a; Hall et al., 2013). The preservation of extensive and deep Neogene weathering requires that cold-based patches develop in the same areas repeatedly and throughout the many cold stages of the late Pleistocene (Hall, 1986). Unsurprisingly, this condition was rarely met as the large Northern Hemisphere ice sheets repeatedly advanced and retreated across lowland shields and platforms under the rapidly changing climates of the Pleistocene. Hence well-preserved late Neogene weathering mantles are rare. In this paper, we provide the first detailed account of an exceptionally preserved, deeply weathered Late Neogene shield landscape in the ice sheet divide zone in northern Finland on the northern Fennoscandian shield (Fig. 1A).

Despite multiple phases of glaciation by the Fennoscandian Ice Sheet (FIS) over the last 2.7 Myr (Kleman and Stroeven, 1997), the Archaean and Precambrian shield of the Vuotso area of northern Finland retains many preglacial and periglacial relief elements (Darmody et al., 2008; Ebert et al., 2015). Significantly, deep weathering is known to exist extensively beneath till (Hirvas, 1991; Islam et al., 2002; Johansson et al., 2011), but the regional distribution and geochemistry of these weathering mantles has not been analysed systematically. In this paper, we mine large databases of drilling and pitting records gathered by the Geological Survey of Finland (GTK) over many years of geochemical mapping and mineral exploration to reconstruct preglacial deep weathering patterns in northern Finland within a GIS framework. Using a large geochemical data set, we give standardised descriptions of saprolite geochemistry using a variant of the Weathering Index (Parker, 1970) as a proxy to assess the intensity of weathering across different rock types. We focus on areas of mineral prospects and mines with very dense pit and borehole data coverage to identify links between geology, topography, and weathering. This part of northern Finland provides a window on a weathered shield landscape that existed at the end of the Neogene and that formed the bed for the first and subsequent Fennoscandian ice sheets.

2. Regional geology and geomorphology

2.1. Geology

The study area lies on the northern Fennoscandian shield in central Finnish Lapland (Fig. 1A and B). The Saariselkä massif at the northeastern edge of the area marks the edge of the Lapland Granulite Belt. A small part of the area lies within the Archaean Karelian craton, but most lies within its intensely metamorphosed Palaeoproterozoic cover of quartzites and basic and ultrabasic volcanics, including the highly mineralised Central Lapland Greenstone Belt (CLGB) (Nironen and Mänttäri, 2003). These greenstones were intruded by the Koitelainen layered gabbro and the Nattanen-type granites that form a group of 1.7 Ga post-orogenic intrusive masses (Haapala et al., 1987; Heilimo et al., 2009). All the granites are coarse- to medium-grained monzogranites, with microcline, plagioclase, and minor biotite. Pre-Svecokarelian cratonic magmatism included several phases, including simultaneous or sequential extrusion of contrasting magmas such as komatiitic and acid lavas, alkali granites, carbonatites, and tholeiites. The shield rocks are cut by fracture and shear zones, mainly trending NW–SE and NE–SE (Fig. 1C).

2.2. Cenozoic environments for weathering and relief development

Uplift of northern Fennoscandia took place from the Late Cretaceous onward in response to the opening of the North Atlantic (Hendriks et al., 2007) and continued intermittently through the Cenozoic (Anell et al., 2009). Significant regional uplift occurred at ~4 Ma in northern Norway, Kola, and the Barents Sea (Knies et al., 2014). The low drainage divide that separated the Baltic and Barents Sea throughout much of the Cenozoic (Anell et al., 2009) was probably heightened in this phase.

The relief of this part of Finnish Lapland is dominated by extensive plains or *palaeosurfaces* (Ebert, 2009) at elevations of >200 m asl. Relative relief on plains is generally <25 m and low gradient rivers flow to the south and southeast in broad depressions that hold extensive mires. Circumstantial evidence from palynomorphs in tills indicates the former existence of Pliocene to early Pleistocene lacustrine sediments on these palaeosurfaces (Hall and Ebert, 2013). Rising up to 250 m above the plains are large hill masses or *fells* and more isolated hills or *inselbergs* with tor-capped summits, typically developed in granite, gabbro, metabasalt, and quartzite. The relief is typical of the extensive inselberg plains found in northern Fennoscandia (Lidmar-Bergström et al., 2007; Ebert and Hättestrand, 2010; Ebert et al., 2011, 2012a) (Fig. 2A).

Although the Fennoscandian Shield drifted to between 50° and 65°N in the Cretaceous, very warm climates were maintained into the Palaeogene, with mean annual temperatures (MATs) reaching ~17 °C even within the Arctic (Weijers et al., 2007). Toward the Eocene–Oligocene boundary (~34 Ma), there was a step change toward the modern ice-house climate (Moran et al., 2006). At the Palaeogene–Neogene transition (~23 Ma), cool to warm temperate conditions were established across Fennoscandia and around the Arctic (Lavrushin and Alekseev, 2005). The MATs reached maxima of 11–13 °C in Iceland and 15.5–20 °C in Denmark (Larsson et al., 2006) for a period of ~12 Myr during the late Oligocene and Miocene. Cooling at ~10 Ma led to the first appearance of sea ice and the establishment of boreal to subarctic biomes around the Arctic Ocean (Lavrushin and Alekseev, 2005). By the early Pliocene (4–5 Ma), MATs had fallen to −1 °C in the high Arctic (Csank et al., 2011). The onset of glaciation on the Fennoscandian Shield occurred in the latest Pliocene (~2.8 Ma) (Flesche Kleiven et al., 2002). Modern MATs are ~1 °C in northern Finland.

Three contrasting types of glaciation affected northern Fennoscandia from its onset: cirque glaciers, mountain-centred ice sheets, and large ice sheets (Kleman et al., 2008). This part of Finnish Lapland lies at too low an elevation to support cirque glaciers. It is disputed, however, if the area lay largely beyond (Fredin, 2002) or generally within