Relict Non-Glacial Surfaces and Autochthonous Blockfields in the Northern Swedish Mountains

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Abstract

Relict non-glacial surfaces occur in many formerly glaciated landscapes, where they represent areas that have escaped significant glacial modification. Frequently distinguished by blockfield mantles, relict non-glacial surfaces are important archives of long-term weathering and landscape evolution processes. The aim of this thesis is to examine the distribution, weathering, ages, and formation of relict non-glacial surfaces in the northern Swedish mountains.

Mapping of surfaces from aerial photographs and analysis in a GIS revealed five types of relict non-glacial surfaces that reflect differences in surface process types or rates according to elevation, gradient, and bedrock lithology. Clast characteristics and fine matrix granulometry, chemistry, and mineralogy reveal minimal chemical weathering of the blockfields.

Terrestrial cosmogenic nuclides were measured in quartz samples from two blockfield-mantled summits and a numerical ice sheet model was applied to account for periods of surface burial beneath ice sheets and nuclide production rate changes attributable to glacial isostasy. Total surface histories for each summit are almost certainly, but not unequivocally, confined to the Quaternary. Maximum modelled erosion rates are as low as 4.0 mm kyr$^{-1}$, which is likely to be near the low extreme for relict non-glacial surfaces in this landscape.

The blockfields of the northern Swedish mountains are Quaternary features formed through subsurface physical weathering processes. While there is no need to appeal to Neogene chemical weathering to explain blockfield origins, these surfaces have remained continuously regolith-mantled and non-glacial since their inception. Polygenetic surface histories are therefore indicated, where the large-scale surface morphologies are potentially older than their regolith mantles.

**Keywords:** blockfield, chemical weathering, cosmogenic exposure dating, glaciated landscape, northern Sweden, periglacial geomorphology, relict surface
This doctoral thesis consists of a summary and four papers:

**Paper I**


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**Paper II**


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**Paper III**


**Paper IV**


I initiated this project with Arjen Stroeven and project planning benefited from additional inputs by Clas Hättestrand, Johan Kleman, and Ola Fredin. I completed aerial photograph interpretation, subsequent mapping, and GIS analysis of relict non-glacial surfaces in Paper II. I completed fieldwork for Papers II – IV with assistance from Arjen, Ola, and field assistants acknowledged in each article. I analysed grain size and X-ray diffraction data with Marc-Henri Derron for Papers III and IV, and X-ray fluorescence data for Paper III, also with Marc-Henri. Scanning electron microscopy analyses for paper III were performed by Ola and Marc-Henri, and for paper IV by Marc-Henri and I. Derek Fabel, Maria Miguens-Rodriguez, and I prepared quartz samples for accelerator mass spectrometry in Paper IV (Australian National University and Scottish Universities Environmental Research Centre), with subsequent terrestrial cosmogenic radionuclide interpretation performed by Derek and I. Clas, Johan, Krister Jansson, Ola, and Marc-Henri were all involved in fieldwork planning and discussion of results. I wrote all articles, with detailed reviews provided by Arjen. Additional reviews for Paper I were provided by Clas and Johan; for Paper II by Clas, Johan, and Krister; for Paper III by Ola; and for Paper IV by Derek, Ola, Marc-Henri, and Marc Caffee.
INTRODUCTION

Relict surfaces in present landscapes were initiated under different environmental and geomorphological conditions than those prevailing in the landscapes today (Battiau-Queney, 1996; Migoń and Goudie, 2001). Whereas most surfaces in formerly glaciated landscapes bear strong imprints of glacial processes, some may show little or no sign of glacial modification. These surfaces, here referred to as relict non-glacial surfaces, have preglacial origins and have developed further under ice-free conditions during interglacials, interstadials, or on nunataks (Kleman and Borgström, 1990; Rea et al., 1996b; Ballantyne et al., 1997). Relict non-glacial surfaces are most readily identified as periglaciated, low relief, upland surfaces separated from lower, more recent, glacial surfaces by sharply defined boundaries, such as trough walls (Brunsden, 1993; Ollier and Pain, 1997; Stroeven and Kleman, 1999; Migoń and Goudie, 2001; Anderson, 2002; Munroe, 2006). Relict non-glacial surfaces have been identified in formerly glaciated landscapes of Scandinavia (Ahlmann, 1919; Gjessing, 1967; Nesje et al., 1988; Kleman and Borgström, 1990; Rea et al., 1996b; Kleman and Stroeven, 1997; Lidmar-Bergström et al., 2000; Hättestrand and Stroeven, 2002; Fjellanger et al., 2006; Paasche et al., 2006), Scotland (Hall, 1985; Ballantyne et al., 1997; Phillips et al., 2006), Svalbard (Jonsson, 1983; Landvik et al., 2003), Greenland (Sugden, 1974), North America (Ives, 1958; Sugden and Watts, 1977; Bierman et al., 1999; Briner et al., 2003; Marquette et al., 2004; Davis et al., 2006), and Antarctica (Sugden et al., 2006). This thesis examines relict non-glaciated surfaces in the formerly glaciated northern Swedish mountains.

Relict non-glacial surfaces are important for:

1. Inferring aspects of regional glacial history, such as thicknesses of former ice sheets, basal thermal regimes, glacial erosion patterns, and relief production (Hall and Sugden, 1987; Nesje et al., 1988; Sugden, 1989; Kleman, 1994; Nesje and Whillans, 1994; Ballantyne et al., 1997; Glasser and Hall, 1997; Kleman and Stroeven, 1997; Small and Anderson, 1998; Bierman et al., 1999; Clarhäll and Kleman, 1999; Kleman et al., 1999; Stroeven et al., 2002b; Briner et al., 2003, 2005; Marquette et al., 2004; Staiger et al., 2005; Sugden et al., 2005; Fjellanger et al., 2006; Linge et al., 2006; Phillips et al., 2006; Goering et al., 2008; Jansson et al., in review). The spatial distribution of relict non-glacial surfaces may also reveal information on glacial period climates (Munroe, 2006).

2. Determining how and at what rates surfaces evolve over long time spans (Small et al., 1999; Anderson, 2002; Staiger et al., 2005; Babault et al., 2007).

3. Potentially determining interstadial, interglacial, and/or preglacial environmental conditions from, for example, fine matrix materials contained within relict non-glacial surface regolith (Hall, 1985; Rea et al., 1996a). Formerly glaciated landscapes currently occupy a range of climatic zones including polar (Stroeven and Kleman, 1999; Sugden et al., 2005), tundra (Fjellanger et al., 2006), maritime (Whalley et al., 1981; Paasche et al., 2006), continental (Small et al., 1999; Stroeven et al., 2002a; Munroe, 2006), alpine (Dahl, 1966; Rea et al., 1996b), and cool temperate (Hall, 1986; Olvmo et al., 2005). Most continue to be subject to a periglacial regime (Kleman and Stroeven, 1997; Dredge, 2000; Marquette et al., 2004; Fjellanger et al., 2006; Munroe, 2006). Knowledge of preglacial climates is limited with a number of studies speculating on warm humid conditions (Roaldset et al., 1982; Hall, 1986; Rea et al., 1996b; Marquette et al., 2004; Paasche et al., 2006). Relict non-glacial surfaces may maintain climatic evidence from different periods due to regional differences in denudation histories.

Autochthonous blockfields, which are coarse, blocky mantles produced from in situ weathering, are key features of many relict non-glacial surfaces. However, the origins of blockfields remain elusive and they are usually considered, in periglaciated landscapes, to represent remnants of pre-Quaternary deep weathering profiles (Caine, 1968; Ives, 1974; Clapperton, 1975; Nesje et al., 1988; Rea et al., 1996b; Boelhouwers et al., 2002; André, 2003; Marquette et al., 2004; Fjellanger et al., 2006; Paasche et al., 2006; André et al., 2008). According to this model, block production was initiated through chemical weathering under a comparatively warm Neogene climate. Subsequent soil stripping occurred during the colder Quaternary and the chemically weakened bedrock was frost shattered and periglacially reworked to produce blockfield mantles. The presence of saprolite and/
or substantial quantities of secondary minerals, and an assumed dependence of chemical weathering on a warm climate, are critical to this interpretation of blockfield origins.

Only a few recent studies have invoked a Quaternary origin for blockfields (Kleman and Borgström, 1990; Ballantyne, 1998; Ballantyne et al., 1998), where blocks are produced through physical weathering processes, such as frost shattering, and, again, periglacially reworked to produce coarse mantles. Quantities of secondary minerals are low and saprolite is absent. Although, at least some, blockfields may result from Quaternary periglacial weathering, a critical issue is that, with the exception of blockfields forming in highly frost susceptible limestone in the Canadian Arctic (Dredge, 1992), there appear to be none that are presently forming in periglaciated landscapes (Boelhouwers, 2004). Blockfields are therefore largely relict features that seem to depend on a climate or weathering process that is different to those presently occurring in periglaciated landscapes.

**Study Rational and Objectives**

Most previous work on relict non-glacial surfaces, particularly in the northern Swedish mountains, has focussed on the information they can provide on former ice sheet dimensions and basal thermal regimes or on using them as references for the development of glacial landforms and relief (Sugden, 1974, 1978; Hall and Sugden, 1987; Nesje et al., 1988; Kleman and Borgström, 1990; Kleman, 1994; Nesje and Whillans, 1994; Ballantyne et al., 1997; Glasser and Hall, 1997; Kleman and Stroeven, 1997; Small and Anderson, 1998; Clarhäll and Kleman, 1999; Kleman et al., 1999; Hättestrand and Stroeven, 2002; André, 2004; Staiger et al., 2005; Phillips et al., 2006; Jansson et al., in review). Cosmogenic dating has confirmed that relict non-glacial surfaces pre-date the last glaciation (Bierman et al., 1999; Briner et al., 2003; Marquettere et al., 2004; Fjellanger et al., 2006; Linge et al., 2006; Linge et al., 2007), with preservation in northern Sweden widely attributable to coverage by non-erosive, cold-based ice sheets (Kleman et al., 1997, 1999; Fabel et al., 2002; Hättestrand and Stroeven, 2002; Stroeven et al., 2002a).

However, despite these surfaces being potentially important archives of long-term weathering and processes of landscape evolution, few studies have directly targeted the long-term, non-glacial development of these surfaces. Small et al. (1999) and Staiger et al. (2005) used terrestrial cosmogenic nuclides (TCNs) to measure surface erosion rates, Anderson (2002) and Babault et al. (2007) characterised their morphological development through numerical modelling, and Bonow et al. (2003, 2007) analysed relict non-glacial surface morphological development according to slope angles. Consequently, the processes acting on these surfaces, particularly those that are blockfield-mantled, the long-term rates at which these processes operate, and the resulting large-scale morphological evolution of these surfaces, remain only partly known.

The aim of this thesis is to examine the distribution, characteristics, weathering, and ages of relict non-glacial surfaces in the northern Swedish mountains to better understand their significance to long-term landscape development in formerly glaciated regions. The study will be conducted over a range of spatial scales (Fig. 1), beginning with a global perspective through a literature review, then progressing to a regional scale through remote sensing and geographical information system (GIS) analyses of the northern Swedish mountains. However, the main focus of this study will be at the regolith scale, where blockfield weathering and ages will be examined, with intra-site and inter-site variations in weathering also being explored. The regolith zone has been labelled the critical zone (NRC, 2001), partly because most surfaces, including relict non-glacial surfaces, are regolith-mantled, resulting in small-scale regolith weathering and erosional processes being fundamental to large-scale landscape evolution. Studying relict non-glacial surfaces at the regolith scale is therefore an appropriate starting point to understanding their significance to landscape development in formerly glaciated regions.

**STUDY LOCATION**

The study area is situated between 66°46’ and 68°37’N in the northern Swedish mountains (Fig. 2). Encompassed within this area are the highest parts of the northern Scandes, including the Kebnekaise (2113 m a.s.l.) and Sarek (2080 m a.s.l.) massifs. Central and western parts of the study area are composed of Caledonian nappes, with the eastern part formed from
Precambrian intrusive and volcanic rocks (Kulling, 1964). The Arctic maritime climate of Norway and the continental climate of northern Sweden converge within the study area. Discontinuous permafrost persists on high surfaces (King, 1986; Isaksen et al., 2001) and the current annual maximum active layer depth in the northern saddle of Tarfalatjårr is 1.5–1.6 m (Isaksen et al., 2007). Although current glaciation is confined to small cirque and valley glaciers in the higher massifs, the study area has been repeatedly inundated by the Quaternary ice sheets, with cirque glaciation inferred to have been dominant before 2.0 million years ago (Myr), mountain ice sheets dominant between 0.7 and 2.0 Myr, and Fennoscandian ice sheets developing over the last 0.7 Myr (Kleman and Stroeven, 1997). This area was selected for study because the repeated formation of cold-based ice during the Quaternary glaciations preserved large areas of an essentially non-glacial landscape, with only superficial glacial modification (Kleman and Stroeven, 1997; Clarhäll and Kleman, 1999; Kleman et al., 1999; Fabel et al., 2002; Stroeven et al., 2002b).

**METHODS**

Landscape analysis was performed over three spatial scales. Mapping and analysis of relict non-glacial surfaces (Paper II) was completed for the entire 24 082 km² area contained in Figure 2. Using a stereoscope, relict non-glacial surfaces were classified from 1:60 000 colour infrared aerial photographs, according to (i) large-scale morphologies, including rounded summits and fluvial valleys, (ii) signs of extensive subaerial weathering, including blockfield mantles, tors, and roughened exposed bedrock, and (iii) surface expressions of dominant periglacial processes, such as soil creep, solifluction, and nivation. The relict non-glacial surface classes were then imposed on a 50 m digital elevation model (DEM) and analysed in a GIS for patterns in their distribution according to bedrock lithology, elevation, and slope gradient. Field control was provided by helicopter surveys of the northern part of the study area from Nulpotjåkk to Alddasčorru, and ground investigations, including hand digging of regolith pits, at Alddasčorru, Duoptečohkka, Ruohthahakčorru, Tarfalatjårr, Tjeurolako, Kebnetjåkk, and Nulpotjåkk (Fig. 2). Additional ground surveys, without pit digging, were completed at Luovárrí, Geargevuomoš, and Njulla.
Fig. 2. Map of the study area in the northern Swedish mountains illustrating topography, bedrock lithology, field sites, and locations referred to in the thesis. The map location is shown in the inset and the black outline indicates the location of Fig 6. Transects of pit excavations and photographs of the field sites are shown in the adjoining panels. Eye symbols in the transect panels indicate the photographic view points.
To gain greater insight into the development of relict non-glacial surfaces, attention was then focussed on the weathering, formation, and ages of the autochthonous blockfields that frequently mantle them. Intra-site variations in the weathering of an amphibolite blockfield were examined on the dry, clast-dominated summit of Tarfalatjåro (67°55’N, 18°39’E; 1626 m a.s.l.) and in its wet, fine matrix-rich northern saddle (Paper III; Fig. 2). One pit was excavated at each location across a periglacially-sorted circle, from a coarse ring consisting of gravel, cobbles, and boulders to a circle centre rich in fine matrix (i.e. sand, silt, and clay). Fine matrix was sampled wherever possible in the coarse rings and at 0.2 m depth intervals in the sorted circle centres (Fig. 3). Fine matrix samples from the summit and saddle were then subjected to grain size, X-ray diffraction (XRD), and X-ray fluorescence (XRF) analyses to test for variations in chemical weathering according to horizontal position in a sorted circle, depth beneath the surface, and ground wetness.

Rock samples were extracted from the summit and saddle pits to establish a base for chemical weathering of fine matrix through XRF analysis. In addition, granule samples were taken from the summit to test for a possible chemical weathering link from parent bedrock to fine matrix via granular disintegration. Snow was collected from the accumulation area of a nearby glacier, Storglaciären, to test for recent aeolian additions to the blockfield fine matrix.

To complement interpretations of blockfield chemical weathering through analyses of fine matrix, numerous randomly selected clasts from both pits were inspected for evidence of weathering processes. Surface and subsurface clasts from the summit and saddle pits were inspected for lithology, roundness, sphericity, pitting, Fe oxidation, and rind development. Summit subsurface clasts were also inspected for these differences according to their location in the wet, matrix-rich sorted circle centre or in the dry, clast-dominated ring.

Inter-site variations in autochthonous blockfield weathering were examined along three altitudinal transects descending from the summits of Alddasçonru (68°25’N, 19°24’E; 1538 m a.s.l.), Duopteçohkka (68°24’N, 19°22’E; 1336 m a.s.l.), and Tarfalatjåro (Paper IV; Fig. 2). As with Tarfalatjåro, the Alddasçonru and Duopteçohkka blockfields are also developed in amphibolite. The transects were designed to test for weathering differences according to slope position rather than for temperature gradient. Consequently, altitudinal differences within autochthonous blockfields along each transect range from only 73 m for Tarfalatjåro to 88 m and 130 m for

![Fig. 3. Blockfield excavations, northern Swedish mountains. a) The summit of Tarfalatjåro. b) The saddle north of Tarfalatjåro. Approximate outlines of the sorted circles into which the pits were excavated are shown by dotted lines and sample locations are illustrated by triangles](image-url)
Alddasčorru and Duoptečohkka, respectively. A total of 26 pits were hand excavated and blockfield sections examined in 15 pits excavated into coarse sorted circle rings or into clast-dominated solifluction lobes. Fine matrix samples were taken from 16 blockfield pits for grain size, XRD, and scanning electron microscopy (SEM) analyses of clay mineralogy. For replication purposes, at least three fine matrix samples were taken from each slope context (i.e. convex summit, straight slope, concave slope base), except for Alddasčorru summit (2 samples) and straight slope (1 sample). For comparative purposes, fine matrix samples were taken for grain size, XRD, and SEM analyses from summit till covers on Ruohthakčorru (68°09'N, 19°20'E; 1349 m a.s.l.) and on Nulpotjåkka (67°48'N, 18°01'E; 1405 m a.s.l.), and from the high-valley till at the base of the Duoptečohkka transect (1060 m a.s.l.).

The Duoptečohkka and Tarfalatjårro summit pits were excavated where shattered quartz veins were visible on the blockfield surfaces. Clasts of vein quartz were collected from vertical regolith profiles in each pit to determine surface exposure durations from in situ-produced $^{10}\text{Be}$ and $^{26}\text{Al}$ concentrations. Vein quartz was sampled because fine matrix locally derived from amphibolite weathering was present in low quantities and lacking in medium sand (250–500 µm) and quartz. Although glacial deposition of vein quartz clasts cannot be entirely excluded, the absence of definite erratics from both summits and the location of pits within shattered quartz veins, where the quartz frequently remains attached to amphibolite, make it likely the sampled clasts were locally derived and therefore representative of surface exposure histories.

Apparent exposure ages were calculated from nuclide production rates scaled to latitude and altitude (Stone, 2000) from sea-level high latitude (> 60°) production rates of $4.6 \pm 0.3$ atoms g$^{-1}$ yr$^{-1}$ for $^{10}$Be (Nishizumi et al., 2007) and $31.1 \pm 1.9$ atoms g$^{-1}$ yr$^{-1}$ for $^{26}$Al (Lal, 1991). Total surface histories, which include periods of burial by ice sheets and changes to nuclide production rates induced by glacial isostasy, were then estimated using a 3-dimensional numerical ice-sheet model forced by benthic δ$^{18}$O records and incorporating an elastic lithosphere, relaxing asthenosphere (ELRA) model to simulate bedrock movement (Bintanja et al., 2002, 2005).

**PRESENTATION OF PAPERS**

**Paper I**


In this review, I investigate the concept of relict non-glacial surfaces, their characteristics and preservation within formerly glaciated landscapes, and the information they convey on long-term landscape evolution. Because relict surfaces have continued to be modified over time, they are polygenetic and the meaning of *relict* becomes dependent upon the spatial scale at which a landscape is viewed. Also because of continued surface modification during the Quaternary, *non-glacial* is preferred to the more common term of *preglacial* when describing relict surfaces within formerly glaciated landscapes.

Relict non-glacial surfaces are frequently periglaciated upland surfaces that are distinguishable from glacial surfaces by large-scale morphologies, including rounded summits, fluvial valleys, and cryoplanation terraces and pediments, and the presence of tors, blockfields, and/or saprolites. Blockfields are the most common landform associated with relict non-glacial surfaces and they remain enigmatic features because very few are documented to be presently forming. They are therefore usually considered to represent periglacially reworked remnants of chemically weathered Neogene regolith profiles. Whereas saprolites have clear Neogene origins, palaeoclimatic interpretations from saprolites are frequently questionable and it is possible that a commonly supposed dependence of saprolite formation on a warm, (sub) tropical, climate has been over-estimated.

Preservation of relict non-glacial surfaces during glacial periods occurs primarily through coverage by non-erosive, cold-based, ice or, in some places, as nunataks. Glacial features, such as erratics, moraines, boulder blankets, and ice-marginal channels, superimposed onto relict non-glacial surfaces indicate former ice covers. TCN analyses of erratics, tors, and bedrock surfaces are more frequently being used to confirm landscape preservation beneath cold-based ice. However, the absence of glacial features from relict non-glacial surfaces does not confirm
former nunataks. Whereas features such as sharply defined trimlines have been used to distinguish former nunataks from surfaces covered by cold-based ice, they might also indicate englacial thermal boundaries. Confirming former nunataks is difficult and the evidence is frequently inconclusive.

Where relict non-glacial surfaces have been labelled preglacial, minimal surface lowering and morphological change is implied. However, because of the high capacity for mass wasting under periglacial conditions, it should not be assumed that relict non-glacial surfaces are characterised by uniformly low rates of erosion or morphological change. Depending on spatial variables such as bedrock lithology, slope gradient, regolith depth, and the abundance of regolith fine matrix and water, some surfaces, such as gently convex summits, are eroding slowly, while others, such as steep slopes mantled by fine matrix-rich regolith, are likely eroding more rapidly. Spatial variability in denudation rates will produce changes in relict non-glacial surface morphologies over time. High temporal variability in relict non-glacial surface erosion rates is also likely, with much surface evolution having perhaps occurred soon after the initial onset of glaciation or during paraglacial phases. The potential for spatially and temporally varying Quaternary erosion rates and morphological evolution should be considered when reconstructing preglacial landscapes and in subsequent quantifications of glacial erosion. However, much remains to be determined regarding relict non-glacial surface erosion rates and the magnitude of morphological changes over time.

**Paper II**


Relict non-glacial surfaces in the northern Swedish mountains were mapped from colour infrared aerial photographs and imposed on a 50 m DEM in a GIS, where their characteristics were analysed. An original feature of this study was the classification of relict non-glacial surfaces according to dominant non-glacial surface process regimes, in addition to large-scale non-glacial morphologies, evidence of extensive weathering, and the type of superficial glacial modification. The surface classes were verified by fieldwork and their relationships with elevation, slope gradient, and bedrock lithology explored in the GIS.

The study revealed five types of relict non-glacial surfaces: (i) Low activity non-glacial surfaces (LA-NG) characterised by a smooth topography attributable to creep processes. (ii) Moderate activity non-glacial surfaces (MA-NG), characterised by an uneven topography attributable to solifluction and nivation. (iii) High activity non-glacial surfaces (HA-NG), characterised by steep slopes, large quantities of fine matrix, and/or surface instability. Clear breaks in slope usually mark their boundaries with other surface types. (iv) Non-glacial surfaces with thin, patchy regolith covers (PR-NG). (v) Non-glacial surfaces blanketed by thin (< 2 m) till covers (T-NG). In addition, two types of extensively weathered glacial surfaces transitional to relict non-glacial surfaces were identified: (i) Glacial erosion (areally scoured) surfaces (E-G) that appear “roughened” through extensive subaerial weathering. (ii) Till-covered glacial erosion surfaces (TE-G), characterised by allochthonous blockfields (formed from till) mantling glacially eroded bedrock.

The surface classes display only weak general trends according to slope and elevation. Because high-elevation surfaces are more likely to be preserved with minimal glacial modification, relict non-glacial surfaces occur at mean elevations exceeding 1000 m a.s.l., with LA-NG, MA-NG, and HA-NG surfaces occurring at higher mean elevations (1514—1296 m a.s.l.) than the glacially modified PR-NG and T-NG surfaces (1200—1018 m a.s.l.). Non-glacial relict surfaces generally occur on low gradient slopes, with T-NG, PR-NG, and MA-NG surfaces possessing mean slope angles of 7—14°. LA-NG and HA-NG surfaces have higher mean slope angles of 19° and 21°, respectively, with the higher than expected LA-NG slope gradients attributable to surface armouring by fine matrix-poor blockfields. Bedrock lithology exerts a clear control on surface classes (in part because of its relationship with surface elevation), with MA-NG, HA-NG, and, especially, LA-NG surfaces occurring predominantly on amphibolite, E-G surfaces occurring almost exclusively on intrusive lithologies, and T-NG and TE-G surfaces mostly occurring on intrusive lithologies and schists,
respectively. Only PR-NG surfaces exhibit a weak trend with bedrock lithology, being more evenly distributed across amphibolite, gneiss, schist, and intrusive lithologies.

The presence of different surface classes is consistent with the concept of spatial variability in surface processes and rates of non-glacial and glacial landscape evolution. Rather than being static preglacial remnants, relict non-glacial surfaces are dynamic features that have continued to evolve during the Quaternary. The classification provides hypotheses for landscape evolution that can be field tested through, for example, TCN studies, geochemical analysis of fine matrix materials, and applied to numerical studies of slope development. The classification may also be applicable to relict non-glacial surfaces in other formerly glaciated landscapes.

**Paper III**

**Goodfellow, B.W., Fredin, O., Derron, M.-H., Stroeven, A.P. Weathering processes and Quaternary origin of an alpine blockfield in Arctic Sweden. Manuscript.**

The weathering and origin of the Tarfalatjärro blockfield, located in the northern Swedish mountains, were investigated. To test for weathering variations according to slope position, clasts and fine matrix were examined from two pits excavated across ridge-top sorted circles; one on a dry summit and the other in a wet saddle. Fine matrix and clasts were sampled, both with depth and across the sorted circles, to also test for intra-site variations in chemical and physical weathering. Seven fine matrix samples from the summit and eight from the saddle were subjected to grain size, XRF, and XRD analyses. Clasts were inspected for lithology, roundness, sphericity, and surface weathering features such as Fe oxidation and pitting, and split with a hammer and chisel to inspect for internal chemical changes, including rind development and Fe oxidation.

Clay quantities are low in all fine matrix samples (3–6%) and chemical mass balance calculations, based on Al as the immobile element, revealed minor chemical weathering, both at the summit and in the saddle. These findings are supported by the clay mineralogy, which indicates that chemical weathering is limited to the production of largely amorphous Al- and Fe-oxyhydroxides at the summit, with some additional vermiculitisation and gibbsite crystallisation in the saddle. The variation in fine matrix chemical weathering between the summit and saddle may be attributable to slope position, with a greater abundance of fine matrix and water in the saddle, and/or a change in lithology from amphibolite on the summit to amphibolite and metapsammite in the saddle. Although variations in fine matrix chemical weathering exist between the summit and saddle, intra-site variations, either with depth or across sorted circles, are almost entirely absent from both locations. The only, minor, intra-site variation occurs in the accumulations of sand and granules in narrow spaces between clasts, which appear slightly less chemically weathered than the dominant mixtures of sand and silt.

In contrast to the fine matrix, more significant intra-site, as well as inter-site, variations occur in clast chemical weathering. Iron oxidation is more common in summit than in saddle clasts and in the wet, matrix-rich sorted circle centres than in the dry, clast-dominated rings. Conversely, surface pitting and rind development are relatively more common in the saddle than at the summit and in the dry clast-rich rings at both sites. Inter-site, summit to saddle, variations in clast chemical weathering are attributable to changes in mineralogy, whereas intra-site variations, across sorted circles, appear to be related to changes in ground moisture. There are additional intra-site variations in physical clast weathering, as revealed by a general trend of increasing roundness and granular disintegration where clasts are exposed to air, either on the ground surface or in dry, clast-dominated, parts of the subsurface. Intra-site variations in the extent of clast cracking also occur, with cracked clasts concentrated at the surface and base of the summit pit, but otherwise largely absent.

There is no evidence that the Tarfalatjärro blockfield is a preglacial weathering remnant. The presence of gibbsite does not indicate advanced chemical weathering, and both fine matrix and clast production can be explained by processes that have operated during the Quaternary. In addition to fine matrix bearing little sign of chemical weathering, blocks appear to be produced from bedrock through pressure release, resulting from the removal of overburden, and the opening of existing cracks
through Fe oxidation and annual freeze-thaw cycles at the blockfield base. Blockfields are not all the same and may represent Neogene weathering remnants in some locations but in others are the product of processes that have operated during the Quaternary.

**Paper IV**


To further examine blockfield origins and variations in weathering according to slope position, blockfields were investigated along three altitudinal transects descending from the summits of Alddasčorru, Duoptečohkka, and Tarfalatjårro, in the northern Swedish mountains. Each blockfield is formed on amphibolite bedrock. Quantities and mineral assemblages of clay were determined through grain size and XRD analyses, with additional SEM analysis of fine matrix chemical weathering. Surface exposure durations of blockfields on the summits of Duoptečohkka and Tarfalatjårro were measured through TCN analyses and incorporated into total surface histories that included periods of burial by ice sheets, subaerial erosion, and the effects of glacial isostasy on nuclide production rates.

Fine matrix analyses indicate only incipient chemical weathering, but which increases in intensity from summits and upper slopes, characterised by the production of poorly crystallised oxyhydroxides, to lower slopes and concave locations, where some additional vermiculitisation and gibbsite crystallisation occurs. Total complex histories, incorporating exposure, burial, isostasy, and subaerial erosion, indicate that the acquisition of cosmogenic isotopes by present surface regolith is almost certainly, but not unequivocally, limited to the Quaternary.

The investigated blockfields are not remnants of Neogene deep weathering profiles. Rather, their formation can be explained predominantly through physical processes that have operated during the Quaternary. Because of the possibility that blockfields have formed at depths where they have been shielded from cosmogenic radiation and gradually been exhumed through erosion of overlying regolith, total complex surface histories that are confined to the Quaternary do not, in isolation, confirm Quaternary blockfield origins. However, taken with the absence of significant chemical weathering, a probable Quaternary origin of the blockfields is indicated.

Present summit blockfield erosion rates are as low as 4.0 mm kyr$^{-1}$, although higher rates are anticipated in other blockfield-mantled parts of the landscape, such as those occurring on steeper slopes, on less resistant lithologies, and/or where fine matrix is abundant. Additionally, late Pliocene/early Pleistocene erosion rates were also likely to have been much higher, as presumably vegetated regoliths were exposed to increased rates of mass wasting under periglacial conditions. However, once fine matrix has been removed, the blockfields become largely relict features.

**DISCUSSION**

**Relict Surface Mapping and GIS Analysis**

Geomorphological mapping from colour infrared aerial photographs revealed that the relict non-glacial landscape of the northern Swedish mountains is composed of a range of surface types (LA-NG, MA-NG, HA-NG, PR-NG, and T-NG; Fig. 4). These surface types, which reflect differences in dominant surface process regimes, are shown, through GIS analysis, to be weakly related to differences in elevation and slope gradient. Field surveys also indicate a relationship between surface type and the quantities of regolith fine matrix and water. A stronger relationship is evident between surface type and bedrock lithology.

LA-NG surfaces have a particularly strong correlation with lithology, with > 80% developed on amphibolite and dolerite complexes. These hard, sheeted lithologies exert control on surface characteristics at the regolith scale i.e. they are weathered and periglacially reworked into thick blockfield mantles that form the classic “velvet” relict surfaces (Jansson and Glasser, in press). However, because of their resistance to weathering, these sheeted lithologies also form the highest surfaces in the northern Swedish mountains, which are consequently isolated from modification during glacial periods, through either protruding above surrounding ice
Fig. 4. Map of relict surface classes based on colour infrared aerial photographs. Non-glacial surfaces: LA-NG, MA-NG, and HA-NG, refer to low, moderate, and high activity of surface processes, respectively; PR-NG, Thin, patchy regolith cover; T-NG, Till-covered. Transitional glacial surfaces: E-G, Glacial erosion (areally scoured); TE-G, Till-covered glacial erosion. Map location is shown in the inset (source: Fig. 2 from Paper II, with permission of Elsevier).
sheets as nunataks or being protected beneath cold-based ice covers. The type of relict non-glacial surface occurring at a particular location is therefore directly influenced by bedrock lithological control on weathering but also indirectly through the presence of particular lithologies at different elevations in the landscape.

The high surfaces of the northern Swedish mountains are frequently illustrated as being composed of amphibolite, for example by Kulling (1964), on the Geological Map, Northern Fennoscandia (1987), on a shapefile geological map available from the Geological Survey of Sweden (2004), and again here in Paper II. However, the highest of these surfaces, such as those on Kebnekaise, are actually composed of dolerite complexes with minor occurrences of hornfelses (Andréasson and Gee, 1989). Like amphibolite, these dolerites are hard, coarse-grained, sheeted, mafic rocks and no differences in the characteristics of LA-NG or MA-NG surfaces developed on either lithology have been observed in aerial photographs or in the field. Therefore, although references to amphibolite in Paper II should be modified to “amphibolite and dolerite,” the inferences based solely on amphibolite remain unchanged.

The main point derived from the presence of a mosaic of surface types is that the relict non-glacial landscape of the northern Swedish mountains is continuing to develop through processes that are spatially variable, both in type and the rates at which they function. Relict non-glacial surfaces are therefore not static preglacial remnants, which has potential implications for reconstructing preglacial landscapes and quantifying volumes of glacial erosion.

Fig. 5. Reconstruction of a local preglacial surface across a glacial trough based on remnant slopes. a). The cross-sectional area of glacial erosion is calculated by subtracting the current topography from the reconstructed topography. b) Under-estimation of glacial and non-glacial erosion based on current non-glacial surfaces and an assumption of static equilibrium. c) An over-estimate of glacial erosion and an under-estimate of non-glacial erosion resulting from evolution of remnant non-glacial surfaces. d) Preglacial surface remnants have undergone a paraglacial response to trough incision, leading to an incorrect preglacial valley reconstruction and an under-estimate of glacial erosion. For simplicity, static equilibrium of remnant preglacial surfaces is assumed. e). A preglacial surface erroneously reconstructed from old glacial surfaces bordering the trough. Glacial trough development based on Harbor (1992). This scenario is an addition to those originally depicted in Figure 7 from Paper I.
The glacial surfaces that are extensively weathered, and so transitional to non-glacial surfaces (TE-G, E-G), may, in some locations, predate the last glaciation and thereby indicate temporal differences in ice sheet characteristics from erosive or depositional, to passive.

A weakness with the surface classification is that it is a largely qualitative landscape assessment. A more quantitative approach to surface identification from a Landsat image and DEM of part of the study area was attempted through a model developed in Erdas Imagine; a computer program that processes geospatial raster data. Because relict non-glacial surfaces are generally non-vegetated blockfields, have relatively even surfaces (i.e. amplitudes of surface roughness < 3 m), and occur mostly at high elevations and on low gradient slopes, the model was designed to identify relict non-glacial surfaces according to spectral signatures, surface texture, elevation, and slope gradient. Landsat bands 2 (green), 3 (red), and 4 (near infrared) and a 50 m DEM were used in the analysis. Based on data from paper II and experimental analyses in Erdas Imagine, the following parameters were used for the selection of relict non-glacial surfaces: elevation > 530 m a.s.l., slope gradient < 28° and, < 30 m relative relief in a 3 x 3 pixel moving window. Areas of low spectral variation in each of the three bands were also selected in ranges that excluded snow, water, vegetation, and shadows.

The model results were, however, poor (Table 1; Fig. 6), with only small areas of the previously mapped relict non-glacial surfaces, and some additional glacial surfaces, being identified. This is largely because: (i) the resolutions of the Landsat image (30 m) and DEM (50 m) are too low, (ii) recently emerged glacier forefields and high-altitude glacial surfaces are also non-vegetated, (iii) the model did not distinguish elongated forms that frequently indicate glacial surfaces from other, non-glacial, surface forms, (iv) snow covered some of the best developed relict non-glacial surfaces in the Landsat image, (v) relict non-glacial surfaces blanketed by thin tills at moderate elevations are vegetated, and, (vi) because of heterogeneous features in the Landsat image, the textural analysis function in Erdas Imagine identified surface edges rather than textures. Although future improvements to the model are possible, the human eye remains the best tool for identifying relict non-glacial surfaces from aerial or satellite images.

Weathering and Origins of the Blockfield Mantles

There is no indication of advanced chemical weathering in any of the examined blockfields. Supporting evidence includes the absence of saprolite, soil horizons, and chemically “rotted” clasts from all blockfield sections (Fig. 7), minor quantities of clay-sized fine matrix, minor formation of secondary minerals, the rarity of chemically etched grains in bulk fine matrix (Fig. 8), and minor elemental losses in fine matrix compared with parent rock. Clast and fine matrix production can be predominantly attributed to physical weathering processes that have operated during the Quaternary and there is no indication of Neogene deep weathering in the origins of blockfields in the northern Swedish mountains.

Intra-site variations in clast weathering on Tarfalatjärro occur with depth beneath the ground surface and across sorted circles. Clasts at the ground surface and in dry parts of the subsurface, i.e. in the clast-dominated rings of sorted circles, are subangular, whereas those in the wet subsurface, i.e. in matrix-dominated sorted circle centres, are very angular (Table 5 in Paper III). These trends occur independently of lithology and indicate the operation of granular disintegration at the surface and in the dry subsurface. At these locations, clasts are exposed to air and therefore subjected to a greater number of, and more rapid, fluctuations in temperature, either, or both, of which are important to granular

<table>
<thead>
<tr>
<th>Landsat band 2 (green)</th>
<th>Band 2 relative difference¹</th>
<th>Landsat band 3 (red)</th>
<th>Landsat band 4 (near infrared)</th>
<th>Surface texture</th>
<th>Elevation</th>
<th>Slope gradient</th>
</tr>
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<td>0.0961</td>
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<td>0.1084</td>
</tr>
</tbody>
</table>

¹Band 2 was selected because it provided the best correlation with relict non-glacial surfaces mapped in Paper II. Areas of low spectral variation (i.e. low relative difference) were selected in an attempt to identify blockfields.
disintegration (White, 1976; Matsuoka, 1990; Ballantyne and Harris, 1994, pp. 164-165). The role of ground moisture in weathering is highlighted by the inhibition of Fe oxidation in the dry subsurface clasts (Table 6 in Paper III). Intra-site differences in weathering indicate the long-term stability of these periglacially-sorted circles.

Some additional, minor, intra-site variations also occur in fine matrix weathering. The coarsest and least chemically weathered fine matrix on the Tarfälätjärro summit had accumulated between horizontally aligned slabs of amphibolite (samples BG-06-23 and BG-06-24 in Tables 1 and 4, Paper III), and the least chemically weathered fine matrix in the Tarfälätjärro saddle had accumulated beneath dry gravel in the coarse sorted circle ring (sample BG-06-07 in Table 4, Paper III). However, soil horizons were absent from both locations (Fig. 9) and there are no intra-site
Fig. 7. A representative blockfield section based from data from 17 pits excavated on Alddasčorru, Duoptečohkka, and Tarfalatjárro, and a ground penetrating radar image of bedrock beneath a till sheet on Ruohhtahakčorru.  a). A coarse surface layer dominated by boulders and cobbles is underlain by a gravely layer, which extends to a depth of about 0.7 m. Below this occurs a layer of boulders imbedded in a silty-sandy matrix to a depth of 1–1.3 m. The bottom of the blockfield is marked by a layer of large slabs of fractured bedrock, which continue to a depth of 2–4 m, where solid bedrock is reached (Isaksen et al., 2001). Chemically “rotted” clasts, soil horizons, and saprolite are absent from all examined blockfields. b). Ground penetrating radar was used in an attempt to determine depths to bedrock beneath blockfield mantles. Distinct bedrock surfaces were not observed, as illustrated at the left of the figure, except for this section through the till-covered summit of Ruohhtahakčorru, where a bedrock surface was observed beneath 2–2.3 m of clast-rich, weathered, till.
variations in the incipient development of secondary minerals (Table 1 in Paper III). Homogenisation of the fine matrix through recent periglacial churning is discounted by the intra-site differences in clast weathering. These data therefore reinforce the interpretation of minimal chemical weathering of this blockfield.

Inter-site variations in blockfield weathering are evident along the three altitudinal transects (Alddasčorru, Duoptečohkka, Tarfalatjårro). The primary difference occurs in clay mineralogy, where chemical weathering on summits is limited to the production of poorly crystallised oxyhydroxides but increases downslope to be relatively most advanced in concave locations, where some vermiculitisation and gibbsite crystallisation occurs (Table 1 in Paper III and Table 2 in Paper IV). Isocon plots of mobile and immobile elements also indicate slight chemical weathering in the Tarfalatjårrro saddle, whereas almost none occurs at the summit (Fig. 10). However, mass balance calculations reveal no statistically significant changes in chemical weathering between the summit and saddle (Table 4 in Paper III), although a real change may be obscured by small sample sizes and variability in bedrock mineralogy. Whereas there are no statistically significant changes in clay volumes along the transects, the Tarfalatjårrro saddle is significantly less sandy than the summit (at 1σ), where clast oxidation is also more prevalent (Tables 1, 5 and 6 in Paper III).

Because of varying mineral proportions in amphibolite between the Tarfalatjårrro summit and saddle, and the additional presence of metapsammite in the saddle (Table 5 in Paper III), it is impossible to distinguish variations in chemical weathering attributable to slope position from those attributable to mineralogy. However, supplementary evidence from the more homogenous amphibolite blockfields of Alddasčorru and Duoptečohkka, where the occurrences of secondary minerals also increase downslope (Table 2 in Paper IV), indicates that slope position is important to blockfield chemical weathering.

Fig. 8. Scanning electron microscope images indicating slight chemical weathering of fine matrix. a) Albite, with a chemically etched surface; the only etched grain identified. b) Chemically unaltered amphibole, typical of all SEM images of amphibole. c) Disintegrating albite, possibly through chemical processes. d) Chemically unaltered epidote, typical of all SEM images of epidote.
weathering. An increase in regolith water quantities and/or longer residence times of fine matrix that has been transported downslope may be the most important factors contributing to the increased chemical weathering of blockfields on lower slopes and in concave locations. Small altitudinal differences within autochthonous blockfields along each transect likely exclude weathering variations according to temperature. Minor chemical weathering in all locations, including similar secondary mineral formation in tills (Table 2 in Paper IV), and clay abundances that are at the low end of the range previously reported for other blockfields (Caine, 1968; Ahnert, 1977; Rea et al., 1996a,b; Dredge, 2000; Marquette et al., 2004; Paasche et al., 2006), support likely Quaternary origins for these blockfields. However, the lower quantities of clay and rarity of gibbsite in till compared with blockfield fine matrix indicates that these blockfields have formed over multiple glacial-interglacial cycles.

Fine matrix chemistry and clay mineralogy have been used only semi-quantitatively in this analysis of blockfield chemical weathering. Further quantitative analyses of fine matrix chemistry, such as comparing the strains of the fine matrix samples, were not undertaken because of the natural variability of the parent bedrock and the minor elemental losses in the fine matrix. Quantitative analysis of clay minerals was not attempted because of the associated technical difficulties (Moore and Reynolds, 1997, p. 298). Peak intensities in soils are uncertain and affected
by the concentrations of Mg and Fe. Quantitative analysis of mixtures of clay and non-clay minerals also requires the preparation of non-oriented samples (i.e. mineral flakes are not oriented parallel with the substrate; Moore and Reynolds, 1997, p. 220), whereas these samples were oriented. In addition, errors in quantitative analysis are much larger if the proportions of clay minerals in a sample are low (Moore and Reynolds, 1997, p. 299). Because these samples indicated incipient chemical weathering, there was little incentive to attempt quantitative clay mineral analysis even if technical issues could be overcome.

The summit blockfields of Duoptečohkka and, particularly, Tarfalatjárro are eroding slowly. From \(^{10}\)Be concentrations in blockfield profiles and modelled periods of surface burial by ice sheets and glacial isostasy, maximum long-term subaerial erosion rates are calculated to be 6.8 mm kyr\(^{-1}\) and 4.0 mm kyr\(^{-1}\), respectively. Whereas subaerial erosion of the Tarfalatjárro summit is likely to be relatively constant through fine matrix removal, the presently thin regolith cover indicates possible regolith plucking by over-riding ice sheets and, therefore, a potential over-estimation of the Duoptečohkka maximum subaerial erosion rate. Because the blockfield forms a thick (1.3 m), fine matrix-poor, mantle on a gently convex summit, the Tarfalatjárro summit erosion rate is likely to be near the minimum for relict non-glacial surfaces in this landscape.

Various surface history scenarios modelled from \(^{10}\)Be and \(^{26}\)Al concentrations indicate that the exposure of present blockfield regolith to cosmogenic radiation is limited to the Quaternary (Table 2). Although surface histories, which incorporate periods of surface burial by ice sheets, changes in nuclide production rates attributable to glacial isostasy, and maximum surface erosion rates permitted by the ice sheet model (at the erosion rate resolutions given in Table 2), are confined to the Quaternary, it remains possible that present surface regolith formed at a depth where it was shielded from cosmogenic radiation and has been gradually revealed through erosion of overlying regolith. Consequently, a Neogene blockfield origin cannot be excluded through TCN analyses alone. However, when total surface histories are considered with the various evidence for minor chemical weathering, there is no reason to appeal to a Neogene origin for blockfields. Blockfield formation in the northern Swedish mountains can be explained by processes that have operated during the Quaternary.

**Proposed Model of Blockfield Formation**

Subsurface weathering processes are crucial in the proposed model of blockfield formation (Fig. 11). Pressure release, through the removal of overburden, cracks and fragments bedrock at the regolith base. Whereas permafrost protects the deepest regolith (> 1.6 m) from further weathering, its impermeable surface ensures that the blockfield profile near the base of the active layer is saturated with water during warmer months. Ideal conditions are therefore provided for further crack growth and eventual rock splitting through annual freeze-thaw cycles (Hallet et al., 1991; Murton, 1996; Murton et al., 2000; Matsuoka, 2001). Oxidising Fe along mineral planes may also promote crack growth by weakening the rock structure and providing an entry point for water. The absence of saturated conditions at the ground surface may explain why frost wedging has rarely been observed in the field (Ballantyne and Harris, 1994, p. 164; Matsuoka, 2001).

Clasts are eventually exposed at the surface through regolith stripping and periglacial sorting during cold, but ice sheet free, periods. Once at the surface, or deposited through circular sediment movement into the dry clast-dominated parts of periglacially-sorted circles or stripes (Hallet and Prestrud, 1986; Ballantyne and Harris, 1994, p. 93), clasts are rounded through granular disintegration. On summits, fine matrix is redistributed by periglacial sorting into circle centres and/or winnowed out by water flowing through the profile, whereas it accumulates downslope in concave locations. The rate of blockfield formation is likely controlled by the rate of surface denudation and active layer depth, where a slow denudation rate, resulting perhaps from the winnowing out of fine matrix (Boelhouwers, 2004) inhibits blockfield development. Whereas a deep active layer exposes more bedrock to weathering, a shallow active layer concentrates weathering and erosion into a shallower near-surface zone. This likely results in more vigorous periglacial mass wasting and downwards translocation of the weathering front through the blockfield, thereby enhancing the rate of blockfield formation. The operation of processes most important to blockfield formation at depth within an existing regolith cover,
rather than at the surface, may explain why so few blockfields seem to be presently forming.

The fine matrix present in blockfields appears to be a product of in situ weathering. There is no evidence from fine matrix chemistry (Table 5, Fig. 10), or from grain shapes revealed by SEM (Fig. 8) and light microscopy (Fig. 12), for the presence of aeolian or glacial sediments. Additional evidence for the lack of aeolian sediments includes the absence of ventifacted boulders, clear aeolian deposits, and current aeolian dust transport as revealed by the presence only of dried lichens in fines collected from the accumulation area of Storglaciären.

Physical breakdown of rock through, for example, frost weathering (microgelivation), appears to be the primary source of blockfield fine matrix. Silt production through frost weathering has been observed in laboratory experiments (Lautridou and Ozouf, 1982; Smith et al., 2002) and the development of relict non-glacial surface regolith over multiple glacial-interglacial cycles apparently offers sufficient time for frost weathering to produce substantial quantities of fine matrix. Erosive processes, such as frost creep and surface and subsurface wash, deplete convex summit areas of fine matrix and concentrate it on slopes and in concave slope bases.

Chemical weathering is a minor contributor to fine matrix development. Chemical data (Table 4 in Paper III) indicate that granules have the same composition as parent rock and are not an intermediate step in

<table>
<thead>
<tr>
<th>Site</th>
<th>Scenario¹</th>
<th>$[^{10}Be]$ atom g⁻¹ (x 10⁵)</th>
<th>Exposure prior to shielding (10⁵ yr)</th>
<th>Shielding (10² yr)</th>
<th>Exposure since deglaciation (10² yr)</th>
<th>Total history (10⁵ yr)</th>
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<td>344.6</td>
<td>11.8</td>
<td>979.7</td>
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</table>

¹Erosion rates were determined iteratively from the complex history models for Duoptečohkka and Tarfalatjárro. The high erosion rate precisions are necessary because of the exponential increase in total surface histories as the maximum erosion rates permitted by the complex history models are approached but never reached. The 15.11518 mm kyr⁻¹ erosion rate is the maximum permitted, at 10⁻⁵ resolution, by the Duoptečohkka complex history model when glacial isostasy is included. Maximum erosion rates, at 10⁻² resolution, permitted by the Tarfalatjárro complex history model are 6.22 mm kyr⁻¹, with isostasy, and 6.64 mm kyr⁻¹, without isostasy. Total surface histories for Tarfalatjárro based on the same erosion rate precision as for Duoptečohkka could not be calculated because they exceeded the time span (1.07 Myr) covered by the complex history models. Total surface histories continue to increase exponentially with further refinements in erosion rate precision.
Relict surfaces and blockfields / northern Swedish mountains

Fine matrix production through chemical weathering. The additional absence of chemically “rotted” clasts and saprolite, and possibly the increase in chemical weathering away from summits, also indicate that most chemical alteration of fine matrix probably occurs after it has been produced.

**Future Research**

This study has focussed, firstly, on identifying and characterising relict non-glacial surfaces in the northern Swedish mountains and, secondly, analysing the weathering and origins of the blockfields that frequently mantle them. Key future research directions lie in determining the long-term hillslope to landscape-scale topographic evolution of these surfaces and placing them in the context of similar landscapes in other periglaciated and/or formerly glaciated locations.

For example, TCN and numerical analyses of some similar blockfield-mantled, relict non-glacial surfaces in the Rocky Mountains indicate the presence of convex summit areas with slope gradients and regolith transport rates that increase linearly away from the summit apexes (Small et al., 1999; Anderson, 2002). Also because regolith thicknesses and production rates are constant downslope, it was concluded that these surfaces are lowering in a state of dynamic equilibrium. However, total station surveys indicate that relict non-glacial surfaces in the northern Swedish
mountains are comprised of straight slopes, with only small convex summit areas (Fig. 13). These surfaces therefore have similar elements to hillslopes in steep, rapidly eroding catchments, such as in the Oregon coastal ranges (Roering et al., 1999), but with lower slope gradients. The straight slopes exhibit a nonlinear relationship between gradient and regolith transport rate, as opposed to the convex summits, which exhibit a linear relationship. Dynamic equilibrium, with respect to surface lowering, is not indicated in this landscape. Although slope retreat may still exist in a state of dynamic equilibrium, the efficacy of processes such as solifluction and nivation make it unlikely (Font et al., 2006). A better understanding of the topographic evolution of these surfaces will allow for better preglacial surface reconstructions, with subsequent improved quantifications of glacial erosion, and contribute to general long-term, large-scale landscape evolution theory.

Work is also needed to further quantify differences in the non-glacial and transitional surface categories identified in this study and to expand these findings to other formerly glaciated regions. At present, erosion rates of only two LA-NG surfaces have been measured. Erosion rates or surface exposure histories for MA-NG, HA-NG, PR-NG, TE-G, E-G surfaces remain unknown apart from one $^{10}$Be measurement of an E-G surface, which provided an erosion rate of 23.6 ± 1.9 mm kyr$^{-1}$ or an apparent exposure age of 23.0 ± 1.8 kyr, indicating that it was not significantly eroded during the last glaciation. TCN analyses may be applied to MA-NG summit regolith profiles, and to bedrock on PR-NG, TE-G, and E-G surfaces. However, they could not be effectively applied to HA-NG surfaces, which occur on straight slopes away from summits, unless quartz bearing bedrock could be reached beneath a shallow regolith cover that was of sufficient stability to be safely excavated. Similar mapping of relict non-glacial surfaces could be attempted in other formerly glaciated landscapes to test the general applicability of this surface classification. An additional benefit of such an exercise may be that the surface categories could be examined through $^{10}$Be and $^{26}$Al measurements on lithologies containing more quartz than the generally mafic rocks occurring on the high surfaces of the northern Swedish mountains.

Surface weathering could be tested along altitudinal transects that extend to lower elevations than in the present study, with recent glacial sediments being examined to better understand rates of chemical weathering under recent environmental conditions. Spring water should also be tested for dissolution products to assess current chemical weathering.

The proposed mechanism of blockfield formation through subsurface frost weathering also requires verification through process studies. Although technically challenging, field measurements of subsurface temperatures are required. In addition, laboratory and numerical studies, similar to those that have been performed on bedrock (Hallet et al., 1991; Anderson, 1998; Murton et al., 2000), could be designed to assess the role of frost weathering beneath blockfield mantles. Such studies would have general
importance in providing insight into a mechanism for bedrock conversion to regolith.

Although the blockfields of the northern Swedish mountains have Quaternary origins, the applicability of the findings of this study to other blockfields remains unknown. It is likely that, unless large quantities of secondary minerals are present, other blockfields are also the product of weathering processes that have operated during the Quaternary. However, while the blockfields of northern Sweden have Quaternary origins, the surfaces they mantle have not been significantly modified through glacial processes and have preglacial origins. In addition to illustrating a spatial scale dependency for the term “relict” (Fig. 14), the extent to which the present “non-glacial” landscape represents a “preglacial” landscape is a question that also requires further exploration.

CONCLUSIONS

Many high elevation surfaces in the northern Swedish mountains exhibit relict non-glacial characteristics. However, considerable spatial variation occurs, with five classes of relict non-glacial
sorted circle centres. Chemical weathering of fine matrix is highly restricted on summits, where only poorly crystallised oxyhydroxides are produced, but increases slightly in concave locations, where some additional vermiculisation and gibbsite crystallisation occurs. There is no evidence for aeolian and/or glacial additions of fine matrix, which appears primarily to be a product of in situ frost weathering.

Subsurface, rather than surface, weathering processes may be most important to blockfield formation. Regolith covers maintain water in contact with bedrock surfaces and (annual cycle) frost weathering may be most effective in the water-saturated bases of blockfield profiles, above impermeable permafrost surfaces. The operation of the processes most important to blockfield formation at depth within an existing regolith cover, rather than at the surface or on subaerially exposed bedrock, may explain why so few blockfields appear, from surface characteristics, to be presently forming.

There has been a heavy reliance on the presence of particular secondary minerals, such as gibbsite and kaolinite, in determining the origins of blockfields or other palaeoregoliths in formerly glaciated landscapes (Rea et al., 1996b; Ballantyne, 1998; Ballantyne et al., 1998; Paasche et al., 2006; André et al., 2008). It is the abundance of these minerals that is important and their presence in a mixture dominated by primary minerals is not diagnostic of

Fig 14. Relict non-glacial surface with a polygenetic history. Large-scale morphology with preglacial origins is mantled by Quaternary regolith, with imprints of Holocene geomorphology (source: Paper I, with permission of Elsevier).
Regolith formation under a warm, preglacial climate. The presence, in this study, of gibbsite in till (Table 2 in Paper IV) and its association with otherwise poorly crystallised oxyhydroxides indicates that it does not represent advanced chemical weathering in this setting. Chemical weathering of blockfields in the northern Swedish mountains is of similar intensity to chemical weathering of Quaternary regoliths in other alpine settings. To best define the extent of chemical weathering in palaeoregoliths, such as blockfields, fine matrix chemistry should be examined in addition to its mineralogy.

The summits of Duoptečohkka and Tarfalatjärro are eroding slowly, at maximum modelled rates of 6.8 mm kyr\(^{-1}\) and 4.0 mm kyr\(^{-1}\), respectively. The Tarfalatjärro erosion rate is likely near the low end of the range for relict non-glacial surfaces in this landscape because it is measured at the apex of a gently convex summit, mantled by a fine matrix-poor blockfield. Complex exposure histories from TCN profiles, incorporating periods of surface burial by ice sheets and the effects of glacial isostasy, are almost certainly confined to the Quaternary on both summits (1070.8 kyr for Duoptečohkka, at 10\(^{-5}\) erosion rate resolution, and 979.7 kyr for Tarfalatjärro, at 10\(^{-2}\) erosion rate resolution).

There is no need to appeal to Neogene weathering processes to explain the presence of blockfields in the northern Swedish mountains. All observations of these blockfields can be explained by processes that have operated during the Quaternary. Whereas relict non-glacial remnants have preglacial origins, their blockfield mantles do not. A polygenetic landscape history is therefore indicated, where the potential age of the landscape increases with the spatial scale at which it is viewed.

Unlike non-glacial surface remnants in some other locations, those in the northern Swedish mountains are characterised by small convex summits and straight slopes. Dynamic equilibrium is therefore not indicated in this landscape and there remains considerable scope to link regolith weathering and erosion rate studies with hillslope- and regional-scale development of relict non-glacial surfaces.

ACKNOWLEDGEMENTS

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Research is impossible without money so I thank the following funding sources: the Swedish Society for Anthropology and Geography (SSAG) Andréefonden, Axel Lagrelius’ fond, C.F. Liljevalch J:ors resestipendium, K & A Wallenbergs Stiftelse, Lars Hiertas minne Stiftelse, Carl Mannerfelts fond, Ahlmanns fond, and the U.S. National Science Foundation (NSF).

Research is also impossible without stimulating ideas so I wish to acknowledge two papers that inspired the initiation of this project: Small et al., 1999. Estimates of the rate of regolith production using $^{10}$Be and $^{26}$Al from an alpine hillslope. Geomorphology 27, 131-150; and Anderson, 2002. Modeling the tor-dotted crests, bedrock edges, and parabolic profiles of high alpine surfaces of Wind River Range, Wyoming. Geomorphology 46, 25-58. Although my project evolved into a study different from these two, they provided the initial “hook”.

While in Sweden I have been privileged to have made many good friends at INK, from my Swedish language classes (we didn’t learn much Swedish but we had a lot of fun…and drank a lot of beer afterwards), through the Australian connection at Karolinska Institutet, and especially from the Aussie Rules Footy club. Life experience is best measured in those you meet and the laughs you have over a beer or on a footy trip, and it is fair to say my time in Stockholm would have been immensely poorer without all of these people. Thanks a lot!

As good as it is, completing a PhD will be the second, and soon the third, best thing that has happened to me since I have been in Stockholm. Easily the best thing has been meeting my partner, Hanna Sjölin, who has provided me with encouragement, laughs, friendship, a roof over my head, and lots of love. Equally best will be the birth of our first child in the summer. I look forward to a happy and exciting future with both of you!

Finally, I dedicate this work to my mother, Lynette Goodfellow, and my grandparents, Ken and Rona Bowie, who only ever gave me love and support. You will always be missed.
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APPENDIX

The following is a summary of research conducted as part of my PhD study, but found to be non-central to the theme of the final thesis. Manuscript in preparation for *Earth Surface Processes and Landforms*.

Vertically mixed and unmixed: Do surface features tell the whole story? An investigation of till depth profiles using in situ-produced cosmogenic radionuclides

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**Introduction**

The degree of vertical mixing is crucial to determining a regolith erosion rate or age from in situ-produced cosmogenic radionuclides. The surface nuclide concentration is the same for a fully mixed in situ regolith as it is for an unmixed regolith (Granger et al., 1996), and a regolith erosion rate or age can be calculated. However, without further information on the mixing history of each regolith sample, it is impossible to calculate the erosion rate or age of a partially mixed regolith. Surface features, such as periglacially-sorted circles, may indicate full regolith mixing, whereas an unsorted summit blockfield may represent an unmixed regolith.

In this study, we examined the mixing of a periglacially sorted till blanketing the summit of Ruoholahkčorru (68°09´N, 19°20´E; 1349 m a.s.l.) in the northern Swedish mountains (Fig. 1). We used \(^{10}\)Be and \(^{26}\)Al in quartzite clasts extracted from

![Image](image.png)

**Fig. 1.** Location of the study site in the northern Swedish mountains and pit excavations 1 and 2 into till on the plateau surface of Ruoholahkčorru.
We anticipated full mixing of the unconsolidated till attributable to clast upfreezing and/or lateral sorting of clasts into sorted circles.

Pit excavation and regolith sampling

Two pits were hand excavated, one to a depth of 1.30 m in the clast-dominated ring of a sorted circle and the second to a depth of 1.10 m in a fine matrix-dominated sorted circle centre (Fig. 1). In each pit, four quartzite clasts were taken from various depths in Pit 1 and five from various depths in Pit 2 for measurement of \(^{10}\)Be and \(^{26}\)Al concentrations.

Unmixed and fully mixed regolith

Both \(^{10}\)Be and \(^{26}\)Al data indicate almost completely unmixed regolith in Pit 1 (Table 1; Fig. 2). Conversely, three samples from Pit 2 are consistent with a fully mixed regolith, while one sample lies almost on the unmixed curve. The latter was taken from a large (> 2 m) boulder. A fifth sample was excluded because of a large discrepancy between measured \(^{10}\)Be and \(^{26}\)Al concentrations, which may indicate nuclide inheritance from a period prior to incorporation into the till. Caution must be exercised in assuming that an entire regolith is either unmixed or mixed from interspersed depth profiles and the degree of mixing may differ significantly from that indicated by surface features.

Table 1: Cosmogenic nuclide data, apparent exposure ages, and nuclide ratios from till sections, Ruohtahakčorru, northern Sweden.

<table>
<thead>
<tr>
<th>Pit no.</th>
<th>Sample no.</th>
<th>Elevation (m a.s.l.)</th>
<th>Lithology</th>
<th>Depth (m)</th>
<th>Thickness correction</th>
<th>(^{10})Be scaling factor</th>
<th>(^{10})Be atom g(^{-1}) (x 10(^5))</th>
<th>(^{26})Al scaling factor</th>
<th>(^{26})Al atom g(^{-1}) (x 10(^5))</th>
<th>(^{10})Be apparent exposure age (10(^3) year)</th>
<th>(^{26})Al apparent exposure age (10(^3) year)</th>
<th>(^{26})Al/(^{10})Be</th>
</tr>
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<tr>
<td>1</td>
<td>BG-04-01</td>
<td>1346</td>
<td>Quartzite</td>
<td>Surface</td>
<td>0.966</td>
<td>3.495</td>
<td>1.66 ± 0.09</td>
<td>9.16 ± 0.67</td>
<td>36.5 ± 2.9</td>
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<td>1.15 ± 0.05</td>
<td>5.35 ± 0.37</td>
<td>25.1 ± 1.8</td>
<td>17.4 ± 1.6</td>
<td>4.7 ± 0.4</td>
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<td>1.28 ± 0.06</td>
<td>7.44 ± 0.48</td>
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<td>0.966</td>
<td>3.487</td>
<td>1.07 ± 0.05</td>
<td>6.63 ± 0.43</td>
<td>23.4 ± 1.8</td>
<td>21.6 ± 0.43</td>
<td>6.2 ± 0.5</td>
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</tr>
</tbody>
</table>

Topographic shielding corrections < 0.1%. Thickness corrections were calculated using a rock density of 2.75 g cm\(^{-3}\) and an attenuation mean free path of 150 g cm\(^{-2}\). Altitude-latitude scaling factors were calculated according to Stone (2000) with a sea surface temperature of 5 °C. Data were normalised to sea-level high-latitude \(^{10}\)Be and \(^{26}\)Al production rates of 4.6 ± 0.3 and 31.1 ± 1.9 atoms g\(^{-1}\) yr\(^{-1}\), respectively (Stone, 2000; Nishiizumi et al., 2007). All measured \(^{10}\)Be concentrations were normalised to NIST SRM 4325.
a close fit. Matching a realistic modelled curve with the $^{26}$Al data, therefore, remains out of reach.

**Indications of regolith origins from $^{10}$Be and $^{26}$Al**

Combined pit data indicate that the regolith has not been produced in situ and is a till (Fig. 4). In an in situ regolith, the cosmogenic nuclide concentration through the fully mixed profile is the same as the surface nuclide concentration of an unmixed profile. This is because the regolith nuclide concentration in a fully mixed profile ($N_{\text{reg}}$) is the sum of nuclides inherited from the bedrock below as bedrock fragments become incorporated into the regolith ($N_{\text{br}}$) and the depth-averaged nuclide production rate in the regolith ($P_{\text{reg}}$) multiplied by the mean regolith residence time ($t_{\text{reg}}$), i.e.:

$$N_{\text{reg}} = N_{\text{br}} + P_{\text{reg}} t_{\text{reg}}$$ (Granger et al., 1996).

Because the fully mixed profile has lower nuclide concentrations than the unmixed profile, the regolith appears not to have been produced in situ. Furthermore, the difference between the nuclide concentration in the fully mixed profile and
the surface nuclide concentration of the unmixed profile equals, within error margins, the nuclide concentration at 1.10 m depth on the unmixed curve, which is equivalent to the fully mixed regolith base. The difference in nuclide concentrations between the profiles therefore equals the missing addition of nuclides from the underlying bedrock. The regolith in each pit may have a common origin and deposition during a single glaciation is indicated.

When was the till emplaced?

The $^{10}$Be concentration of the Pit 1 (unmixed profile) surface sample can be used to estimate when the till was emplaced if the surface erosion rate, durations of surface burial by ice sheets, and glacial isostasy can also be estimated. An erosion rate of 8–10 mm kyr$^{-1}$ is estimated from a nearby summit blockfield erosion rate of 4 mm kyr$^{-1}$ (Paper IV), which has been adjusted upwards to account for the greater abundance of fine matrix. Erosion rates of similar magnitude have been calculated on another, fine matrix-rich, periglaciated plateau surface (Small et al., 1999). A slower estimated erosion rate will reduce the time that the sampled till has been blanketing Ruotahakčorru, whereas a faster erosion rate will increase the residence time of the till. Burial durations and glacial isostasy have been estimated
using a 3-dimensional numerical ice-sheet model forced by benthic $\delta^{18}O$ records and incorporating an elastic lithosphere, relaxed asthenosphere (ELRA) model to simulate bedrock movement (Fig. 5; Bintanja et al., 2002, 2005). From the $^{10}$Be concentration of the Pit 1 surface sample, and accounting for erosion, burial, and glacial isostasy as indicated, till emplacement is attributed to the Saalian glaciation, which occurred between 300 and 130 kyr ago. It has survived subsequent glaciation through being covered by cold-based ice.

References


