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A relict landscape in the centre of Fennoscandian glaciation: Geomorphological evidence of minimal Quaternary glacial erosion

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Abstract

The Parkajoki area in northeastern Sweden is situated near the central area of Fennoscandian glaciation. Despite its location, the area is dominated by landforms induced by subaerial weathering and erosion processes, such as well-developed tors and associated saprolites, boulder fields, and boulder depressions. The glacial geomorphology is dominated by lateral and proglacial meltwater channels. Subglacial imprints indicative of thawed-bed conditions and reshaping by glacier sliding (e.g., fluting, drumlins, striae) are lacking. Hence, most of the landscape still exhibits a preglacial appearance. Because of its location, near the central area of glaciation, we attribute preservation to frozen-bed conditions of overriding ice sheets. The widespread distribution of well-developed tors and boulder fields, and the degree of chemical weathering of the bedrock, indicate that the area has been protected from glacial erosion during all glacial cycles since ice sheet initiation in the late Cenozoic. Unlike most other areas with tors in glaciated regions, the Parkajoki area is uniquely situated in the lowlands at 150–400 m.a.s.l. Moreover, this relict landscape is surrounded by glacial landscapes (including drumlins, ribbed moraine, and eskers) of varying age and at similar elevation. Hence, topographical reasons for this area being persistently cold-based cannot be invoked. By inference, we conclude that strain heat release never managed to cancel the initial subglacial permafrost conditions. We attribute this to divergent ice flow towards the convex outline of the ice sheet margin during deglaciations and to the relative roughness of the area compared to its surroundings. The implication is that to explain preservation throughout the Quaternary, all large-scale glaciations must have had a similar evolution concerning ice sheet configuration and internal dynamics as the last glaciation for which good constraints on evolution and outline are available.

Keywords: Quaternary; Ice sheets; Tors; Boulder depressions; Boulder fields; Sweden

1. Introduction

Reliable reconstructions of ice sheet extent for the Last Glacial Maximum (LGM) through the Late Glacial time period [~ 20–8 ka (thousand calendar years ago)], are now available for most former ice sheets (e.g., Dyke and Prest, 1987; Kleman et al., 1997; Dyke, 1999; England, 1999). However, estimates of LGM ice thickness and volume have varied widely even for the quite thoroughly studied Laurentide and Fennoscandian ice sheets (e.g., Denton and Hughes, 1981; Peltier, 1994; Lambeck et al., 1998; Tarasov and Peltier, 1999).

For General Circulation Modellers, it is pertinent that the third dimension of ice sheets (thickness) also

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be specified reliably. The most direct method is by calculating the ice thickness in time-dependent three-dimensional thermomechanic model runs for ice margins of known age. For this procedure to be successful, it is necessary that the subglacial temperature evolution during the course of a glaciation for the glaciated region is specified. This type of information has only recently been emerging for the Laurentide and Fennoscandian ice sheets (Kleman et al., 1997, 1999). These reconstructions of the subglacial temperature distribution since the LGM show, for example, that former centres of glaciation, comprising 25–35% of the total glaciated area, were cold-based during the LGM.

In Fennoscandia and North America, the ice sheets advanced during marine isotope stages 4–2 (70–20 ka) over surfaces with permafrost conditions and, initially, were characterised by overall cold-based subglacial conditions (Kleman et al., 1997; Hättestrand, 1998). Because ice thickness steadily grew and effective ice discharge patterns were slowly established, warm-based subglacial conditions developed, especially in the outer parts of the ice sheet. However, cold-based conditions were maintained throughout the last glacial cycle in core areas and in high elevation areas with thin ice (Kleman et al., 1999). The presence of ribbed moraines can be used to identify parts of the ice sheet bed that underwent a transition from frozen to thawed during the deglaciation (Hättestrand, 1997, 1998; Hättestrand and Kleman, 1999). In principle, these traces reflect the behaviour of the ice sheets since the LGM. A few ribbed moraine traces at odds with the last deglaciation ice flow exist (cf. Kleman et al., 1994), but these older traces are too few and too far apart to permit reconstructions of pre-LGM subglacial conditions.

Areas of persistent frozen-bed conditions are usually identified by the presence of relict landforms and landscapes (e.g., Dyke, 1993; Kleman, 1994; Kleman and Borgström, 1994). Most relict landscapes consist of older glacial landforms, directionally incompatible with an inferred younger ice flow (Lagerbäck and Robertsson, 1988; Dyke et al., 1992; Hättestrand, 1998), or periglacial landforms which require longer and colder periods of formation than was available during the Holocene (Lagerbäck, 1988a; Kleman and Borgström, 1990; Dyke, 1993). In general, these types of data reflect basal ice sheet conditions during the last glaciation or the last stadial. To reconstruct the subglacial conditions of older ice sheets, we need complete pre-Late Weichselian glacial landscapes indicating polythermal basal conditions, including, for example, ice sheet zones that display only lateral meltwater channels, which are indicative of cold-based conditions during a deglaciation (Dyke, 1993; Sollid and Sørbel, 1994), or ribbed moraines. Such polythermal pre-Late Weichselian landscapes have seldom been described (e.g., Kleman et al., 1994).

An alternative means of reconstructing subglacial conditions of consecutive glaciations is to use landforms and landscapes formed before the onset of Quaternary glaciation, and that could not have survived erosion by warm-based ice flow. The presence of such landforms and landscapes in formerly glaciated terrain, for example in passive margin mountains bordering the North Atlantic (e.g., Ahlmann, 1919; Gjessing, 1967; Sugden and Watts, 1977; Hall and Sugden, 1987; Rea et al., 1996; Kleman and Stroeven, 1997), delineates areas where the cumulative effect of Quaternary glaciations has been negligible. However, it is pertinent that data become available also for areas other than mountains, which can illuminate the subglacial temperature evolution during periods of ice sheet growth and for pre-Weichselian glaciations. In this paper, we present an intact relict landscape, essentially of preglacial origin, that was preserved throughout many consecutive Fennoscandian ice sheet glaciations. The evidence allows constraints to be put on the basal temperature conditions of pre-LGM ice sheets for this location.

2. Area description

2.1. Physiography

The Parkajoki area, named after its most prominent river, measures c. 1450 km^2 and is situated in northeastern Sweden at the Finnish border (Fig. 1). The bedrock geology of the area is typical of northern Fennoscandia and consists of Archean/Proterozoic gneiss bodies with an age of ~ 2.5 Ga. These complexes have been intruded by Proterozoic granite, granodiorite, diorite, and gabbro at ~ 1.8 Ga (Nordkalott Project, 1987). No correlation between bedrock type and relief can be seen.

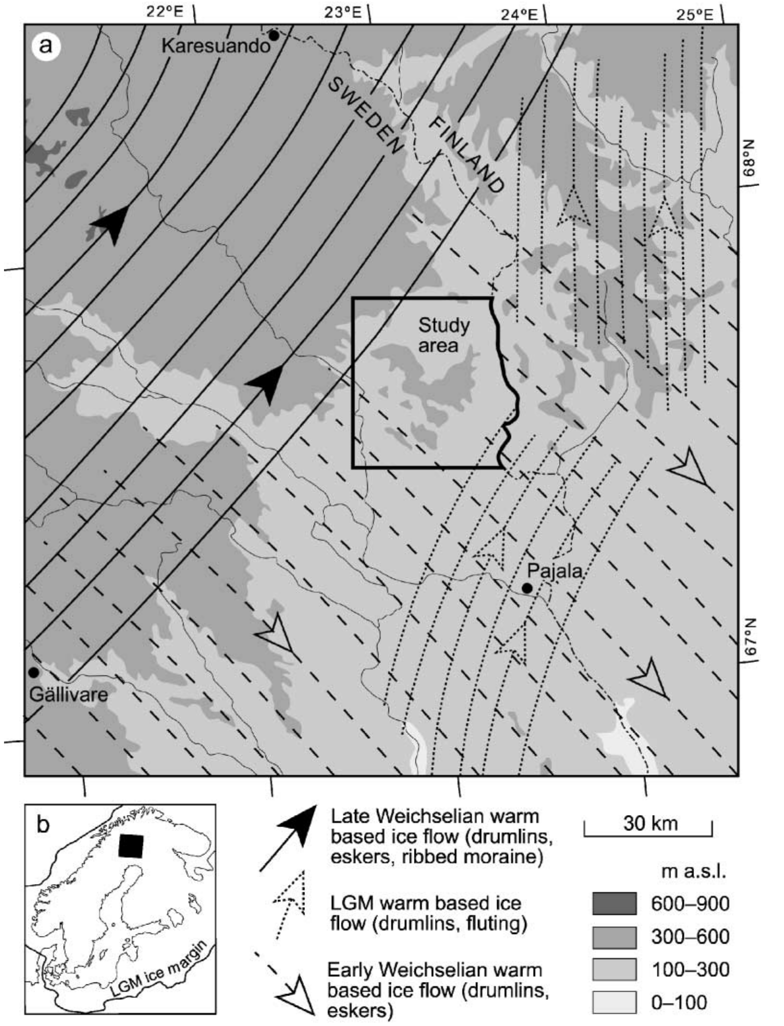

Fig. 1. Geographical and palaeoglaciological setting of the Parkajoki area. The warm-based ice flow patterns and age assignments depicted in (a) are based on the distribution of warm-based ice flow indicators (Nordkalott Project, 1986b,c; Kleman et al., 1997; Hättestrand, 1998). In this region, the Weichselian ice sheet was either absent or cold-based during the time periods between these partly warm-based ice flow events. The two LGM ice flow systems east of the Parkajoki area could not have been formed simultaneously. However, because both are associated with a very easterly location of the ice divide, both are interpreted to have formed near the LGM (Kleman et al., 1997). LGM ice margin in (b) from Denton and Hughes (1981).

The relief of northern Sweden, east of the Scandinavian mountain chain, consists of vast plains with residual hills (Rudberg, 1960; Lidmar-Bergström, 1995). The plains are arranged in a stepwise manner along the major rivers and are thought to reflect changes in the general base level, probably due to repeated Tertiary uplift leading to polycyclic events of etching, stripping and pedimentation (Wråk, 1908; Rudberg, 1954; Lidmar-Bergström, 1996).

The Parkajoki area is characterised by a gently undulating terrain with a typical local relief of 50–200 m (Figs. 2 and 3). Most hills are more or less circular with gentle slopes and those that are elongated have no preferred orientation. The drainage pattern of the Parkajoki area appears to be a palimpsest of a typical dendritic fluvial drainage pattern (e.g., the Parkajoki River; Fig. 2), crosscut by large linear glaciofluvial canyons.

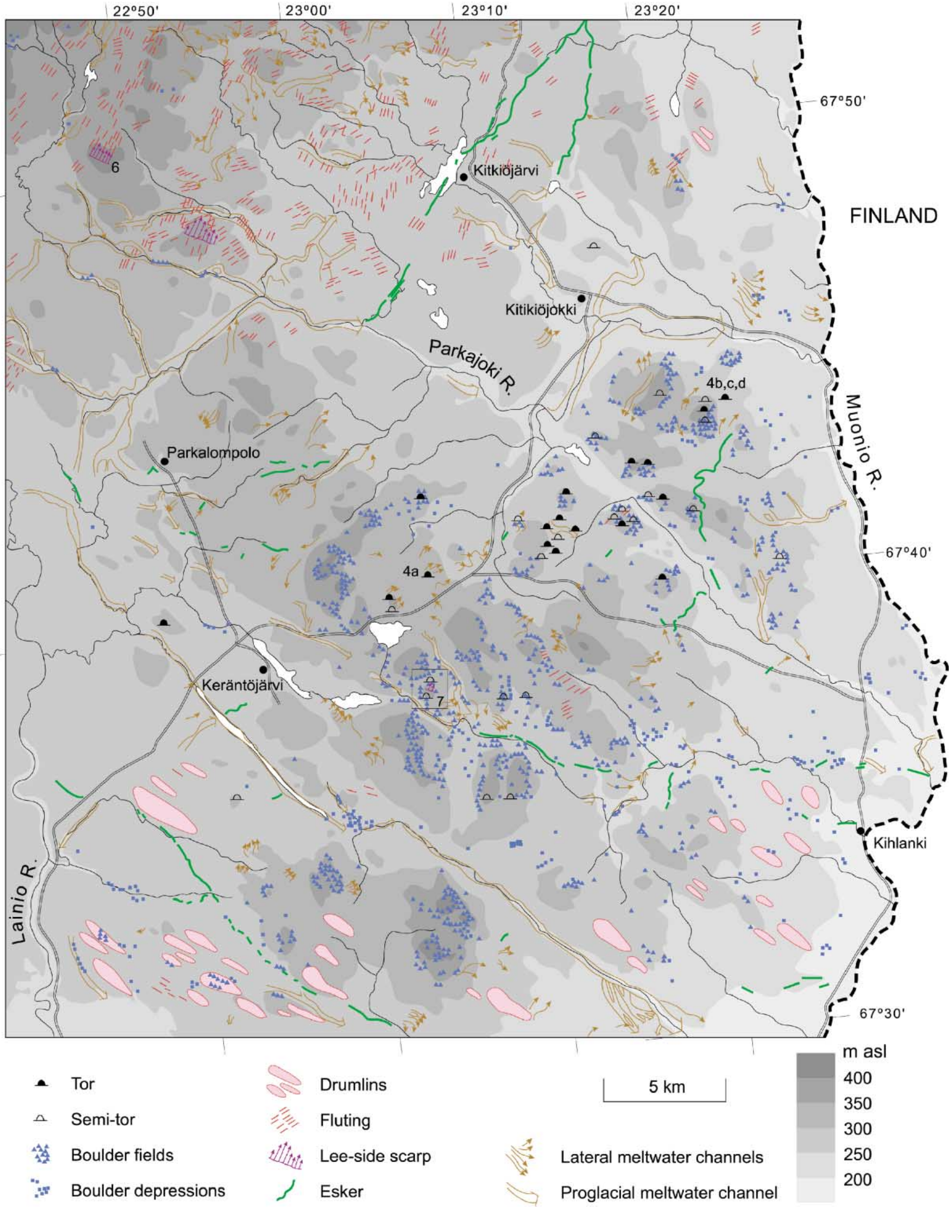

Fig. 2. Geomorphological map of the Parkajoki area. The numbered areas refer to the location of Figs. 4a–d, 6 and 7.

Fig. 3. The gently undulating landscape in central Parkajoki area, looking east. On the low hill in the central part of the photo is a tor, also shown in Fig. 4a. The higher hills, which extend above the tree-limit in the background, are located in Finland, east of the Parkajoki area.

2.2. Glacial geomorphology and glaciation history

The Parkajoki area was located near the former ice divide of large late Quaternary Fennoscandian ice sheets, for example during the LGM (Kleman et al., 1997). However, more restricted Quaternary glaciations, such as during the early Weichselian (70–110 ka) and during periods of the late Tertiary and the early Quaternary (> 700 ka), were centred over the elevation axis of the Scandinavian mountain range, c. 200 km west of the Parkajoki area (cf. Porter, 1989; Kleman and Stroeven, 1997). During many of these more restricted glaciations, the Parkajoki area was glaciated as well, but was situated closer to the ice margin.

Northern Fennoscandia holds an abundance of subglacial landform systems of varying age and direction, formed during different parts of the Weichselian glaciation (e.g., Kujansuu, 1967; Lagerbäck, 1988b; Lagerbäck and Robertsson, 1988; Johansson, 1995; Kleman et al., 1997, Hättestrand, 1998). Three major glacial landform systems can be identified in the region around Parkajoki (Fig. 1). The oldest landform system consists of drumlins, eskers, and hummocky moraine, formed by ice flow from the northwest during the early Weichselian (marine isotope stage 5d; Lagerbäck and Robertsson, 1988; Hättestrand, 1998). The early Weichselian drumlins and hummocky moraine are crosscut by swarms of drumlins and flutings, indicating an ice flow from the south and south–southeast (Fig. 1). This system, the Pajala fan of Kleman (1992), probably indicates LGM ice flow (Kleman et al., 1997) because it emanated from the most easterly ice spreading centre of the last glaciation. The youngest landform system occurs in a wide but laterally constrained zone from Gällivare towards the northeast (Hättestrand et al., 1999). This landform system, formed during the last deglaciation, consists of drumlins, eskers, and ribbed moraine. These three landform systems are spatially restricted and partly crosscut because most of the ice sheet in this region was frozen to its bed (Hättestrand et al., 1999; Kleman et al., 1999). Only during relatively short periods did the ice sheet bed appear to have thawed in patches to create subglacial landforms.

2.3. Surficial deposits

The Quaternary geology of the Parkajoki area was studied by Fagerlind (1981). Most of the area is covered by till. In general, the stratigraphy comprises several beds of decimetres to a few metres thick till, in places bracketing sorted sediments. Till fabric analyses reveal fairly weak fabrics and inconsistent directions for individual till beds. The clasts in the tills exhibit a wide range of provenance and indicate glacial transport from surrounding regions with different bedrock, although mainly from the northwest. The tills are sandy to gravely and show an obvious deficiency of fines (Fagerlind, 1981).

Tills were observed to cover saprolites wherever they were penetrated by loggings (Nordkalott Project, 1986a). Because the contact between the chemically weathered and fresh bedrock was never recorded, observed saprolite thicknesses (1–3-m thick) must be considered a minimum.

Large areas in the northern part of the Parkajoki area are covered by sandy sediments, deposited in extensive ice-dammed lakes during the last deglaciation (Kujansuu, 1967; Fagerlind, 1981). Bedrock outcrops are very rare in the area (Fagerlind, 1981).

3. Methods and terminology

The geomorphology was mapped by interpretation of aerial photographs and field-checked in September 1998, August 1999, and September 2000. The aerial photographs used were colour infrared photographs at the scale of 1:60,000 and panchromatic photographs at the scale of 1:150,000. Using two scales ensured that both small- and large-scale objects could be identified. Glacial landforms were easily identified in aerial photographs because their size is much larger than the geometric resolution of both image types (2.4 and 4.5 m, respectively). Hence, the quality of the glacial geomorphological mapping is regarded as good. Boulder fields and boulder depressions (see description below) can also be mapped with high accuracy in colour infrared photographs because they have a distinctly blue tone, are larger than the resolution limit, and carry a limited canopy cover.

Tors are generally larger than the resolution of the images. However, because they are usually situated in forested terrain, many cannot be identified in aerial photographs. Of the 39 tors or tor-like features found in the area, only nine were mapped from aerial photographs. The others were encountered during field work, during which most hills in the area were visited.

3.1. Glacial landforms

The flow-parallel glacial lineations mapped are *drumlins* and *flutings*. Drumlins constitute large-scale landforms, while flutings are defined here as striations superimposed on the land surface topography. Drumlins in this area have typical size values; length: 1–2 km, width: 300–400 m, height: 30–40 m. Both drumlins and flutings are interpreted as indicators of warm-based subglacial conditions.

Lee-side scarps (Kleman and Borgström, 1994; Clarhäll and Kleman, 1999) are transverse scarps, located mostly across or just down-ice of hill summits; where the till sheet is absent and bedrock is exposed on the lee-side of the scarp. Kleman and Borgström (1994) concluded that these scarps were diagnostic landforms for a subglacial temperature change from up-ice frozen to down-ice thawed conditions.

Eskers in the area are generally small, discontinuous and winding. A few eskers located in the northwestern sector of the mapped area are larger and signify typically wet-bed ice flow during deglaciation. However, the small eskers (mostly only a few metres high) can likely form under cold-based conditions (cf. Kleman et al., 1997), as crevasse or channel fills.

The *glacial meltwater channels* in the area are of two categories; lateral channels and proglacial channels. Lateral channels run obliquely to contour lines and normally occur in series on till covered hillslopes. They are relatively short (< 500 m) and shallow (< 10 m). Series of lateral channels are interpreted to be formed along the ice margin during deglaciation of cold-based ice sheets (cf. Dyke, 1993; Sollid and Sørbel, 1994). Strictly, series of lateral channels indicate only that the surface of the glacier was impermeable (cold). However, because series of lateral channels occur from the summits to the valley floors, it can be assumed that the ice mass was below the pressure melting point throughout. The proglacial channels are located in the lowest parts of the terrain and are often canyons. In this area, many are exceptionally large and well developed (Olvmo, 1989). Some channels exceed 20 km in length, are 30–40-m deep, and can be as much as 1-km wide. These channels may have formed both subglacially and proglacially. However, because some channels have outwash fans at their mouths, we support the latter interpretation and, hence, they neither indicate frozen nor thawed bed conditions.

3.2. Nonglacial landforms

The nonglacial landforms mapped in this area include tors, semi-tors, boulder fields, and boulder depressions. A *tor* is defined here as a bedrock outcrop exhibiting extensively weathered joints and which protrudes with vertical faces above its immediate surrounding (Fig. 4). The tors in the Parkajoki area are typically 4–20 m across, 1–7-m high, and occur in summit positions in gneiss or slightly gneissic granite bedrock. Grus covers the base of the tors, which, upon excavation, reveals that vertical cliff faces and extensively weathered joints extend at least 0.5 m below the ground surface. Transport of the weathered material away from the tors seems to be dominated by mass movement, as solifluction lobes and ploughing boulders are frequent on slopes surrounding the tors. *Semi-tors* are similar to the tors except that the outcrops do not fully protrude through the till, saprolite, or colluvium. Semi-tors occur typically on the slopes of hills, and show a down-slope 1–3-m vertical cliff-face with weathered joints, but up-slope are covered by regolith. For cartographic

Fig. 4. Tors of the Parkajoki area (cf. Fig. 2). (a) Tor about 5-m high and 25-m wide. (b) Semi-tor partly covered by solifluction-transported sediments. (c) Close-up of a well-developed tor in summit position. (d) Deeply weathered joints. Knife (c. 15-cm long) for scale.

reasons, restricted areas with several individual tors (or semi-tors) were represented by one tor symbol on the map (Fig. 2).

Boulder fields are surfaces where boulders completely cover the underlying material (Dahl, 1966; White, 1976; Kleman and Borgström, 1990; Rea et al., 1996). In the Parkajoki area, they range from 10 to 200 m across and are usually located around or on hill crests. The boulder fields comprise in situ frost-shattered bedrock (especially when in summit positions), talus slopes, and possibly aggregations of core stones, exhumed from a saprolite cover by slope, fluvial, and periglacial processes.

Boulder depressions are local topographic lows, where the surface is completely covered by boulders, and exhibits a characteristic flat appearance (Lundqvist, 1951; Kleman and Borgström, 1990; Hättestrand, 1994). They are formed by frost-sorting of diamict parent material, usually till, in positions near the ground-water table (e.g., Lundqvist and Hjelmqvist, 1937; Lundqvist, 1962). This process creates a top layer of boulders and results in a decreasing grain size with depth down to c. 1.5–2 m. Boulder depressions are fairly common features in Fennoscandia but most appear to be inactive today (e.g., Söderman, 1982). The size of the boulder depressions in the Parkajoki area generally ranges from 10 to 300 m across.

4. Distribution of landforms and landscape zonation

4.1. Glacial landforms

Glacial landforms occur throughout the area, although with a highly selective distribution. In general, subglacial landforms (drumlins, flutings, eskers) are confined to the southern and northern sector, whereas glacial meltwater channels dominate in the central section (Fig. 2). From the directional character-

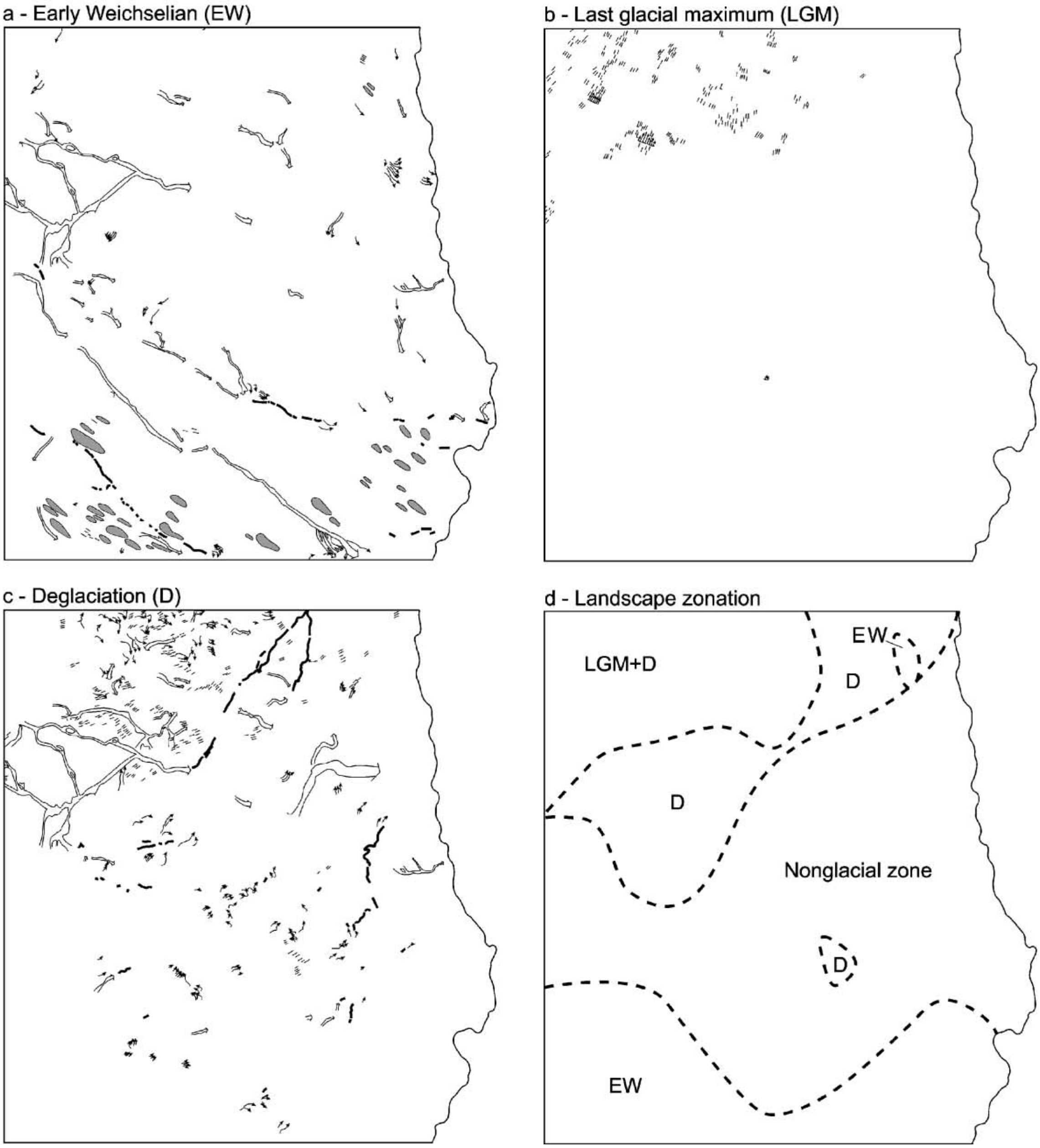

Fig. 5. Glacial landform systems in the area. The ages of the glacial landforms systems are based on the directions of, and cross-cutting relationships between, individual glacial landforms and their relation to known glacial ice flow systems shown in Fig. 1. For symbol legend, see Fig. 2. Based on the distribution of the subglacial landforms in (a)–(c), the area is divided into subareas (d), showing zones where basal melting and subglacial erosion was present during at least some period of time during the three stages indicated, and a central nonglacial zone. Note that this nonglacial zone is delineated by the absence of subglacial landforms and not by the distribution of nonglacial landforms.

istics of the glacial landforms, three glacial landform systems, formed during different events, can readily be distinguished, and there is a clear tendency towards specific landform assemblages for each ice flow event (Fig. 5a–c).

Flutings are widespread in the northern sector of the area. These flutings can be separated into two systems, indicating ice flow from SSW and WSW, respectively. Wherever these two systems crosscut (at a $\sim 45°$ angle), the SSW system is the oldest. There are also meltwater landforms indicating ice flow from the SW sector; such as eskers, numerous series of lateral meltwater channels and some large pro-glacial channels.

A third system, formed by ice flow from the NW, consists of large (1–3-km long) drumlins, often with a clear crag-and-tail shape indicating ice flow direction, and a few slightly fragmented eskers. These subglacial landforms are widespread in the southern part of the area. In addition, glacial meltwater channels indicating ice flow from the NW sector occur throughout the area. These channels consist of both lateral channel series and large pro-glacial channels.

All three landform systems in the Parkajoki area are well documented in neighbouring areas of northern Fennoscandia, where their absolute age is relatively well established (cf. Fig. 1 and Section 2.2). Hence, we can use existing chronologies to put tentative ages to the ice flow events creating these glacial landform systems.

The NW-system (Figs. 1 and 5a) is an integral part of the extensive early Weichselian NW-landscape covering large parts of northern Sweden. This NW-ice flow event formed the large drumlins and eskers in the southern sector of the area under warm-based conditions. The central and northern sectors of the area appear to have been deglaciated under cold-based conditions during this event because there are compatible NW-oriented lateral and proglacial meltwater channels. The intermediate ice flow event creating the *SSW-system* (Figs. 1 and 5b) is of inferred LGM age and is solely represented by small-scale flutings and lee-side scarps.

The youngest flow event, creating *the WSW-system*, is aligned with the late Weichselian deglaciation (Figs. 1 and 5c) and is represented particularly by small-scale flutings, but also by lateral and proglacial channels, and a prominent SW–NE oriented esker system. The central part of the area also displays a few small and winding eskers of inferred last deglaciation age.

The proglacial meltwater channels may have been used more than once. This is because once formed, they constitute natural lows in the terrain, where proglacial meltwater of each deglaciation added to channel incision and widening. Some channels are

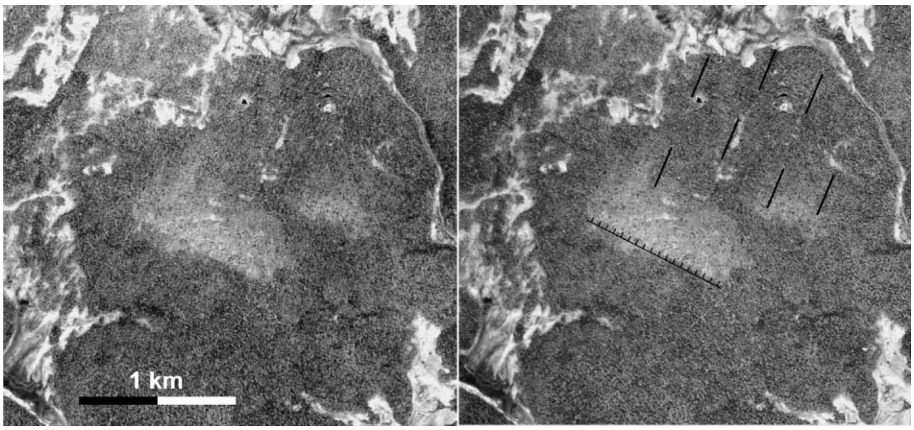

Fig. 6. Stereogram of a lee-side scarp on Mt. Palo-Marjavaara (432 m.a.s.l), formed during the LGM-ice flow event. Ice flow was from SSW and the scarp (saw-toothed line) is oriented transverse to that ice flow, right across the hill summit. The two light-grey areas in the centre of the photo are exposed bedrock, other parts are forest-covered till (dark) or peat bogs (greyish-white). Note also the small-scale fluting down-ice of the scarp (thin black lines). North to the top. For location, see Fig. 2.

therefore assigned to both the early and late Weichselian deglaciations.

From the distribution of subglacial landforms indicative of warm-based conditions (drumlins, flutings, and large eskers, in Fig. 5a–c), it was possible to divide the Parkajoki area in zones that are dominated by one particular ice flow event or by no ice flow event at all (Fig. 5d).

Three lee-side scarps were found in the Parkajoki area (Fig. 2). They seem to be associated with the SSW–NNE-trending LGM-ice flow because they are oriented transverse (WNW–ESE) to this ice flow direction. The two scarps in the north are largest, about 1 km in length (Fig. 6), while the third, at Manalainen hill, is considerably smaller (Fig. 7). At Manalainen, semi-tors are located both on the up-ice (stoss-) and the down-ice (lee-)side of the hill summit (Fig. 7a). Bedrock is widely exposed on the lee-side of the scarp in-between the tors. Angular and rectilinear boulders are scattered over the exposed bedrock surface of the summit area and occur predominantly in association with (and just down-ice of) small steps in the horizontal unloading joints of the bedrock (Fig. 7b). The semi-tors are characterised by degraded bedrock knobs with extensively weathered joints and are surrounded by rounded or spherical boulders (Fig. 7c).

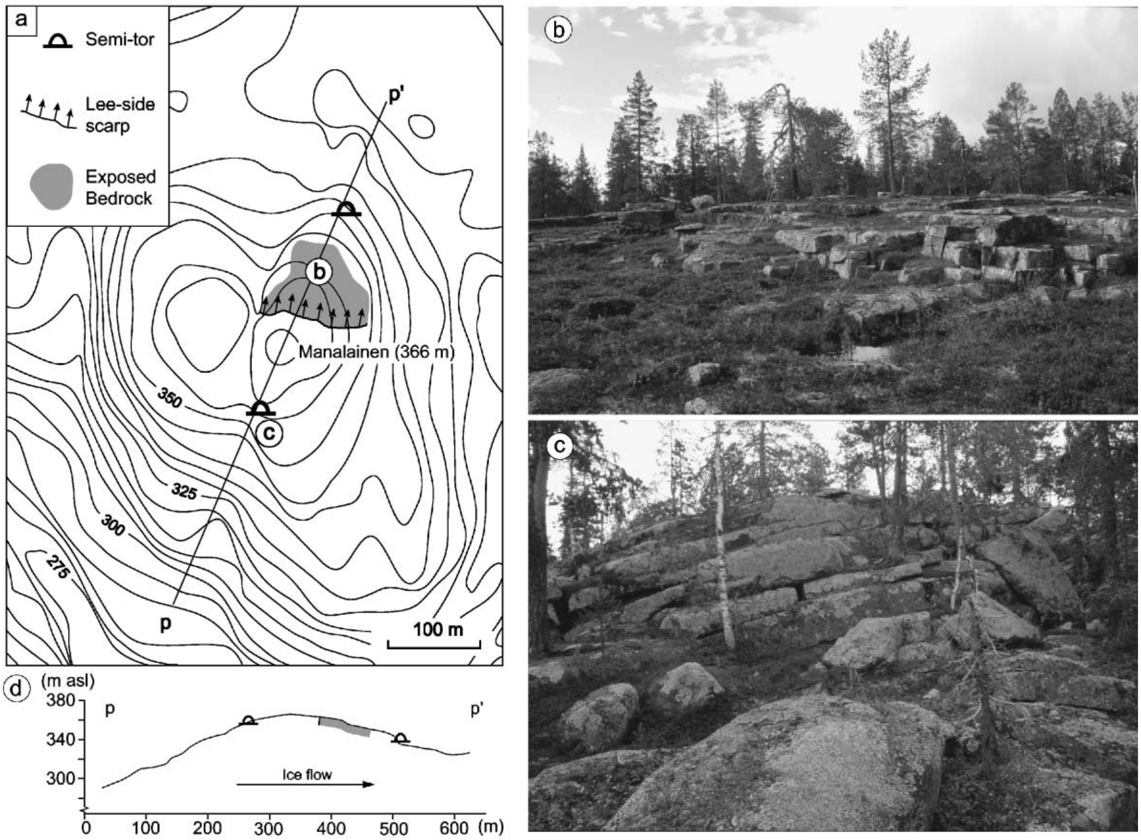

Fig. 7. (a) Geomorphology of the hill Manalainen. (b) Photograph of the exposed bedrock in the front and the lee-side scarp denoted by the forest limit in the background. Note the angular boulders. Photograph taken from "b" towards the south. (c) Photograph of a semi-tor with deeply weathered joints and rounded boulders to the south of the lee-side scarp. Photograph taken from "c" towards the north. (d) Profile across Manalainen, roughly parallel with the LGM ice flow direction. Note that the glacially eroded exposed bedrock area (shaded) is located near the hill summit while the semi-tors are located on the flanks of the hill.

4.2. Nonglacial landforms

Nonglacial landforms predominantly occur in the zone that lacks signs of wet-bed ice flow in the central Parkajoki area (Fig. 5d) although the different types of landforms have slightly differing distributions (Fig. 8, Table 1). In total, 17 tors and 22 semi-tors were mapped, which is the largest concentration of tors in

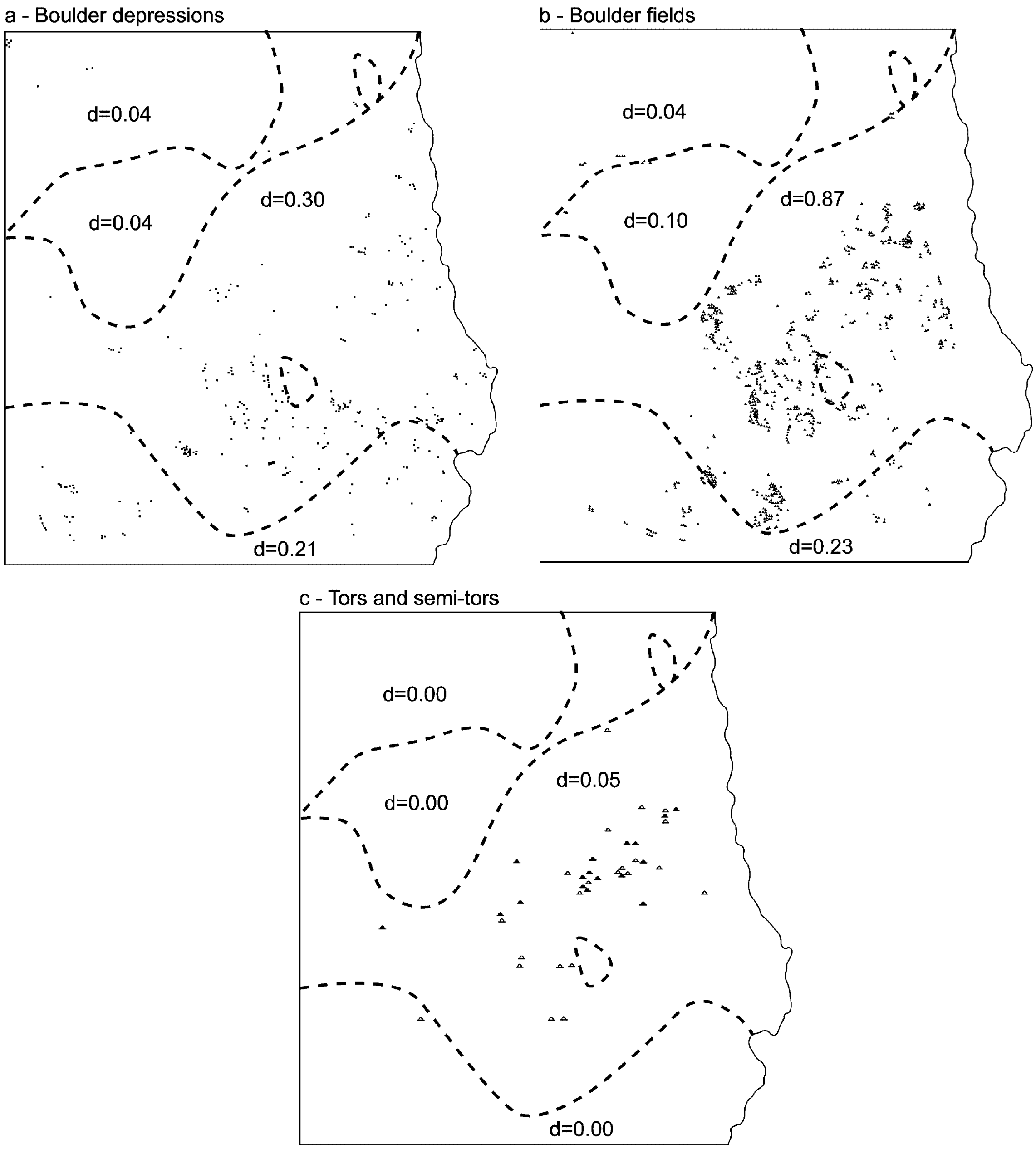

Fig. 8. Distribution of weathering-and periglacial landforms with respect to the subglacial zones outlined in Fig. 5d, where d is the surface density ($d = n/A$) of a particular landform in each zone (Table 1).

Table 1
Number (n), percentage, and surface density (d) of nonglacial landforms in given landscape zones (Figs. 5d and 8)

Zone[a]	Area (A)		Tors			Boulder fields			Boulder depressions		
	km^2	Percentage	n	Percentage	d (n/A)	n	Percentage	d (n/A)	n	Percentage	d (n/A)
LGM + D	203	14	0	0	0.00	8	1	0.04	8	3	0.04
D	203	14	0	0	0.00	21	3	0.10	9	3	0.04
NG	769	53	38	97	0.05	669	88	0.87	231	75	0.30
EW	275	19	1	3	0.00	62	8	0.23	58	19	0.21
Total area	1450	–	39	–	0.03	760	–	0.52	306	–	0.21

[a] LGM—Last Glacial Maximum; D—Deglaciation; NG—Nonglacial; EW—Early Weichselian.

Sweden. The tors are found exclusively within the nonglacial zone, except for the southwesternmost tor, which is situated on the border to the early Weichselian zone. Boulder fields are most common in the nonglacial zone but occur (less frequently) also in the early Weichselian zone. Only a few boulder fields are located in the deglaciation zone, which are talus deposits below bedrock walls of proglacial canyons formed during the last deglaciation. Boulder depressions occur equally frequently in the nonglacial zone and the early Weichselian zone. Again, a few boulder depressions occur in the deglaciation zone.

The selective distribution of the nonglacial landforms (Fig. 8, Table 1) allows some constraints to be advanced regarding their age of formation. This is because variables other than time since subglacial erosion, such as bedrock geology, topography, and elevation, vary insignificantly over the Parkajoki area. Hence, time since glacial erosion is the only variable that can account for the observed selective spatial distribution.

Tors are located almost exclusively in the nonglacial zone. The implication is that the tors predate the oldest recorded ice flow in the area because they are not resistant to glacial erosion. That is, they must be older than the early Weichselian.

The predominant occurrence of boulder fields in the nonglacial zone, and to some extent in the early Weichselian zone (Table 1), indicate that most have an early or pre-Weichselian age. A few boulder fields occur in the deglaciation zone and, hence, must have formed since the last deglaciation. However, these are exclusively talus forms. In contrast, the boulder fields in the early Weichselian zone contain also those derived from frost-shattered bedrock, and those in the nonglacial zone in addition include those exhumed from saprolites. The boulder fields of these latter origins seem to have required longer time for formation and/or demanded a more severe climate than occurred during the Holocene.

The equal density of boulder depressions in both the nonglacial and the early Weichselian zones (Table 1) indicates that the Weichselian interstadials had a climate that was favourable enough, and was of sufficient duration, to account for all the boulder depressions. However, the boulder depressions within the nonglacial zone may have been in existence already at the onset of the Weichselian glaciation. It also seems that the formation of boulder depressions is a "finite" process. That is, once a number of boulder depressions have formed in an area, longer time of favourable formative conditions does not produce more boulder depressions. If so, one would expect more boulder depressions in the nonglacial zone compared with the early Weichselian zone. The implication is that the formation of boulder depressions halted because of other restrictions, such as lack of favourable locations (all depressions already filled-up), or exhaustion of boulders in the parent material. The "finite" formation of boulder depressions contrasts to the formation of boulder fields, which appears to be a much longer process where time is the constraining factor.

5. Discussion

The presence of tors in formerly glaciated terrain is not unique for this particular area. There are many examples of well-developed tors in formerly glaciated areas, such as in Fennoscandia (Kaitanen, 1969), on the British Isles (Sugden, 1970; Ballantyne, 1994), in Canada (Sugden and Watts, 1977), and in Greenland (Sugden, 1974). However, in contrast to the Parkajoki area, these other tor areas are located in high-relief terrain. In mountainous regions, a polythermal ice sheet has a tendency to establish cold-based zones over high ground, thus preserving high-elevation landscapes, and warm-based erosional zones in topographical lows, where the ice is thickest (e.g., Sugden, 1974; Glasser, 1995; Stroeven and Kleman, 1999, Näslund et al., 2000). This subglacial thermal zonation is stable, almost regardless of ice sheet size and configuration (Kleman and Stroeven, 1997) because the ice sheet is thickest and flows fastest through valleys, optimising the conditions for pressure melting of ice.

However, because the Parkajoki area is situated in lowland terrain, other reasons for landscape preservation must be sought. Very low ice flow velocities underneath ice divide positions could favour landform preservation, even under warm-based ice sheets. However, for the Parkajoki area, this explanation does not hold because over the course of a single glacial cycle, this region will have experienced a range of ice flow conditions; from ice marginal conditions during ice sheet advance and retreat to ice divide conditions at the time of maximum glaciation. Hence, it appears that sustained frozen-bed conditions after initial formation of the tors is the only reasonable explanation for their preservation.

The basal temperature of ice sheets is a function of several parameters, of which the most important are ice thickness (basal topography), ice surface temperature and accumulation rate, geothermal heat flux, and strain heat release from ice deformation (e.g., Sugden, 1974; Robin, 1977). Of these, only strain heat and basal topography have the ability to vary significantly within a limited area such as within the Parkajoki area or between this area and its nearest surroundings. For example, in high-relief areas with tors, these two parameters combine to yield cold-based conditions and, hence, preservation at high elevations in the landscape. However, in the Parkajoki area, basal topography is probably not the key condition controlling the distribution of cold-based zones. For example, the Parkajoki area is lower in elevation than the neighbouring area to the northwest. Yet, only the latter (higher) area was reshaped by warm-based ice flow during the last deglaciation (Fig. 1). Also within the Parkajoki area, one can argue that the outline of the preserved nonglacial zone has no consistent relation to topography (Fig. 2). This is because the nonglacial zone is higher in elevation than the southern early Weichselian zone but lower in elevation than the northwestern deglaciation and LGM zones (Figs. 2 and 5d).

The lee-side scarp erosion at Manalainen (Fig. 7) illustrates that the distribution of thermal zones at the ice sheet bed was more complicated than the conventional view of cold-based summits and warm-based depressions (e.g., Hughes, 1981) also on a local scale. The preservation of semi-tors at lower elevation (Fig. 7d) indicates that pressure melting and refreezing occurred only at the summit but not lower down. These reversed conditions remain to be explained properly but we expect that strain heating around the summit was decisively important. In general, the subglacial temperature regime across the area was such that the ice sheet was frozen to the substrate. However, during the LGM, and possibly during earlier glaciations with a similar configuration, the subglacial temperature regime across the Parkajoki area was probably close to the pressure melting point. This is a reasonable assumption because warm-based LGM ice flow affected the Parkajoki area in its northwestern sector (Fig. 5b), and because the LGM Pajala fan wet-bed flow traces nudge the area to the southeast (Fig. 1). If true, local pressure melting could occur given an additional source of heat. Because, as argued above, basal topography was insufficient to establish the conventional subglacial temperature distribution, only strain heat release from ice deformation could have been this source. This effect increases with the volume of the object it flows across and increases in the down-ice flow direction across the stoss-side towards the crest, and the effect is predictably the largest right at the summit. We argue that at Manalainen, it was only at the summit that the added heat was able to raise the subglacial temperature to the pressure melting point and generate meltwater. However, a very short distance down-ice from the summit, the pressure dropped, resulting in refreezing of water and plucking of regolith and slightly weathered-bedrock with closely spaced joints. Hence, the upper jointed part of the relatively fresh bedrock and angular boulders became exposed (Fig. 7b).

In analogy with the example from Manalainen, and given that local and regional basal topographies are not clearly related to the distribution of cold-based areas, we infer that variations in strain heat release from ice deformation are decisively important. Hence, it appears that the preservation of the nonglacial landscape in the Parkajoki area was due to regionally low values of strain heating. Kleman et al. (1999) suggested that the key explanation for the distribution of large cold-based areas in this part of northeastern Sweden during the last deglaciation was the location of areas with divergent ice flow. In surrounding areas, where warm-based conditions prevailed, ice flow was parallel or slightly convergent. Divergent ice flow results in decelerating ice flow velocities and, hence, decreasing values of strain heat release at the ice sheet base. We concur with Kleman et al. (1999) concerning the importance of divergent ice flow in maintaining subglacial freezing conditions, and infer that this also holds true for the preservation of the nonglacial landforms in the Parkajoki area during the last deglaciation. In addition, small-scale variations in strain heat release were probably responsible for small-scale differences in thermal conditions (e.g., Manalainen).

In contrast to the divergent deglaciation ice flow in this region, strictly parallel ice flow prevailed during the early Weichselian (Fig. 1). Hence, explanations other than "low strain heat due to divergence" must be sought for the location of cold-based conditions in the Parkajoki area during this ice flow event. We attribute this pattern of cold-based and warm-based regions to the amount of relief obstructing basal ice flow. To the southeast, south, and southwest of the Parkajoki area, early Weichselian ice flow was across a plain with residual hills. Here, basal ice flow encountered less topographical roughness, which promoted faster ice flow and warm-based conditions. Once sliding occurred on either side of the study area, a slightly divergent ice flow towards these areas of faster flow would have kept the Parkajoki area frozen to its substrate.

The following questions need to be addressed when exploring the potential age of this landscape with tors and boulder fields and, hence, how long this landscape escaped glacial erosion due to frozen-bed conditions of overriding ice sheets prior to the Weichselian:

1. How was the nonglacial landscape formed (particularly the tors)?
2. When did the erosion/exhumation of the saprolite from the tors occur?
3. How long did it take to produce these tors?

The presence of saprolite beneath till (Nordkalott Project, 1986a) and in situ weathered materials surrounding the subsurface root of the tors, indicate that the tors in this area were developed by chemical deep-weathering of the bedrock, followed by stripping and exhumation of the weathering front (Thomas, 1994). We dismiss subaerial weathering formation processes by frost-shattering or grain-by-grain disintegration of the bedrock (Palmer and Neilson, 1962). This is because such processes would produce angular debris around the tors. In contrast, rounded boulders occur ubiquitously and tor outcrops themselves are rounded rather than angular. In addition, the tors exhibit weathered joints that occur below the ground surface. These could not have formed by subaerial weathering processes.

An assessment of the minimum age of the tors is gained from a comparison of the tor-height (hence, weathering depth) with known rates of bedrock weathering. Considering the $\sim$ 10 m relief of the tors in the Parkajoki area, we estimate that a comparable amount of weathering and subsequent saprolite removal would be required. Estimated deep-weathering rates in tropical and subtropical environments range between 2 and 48 m/10^6 years (see Thomas, 1994). Bedrock weathering rates for northern Fennoscandia during the late Tertiary and the Quaternary were likely in the lower part of that range. A hypothetical rate of 10 m/10^6 years would thus yield a minimum time of 10^6 years for the formation of the weathering features in the Parkajoki area. Even an unrealistically high rate of 48 m/10^6 years yields a minimum of 200,000 years of weathering. Because chemical deep-weathering could occur only during ice-free conditions in interglacials and interstadials, the time periods with ice cover must be added to get an age of the initiation of the tor formation. An estimate of the time of ice cover in northern Sweden based on marine oxygen isotope data was given by Kleman and Stroeven (1997). Following this, we estimate that the Parkajoki area was covered by ice during 60–80% of the last 700,000 years and during 40–50% of the time before 700 ka in the early Quaternary. The strength of these figures (however crude) is to convey the message that the formation of the tors in the Parkajoki area took, at the very least, all of the Quaternary.

If the Holocene climate can be regarded representative for other Quaternary ice-free periods, then Holocene weathering rates can help in evaluating the total Quaternary weathering that has occurred. Observations by the authors of thousands of striated outcrops in Sweden yield that Holocene surface weathering rates on exposed granite outcrops generally amounts to less than 20 mm (equivalent to 2 m/ 10^6 years). Striated outcrops recently exposed in gravel pits and road sections have rarely (if ever) weathering imprints. The implication is that Quaternary deep-weathering was insignificant. More probably, the deep-weathering dates to the late Tertiary, as suggested by Lidmar-Bergström et al. (1997). In summary, we argue that the chemical deep-weathering of the bedrock is preglacial and, hence, that the erosional effect of Quaternary glaciations was negligible due to cold-bed conditions.

The conclusion of persistent cold-based conditions in the Parkajoki area throughout the Quaternary appears at odds with the presence of tills in the area. However, a till sheet in general is not by necessity evidence of former warm-based conditions. The tills in the Parkajoki area may be of a melt-out origin; for example as a supraglacial ablation till. This interpretation is supported by the deficiency of fines, the weak and inconsistent fabrics, and the lack of subglacially formed landforms in the till. If true, the presence of till is compatible with the observation of preserved tors in the area and, hence, is consistent with cold-based deglaciations across this region.

The most likely explanation for persistent cold-based conditions during the entire history of late Cenozoic glaciation is that consecutive ice sheets must have had essentially similar evolution patterns (Fig. 9). These would be comparable to the patterns that occurred during the last glaciation: (i) mountain-centred ice sheets (e.g., early Weichselian) with persistent and pervasive flow from the northwest. We infer that the Parkajoki area remained cold-based during these configurations because it displayed a rougher terrain, retarding ice flow relative to surrounding areas in the southern sector, which drained ice more effectively; (ii) continental ice sheets (e.g.,

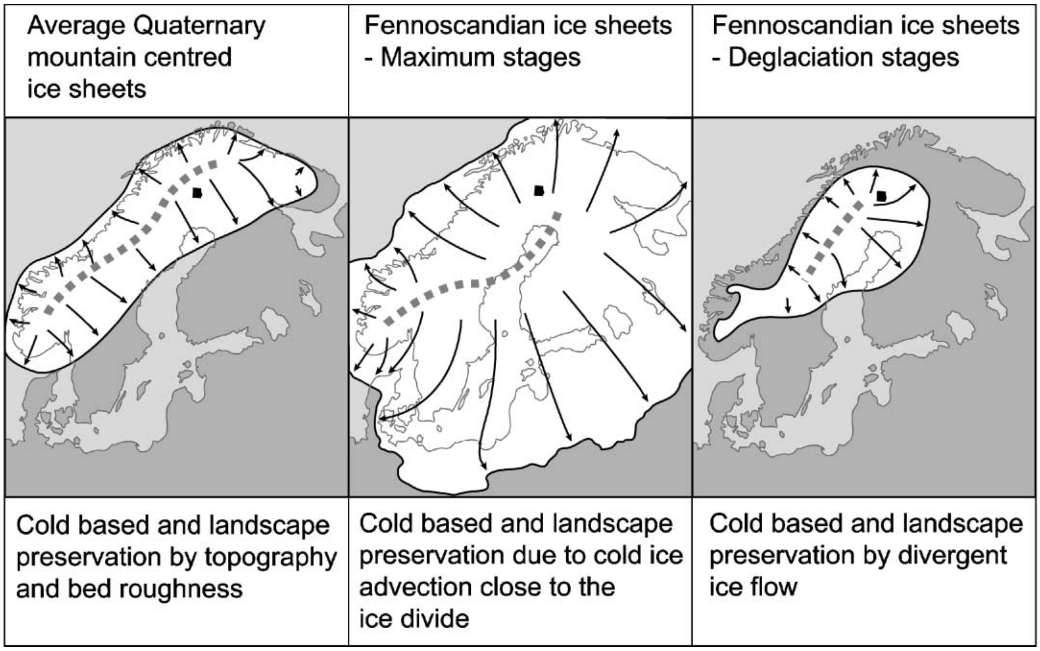

Fig. 9. Palaeoglaciological parameters controlling landscape preservation in the Parkajoki area (black box) during different glaciation modes. Ice sheet configurations with inferred ice divide positions (broken grey line) and ice flow lines from Kleman et al. (1997).

LGM) with generally cold-based conditions, because of initial permafrost and cold ice advection in near-ice divide positions; and (iii) ice sheet retreat (e.g., last deglaciation) with cold-based conditions due to divergent ice flow towards the convex margin.

6. Conclusions

The Parkajoki area displays a nonglacial morphology, including tors and extensive boulder fields, that appears to have escaped glacial erosion throughout, at least, the Quaternary. We argue that all overriding ice sheets were nonerosive due to cold-based subglacial conditions over this area. For the last glacial cycle, these conditions can be related to specific ice sheet configurations, with respect to margin outline and ice divide position, and we suggest that most Plio–Pleistocene ice sheets had similar evolution patterns and, therefore, similar basal thermal conditions. We also show that for restricted regions, it is possible to delineate the distribution of cold- and warm-based zones for pre-LGM polythermal ice sheets.

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