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Cirque infills in the Khibiny Mountains, Kola Peninsula, Russia — palaeoglaciological interpretations and modern analogues in East Antarctica

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ABSTRACT: We report here on cirque infills mapped in the Khibiny Mountains, Kola Peninsula, Russia. Cirque infills are morainic deposits located near the headwalls of valleys and cirques. Their location and shape, often with concave margins towards the valley side, indicate that they were deposited by ice flowing up-valley, into the mountains, rather than by local glaciers. We suggest that they formed during the last deglaciation, when Khibiny was a nunatak and Fennoscandian ice sheet lobes extended into valleys and cirques of the massif. The formation of cirque infills is probably more related to ice sheet dynamic factors, occurring when the ice margin retreated from the cirques, than to climate-driven interruption in the ice-marginal retreat. Glacial conditions similar to those prevalent when the Khibiny cirque infills were formed, occur today in Antarctica where the ice sheets engulf nunatak ranges. In Heimefrontfjella, Antarctica, the formation of supraglacial moraines at the head of cirques are linked to blue-ice conditions, indicating locally low accumulation rates, a dry continental climate and sublimation dominated ablation. We suggest that these Antarctic moraines are modern analogues of cirque infills on the Kola Peninsula, and possibly, that the cirque infills may be used as palaeoenvironmental indicators. Copyright © 2007 John Wiley & Sons, Ltd.

KEYWORDS: cirque infills; moraines; blue ice; glacial geomorphology; Kola Peninsula.

Introduction

Glacial landforms in mountainous terrain are valuable palaeoglaciological tools that have been used for reconstructions of glaciation history since the formulation of glaciation theory (e.g. Flint, 1947; Karlén, 1973; Porter, 1975; Ehlers and Gibbard, 2004). Such reconstructions are often straightforward; features found furthest away from the high elevation areas can be attributed to larger scale glaciation than features found closer to valley heads. However, in mountain areas that have been inundated by continental ice sheets, interpretation can be more complex, since individual landforms can either originate from mountain glaciation (occurring before or after last ice sheet coverage) or derive from continental scale ice sheet activity (Borgström, 1979; Chinn, 1994). Correct interpretations of their origin can often be made based on the location, morphology and structural composition of the features (e.g. Benn and Evans, 1998). However, in some cases interpretation is ambiguous. For example, end moraines which are located across valley floors can easily be misinterpreted. Heyman and Hättestrand (2006), in a comprehensive review of over 400 Swedish end moraines along the Scandinavian mountain range, argue that up to 40 end moraines, that had earlier been interpreted as formed by local glaciation, in fact originated from continental glaciation and ice sheet tongues flowing up-valley. Similar conditions are also found in many Antarctic locations, for example in the Dry Valleys region, where ice lobes have entered the valleys from the East Antarctic ice sheet, former Ross Sea ice expansion and surrounding smaller local glaciers (e.g. Hall *et al.*, 2000).

The Khibiny and Lovozero mountains in the central Kola Peninsula, northwest Russia (Fig. 1), are extraordinarily rich in ice-marginal glacial landforms (Armand, 1960; Korsakova and Kolka, 2005). Many of these landforms are interpreted to originate from ice-marginal erosion and deposition by the Fennoscandian ice sheet, while others appear to testify to mountain glaciation (Fig. 2; Armand, 1960). During recent detailed mapping of the glacial geomorphological record in these mountains (Korsakova and Kolka, 2005; Hättestrand and Clark, 2006a), we encountered a particular type of moraine formation, termed 'cirque infills', which are well-defined hummocky morainic deposits located on cirque floors. In this study, we describe the morphological characteristics and

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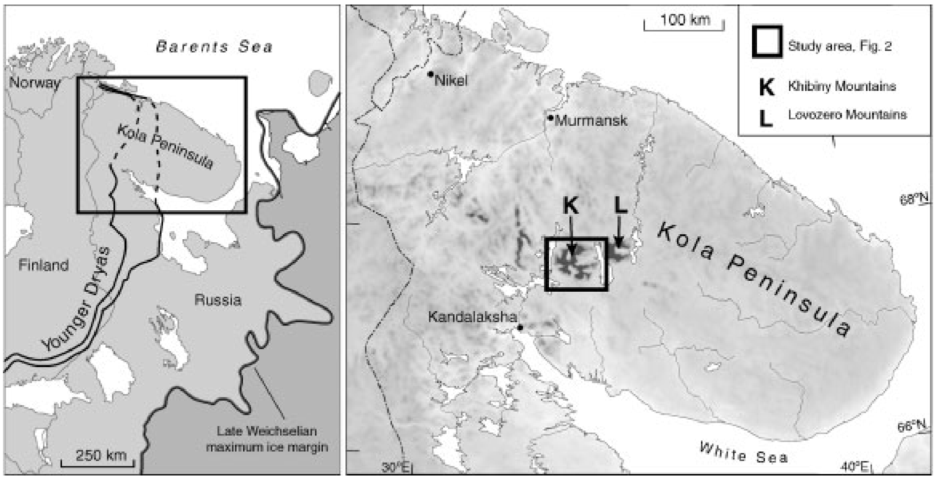

Figure 1 Location map. Late Weichselian maximum ice margin from Demidov *et al*. (2006) and YD ice margin from Svendsen *et al*. (2004)

distribution pattern for these deposits, and discuss formative conditions. Moreover, we make a comparison with similar features in a present-day glaciated region in East Antarctica, where the innermost parts of cirques are covered by large expanses of supraglacial moraines, and discuss the possible palaeoclimatic significance of the Khibiny cirque infills.

Physical and palaeoglaciological setting

The Khibiny Mountains are located in the Kola Peninsula, northwest Russia (Fig. 1), and cover an area of approximately 45×40 km. The entire mountain block is composed of a large alkaline plutonic intrusion (the largest in the world), which is concentrically zoned and consists mostly of nefeline-syenite and ultrabasic alkaline rocks (Arzamastsev *et al*., 2000). The massif rises above the surrounding undulating hilly terrain (at 100–300 m a.s.l.) and its morphology is characterised by a flat summit surface at 1000–1200 m a.s.l. The Khibiny Mountains are deeply dissected by glacial and fluvial valleys, leaving only small relict remnants of the summit surface in the highest parts, which are characterised by well-developed *in situ* weathering features, such as blockfields and tors. The highest summit is Yodichvumchorr, reaching 1200 m a.s.l., which is also the highest point on the Kola Peninsula.

Most of the valleys in the peripheral parts of the Khibiny Mountains display only fluvial characteristics, while valleys within the massif commonly are U shaped and have glacial cirques at their heads. The floors of the cirques are situated between 400 and 700 m a.s.l. and ~500 m high headwalls rise as near vertical cliffs above the cirques. The cirques and

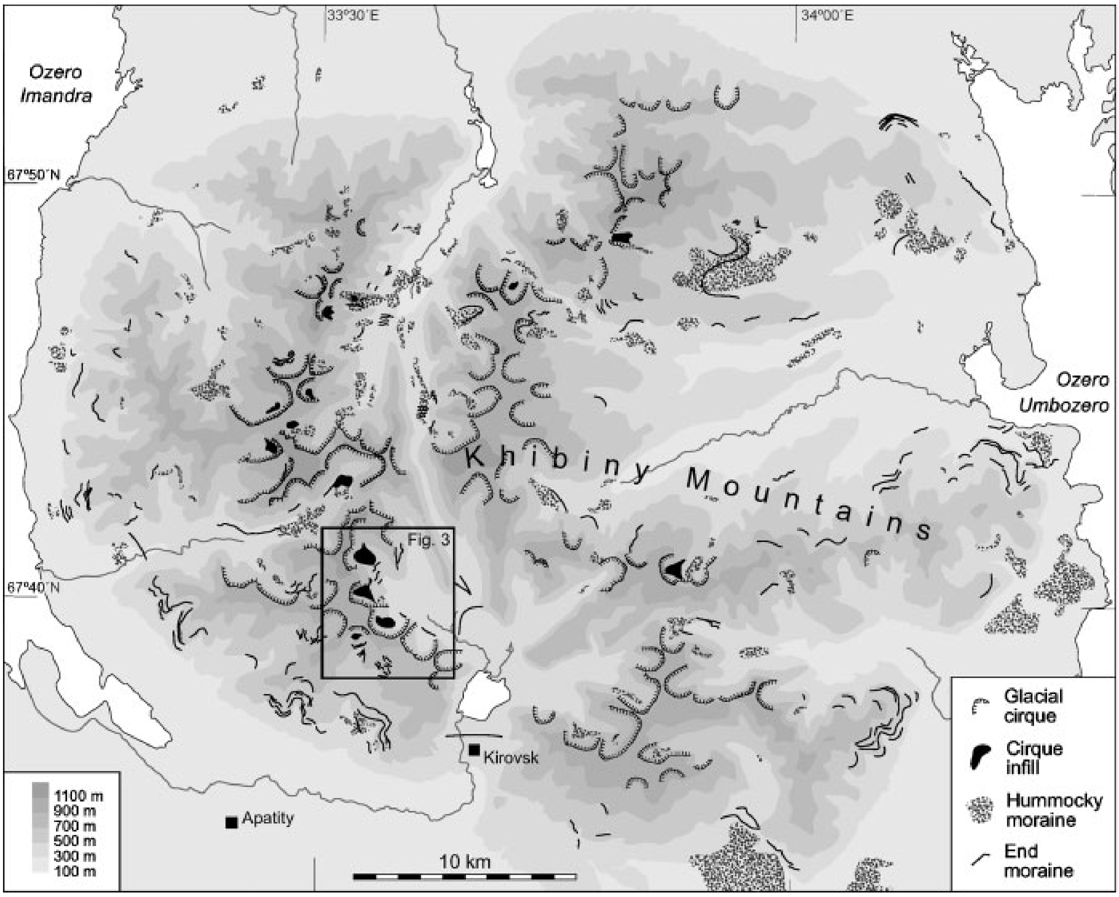

Figure 2 Cirques and morainic landforms in the Khibiny Mountains

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U-shaped valleys face radially out from the high summit areas of the Khibiny Mountains, indicating a local origin by cirque and valley glaciers or small ice caps with outlet glaciers. Glaciers do not exist in the area today, and signs of previous Holocene glaciation are lacking. If the Holocene is considered as normal climatic conditions for interglacials, the conclusion would be that the cirques were formed during periods colder than today, but still not cold and precipitation-rich enough for Fennoscandian ice sheet growth and overriding (which would probably prohibit cirque formation). Hence, these cirques and valleys are likely to be the accumulated effect of local glacier activity during interstadials and glacial inception/deglaciation stages throughout the Quaternary.

On a more detailed level, Khibiny holds extensive suites of ice-marginal features, such as end and lateral moraines, meltwater channels, ice-contact deltas and ice-dammed lake features, found on both surrounding slopes and valley sides inside the mountains (Figs 2 and 3; Korsakova and Kolka, 2005).

General ice flow direction during the last deglaciation was from the west-northwest (Hättestrand and Clark, 2006b). This is reflected by ice-marginal moraines and lateral meltwater channels that show an average slope towards the east-southeast (Korsakova and Kolka, 2005). North of Khibiny (and the neighbouring Lovozero mountains to the east), a series of moraines extend northwards (Niemelä *et al.*, 1993; Hättestrand and Clark, 2006a). These moraines have been suggested to be of Younger Dryas (YD) age (Yevzerov and Kolka, 1993; Fig. 1a), and by association, many of the lateral and frontal moraines in Khibiny may also be related to glacial stillstands or readvances during this time.

East of, and above, the inferred YD position there are extensive series of lateral meltwater channels, particularly in the eastern Lovozero Mountains (Hättestrand and Clark, 2006a). This indicates that in pre-YD time, when the highest summits began to protrude through the ice surface as nunataks, meltwater was routed across the ice sheet surface rather than penetrating down into the ice mass. Hence, it appears that these mountains were deglaciated under cold-based conditions in pre-YD time (Hättestrand and Clark, 2006b). As deglaciation progressed and the ice surface lowered, more of the mountains became exposed and basal conditions changed to predominantly warm based. This is indicated by the presence of numerous ice-marginal moraines on the intermediate and lower slopes (300–600 m a.s.l.) of the Khibiny (Fig. 2) and Lovozero mountains.

Methods

We mapped the glacial geomorphology of the Khibiny and Lovozero mountains using both remote sensing techniques and field controls. Our primary data source involved aerial

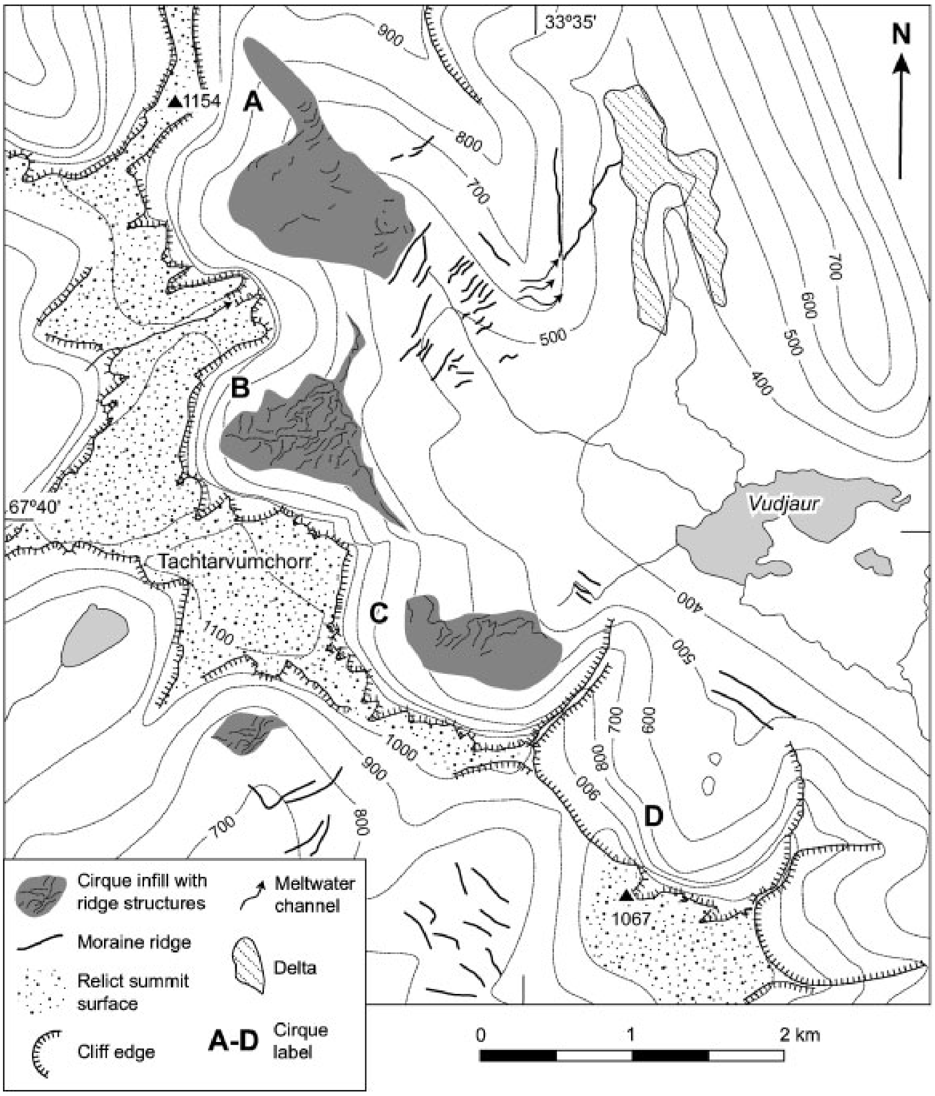

Figure 3 Detailed map of the glacial geomorphology of the Tachtarvumchorr area in southwestern Khibiny. For location, see Fig. 2. Cirques labelled A–D are used for reference in Figs 5 and 6

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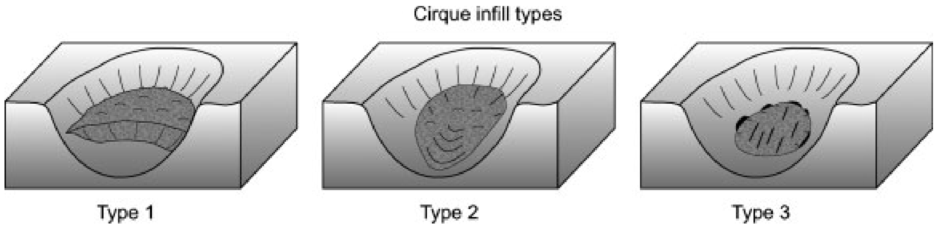

Figure 4 Schematic illustration of the three types of cirque infills found in the Khibiny Mountains. Type 1 cirque infills have a flat upper surface and a steep valley slope. Type 2 cirque infills follow the cirque floor slope out towards the main valley and occasionally have deformation structures. Type 3 cirque infills are slightly convex and often impound small lakes along its fringe

photographs at a scale of 1:40 000 (1.3 m resolution), that were interpreted in stereo using a Zeiss Jena Interpretoscope, with 2–16 x magnification, combined with Landsat 7 ETM satellite images (15 m resolution), that were also used for mapping the surrounding lowland areas (Hättestrand and Clark, 2006a). The aerial photograph and satellite image-based mapping was field-checked and complemented with field-based mapping during 2001, 2002 and 2004. Fieldwork was concentrated in the Tachtarvumchorr area in central Khibiny (Fig. 3).

The complete glacial geomorphological map, which comprises all landforms pertaining to glacial activity in both the Khibiny and Lovozero mountains, will be presented elsewhere.

Results

Distribution

The Khibiny Mountains have 78 well-developed cirques, which have near vertical backwalls and sharp upper rims. Of these, 14 hold cirque infills, 23 have linear moraine ridges crossing the cirque floor or mouth and 34 contain irregular hummocky moraine deposits. There are 31 cirques that lack morainic landforms altogether, of which all but four are located in the eastern part of Khibiny. Most cirque infills are found in east-facing cirques in the western part. The size of the infills varies between 0.05 and 0.5 km^2, with an average of 0.2 km^2. The best-developed infills are situated in the central part of Khibiny, in the Tachtarvumchorr area (Fig. 3).

The cirque infills are found at relatively high altitudes, between 600 and 920 m a.s.l., with most located around 750 m a.s.l. The highest are found in the northwestern part of the Khibiny Mountains, in the cirques encircling the highest summits of the massif. Because of their definition as ‘deposits in cirques’, the elevation of the cirque infills is directly related to the elevation of cirque floors of the area. In comparison, 88% of the 206 mapped regular end moraine and lateral moraine ridges in the Khibiny Mountains (Fig. 2) are located at lower altitudes, between 300 and 700 m a.s.l.

Cirques that neither have cirque infills nor regular moraines often hold a thinner layer of hummocky moraine which spreads out into the main valleys and can cover large areas (Fig. 2). This hummocky moraine terrain is also found at altitudes between 300 and 700 m a.s.l.

The linear end moraines that are found in or just outside some of the cirques are primarily of the cross-valley/De Geer moraine type (Andrews, 1963a, b; Borgström, 1979). These moraines occur in series and are straight or gently convex into the cirque (Figs 2 and 3). No ‘regular’ end moraines, with a distinct convex down-valley outline, indicating cirque glaciation, have been found. This contrasts with the nearby Lovozero Mountains (Fig. 1), where several end moraines clearly formed by local glaciers are found (Hättestrand and Clark, 2006a).

Morphology

Based on their morphology, three types of cirque infills can be distinguished (Fig. 4):

1. Type 1 cirque infills are terrace-shaped deposits with a distinct down-valley termination, a steep slope which is

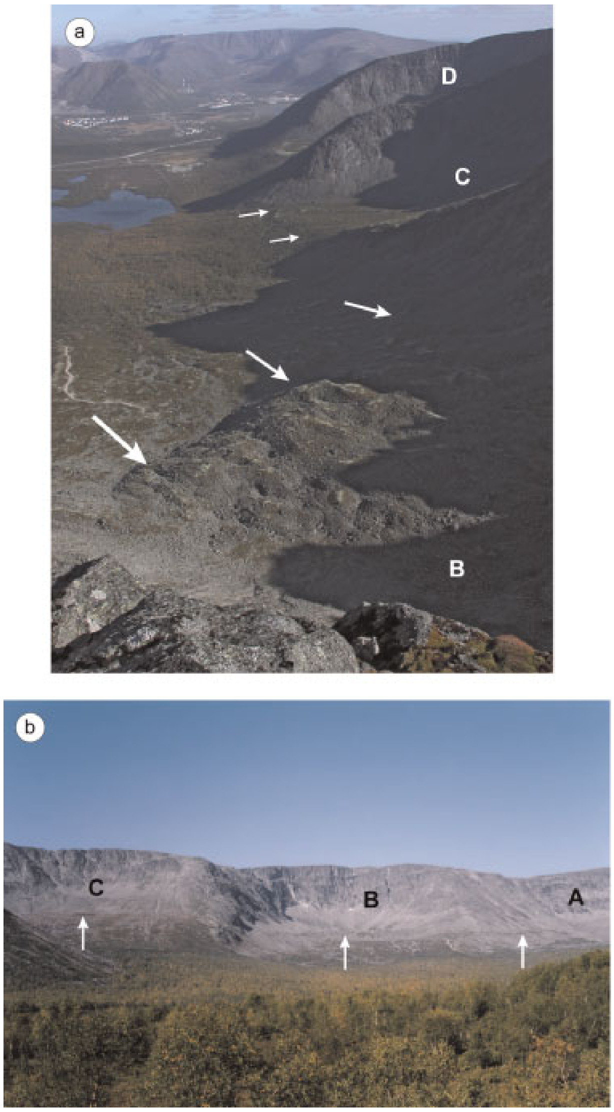

Figure 5 Photographs illustrating the morphology of cirque infills in the Tachtarvumchorr area. Letters A-D refer to labelled cirques in Fig. 3. (a) Overlooking cirque infills in cirques B (Type 1) and C (Type 2). The arrows mark the valley side slope of the deposits. The cirque infills in this area have coarse surface material consisting almost entirely of boulders (0.2–5 m in diameter). (b) Distant view of cirques A-C. Note the lateral moraine connecting cirque infills (arrows) in cirques A and B, defying formation by local glaciers or rock glaciers. This figure is available in colour online at www.interscience.wiley.com/journal/jqs

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concave in plan view (Fig. 4). This down-valley slope can be up to 50 m high, indicating that maximum thicknesses of these deposits are in the order of tens of metres. The surface of the deposit is often irregular with ridges and hummocks. A typical example is found in the Tachtarvumchorr area (cirque infill B in Figs 3 and 5a).

2. Type 2 cirque infills have a more subdued morphology than Type 1. They often extend out towards the main valley and sometimes seamlessly onlap the lower parts of the cirque headwalls (Fig. 4). The surface of Type 2 cirque infills display an irregular pattern of ridges and hummocks and in places meltwater channels cut through the deposit. A few cirque infills of this type also have flow deformation structures on the surface (Fig. 6a). This is the most commonly seen type of cirque infill in the Khibiny Mountains.
3. Type 3 cirque infills are slightly convex in both long- and cross-profile, have a smoothly undulating surface and characteristically have a semicircular string of lakes along the inner margin where the infill meets the headwall (Fig. 4). The surface is often fluted parallel to the valley direction. (Fig. 6b).

A characteristic feature for most cirque infills is their overall arcuate outline, with a convex margin paralleling the cirque headwall and a down-valley margin that is irregular or concave (Figs 2 and 3). Cirque infills in neighbouring cirques are often located at a similar altitude and sometimes joined around mountain shoulders by thin horizontal lateral moraine strings (Fig. 5b).

There are no sections through the cirque infills. Hence, information on internal structure and composition is lacking. The surface material of the visited cirque infills is commonly coarse and dominated by boulders of the local alkaline type. However, some shieldrock erratics, which must have been transported into the area from the surrounding lowlands, were encountered in the surface material.

Discussion

Formation of the cirque infills

Several alternative formation mechanisms of the cirque infills in the Khibiny Mountains are possible: (1) formation as rock glaciers/slope deposits, (2) deposition by cirque glaciers,

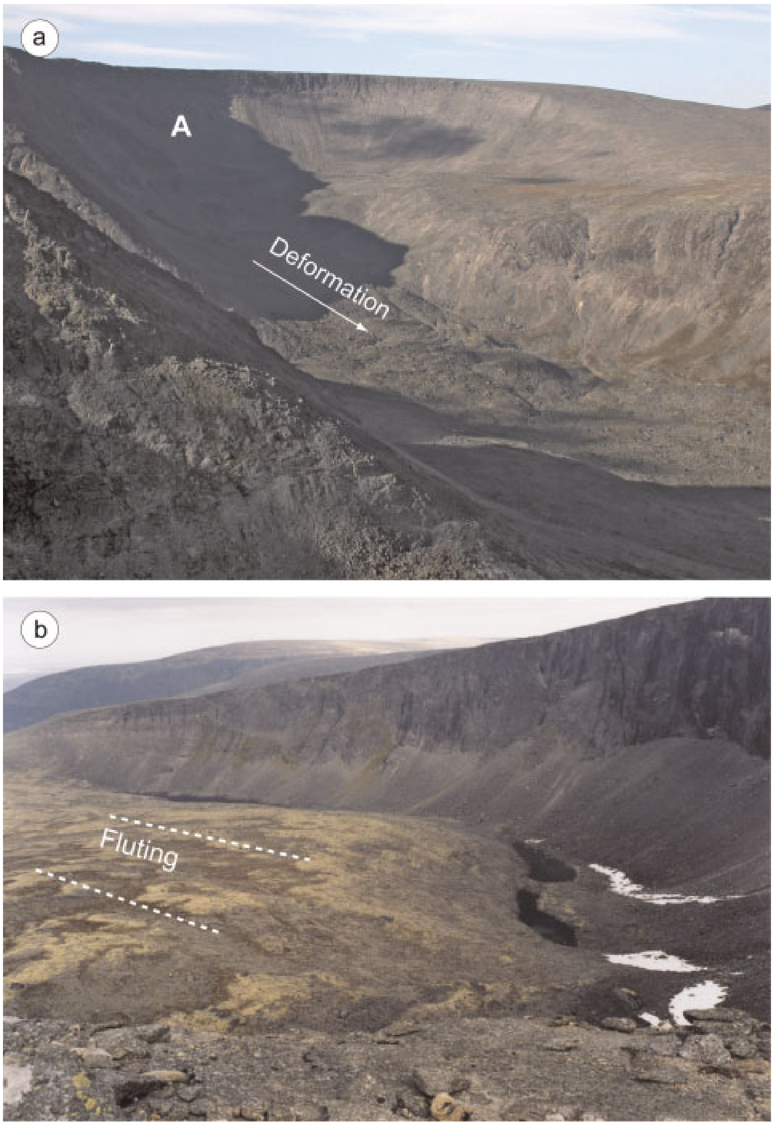

Figure 6 Morphology of cirque infills of Type 2 and 3. (a) A Type 2 cirque infill in the Tachtarvumchorr area, with ridge structures indicating downhill deformation of the deposit. The letter A refers to the labelled cirques in Fig. 3. (b) The inner part of a Type 3 cirque infill. Note the fluted surface and the depression between the cirque infill and the backwall. This example is from a north-facing cirque in the Lovozero Mountains, ~15 km to the east of the Khibiny Mountains. This figure is available in colour online at www.interscience.wiley.com/journal/jqs

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or (3) deposition by continental ice sheet lobes flowing into valleys and cirques.

Formation by rock glacier processes agrees well with the observation of deformation structures on Type 2 cirque infills. However, their plan shape, being lobate into the cirques rather than out towards the valley, does not fit with typical rock glacier morphologies (Martin and Whalley, 1987). Also, some of the cirque infills have more or less horizontal surfaces extending several hundred metres from the cirque walls. This is inconsistent with rock glaciers and slope deposits, which require slopes to form. Rock glaciers are typically fed by rockfalls (Barsch, 1988, 1992). In contrast, the presence of erratics in the Khibiny cirque infills indicates that the material was brought in to the area from surrounding shieldrock areas, and argues against a local origin (as fossil rock glaciers, or colluvial deposits). However, if the cirque infills were formed before the last glaciation, the surficial erratics may have been deposited onto the cirque infill during the late Weichselian glacial overriding.

Formation by local glaciers fits well with the close association between cirque infills and glacial cirques. However, the plan view shape of Type 1 cirque infills, with a down-valley concave margin and occasional lateral moraine segments extending around the shoulders separating the cirques (e.g. cirque infill at B in Fig. 3), testifies against formation by cirque glaciers. Moraines built by cirque glaciers are invariably arcuate in the opposite direction, that is, convex down valley. Moreover, both Type 1 and Type 2 cirque infills are areally extensive deposits that cover the cirque floor all the way to the backwall. In contrast, cirque glaciers typically produce linear deposits concentrated as end moraines towards the mouth of the cirque. The presence of erratics is also an argument against formation by local glaciers. Debris deposited by local glaciers can be derived by either subglacial erosion or rockfall onto the glacier surface (Bennett and Glasser, 1996; Benn and Evans, 1998). In either case, only local bedrock types are expected in the moraines in front of such glaciers.

The location of infill near the head of the cirques, the occasional down-valley concave margins, the presence of physical links (lateral moraines) between cirque infills in neighbouring cirques and the surface boulder lithology of the deposits are positive indicators compatible with the hypothesis that the cirque infills were formed by ice flowing into the cirques from the main valleys. We cannot identify any of the observations that do not fit such a formation process. Formation by ice flowing into the valleys is also consistent with the general palaeoglaciology of the area. Lateral moraines and lateral meltwater channels occurring on the peripheral slopes of the Khibiny Mountains (Fig. 2; Korsakova and Kolka, 2005) clearly show that the waning Fennoscandian ice sheet was engulfing the massif during the last deglaciation. In addition, two major end moraines that cross the lower part of the main valley of south-central Khibiny at Kirovsk (Fig. 2) and east of Vudjaur (Fig. 3, just east of the area covered by Fig. 3) are

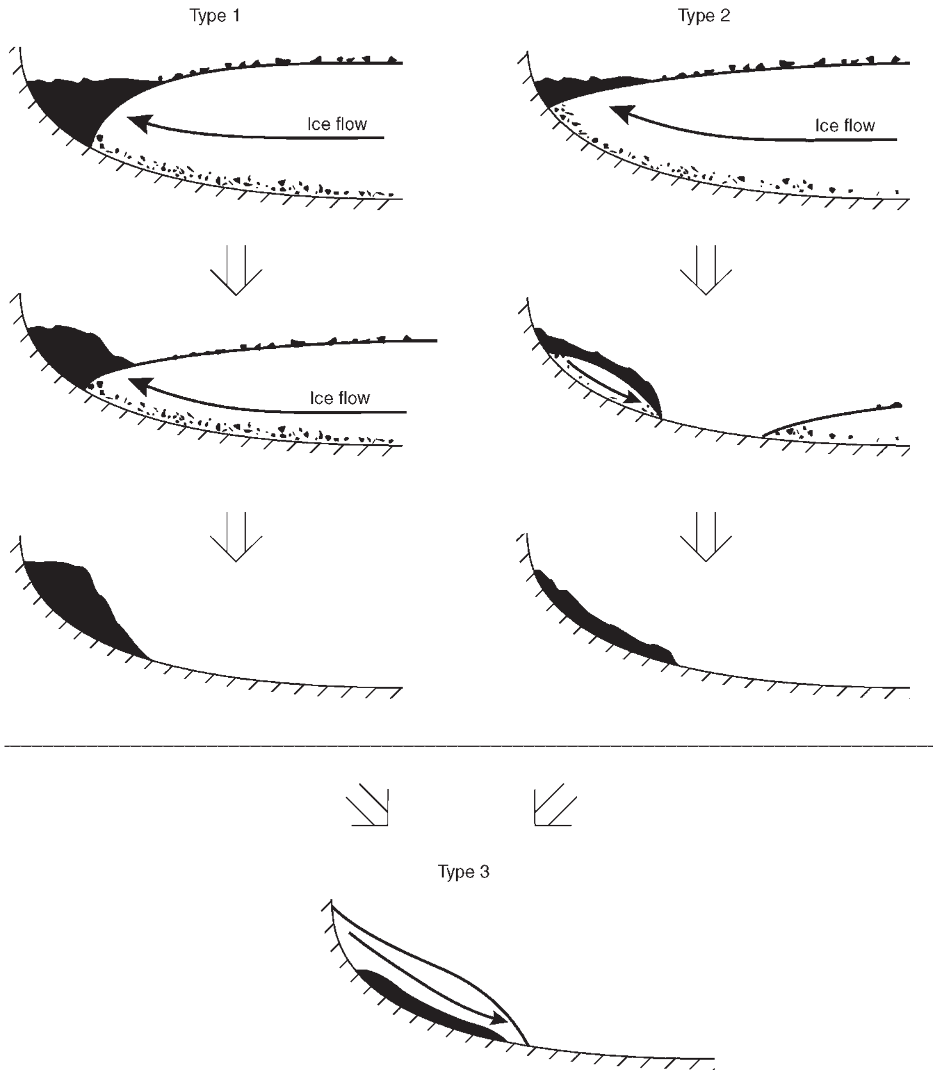

Figure 7 Model of formation for the Khibiny cirque infills, showing a longitudinal cross-section through a cirque and deposition of debris in a marginal formation (black)

composed of till that has an erratic content of up to 95% (Korsakova and Kolka, 2005), and the northernmost of these moraines is clearly arcuate with the convex side facing in towards the massif. Hence, there is independent evidence that ice was entering the central parts of the massif during the last deglaciation, and we suggest the cirque infills were deposited in a similar way, but at an early stage of deglaciation.

Given that the cirque infills were deposited by continental ice flowing into the cirques, two alternative formative histories can be postulated, depending on the specific ice-marginal environment and debris thickness (Fig. 7). Thick debris accumulation between the glacier snout and the cirque wall will form a terrace-like deposit, analogous to the morphology of Type 1 cirque infills. In contrast, a layer of supraglacial debris spread out over the glacier snout would induce reduced melting and, possibly, detachment of the buried glacier ice from the main ice mass in the valley. If the remaining buried ice is thick enough, secondary flow structures can form during down-slope deformation of the ice/debris mass; much like rock glaciers can form from debris-covered glaciers and ice-cored marginal moraines (Barsch, 1971; Clark *et al.*, 1998).

Type 3 cirque infills (Figs 4 and 6b) bear clear evidence of ice overriding in the form of a fluted surface. We suggest that these are relict cirque infills deposited during an earlier glacial phase that have been subglacially deformed and drumlinised during subsequent glaciation by local cirque/valley glaciers or ice caps (Fig. 7), or by continental ice sheet lobes similar to those that once formed the deposit.

Can the cirque infills be used as climate indicators?

End moraines are typically formed either at periods of ice-marginal stillstand, as a result of quasi steady-state conditions during which material brought forward by ice flow is deposited at the ice margin as dump moraines, or during ice-marginal (re-)advances as push/squeeze/thrust moraines (e.g. Boulton, 1970; Sugden and John, 1976; Benn and Evans, 1998; Evans and Twigg, 2002). However, the cirque infills in Khibiny need not necessarily represent an advance or stillstand in the deglaciation sequence. If the bed gradient is steeply reverse, against the direction of ice flow (as it will be when an ice sheet lobe retreats from a cirque valley head), the ice margin will be located at nearly the same horizontal position, at the

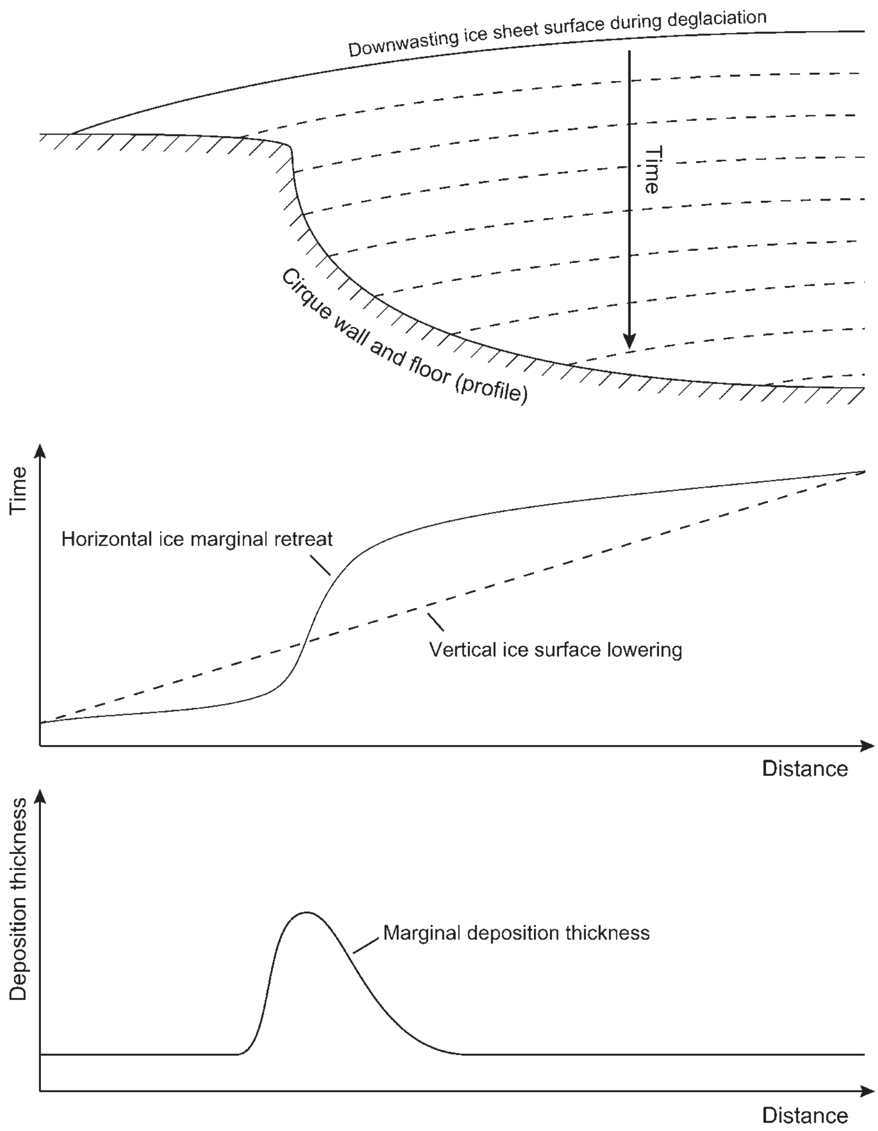

Figure 8 A model of ice-marginal retreat and till deposition in cirques during deglaciation of an ice sheet over a mountain range, assuming a constant ice thinning rate. Although the ice surface is lowered at a nearly linear rate, horizontal retreat of the ice margin will be markedly reduced when the ice margin retreats over the cirque edge and is lowered down the headwall. If a constant amount of glacial debris is produced at the ice margin, the till sheet thickness will be much thicker close to cirque headwalls, and moraines may be built. Such moraines are then ice dynamic in character and are unrelated to climatic events

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headwall, even if vertical thinning is substantial (Fig. 8). Hence, all material brought in towards the ice margin during this time will be trapped in the cirque. This 'stationary' accumulation of debris will continue until the ice margin has lowered to the level of the cirque floor (Fig. 8).

The accumulation of glacial debris as described here may occur in all cirques where ice sheet tongues flow into valleys that have steep backwalls. The location and elevation of such deposits (i.e. the cirque infills) will then be related to the location of steep headwalls and the elevation of cirque floors. Hence, the presence and altitudinal location of such deposits cannot in itself be used to infer regional ice sheet stillstands.

Supraglacial moraines occur in many glacial environments, mostly at the snouts of polar or subpolar glaciers and ice shelves, and have been described in both Antarctica and the northern hemisphere polar regions (e.g. Boulton, 1967; Chinn, 1991; Cassidy *et al.*, 1992; Delisle, 1993). For example, based on the present-day appearance of such moraine complexes in the Convoy Range, Transantarctic Mountains, Antarctica, Chinn (1994) made reconstructions of former ice flow patterns and configurations.

Similar conditions to the formation environment suggested for the Khibiny cirque infills, with an ice sheet engulfing a mountain area, can be found today in Antarctica and Greenland. One example is the ice-filled Scharffenbergbotnen valley in Heimefrontfjella, East Antarctica, which is characterised by blue-ice fields and partly covered by hummocky, supraglacial moraine complexes (Fig. 9; Hättestrand and Johansen, 2005). These moraines, thickest close to the cirque headwalls, were interpreted to originate from colluvium and pre-existing moraines that were brought into the valley by an advancing glacier during the last glacial maximum (LGM). Some of the moraines were found to have reversed flow structures out towards the main valley, similar to those of the Type 2 cirque infills in Khibiny, resulting from secondary deformation as the ice surface out in the main valley has lowered since the LGM.

Hättestrand and Johansen (2005) concluded that deposition of these supraglacial moraines could be directly tied to the presence of blue-ice conditions, and suggested related features may constitute an unexploited resource when reconstructing the former extent of blue-ice areas, in both present day and formerly glaciated regions. Because blue-ice areas develop in response to specific climatic conditions, including locally high sublimation rates and negative mass balance as a result of local föhn wind effects over high relief terrain (Jonsson, 1990; Bintanja, 1999; Bintanja and Reijmer, 2001), any information on the presence of blue ice in formerly glaciated regions may provide detailed palaeoclimatic information.

Following the reasoning by Hättestrand and Johansen (2005), is it possible that the cirque infills of Khibiny are indicative of former blue-ice conditions in the Kola Peninsula region? Provided that the cirque infills were formed by supra- and proglacial deposition of debris from continental ice sheet lobes flowing into valleys and cirques (as suggested in Fig. 7), two ablation environments can be postulated. Either meltwater was released during positive temperatures, or ablation was dominated by sublimation in a cool climate, analogous to the Antarctic example described above. If meltwater was released, it had to be impounded between the glacial snout and the cirque wall. There are signs of glacial lakes in Khibiny, such as glacial lake shorelines, perched deltas, overflow channels and spillways (Armand, 1960). However, in most cirques with cirque infills such glacial lake evidence is lacking. Apart from

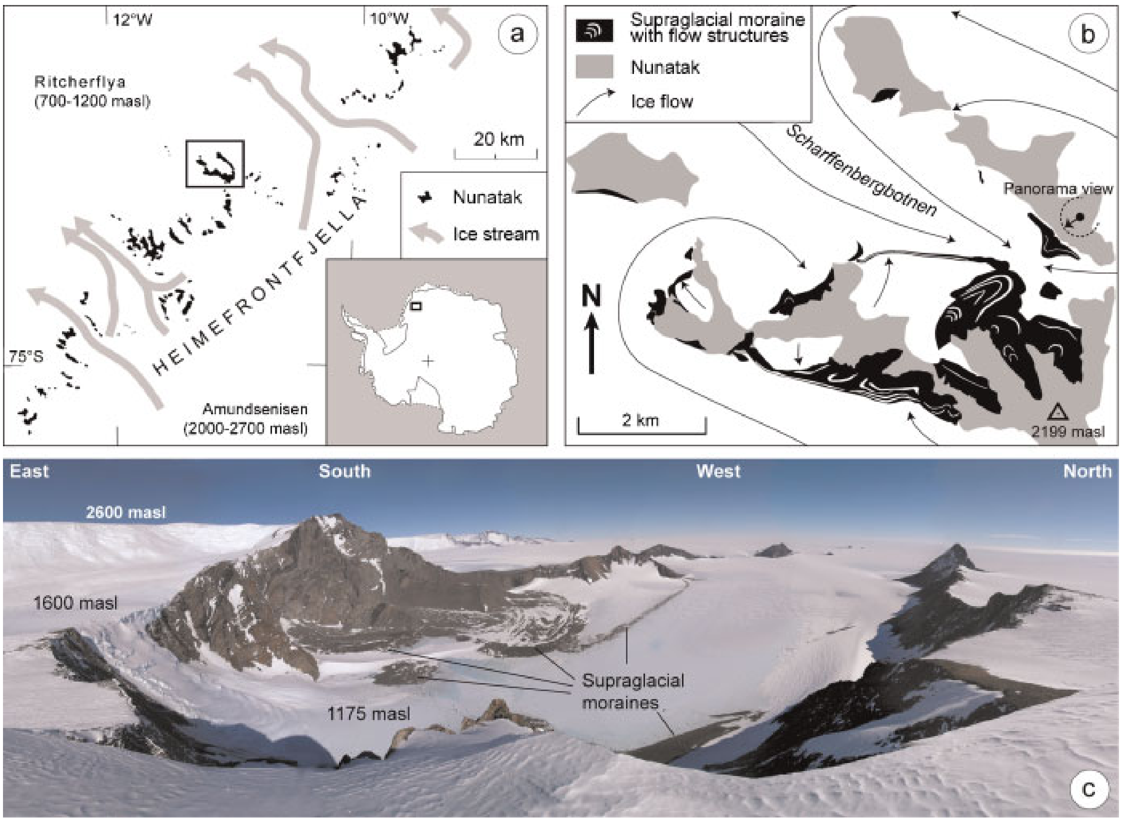

Figure 9 A modern example of cirque infill formations in Scharffenbergbotnen, Heimefrontfjella, East Antarctica (modified from Hättestrand and Johansen, 2005). (a) Location map. (b) Map of the ice filled valley Scharffenbergbotnen and its supraglacial moraines. The inner parts of the valley, where ice flow trajectories meet, are the lowest point in the area and constitute a local ablation centre with blue-ice fields. The present outline and morphology of the moraines are the cumulative effect of deposition at the LGM, when the ice surface was ~200 m higher, and subsequent deformation as the ice surface has lowered. (c) Panorama photograph of Scharffenbergbotnen valley. For location of photograph, see (b). This figure is available in colour online at www.interscience.wiley.com/journal/jqs

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some spillways over the highest summit surfaces, around 1000 m a.s.l., nearly all glacial lake features are found at altitudes lower than 600 m a.s.l., which is below the altitude of the cirque infills.

It has been proposed that deglaciation of the Khibiny Mountains straddles the YD climate reversal (Yevzerov and Kolka, 1993). It is therefore likely that the cirque infills were deposited either during, or in close connection to the YD. One possibility is that after the summit surface of the massif had been deglaciated, there was a reduction in surface melting during the YD, as a result of cool and dry conditions that enhanced the possibility for sublimation dominated ablation, particularly in valleys and cirques (Bintanja, 1999). Such dry conditions may also explain the lack of signs of local glaciers formed during the YD. Hence, we suggest that the cirque infills were deposited as 'dry' supraglacial sublimation moraines, and could be indicators of blue-ice conditions during the YD in this part of the Fennoscandian ice sheet.

Conclusions

The cirque infills described in this paper are interpreted as being deposited at the margins of ice lobes of the Scandinavian ice sheet, extending into valleys and cirques of the Khibiny massif on the Kola Peninsula, Russia. Based on general deglaciation chronology of the area from previous studies, it is likely that these forms were deposited during the YD cold period. Yet, we argue that cirque infills in general cannot be used as indicators of climate reversals or halts in ice sheet retreat. This is because all ice sheets retreating out from mountain areas are likely to deposit such forms at valley heads, as a result of low horizontal deglaciation rates at steep reversed slopes. However, through comparison with modern analogues of such deposition environments in Antarctica, we suggest that the cirque infills in Khibiny may be indicative of blue-ice conditions and sublimation dominated ablation in the area during YD.

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