The Larajæg'gi outcrop – a large combined Neoproterozoic/Pleistocene roche moutonnée at Karlebotn, Finnmark, North Norway.

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The gneiss hillocks , which emerge above the Karlebotn quartzite of the Neoproterozoic Smalfjord Formation in the Karlebotn area, North Norway, have been interpreted as primary, uneven basement relief under the Neoproterozoic cover. A study of the largest gneiss occurrence, the Larajæg'gi outcrop (c. 200 x 350 m), showed these features to be large, inherited Neoproterozoic (Varangerian) roches moutonnées, modified later by Pleistocene glaciation(s).

The western surface of the Larajæg'gi gneiss outcrop is clearly a Pleistocene stoss slope as its smoothly rounded surface inclines up-glacier to the latest Pleistocene ice movement, which was from west to east in the area. However, the foot part of the opposite side of the gneiss outcrop does not show any evidence of being a Pleistocene lee side, but the gneiss surface is smoothly rounded, in part grooved, and has a convexo-concave surface topography with crestal hinge-lines plunging gently to the east, under the Karlebotn quartzite. This is attributed to abrasion caused by the Neoproterozoic ice, which moved from the present east to the present west; i.e. from the opposite direction to that of the latest Pleistocene ice. This interpretation is supported by relics of Neoproterozoic diamictite filling fractures and hollows in the basement gneiss on the Pleistocene stoss side indicating that this side originally represented the rough and hackly Neoproterozoic lee side.

The preserved Neoproterozoic features of the Larajæg'gi roche moutonnée support the hypothesis that during the later stage of the first Varangerian glaciation the ice flowed from the present east to the present west.

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Introduction

The flow direction of the ice that abraded a hard rock basement is often difficult to determine from glacial striations alone, but specific flow indicators, e.g. diverse crescentic fractures and scars, nail striations etc. (e.g. Prest 1983), are needed for this purpose. Another way to determine the flow direction is to study ancient landforms, of which roche moutonnées are a most useful tool in cases where the palaeogeomorphology is only partially visible. Palaeozoic roches moutonnées are relatively common (for review see Table 3 in Laajoki 2002), whereas the only convincing larger Precambrian examples have been described from the Neoproterozoic Taoudeni Basin, West Africa (Biju-Duval & Gariel 1969; Deynoux & Trompette 1981), although some of the striated, rounded, pavement forms in the Kimberley area, West Australia, could also be included in this category (Dow 1965). The whalebacks under the Mineral Fork tillite, Utah, represent small Neoproterozoic roches moutonnées (Ojakangas & Matsch 1980). Davison and Hambrey (1996, 1997) interpreted the larger elongated Lewisian basement landforms at the base of the Stoer Group as ancient roches moutonnées and used them, together with the overlying diamictites, as significant indicators of the earliest Torridonian glaciation, but this idea has been questioned (Stewart 1997; Young 1999).

The glacially striated Neoproterozoic (Varangerian) Bigganjargga pavement, North Norway, has been known for over one hundred years (Reusch 1891). It offers the best preserved part of the glacial Varangerfjorden unconformity under the Smalfjord Formation, but does not contain any trustworthy ice flow direction indicators although Bjørlykke (1967) stated that a crescentic gouge on the striated surface under the Bigganjargga tillite suggests ice flow from SE to NW. This structure is, however, more likely a recent superficial crack (see Bjørlykke's Fig. 6b). On the other hand, diverse provenance and palaeocurrent studies carried out on the overlying Smalfjord Formation indirectly support the northwesterly ice flow direction (e.g. Bjørlykke 1967, Edwards 1975, 1984; Arnaud & Eyles 2002; Laajoki 2002). Riedel shear fractures in the breccia developed at the polished quartzite surface at Bigganjargga indicate a NW directed flow (Rice & Hofmann 2000). In the summer of 2002, the author visited briefly the gneiss hillocks which rise above the Smalfjord Formation in Karlebotn, some 3 km west of Bigganjargga.

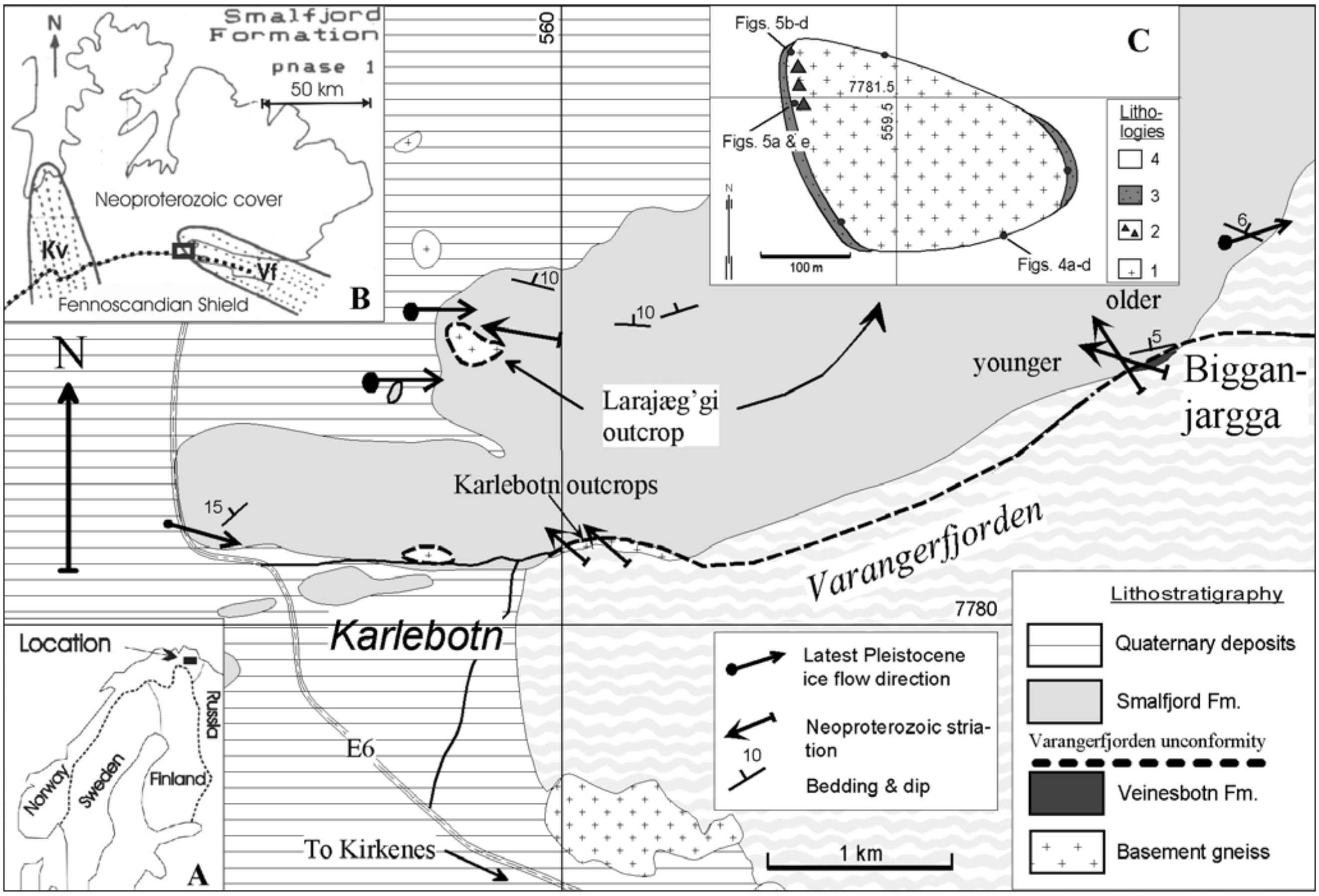

Fig. 1. Geological map of the Karlebotn area (UTM coordinates, modified from Siedlecka 1990). Neoproterozoic and Pleistocene striation observations by the author. Inset A: Geographic location of the map area. Inset B: Location of the study area (rectangle) in relation to the Varangerfjorden (Vf) and Krokvatnet (Kv) glacial palaeovalleys during the phase 1 of the Smalfjord Formation. The Fennoscandian Shield / Neoproterozoic formations boundary is indicated by the dashed line (modified from Fig. 80A in Edwards 1984). Inset C: Map of the Larajæg'gi outcrop. Lithologies: 1. Basement gneiss. 2. Diamictite. 3. Massive sandstone (thickness exaggerated). 4. Karlebotn quartzite. Locations of photographs in Figs. 4 and 5 are indicated.

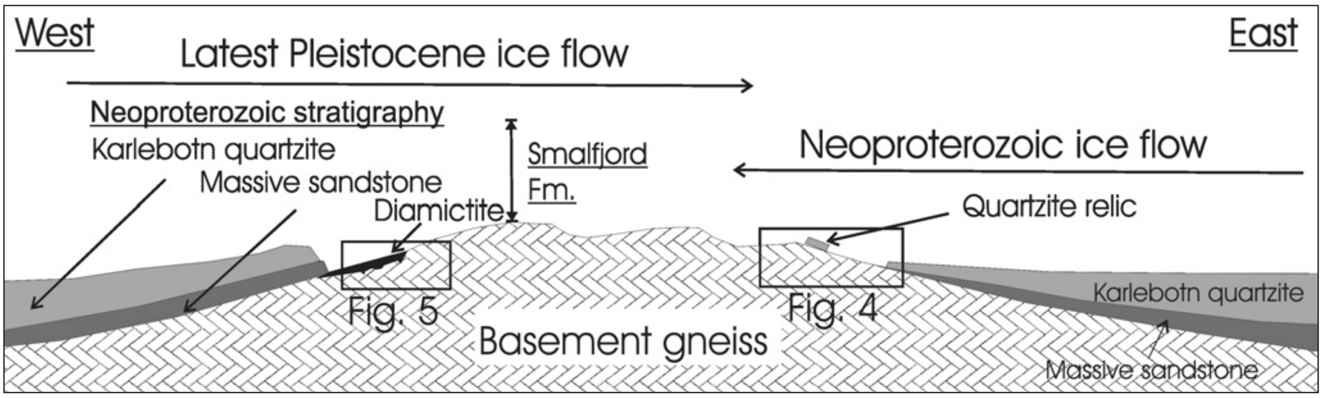

Fig. 2. Schematic profile of the Larajæg'gi outcrop. Relative positions of photographs in Figs. 4 and 5 are framed. Not to scale.

It appeared that the largest outcrop shows features indicating that it may represent a Neoproterozoic roche moutonnée modified by the Pleistocene glaciations. This paper describes and interprets this, the Larajæg'gi outcrop.

Geology of the Karlebotn area

Karlebotn (Karlbotn in older literature) is located at the boundary between the Neoarchaean-Palaeoproterozoic Fennoscandian Shield and its Neoproterozoic cover at the western end of Varangerfjorden, Finnmark

County, North Norway (insets a & b in Fig. 1). Recent reviews of the Neoproterozoic geology of the region can be found, for instance, in Siedlecka and Roberts (1992), Gorokhov et al. (2001), Rice and Hofmann (2000), Arnaud and Eyles (2002), Laajoki (2002), and Røe (2003). For the purpose of this paper, it is sufficient to say that the Neoproterozoic cover belonging to the autochthonous-parautochthonous part of the Norwegian Caledonides was deposited nonconformably on the metamorphosed gneiss basement of the Fennoscandian Shield. The basement is exposed south of and in Karlebotn and rises as small gneiss hillocks through the Neoproterozoic cover northwest of Karlebotn (Fig. 1). The Neoproterozoic cover consists of two major sequences: the older fluvial – shallow marine Vadsø and Tanafjorden groups and the Vestertana Group with two Varangerian glacial units, the Smalfjord (basal) and Mortensnes formations. A pre-tillitic angular unconformity occurs at the base of the Vestertana Group. Around Varangerfjorden, it forms a glacial, likely fault-controlled (Holtedahl 1918; Røe 2003), palaeovalley, whose axis and margins follow approximately the trend of Varangerfjorden (Bjørlykke 1967; Edwards 1984), and is referred to as the Varangerfjorden unconformity (Laajoki 2002). The age for the Varangerian glaciation in its type area has been dated to the 630- 590 Ma interval (Gorokhov et al. 2001).

In the Karlebotn area, the only representative of the older Neoproterozoic sequence is the quartzite of the Veinesbotn Formation of the Vadsø Group, exposed under the Varangerfjorden unconformity at Bigganjargga (Fig. 1). The Smalfjord Formation starts with the disputed Bigganjargga diamictite (Jensen & Wulff-Pedersen 1996, 1997; Edwards 1997; Arnaud & Eyles 2002), which lies unconformably on a striated quartzite pavement forming the surface of the Veinesbotn Formation. The diamictite is overlain by coarse-grained chaotic turbiditic sandstones and "white" medium- to fine-grained turbidite sandstones of Arnaud's and Eyles' (2002) lower (c. 8 m) and middle (c. 20 m) facies associations, respectively. The upper facies association (> 50 m) consists of large conglomerate lenses within the stacked, massive, white sandstone with the same characteristics as the quartzites of the middle facies association. The authors correlate this with the Karlebotn quartzite.

The Varangerfjorden unconformity can be followed for about 500 m to the west of Bigganjargga before it enters the sea. It rises again on to dry land near the Karlebotn village and though not exposed must separate the gneiss basement outcrops on the shoreline from the overlying quartzite (Fig. 1). Following Bjørlykke (1967), the white Neoproterozoic quartzite surrounding the gneiss hillocks north of Karlebotn is called the Karlebotn quartzite in this paper. Lithostratigraphically, it belongs to the Smalfjord Formation (Siedlecka 1990) and may be correlated with Arnaud and Eyles' (2002) middle-upper facies association at Bigganjargga. The bedding of the Karlebotn quartzite is subhorizontal, but openly folded.

Previous work on the Karlebotn gneiss hillocks

Holtedahl (1918) wrote that relics of sedimentary rocks with occasional granite clasts of fist-size often occur on top of the gneiss outcrops in the Skipagurra area (a few kilometres west of the map area in Fig. 1). He concluded that these features reflect the uneven character of the gneiss basement. Bjørlykke (1967) found thin (1 – 2 cm) quartzite layers on the gneiss hillocks north of Karlebotn. His thin section studies across the gneiss/quartzite contact revealed no evidence of weathering of the gneiss, which was considered to favour a glacial environment. The hillocks were considered to be monadnocks and their relief mostly primary. Their distribution is delineated on the map by Siedlecka (1990). Laajoki (2001) suggested that the gneiss outcrops in Karlebotn might be Neoproterozoic roches moutonnées.

Lithostratigraphy around the Larajæg'gi outcrop

All the Neoproterozoic sedimentary rocks around the Larajæg'gi outcrop belong to the Smalfjord Formation (Fig. 1) (Siedlecka 1990). The lowermost unit comprises relics of diamictite, which fill fractures and hollows in the basement gneiss or cover the gneiss as 10 – 20 cm thick patches in the northwestern foot part of the outcrop (Inset c in Fig.1 & Fig. 2). It seems likely that the relics represent the eroded margin of a thicker diamictite unit lying under the Karlebotn quartzite. The coarse lithology and basal stratigraphic position suggest that the diamictite belongs to the lower facies association in Bigganjargga, but lack of outcrops and the significantly greater height of the Larajæg'gi outcrop above sea level (c. 80 m a.s.l. vs. c. 5 m a.s.l.) make this correlation unsure. At the foot zone itself, a thin (c. 1 m), massive, immature, feldspathic and lithic sandstone, rusty red on its weathered surface, overlies the gneiss. The same rock occurs as occasional small knobs and local loose boulders all around the hillock between the gneiss and the Karlebotn quartzite. Its upper contact is not exposed, but the unit seems to dip under the Karlebotn quartzite. The latter, at least several tens of meters thick, consists of stacked white massive sandstone beds and may correspond to Arnaud and Eyles' (2002) middle – upper facies association at Bigganjargga.

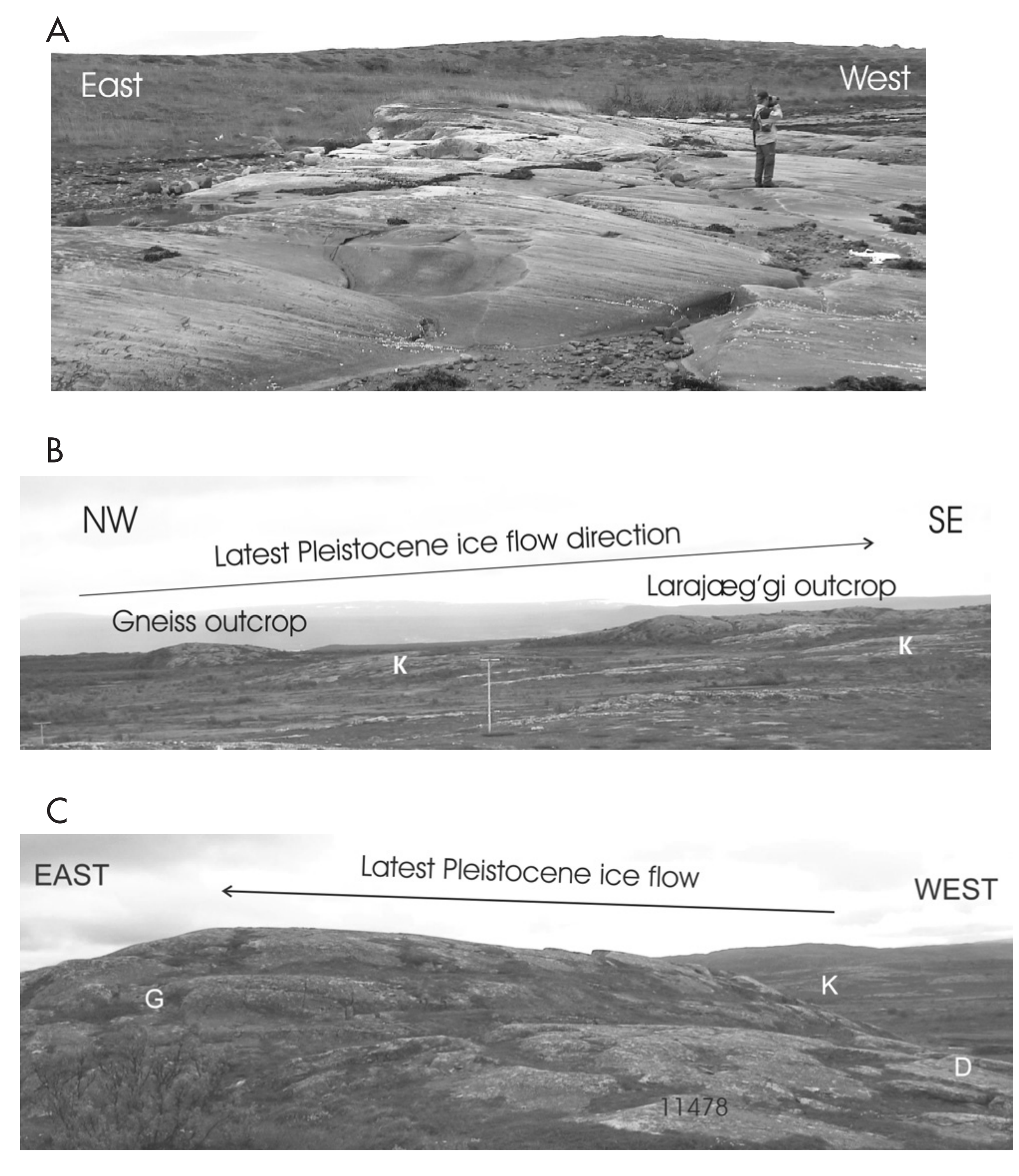

Fig. 3. (A) Pleistocene roche moutonnée on sandstone of the Smalfjord Formation near Nesseby church (UTM 570300/7782950). Ice flow to the left (east). Note striated western stoss sides and sculpted eastern lee sides (s-forms, Kor et al. 1991). (B) View from southeast towards the Larajæg'gi outcrop. The shallow Pleistocene roches moutonnées on the Karlebotn quartzite are marked by K. Note the rather steep Pleistocene stoss sides of the gneiss outcrops. (C) Approximate east-west view of the Larajæg'gi outcrop (559395/7781486). Right and left parts represent stoss and lee sides of the Pleistocene roche moutonnée, respectively. Note the abrupt end of a large groove (G) on the left. Neoproterozoic diamictite relics (D) occur on the stoss side (Fig. 5). The hill on the right (K) represents a Pleistocene roche moutonnée developed on the Karlebotn quartzite. The margin of the Fennoscandian Shield is visible in the far distance.

Pleistocene features of the Larajæg'gi outcrop

The Map of Quaternary geology, sheet 5, Ice flow directions, Northern Fennoscandia (1986) shows that Pleistocene ice flowed towards the north during the Early, Middle, and Late Weichselian glacial stages in eastern Finnmark, whereas during the last deglaciation the ice flow deviated locally. In the Karlebotn area, the author has not detected any direct evidence of northerly ice flow, but all the observations of Pleistocene striations and roches moutonnées indicate deviating ice flow to the east. As these features are so prominent (Fig. 3a) and there is no evidence of a younger ice flow, this flow is referred to as *the latest Pleistocene ice flow* in the following text.

The western part of the Larajæg'gi outcrop (UTM 559395/7781486) clearly represents a Pleistocene roche moutonnée. This forms a smoothly rounded surface inclining up-glacier to the latest Pleistocene ice movement, which was from west to east (Figs. 3b & c). Secondly, the trends of large and small grooves (terminology after Laverdière et al. 1985) (Fig. 3c), and elongated rounded crests match well those measured in the adjacent Karlebotn quartzite outcrops (Fig. 1). Pleistocene striations and small grooves are, however, rare on the gneiss surface. This is attributed to the coarse grain size and abundance of potassium feldspar in the gneiss, which have made it susceptible to post-glacial weathering. The eastern part of the outcrop is uneven and covered in part by surficial deposits. Hence the western and eastern parts of the Larajæg'gi outcrop represent Pleistocene stoss and lee sides, respectively.

An unusual feature of the Larajæg'gi outcrop is that the inclination of its Pleistocene stoss surface is markedly steeper than that of the lee side (Figs. 3b and c). This geomorphology is the reverse of that of a typical roche moutonnée and of that visible on the Pleistocene roche moutonnées developed on the Karlebotn quartzite (Figs. 3a & b). Furthermore, smooth gneiss surfaces inclining down-glacier to the Pleistocene ice movement have been exposed from under the Karlebotn quartzite on the Pleistocene lee side. These elements, attributed to the Neoproterozoic glacial abrasion, will be discussed in the next section.

Neoproterozoic features of the Larajæg'gi outcrop

Indicators of partial preservation of the primary Neoproterozoic features include palaeogeomorphologic features (Fig. 4) and diamictite relics (Fig. 5). These can be studied on the eastern and western parts of the Larajæg'gi outcrop, respectively (Inset c in Fig. 1).

Palaeogeomorphologic features

The most convincing evidence of pre-Pleistocene erosion of the basement gneiss surface can be seen in the southeastern part of the outcrop. The lowermost 1 – 2 m of the foot zone of the gneiss surface is smoothly rounded and shows convexo-concave geometry with one large but shallow groove (Figs. 4a-d). The surface dips under the Karlebotn quartzite but in the direction of the Pleistocene ice flow. One small quartzite relic is attached to upper part of one of the smooth gneiss crests proving that the gneiss surface under this level has been exposed from below the Karlebotn quartzite either by Pleistocene plucking or recent erosion or both(Figs. 4a & b). This is quite evident in Fig. 4b, which shows that the Karlebotn quartzite onlapped a smoothly rounded gneiss surface. The quartzite relic is close to the sharp boundary which separates the Pleistocene stoss side from the smooth gneiss surface inclined to the east. This boundary is interpreted as an intersection curve between Neoproterozoic and Pleistocene glacial abrasion surfaces dipping in opposite directions (Fig. 4a). What makes this landform unique is a minimum 560 Ma age difference between the two surfaces, both of which have similar glacial origins.

On the basis of these geomorphologic features it is sound to conclude that the smooth foot part of the outcrop represents the stoss side of a large roche moutonnée formed before deposition of the Karlebotn quartzite. The general geomorphology and the solitary groove in Fig. 4c indicate that the palaeoice-flow was from the present east to the present west. The lack of Neoproterozoic striations and small grooves on the gneiss surface can be attributed either to recent weathering or to weathering during deposition of the Smalfjord Formation or both.

In addition to the example described above, the gneiss/Karlebotn quartzite contact zone is exposed in a few other places on the northern side of the Larajæg'gi outcrop. These also show that the underlying gneiss surface was smooth before deposition of the Karlebotn quartzite.

Diamictite relics

Neoproterozoic diamictite relics were only found in the northwestern part of the outcrop, where they have been abraded down to the level of the Pleistocene stoss side (Fig. 5a). They fill depressions and fractures in or occur as a thin cap layer on the basement gneiss (Figs. 5a-d). This indicates that, in contrast to the eastern part described above, the gneiss surface was rugged, jointed and fractured either before or during deposition of the diamictite. The diamictite relics form an irregular network (Fig. 5b), where the widest diamictite dykes are ca. 50 cm wide, but only 10 – 20 cm deep (Fig. 5a). Locally,

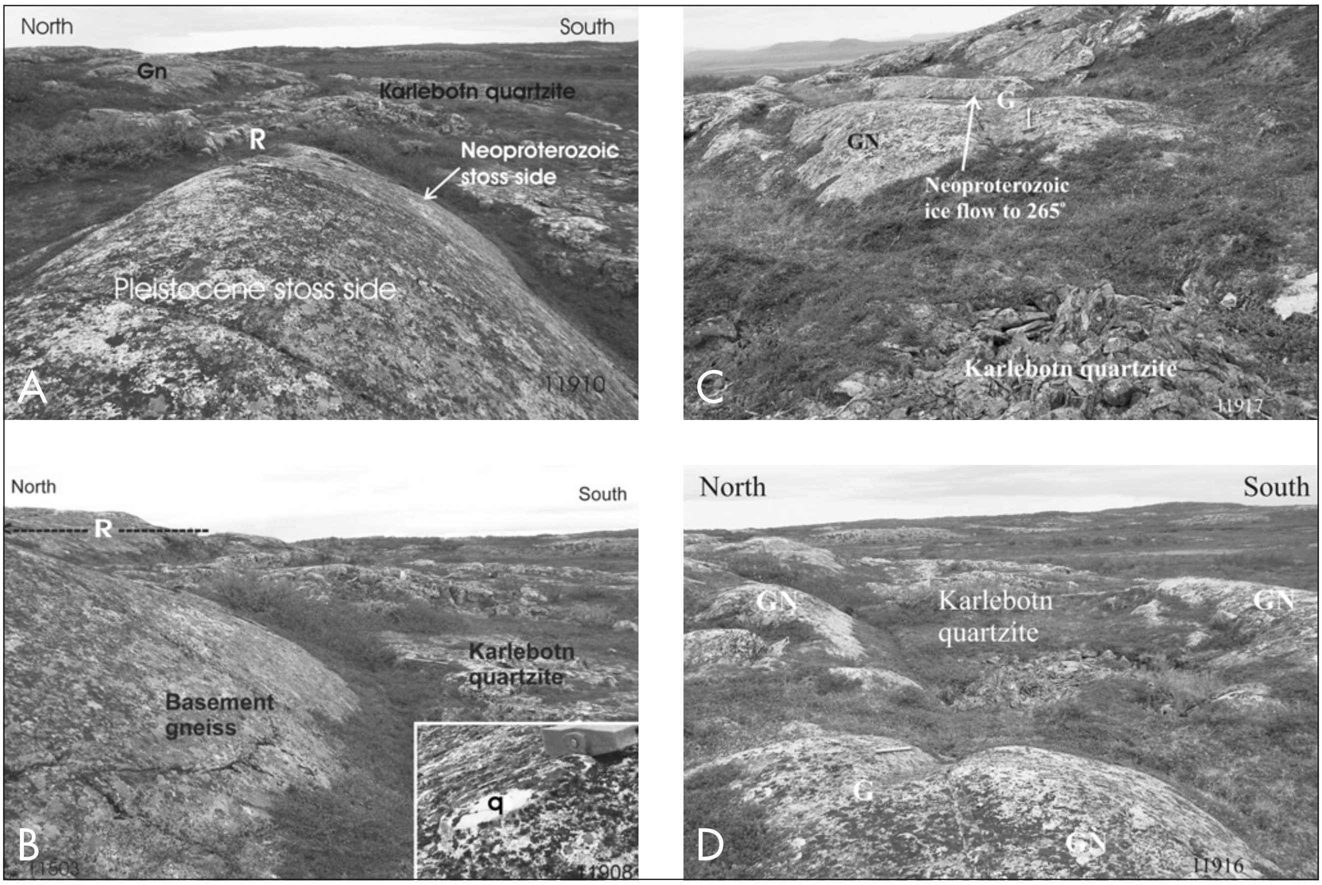

Fig. 4. Photographs of the eastern part of the Larajæg'gi outcrop (UTM 559635/7781349) showing Neoproterozoic geomorphologic features. In a,b, & d the latest Pleistocene ice flow is away from the viewer. GN = basement gneiss. (A) A smoothly rounded gneiss crest. The part in the foreground represents the Pleistocene stoss side, whereas the part farther from the viewer represents the Neoproterozoic stoss side, whose crest line plunges under the Karlebotn quartzite. Note the sharp intersection edge between the Pleistocene and Neoproterozoic surfaces and a small quartzite relic (R) close to it. Another smooth gneiss form occurs on the left. (B) Smooth southern side of the gneiss crest in Fig. 4a exposed from below the subhorizontal Karlebotn quartzite. The approximate level of the Karlebotn quartzite relic (q in inset) is indicated by R. (C) Grooved gneiss surface seen in the direction of the Neoproterozoic ice flow (up-glacier to the latest Pleistocene ice flow). (D) Gneiss surfaces showing convexo-concave palaeotopography. The Karlebotn quartzite fills the depression between smooth-crested gneiss outcrops. The hammer is parallel to a Neoproterozoic groove (G) plunging under the Karlebotn quartzite.

the diamictite, together with *in situ* gneiss fragments, fills narrow fractures, where the fracture boundaries and margins of the gneiss fragments are knife-sharp (Fig. 5c). These features are similar to those at the base of the Palaeoproterozoic Gowganda formation in Canada attributed to substrate quarrying (Mustard & Donaldson 1987a, compare their figures 3b & 3c with Figs. 5a & c). Their presence excludes the theoretical possibility that the reverse geometry of the hillock could have been inherited from a Neoproterozoic rock drumlin (for definition see Sudgen & John 1976).

The diamictite contains diverse basement gneiss and quartzite clasts up to cobble size in a rusty-red matrix (Fig. 5e). No clear orientation of the clasts can be seen. The quartz-rich sandy matrix rock is immature both as regards texture and mineralogy containing highly angular to well-rounded quartz, feldspar, gneiss and quartzite clasts (Fig. 5f). In both clast content and texture, the diamictite resembles the Bigganjargga diamictite.

Because only relics of the diamictite have been preserved, it is not possible to interpret its origin reliably. If it represents a non-glacial debris flow deposit, as has been suggested for the Bigganjargga diamictite (Jensen & Wulff-Pedersen 1997; Arnauld & Eyles 2002 and references therein), its deposition and the formation of the fractures on the Neoproterozoic lee side are two independent events.

Discussion

The observations described above show that the Neoproterozoic surface shaping the eastern part of the Larajæg'gi gneiss outcrop under the Smalfjord Formation was smooth and inclined towards the east before deposition of the Karlebotn quartzite, whereas the western surface was rugged. This suggests that these parts represent, respectively, stoss and lee sides of an ancient

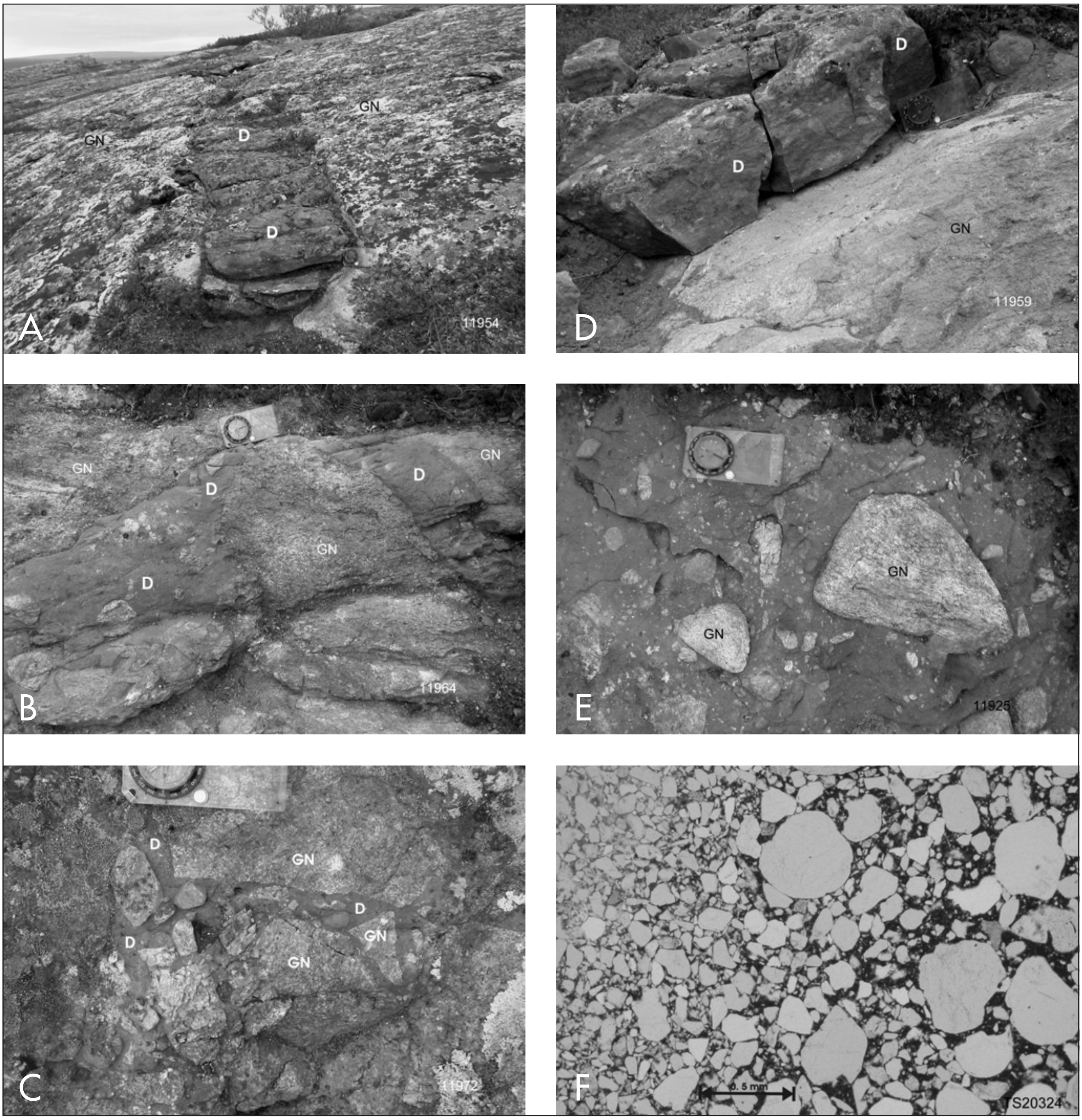

Fig. 5. Photographs of the Neoproterozoic diamictite relics on the Pleistocene stoss side of the basement gneiss outcrop in Fig. 3c (559395/7781486). D = diamictite, GN = basement gneiss (A). Neoproterozoic diamictite filling a c. 40 cm wide and 10 - 20 cm deep joint-bounded hollow in the basement gneiss. Seen from the southeast. Compass is 12 cm long. (B) Diamictite filling irregular network of joint-bounded hollows in the gneiss. Note the recent weathering of the surface. (C) Diamictite and in situ gneiss fragments with clear joint faces filling joint-bounded fractures in the gneiss. (D) Newly excavated part of the Varangerfjorden unconformity from under a diamictite patch. (E) View of recent weathering surface of diamictite with basement granitoid and gneiss clasts. (F) Matrix of the diamictite showing well-rounded and angular quartz clasts. Thin section 20324. One polar.

roche moutonnée. The palaeogeomorphology and the solitary groove on the eastern gneiss surface indicate that the Neoproterozoic ice flow was from the present east to the present west (Fig. 4). This is in agreement with general provenance and palaeocurrent studies carried out on the Smalfjord Formation, which show that the sediment transportation within the Varangerfjorden glacial palaeovalley was to the present west - northwest (Bjørlykke 1967; Edwards 1984, Arnaud & Eyles 2002; Laajoki 2002). The westerly palaeoice direction indicates that the same glacier that produced the younger striation set on the Bigganjargga surface may have formed the Larajæg'gi roche moutonnée.

The gneiss hillocks rise some 10 meters above the present erosional level of the Karlebotn quartzite. If the thickness of the Neoproterozoic cover around the hillocks is of the same order than at Bigganjargga (c. 80 m), the Neoproterozoic relief of the hillocks was of the order of 100 m indicating that the floor topography of the Varangerfjorden palaeovalley was hilly. In this respect it is comparable, for instance, with large Pleistocene roches moutonnées in Scotland (Sugden et al. 1992) or medium scale landforms of glacial erosion in Greenland (Glasser & Warren 1990) and the Late Palaeozoic subglacial valleys in Southwest Africa (Frakes & Crowell 1970). The reverse Pleistocene geomorphology of the gneiss outcrop can be considered as an inherited feature of a Neoproterozoic roche moutonnée, whose orientation and form were opposite to that of the present Pleistocene form.

Laajoki (2001) has suggested that gneiss outcrops on the shoreline near Karlebotn (Fig. 1) represent Neoproterozoic roches moutonnées. This is supported by a new observation of a likely wedge striation on the eastern side of the westernmost outcrop, which gives a westerly palaeo ice flow direction. Consequently, it is likely that all the gneiss hills northwest of Karlebotn represent Neoproterozoic roches moutonnées modified later by the Pleistocene glaciation and that the older and younger striation trends in Bigganjargga were formed by ice flowing to the northwest and west, respectively.

As the diamictite-filled fractures and hollows occur on the lee side of the Neoproterozoic roche moutonnée, plucking associated with the first Varangerian glaciation probably formed them. The knife-sharp edges of the fractures and gneiss fragments in Fig. 5c indicate that the ice froze on to the gneiss basement creating fractures which facilitated quarrying on the Neoproterozoic lee side. According to Sugden et al. (1992) plucking of a large roche moutonnée is favoured either by subglacial meltwater or thin ice near the margin. As the foot zone of the Neoproterozoic part of the Larajæg'gi outcrop is hidden under the Smalfjord Formation it is not possible to study this question closer. An additional favourable factor for ice-plucking is the orientation and frequency of pre-existing joints. The diamictite network in Figs. 5a & b indicates that the pre-Smalfjord joint system was non-systematic representing non-tectonic or exhumation jointing of a granitoid.

The elongated landforms on the Lewisian gneiss basement at the base of the Stoer Group, interpreted by Davison & Hambrey (1996, 1997) as Neoproterozoic roches moutonnées, resemble in some way the Larajæg'gi case. The main criteria used were the asymmetrical nature of the sediment distribution on opposite sides of the landforms, and the difference in morphology of the gneiss surface on which they lie (Fig. 4 in Davison & Hambrey 1996). This interpretation has been questioned by Stewart (1997) and Young (1999). Davison and Hambrey's (1996) photograph 3a shows an elongated gneiss ridge, the surface of which is so uneven and weathered that it cannot be considered as ice-smoothed. On the other hand, their Fig. 3b displays features, which, like the authors suggested, could represent glacially plucked bedrock of a lee side. One of the best proofs of Precambrian plucking is offered by the sub-Gowganda unconformity and associated breccias described by Mustard and Donaldson (1987a, b). Their studies and those of Davidson and Hambrey (1996) as well as the present work show that valuable palaeoglacial information can be obtained by studying ancient gneiss surfaces under known or suspected glacial units.

Conclusions

Originally, the Larajæg'gi outcrop represented a large Neoproterozoic roche moutonnée on the floor of the Varangerfjorden glacial palaeovalley, formed by a glacier flowing from the present east to the present west. The latest Pleistocene glacier moving from the opposite direction modified its upper part, with the consequence that the Neoproterozoic lee side was transformed to an unusually steep Pleistocene stoss side. The reverse geomorphology of the gneiss outcrop and the relict diamictite fills form the clearest evidence of this. Pleistocene plucking and later weathering processes have destroyed and modified that part of the Neoproterozoic stoss side exposed to erosion from below the Smalfjord Formation. Parts of it have, however, been preserved at the very foot of the Pleistocene lee side as smoothly rounded gneiss surfaces with convexo-concave geometry.

The inherited Neoproterozoic stoss side of the Larajæg'gi roche moutonnée is the most reliable indicator of the ice flow direction of the first Varangerian glaciation, which scoured the floor topography of the Varangerfjorden palaeovalley and abraded the younger Neoproterozoic striations at Bigganjargga and at other localities around Varangerfjorden (Rice & Hofmann 2000; Laajoki 2002).

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