RATES OF POSTGLACIAL ROCK WEATHERING ON GLACIALLY SCOURED OUTCROPS (ABISKO-RIKSGRÄNSEN AREA, 68°N)

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ABSTRACT. Ice-polished quartz veins, feldspar phenocrysts and quartzite layers were used as reference surfaces to assess the impact of Postglacial rock weathering in Lapland (68°N). Over 3200 measurements were carried out on *roches moutonnées* and glaciofluvially scoured outcrops distributed within three study areas covering 8 km^2. Inferred weathering rates demonstrate that 10 000 years of Holocene weathering did not significantly modify the geometry of Weichselian rock surfaces. However, rates of general surface lowering range from 1 to 25, depending on the rock type, with average values at 0.2 mm ka^{-1} for homogeneous crystalline rocks (irrespective of their acidity and grain size), 1 mm ka^{-1} for biotite-rich crystalline rocks, and 5 mm ka^{-1} for carbonate sedimentary rocks. Accelerated rates were recorded in weathering pits and along joints with values up to ten times higher than on the rest of the rock surface. Comparisons with cold and temperate areas suggest that solution rates of carbonate rocks are highly dependent on climate conditions, whilst granular disintegration of crystalline rocks operates at the same rate whatever the environment. It probably means that microgelivation is not efficient on ice-polished crystalline outcrops even under harsh climate conditions, and that granular disintegration proceeds under various climates from the same ubiquitous combination of biochemical processes. Last, the weathering state of Late-Weichselian *roches moutonnées* can be usefully compared to that of Preglacial tors of the nearby Kiruna area.

Introduction

Since Dahl's (1967) classic study in the Narvik Mountains of Norway, little attention has been paid to Postglacial microweathering of crystalline rocks in northern Scandinavia. More generally, weathering rates reported from Arctic areas are much scarcer than those published for temperate regions where there is greater concern regarding building deterioration (e.g. Trudgill *et al.* 1989; Philippon *et al.* 1992; Vicente-Hernandez *et al.* 1993; Mottershead 1997).

The need for new evaluations of the overall impact of Holocene weathering in the Arctic led the present author to apply Dahl's methods, based on the systematic use of glacial reference surfaces, to three main sites covering 8 km^2, located accross the Swedish-Norwegian border at approximately 68°N in an area deglaciated since about 10 000 BP. The selection of study sites in the Riksgränsen-Abisko region (Fig. 1) was supervised by Anders Rapp, and field measurements were carried out by the author during several field seasons at the Abisko Scientific Research Station (Royal Swedish Academy of Sciences). Partial results were published in three articles, each of them dealing with a specific rock type: Rombak granite (André 1995), carbonate rocks (André 1996a), amphibolite and quartzite (André 1996b).

The objectives of the present paper are: (1) a synthesis of Postglacial weathering rates inferred from three indicators: general bedrock surface lowering, deepening of weathering pits, widening of joints (for all investigated rock types); (2) a comparison of these rates with previous and ongoing results obtained on similar *roches moutonnées* in both cold and temperate areas; (3) a comparison, for one specific rock type (syenite), of weathering characteristics of the Postglacial *roches moutonnées* of the Riksgränsen Pass and of the Preglacial tors preserved on the nearby plateaus south of Lake Torneträsk.

Study area

The study area is located in northern Scandinavia at approximately 68°26'N, 18°18'E in the Scandes Mountains (Fig. 1A). This 8 km^2 area is divided into three main study sites distributed along the Kiruna–Narvik railway from west to east: Björnfjell, Vassijaure, Pallentjåkka, with two adjacent sites, one located at the mouth of Kärkevagge (Valley of Boulders), the other close to the Låktatjåkka railway station. Most of the area displays a typical 'knob and basin' topography with a succession of

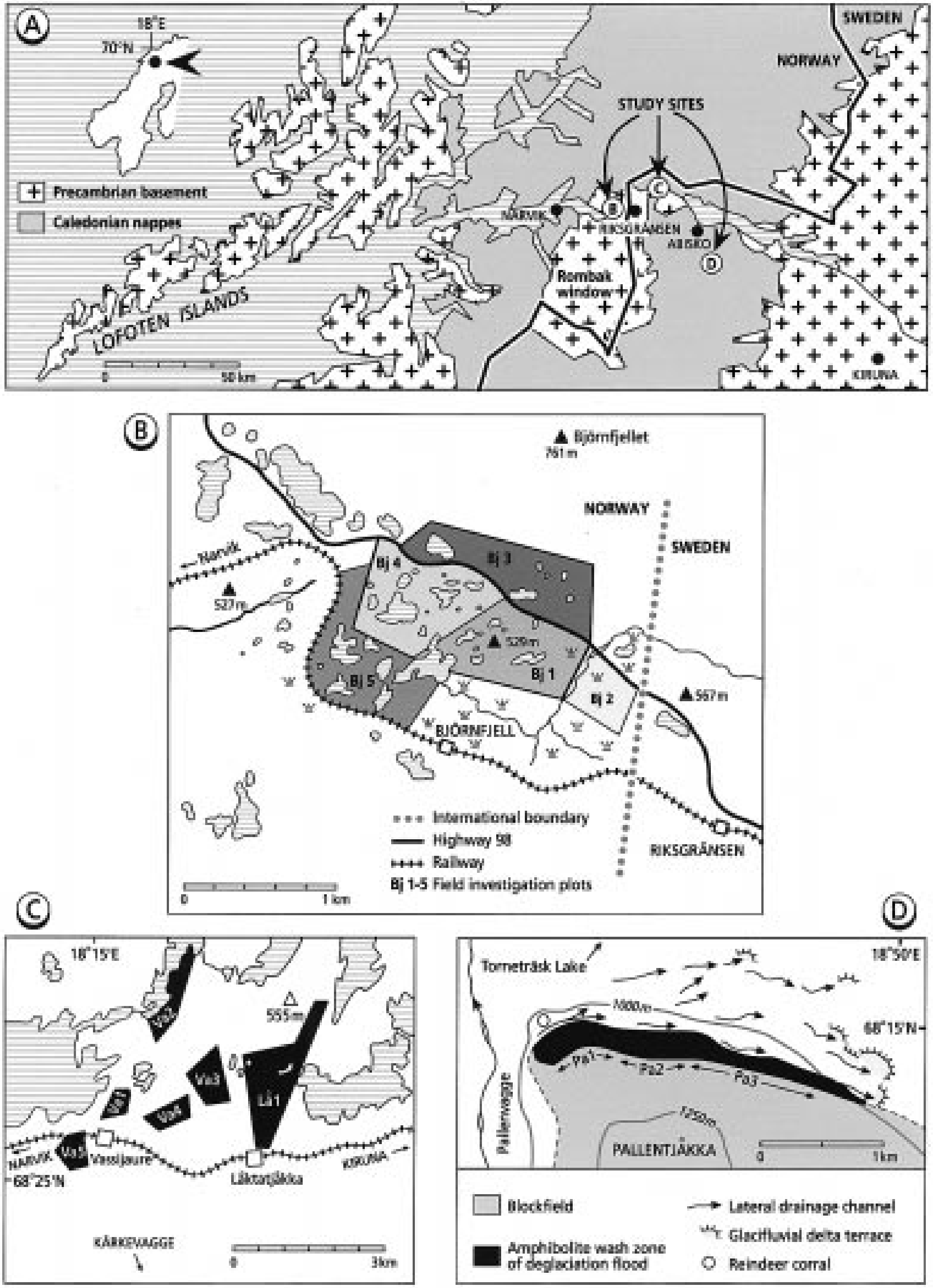

Fig. 1. Location maps: (A) general location of the study area; B) Björnfjell site; (C) Vassijaure site; (D) Pallentjåkka site.

Fig. 2. Ice-scoured granite surface deglaciated since 10 000 BP (Björnfjell-Riksgränsen area, 68°N).

glacially scoured outcrops, lakes and mires. Swarms of *roches moutonnées* cut in the Precambrian basement and the Caledonian allochthonous cover rocks show the classic asymmetry between smooth stoss sides, sloping gently eastwards, and fairly steep lee sides, 1–5 m, facing west. Erratics and glacial till composed of amphibolite, hard schist and pink granite of eastern origin are resting on top of the *roches moutonnées* which display glacial polish (Fig. 2), striations, grooves and plastically sculptured glacifluvial forms (‘P-forms’).

The Björnfjell study site (Fig. 1B) is located at 500 m a.s.l. on a pass between the Norwegian Rombak fjord and the Swedish Torneträsk basin, just above the upper limit of the birch forest (*Betula pubescens* f. *tortuosa*). In this subarctic environment (–11°C in January / +10°C in July at the nearby Riksgränsen weather station), most of the scoured outcrops are colonized by a lichen–cyanobacterial community including *Parmelia centrifuga*, *Lecidea lithophila*, yellow *Rhizocarpon*, *Umbilicaria* sp. and *Ophioparma ventosa* (previously *Haematomma ventosum*). Scattered till deposits support heath vegetation dominated by *Betula nana* and *Empetrum nigrum* ssp. *hermaphroditum*. Bedrock lithologies are those of the Precambrian basement of the Rombak window, with the main rock type called ‘Rombak granite’ in Norway and ‘Vassijaure granite’ in Sweden. It is a grey coarse-grained biotite granite or syenite displaying large phenocrysts of microcline. Local variations in grain size and biotite content can be observed, with biotite-rich xenoliths and leucocratic fine-grained banded migmatites. Most of the Rombak granite outcrops are intersected by aplite, quartz and pegmatite veins (Fig. 3; see below).

The Vassijaure study site (Fig. 1C) is located at an elevation of 500 m in a subarctic environment, with a mean annual temperature of –1.5°C, i.e. the same as in the above-mentioned weather station of Riksgränsen-Katterjåkk. Due to the proximity of the birch forest, the lichen-covered *roches moutonnées* tend to be colonized by a dry heath which makes the field investigations and measurements less easy than in the barren Björnfjell area. Bedrock geology at Vassijaure is highly diverse. The main rock type is a thinly foliated ‘hard schist’ (Holmquist 1910; Bax 1984), which is here referred to as ‘quartzophyllite’ for it displays light laminae dominated by quartz and albite and darker ones mainly consisting of chlorite, biotite and epidote. This quartzophyllite, which belongs to the Caledonian Abisko nappe, is interposed with layers of pure quartzite, micaceous phyllite, and dolomite. Moreover, Precambrian granite and syenite outcrops belonging to the Kuokkel window are also present and are composed of up to 60% alkali feldspar (Bax 1984).

The Pallentjåkka site (Fig. 1D) is located at an elevation of 1000 m in an arctic-alpine environment with a mean temperature of about –5°C extrapolated from the annual temperature of –0.9°C recorded at the nearby Abisko Station (390 m a.s.l.). Precipitation is more difficult to estimate because there is a strong climatic gradient within 30 km from oceanic to continental conditions: from 940 mm at the Norwegian border, the amount of precipitation falls

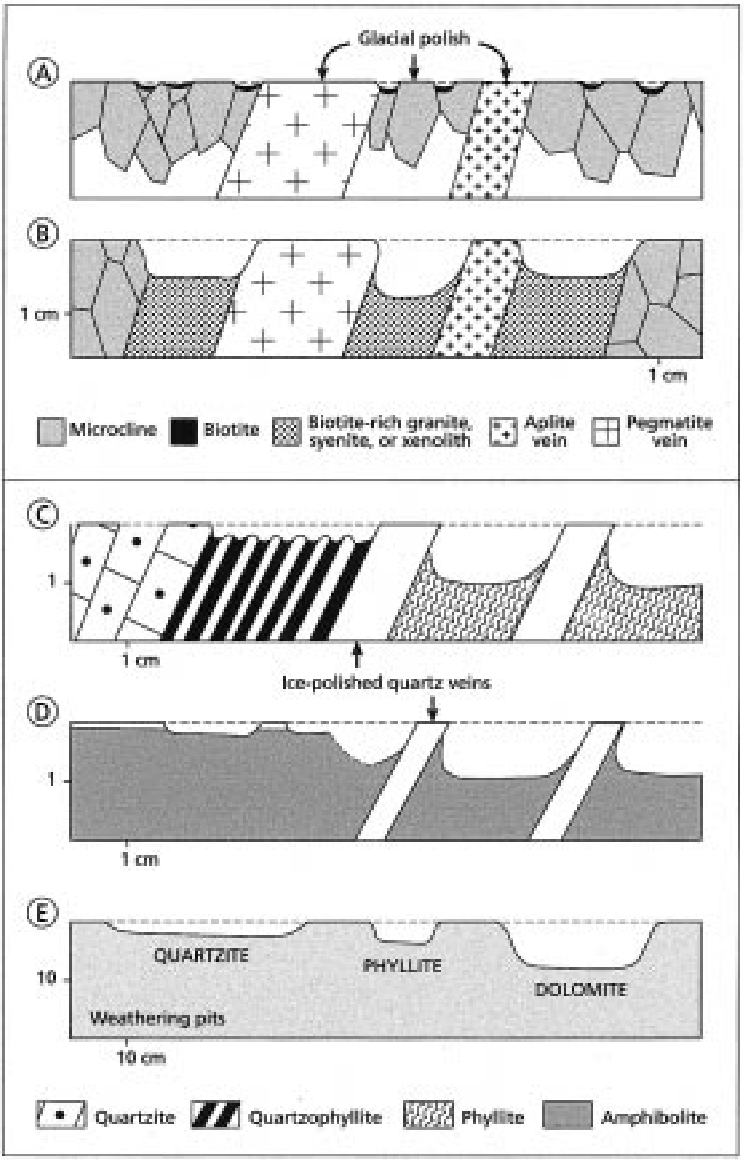

Fig. 3. Various patterns of Postglacial microweathering on top of late-Weichselian *roches moutonnées*. (A, B) Precambrian granite and syenite. (C, D) Caledonian quartzophyllite and amphibolite. (E) Cross-profiles of Postglacial weathering pits in various rock types. The dotted line corresponds to the glacial reference surface.

to 320 mm at the Abisko Station, so an estimation of 800 mm seems reasonable (Eriksson 1987; Holmgren, personal communication). About half of the precipitation in the study area falls as snow, with maximum snow depths of 1 m in March–April at the weather stations, but probably less at the individual study sites owing to the *roches moutonnées* morphology: the outcrops are extensively covered by foliose thalli of *Parmelia centrifuga* which is known to colonize snow-free sites (Ursing 1964). The Pallentjåkka site was described and interpreted by Rapp (1992) from a geomorphological point of view. It displays an amphibolite outcrop, 3 km long and 300 m wide, belonging to the Caledonian Seve nappe, which was exposed during the last deglaciation by catastrophic floods which washed off the overlying blockfield material which accumulated in a staircase of glaciofluvial delta terraces. The topography of this 1 km^2 'wash zone' is roughly conformal to the sheeting structure dipping northwestwards at 10–15°. The amphibolite mainly consists of hornblende, but is quartz-rich, fine-grained, thinly foliated and locally schistose, and includes thin veins (1–5 mm) and thicker amygdules of quartz (up to 5 cm).

Methods

In order to measure microweathering of *roches moutonnées* since the last deglaciation, the author strictly followed the procedure adapted by Dahl (1967) from Ljungner (1930), which is based on the search for reliable reference surfaces and chronological control.

In northern Sweden, 50 gyttja and peat samples from the Torneträsk basin provided radiocarbon ages ranging in Vassijaure-Abisko area from 10 820 ±110 to 8980 ±110 years BP (Sonesson 1974). More recently, Kleman (1992) proposed a global deglaciation model based on the existing chronological data. By combining the uncertainty of the ^{14}C method and the results of the GISP 2 ice core, he has more recently suggested 10 200 ± 500 years BP as a reasonable order of magnitude for the deglaciation of the study area (Kleman, personal communication). Moreover, Dixon *et al*. (2002) obtained an age of 10 300 ± 1300 yrs from cosmogenic ^{36}Cl dating of one of the *roches moutonnées* studied in the present paper, supporting our previous use of 10 000 BP as a rough chronological starting-point to evaluate the Postglacial weathering rates (André 1995, 1996b).

Reference surfaces used to measure the Postglacial microweathering mainly consist of glacially polished surfaces, which often display a yellowish colour and a shiny appearance (Fig. 2). The glacial polish is particularly well preserved on top of acid veins, mainly consisting of aplite and pegmatite. Veins less than 1 cm wide were avoided owing to their brittleness which caused their frequent failure as a result of the weathering experienced by surroundings rocks. Many quartz veins were not used because of the dense joint pattern affecting them which led to their destruction by macrogelivation. Tops of veins for which geometry after deglaciation was uncertain, were either avoided, or used cautiously based on Dahl's recommendations (see Dahl 1967, p. 157). In addition to veins, quartzite layers and microcline phenocrysts up to 4 cm long proved to be reliable indicators of the initial level of the deglaciated surface. Whilst conditions for measurements were optimal in the Björnfjell area, the dense lichen cover sometimes impeded both the identification of the reference surfaces and the observation of local petrographical variations in the Vassijaure area. It must be added that the Pallentjåkka 'wash zone' does not offer reference surfaces as smooth as the *roches moutonnées* because it corresponds to an irregular weathering front which was cleaned from its overlying loose material. It nevertheless presents quartz veins with a shining polished surface probably inherited from fluvioglacial floods. The local existence of quartzic surfaces of listric origin is assumed, but it seems reasonable to also use them as reference surfaces because they most probably coincide with the weathering front exposed during the deglaciation flooding events.

The use of very simple field equipment was dictated by the necessity to cover as extensively as possible the 8 km^2 study area to obtain representative orders of magnitude of Postglacial microweathering. The use of a laser gauge probe has proven to be most useful in other micromapping studies of rock surfaces (Swantesson 1992, p. 277), but could not be considered for the global evaluation of Holocene weathering. The equipment was therefore directly inspired by Dahl (1967) and comprised metal rulers of various sizes and a caliper equipped with a thin rod for penetrating into holes of approximately 1 mm in diameter; the accuracy of measurements was 0.1 mm. When possible, the caliper alone was used, a part of it resting on top of the vein, while the pointed rod moved down to the weathered surface. In other cases, a large and rigid ruler was placed straight across the vein and the measurement was made with another ruler or the caliper. The number of measurements for each vein depended on its length and the conditions.

On the whole, over 3200 measurements were made, including: 1550 to estimate the Postglacial *deterration*, i.e. 'the lowering of bedrock surfaces owing to micro-weathering and removal of the weathering products' (Dahl 1967, p. 155); 820 to evaluate the widening rate of joints; and 840 to measure the dimensions of Postglacial weathering pits.

Tripartite bedrock lowering

Since 10 000 BP, the geometry of glacially scoured bedrock surfaces seems to have been very well preserved in northern Scandinavia, especially in granite and metamorphics. On the whole, Postglacial weathering rates range from 0.2 to 5.0 mm ka^{-1} (i.e. from 1 to 25) depending on the rock type (Table 1 and Fig. 3).

Table 1. Rates of Postglacial surface lowering (based on 1550 measurements) in various rock types.

Rock type	Study site*	Rates of Postglacial weathering (mm ka^{-1}) mean	mini/maxi
Amphibolite	Pa 1	0.4	0.2–1.3
	Pa 2	0.3	0.1–1.0
	Pa 3	0.3	0.1–0.8
Quartzophyllite and Quartzite	Va 2	0.2	0.1–0.5
	Va 3	0.2	0.1–0.5
	Va 4	0.2	0.1–0.7
Acid granite and Syenite	Bj 1	0.3	0.0–1.2
	Bj 2	0.2	0.1–0.4
	Bj 3	0.1	0.0–0.5
	Bj 4	0.2	0.0–0.5
	Bj 5	0.2	0.0–0.9
	La 1	0.2	0.1–0.5
	Va 5	0.1	0.0–0.5
Biotite-rich granite and Syenite	Bj 1	2.6	0.8–6.0
	Bj 2	1.0	0.7–1.9
	Bj 3	0.8	0.2–2.3
	Bj 4	1.2	0.3–5.6
	Bj 5	1.1	0.4–6.5
	La 1	0.8	0.3–1.8
	Va 1	1.0	0.2–3.2
	Va 5	1.4	0.3–5.2
Phyllite	Va 2	0.5	0.2–2.0
	Va 3	0.8	0.5–1.5
	Va 4	0.9	0.2–2.5
Dolomite	Kä 1	5.5	2.0–12.8
	Va 4	5.2	1.4–13.7

*Pa, Pallenjåkka; Va, Vassijaure; Bj, Björnfjell; La, Låktatjåkka; Kä, Kärkevagge.

Leucocratic crystalline rocks

This group of rocks, which includes granite, syenite, metaquartzite and quartzic amphibolite, appears to be very resistant, with average weathering rates at only 0.1 to 0.3 mm ka^{-1}, which means a millimetric Postglacial bedrock lowering. In particular, pure quartzite layers appear almost intact and often display very well preserved glacial grooves and striations which can be used as reference surfaces for evaluating the lowering of the surroundings rocks; even the finest striations are visible below the pellicular crustose lichen or cyanobacterial cover, as they are on top of pegmatite and aplite veins which represent special types of acid granite.

Biotite-rich crystalline rocks

This second group of rocks, including all of the biotite-rich crystalline rocks, underwent a centimetric Holocene surface lowering, with average weathering rates usually ranging from 0.8 to 1.5 mm ka^{-1}. In the Precambrian basement, the biotite-rich outcrops of Rombak granite display a pitted surface due to the removal of biotite flakes, and the biotite-rich pegmatite veins locally display genuine honeycombs with pits up to 4 cm wide and 1 cm deep that are colonized by mosses and black lichens and cyanobacteria. In the Caledonian 'hard schist', biotite, chlorite and sericite-rich phyllites often display a rippled surface due to microweathering which totally erased most of the glacial grooves and striations. A centimetric surface lowering was also inferred from additional scarce measurements on garnet micaschist in the nearby Slåttatjåkka and Kärketjårro sites, which yielded rates of 1.1 to 2.0 mm ka^{-1}. However, the similarity of these rates with those found in the Vassijaure and Björnfjell sites might only be coincidental and result from contrasting mineralogical and exposure

Table 2. Dimensions of weathering pits (840 measurements) formed since 10 000 BP on top of *roches moutonnées*.

Rock type	Study site	Depth (cm)		Width (cm)		Length (cm)	
		mean	mini–maxi	mean	mini–maxi	mean	mini–maxi
Quartzophyllite	Va 2	2.2	2.0–2.5	22	13–33	50	28–61
	Va 4	2.3	1.2–5.6	28	13–59	45	17–83
Acid granite and Syenite	Bj 1	2.2	1.0–3.5	31	11–84	45	19–102
	Bj 2	2.5	1.5–5.5	35	15–96	65	30–172
	Bj 3	2.1	0.5–4.0	29	8–56	45	9–107
	Bj 4	2.1	0.4–4.7	26	12–112	58	18–226
	Bj 5	1.3	0.4–4.3	26	7–84	53	11–214
	La 1	2.4	1.2–5.7	12	8–31	38	23–75
	Va 5	1.8	0.8–2.9	15	8–29	28	16–66
Biotite-rich granite and syenite	Bj 1	2.8	2.0–3.5	16	8–30	30	22–45
	Bj 3	3.9	2.5–5.5	26	14–39	41	25–54
	Bj 4	3.2	2.0–5.0	24	12–42	60	19–94
	Bj 5	3.7	1.9–5.1	16	8–48	32	18–77
Phyllite	Va 3	3.8	2.3–4.4	8	3–20	33	12–81
Dolomite	Va 4	7.0	6.0–8.2	18	17–19	42	21–73

times: the dominant phyllitous mineral of garnet micaschist is muscovite (which is more resistant than biotite) and the higher altitude of the two additional sites suggests an earlier deglaciation and therefore a potentially longer exposure time.

Carbonate sedimentary rocks

The third group of rocks includes carbonate rocks which are susceptible to solution processes. In the Vassijaure area and at the mouth of Kärkevagge, dolomite layers interbedded with quartzophyllite are systematically excavated except when dolomite is hardened by a dense network of quartz veins. On nearly horizontal surfaces as well as on the steep lee side of *roches moutonné*es where they form small shelter-caves, the Postglacial retreat of dolomite layers ranges from 15 to 130 mm and averages 50 mm. Therefore, the mean solution rate of dolomite calculated for the last 10 000 years exceeds 5 mm ka^{-1}.

On the whole, solution processes affecting carbonate rocks appear up to 25 times more efficient than the combination of processes involved in the granular disintegration of acid crystalline rocks. Such a contrast between metamorphics and carbonate sedimentary rocks can also be found among erratics of the Pallentjåkka and Slåttatjåkka areas. Whilst quartzite erratics are unweathered, many dolomite erratics display centimetric solution pits and incipient *Rinnenkarren*. Within the crystalline rocks, the biotite (and chlorite) content seems to be the main factor controlling the susceptibility to weathering. As long as the biotite content of the bedrock remains low, glacial polish and striations have been preserved since 10 000 BP irrespective of the bedrock grain size. In biotite-rich granite, syenite and metamorphics, weathering rates are five to ten times higher than in the similar leucocratic varieties. The very low weathering rates of amphibolite, can be explained both by its high quartz content and the textural homogeneity of this rock type.

Postglacial microforms

In addition to the general bedrock lowering, the depth of weathering pits and the width of joints can be used as measures of the Postglacial surface denudation.

Weathering and solution pits

A summary of the dimensions of pits excavated by weathering and debris removal since 10 000 BP at the surface of glacially scoured outcrops is provided in Table 2. As underlined by Delmas (1998) in the eastern French Pyrénées, the shape of pits is highly dependent on local configurations which account for the variability of lengths and widths within the same rock type (e.g. from 9 to 226 cm in length for granite in our study area). In contrast, the depth measurements appear more significant in so far as the three groups of rocks previously distinguished can be found again. In leucocratic crystal-

Fig. 4. Shallow weathering pits in quartzophyllite of the Vassijaure area. Note the glaciofluvially scoured surface and the granite erratics on top of the photograph. Hammer for scale is 30 cm.

line rocks (quartzite, granite, syenite), weathering pits are very shallow (2 cm on average, see Fig. 4) whilst in biotite-rich varieties, their depth is almost double that amount. Solution appears once more as the most efficient weathering process with Postglacial solution pits as much as 8 cm deep in dolomite (and probably more). In the Pallentjåkka amphibolite, no weathering pits were clearly identified, mainly because of the gradient slope of the 'wash zone', at 10–15°, which prevents the formation of such pits.

Widened joints

In contrast to the widely opened joints (5–20 cm wide and 100 cm deep) observed in some wet locations undergoing frost heave processes, the opening of joints due to Postglacial microweathering has been negligible on top of *roches moutonnées* and glaciofluvially scoured outcrops (Table 3). In quartzic amphibolite, the joint width averages 1 mm whilst in quartzophyllite a mean width at 3 mm hides a strong contrast between pure quartzite (opening of joints almost nil) and phyllite (joint width at 3 cm). This last value is close to the average width found in biotite granite (2.5 cm) which is more susceptible to granular disintegration than quartzite.

Comparison with previous results

The Postglacial weathering rates reported above can be usefully compared with previous evaluations made in similar sites investigated in Arctic and Alpine areas, as well as in southeastern Scandinavia and Canada. Another meaningful comparison can be made between the weathering conditions of the fresh *roches moutonnées* of the Riksgränsen Pass – Torneträsk basin examined in the present paper and of the old tors preserved below the cold-based Scandinavian ice sheet on the nearby Aurivaara plateau (André 2002).

Climatic control of solution rates of carbonate rocks in cold areas

Ice-scoured limestone pavements have previously yielded estimates of Holocene solution rates in various Arctic and Alpine environments, which permits the 5 mm ka^{-1} rate found in northern Sweden

Table 3. Width of joints (820 measurements) opened by Postglacial microweathering in various rock types.

Rock type	Study site	Width of joints (cm) mean	Width of joints (cm) mini–maxi
Amphibolite	Pa 1	0.1	0.0–0.6
	Pa 2	0.1	0.0–1.0
	Pa 3	0.1	0.0–0.5
Quartzophyllite	Va 2	0.3	0.1–3.2
	Va 4	0.3	0.1–2.5
Granite	Bj 1	2.5	0.8–6.0
	Bj 2	3.0	0.5–12.0
	Bj 3	2.7	0.2–14.0
	Bj 4	2.3	0.5–11.0
	Bj 5	2.8	0.1–10.0

to be placed within the general framework of an Arctic/Alpine diagonal extending from Spitsbergen to the uplands of New Guinea (Maire 1990; André 1996b). Within this 'cold diagonal', solution rates in carbonate rocks (limestone and dolomite) range from 2.5 to 32.0 mm ka^{-1} and their distribution is primarily controlled by the water availability related to the precipitation amount. Arctic environments like Spitsbergen with annual precipitation of 400 mm show very low solution rates (less than 3 mm ka^{-1}) according to Åkerman (1983) and André (1993). Subarctic environments with precipitation around 700 mm like Quebec and northern Sweden are characterized by low solution rates, on the order of 6 mm ka^{-1} (Dionne and Michaud 1986; André, this study). Temperate high mountains like the Swiss, Austrian and French Alps receive on average 2500 mm of precipitation and provide fairly high solution rates of 15 mm ka^{-1} (Bögli 1961; Bauer 1964; Maire 1990). The highest solution rates (32 mm ka^{-1}) are yielded by the equatorial mountains of New Guinea which receive 4000 mm of annual precipitation (Peterson 1982).

Similarity of weathering rates of crystalline rocks in cold and temperate inland areas

In our study area, average Postglacial weathering rates of granite and metamorphics range from 0.2 to 1.2 mm ka^{-1} which appears consistent with rates of 1 mm ka^{-1} found by Dahl (1967) in the nearby Narvik Mountains. More surprisingly, such rates are similar to those found both in the lowlands of southern Canada and southern Sweden, i.e. in temperate environments. In the Late-Wisconsinian *roches moutonnées* of the Sherbrooke area (Quebec), Clément *et al.* (1976) found weathering rates ranging from 0.5 to 1.2 mm ka^{-1} for various metamorphics, with the lowest rates in quartzitic sandstone. In the Göteborg area (S Sweden), weathering rates reported by Lindberg and Brundin (1969) and Rudberg (1970) for micaschist and gneiss reach 1.5 mm ka^{-1}, i.e. the same as in the Lapland biotite-rich metamorphics. Swantesson (1989), who published an extensive study of Holocene weathering phenomena in central and southern Sweden, reports a 2 cm widening of joints in granodiorite gneiss, which is similar to results obtained in the Rombak granite of northern Scandinavia. Depths of Postglacial weathering pits in granitic and gneissic *roches moutonnées* reach 1 to 3 cm in various environments such as Arctic Labrador (André 1982), subarctic Scandinavia (André, this study) and temperate mountains like the Irish Derryveagh Mountains (Sellier 1998) and the French eastern Pyrénées (Delmas 1998).

Such similar weathering rates, reported from contrasting climatic regions, suggest that azonal biological agents might play a prominent role in the complex interplay of processes involved in the breakdown of crystalline rocks. The disrupting action of endolithic lichens has already been demonstrated on micaschist of Antarctica (Ascaso *et al.* 1990) and on sandstone of Ellesmere Island (Eichler 1981). Moreover, the role of chasmolithic algae in granite breakdown was firmly established in Alaska (Hall and Otte 1990). In northern Scandinavia as in the temperate mountains and lowlands, the biofilm consisting of lichens, algae, fungi and/or bacteria, combined with the hydrolysis chemical reactions and/or the mechanical effect of wetting–drying cycles, might result in a similarly slow granular disintegration of the glacially scoured outcrops. In the study areas of northern Scandinavia, fragments of feldspar crystals and biotite flakes were found embedded in the thalli of *Parmelia centrifuga* and *Ophioparma ventosa* (André 1995). The lichen cover on *roches moutonnées* often reaches 75% and the seldom fresh scars of newly exposed bedrock are obviously linked to the decay of lichen thalli. Whilst field investigations provide evidence for biogenic disintegration, none could be found to support the action of microgelivation (which is not surprising owing to the low porosity of crystalline rocks).

Postglacial versus Preglacial weathering in north Scandinavia

The very superficial impact of Holocene weathering affecting the Late-Weichselian glacial outcrops strongly contrasts with the evolution of tor-like features which consist of the same syenitic rock type and which are located on mountain tops surrounding the Torneträsk basin. While the *roches moutonnées* of the Riksgränsen-Abisko area display joints 2 cm wide, the best preserved tors of the Aurivaara plateau display joints up to 150 cm in width (Table 4) which are filled with glacial till and erratics at various weathering stages. Moreover, microscope examination of thin sections shows a marked contrast between the very fresh material of the glacial outcrops and the widespread diffusion of iron oxides through the microjoint network and the cleavage planes of minerals in bedrock comprising the tors. In addition, pyroxenes are often uralitized

Table 4. Time-dependent joint widening: sharp contrast between late-Weichselian roches moutonnées at Riksgränsen and preglacial tors at Aurivaara in the same syenitic rock type (Norwegian and Swedish Lapland).

Location	Geomorphic feature	Width of joints (mm)		Source
		mean	mini–maxi	
Riksgränsen-	roche moutonnée	2.5	0.8–6	André,
Björnfjell, 68°N	roche moutonnée	3.0	0.5–12	(1995)
(Norwegian Lapland)	roche moutonnée	2.7	0.2–14	
	roche moutonnée	2.3	0.5–11	
	roche moutonnée	2.8	0.1–10	
	roche moutonnée	2.7	0.4–11	
Aurivaara, 68°N	tor root shaped into a			
(Swedish Lapland)	roche moutonnée	4	0.5–22	André,
		4	0.5–28	(2002)
	ice-scoured tor root	7	1–40	
	tor with 'woolsack'			
	morphology	16	5–80	
		13	3–47	
		12	3–51	
		12	3–93	
	tor with weathered			
	spalling corestones	13	3–145	
		21	2–144	
		21	4–153	

(André 2002). Microforms are unfortunately not preserved on the investigated tors because most of them have had their tops removed by glacial erosion. However, in similar sites in the Scottish Highlands, preglacial granite tors are known to display weathering pits up to 200 cm deep (Ballantyne 1994) while granite *roches moutonnées* of northern Scandinavia display only incipient pits, 2 cm deep (Table 2, see above).

Conclusions

In northern Scandinavia, the systematic use of glacial reference surfaces (3200 measurements) provides new insights into the weathering effects of the Holocene on various lithologies within the same subarctic environment. On the whole, five main conclusions are drawn from the present study.

- The overall Postglacial microweathering is pellicular and does not significantly modify the geometry of the glacially scoured outcrops: such a low geomorphic impact is in sharp contrast with the effects of the long-lasting weathering which affected the pre-Quaternary tors preserved below cold-based ice sheets on the surrounding plateaus.
- A tripartite bedrock surface lowering rate is found: 0.2 mm ka^{-1} for homogeneous crystalline rocks whatever their acidity (from quartzite to amphibolite) and grain size (from aplite to pegmatite); 1 mm ka^{-1} for biotite-rich crystalline rocks; 5 mm ka^{-1} for carbonate sedimentary rocks.
- An accelerated weathering rate is found in some microenvironmental settings where joint widening and weathering pit deepening were observed: rates as much as ten times higher than on the rest of the rock surface.
- Solution of carbonate lithologies proceeds five to 25 times more rapidly than granular disintegration of granite and metamorphics, which is in accordance with results of a recent field experiment carried out by Dixon *et al.* (2001) in the nearby site of Kärkevagge: freshly crushed fragments of dolomite and granite were exposed at the soil surface during a five-year observation period, resulting in an annual weight loss 5.7 times higher in dolomite than in granite (0.40% against 0.007%).
- The increase in solution rates from Arctic Scandinavia to the New Guinea Alps suggests that solution rates are primarily controlled by the precipitation amount. In contrast, rates of granular

disintegration of crystalline rocks are apparently controlled by factors other than climate as weathering rates are similar from the Arctic to southern Europe and Canada, irrespective of precipitation and temperature conditions.

This last conclusion is of particular interest for it suggests that microgelivation is not efficient on ice-polished crystalline outcrops. Instead, granular disintegration might proceed in various environments from the same chemically and biologically driven combination of processes. The significance of biogenic weathering has long been underestimated in Arctic environments and should be re-evaluated (Etienne 2001). The ubiquity of biofilms consisting of lichens, algae, fungi and/or bacteria at the surface of glacially scoured outcrops might explain why microweathering rates are similar from Arctic Norway to the lowlands of southern Canada. Moreover, it seems from ongoing studies that, in some cases, rates of granite microweathering are even higher in temperate than in cold areas (Delmas 1998; Sellier 1998). It might result from a longer vegetative period in southern areas. But other controlling factors should be considered such as the nature (and efficiency) of the different colonizing communities, and the local moisture conditions which influence the number of wetting–drying cycles affecting the thalli and mucilages.

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References

Åkerman, J., 1983: Notes on chemical weathering, Kapp Linné, Spitsbergen. Proceedings of 4th International Permafrost Conference. Calgary. 10–15.

André, M.F., 1982: Reconnaissance géomorphologique dans les socles des hautes latitudes: l'exemple du Nord du Labrador. Thèse de 3e cycle, Univ. of Paris-Sorbonne (unpublished). 357 p.

— 1993: Les versants du Spitsberg – approche geôgraphique des paysages polaries. Presses Universitaires de Nancy, Nancy, 361 p.

— 1995: Postglacial microweathering of granite *roches moutonnées* in northern Scandinavia (Riksgränsen area, 68°N). *In*: Slaymaker, O. (ed.): Steeplands Geomorphology, Wiley. Chichester. 103–127.

— 1996a: Vitesses de dissolution aréolaire postglaciaire dans les karsts polaires et haut-alpins (de l'Arctique scandinave aux Alpes de Nouvelle-Guinée). *Revue d'Analyse Spatiale Quantitative et Appliquée*, 38–39: 99–107.

— 1996b: Rock weathering rates in arctic and subarctic environments (Abisko Mts, Swedish Lapland). *Zeitschrift für Geomorphologie*, 40(4): 499–517.

— 2002: Geomorphic evidence for recurrent cold-based ice conditions in Nordic uplands during the Quaternary glaciations (Aurivaara Plateau, North Sweden). *Norsk Geografisk Tidsskrift*, 56: 74–79.

Ascaso, C., Sancho, L.G. and Rodriguez-Pascual, C., 1990: The weathering action of saxicolous lichens in maritime Antarctica. *Polar Biology*, 11: 33–39.

Ballantyne, C.K., 1994: Scottish landform examples- 10. the tors of the Cairngorms. *Scottish Geographical Magazine*, 110(1): 54–59.

Bauer, F., 1964: Kalkabtragungsmessungen in den österreichischen Kalkhochalpen. *Erdkunde*, 8: 95–102.

Bax, G., 1984: Geologie des Tornehamngebietes am Westufer des Torneträsk, Schwedisch-Lapland. Diplomarbeit. Marburg/Lahn, 142 p.

Bögli, A., 1961: Karrentische–ein Beitrag zur Karstmorphologie. *Zeitschrift für Geomorphologie*, 5(3): 185–193.

Clément, P., Landry, B. and Yergeau, M., 1976: Déchaussement postglaciaire de filons de quartz dans les Appalaches québécoises (région de Sherbrooke, Canada). *Geografiska Annaler*, 58A(1–2): 111–114.

Dahl, R., 1967: Postglacial micro-weathering of bedrock surfaces in the Narvik district of Norway. *Geografiska Annaler*, 49 A: 155–166.

Delmas, M., 1998: Le massif du Carlit, étapes de la déglaciation et dynamiques holocènes. Mémoire de DEA. Univ. de Provence. 144 p.

Dionne, J-C. and Michaud, Y., 1986: Note sur l'altération chimique en milieu périglaciaire, Hudsonie, Québec subarctique. *Revue de Géomorphologie Dynamique*, XXXV(3): 81–92.

Dixon, J.C., Thorn, C.E., Darmody, R.G. and Campbell, S.W., 2002: Post-glacial rock weatering processes on a roche moutonnée in the Riksgränsen area (68°N), northern Norway. *Norsk Geografisk Tidsskrift – Norwegian Journal of Geography*, 56 (4).

Dixon, J.C., Thorn, C.E., Darmody, R.G. and Schlyter, P., 2001: Weathering rates of fine pebbles at the soil surface in Kärkevagge, Swedish Lapland. *Catena*, 45: 273–286.

Eichler, H., 1981: Kleinformen der hocharktischen Verwitterung im Bereich der Oobloyah Bay, N-Ellesmere Island, N.W.T., Kanada–Formengenese und Prozesse. Results of the Heidelberg Ellesmere Island Expedition (D. Barsch and L. King, eds), *Heidelberger Geographische Arbeiten*, 69: 465–486.

Eriksson, B., 1987: The precipitation climate of the Swedish fells during the 20th century, some remarkable features. *In*: Alexandersson H. and Holmgren B. (eds): Climatological extremes in the mountains, physical background, geomorphological and ecological consequences. Uppsala Naturgeografiska Institution, UNGI Rapport 65: 105–114.

Etienne, S., 2001: Les processus de météorisation des surfaces volcaniques en Islande–approche épistémologique de la géomorphologie des milieux froids. PhD Thesis, University of Paris-Sorbonne. 477 p.

Hall, K. and Otte, W., 1990: A note on biological weathering on nunataks of the Juneau icefield, Alaska. *Permafrost and Periglacial Processes*, 1: 189–196.

Holmquist, P.J., 1910: Die Hochgebirgsbildungen am Torne Träsk in Lapland.–*Geol. Fören. Förhandl.*, 32(4): 913–983.

Kleman, J., 1992: The palimpsest glacial landscape in Northwestern Sweden. *Geografiska Annaler*, 74A(4): 305–325.

Lindberg, L. and Brundin, T., 1969: Postglacial mikrovittring. Mätningar av kvartsgångar på Tjörn. Unpublished seminar paper. Göteborgs Universitet, Naturgeografiska Institutionen. 1–42.

Ljungner, E., 1930: Spaltentektonik und Morphologie der schwedischen Skagerrat-Küste, III.1. *Bulletin of the Geological Institute of the University of Uppsala*, 21.

Maire, R., 1990: La haute montagne calcaire.–Thèse de doctorat d'Etat. Karstologia, Mémoires, 3. 731 p.

Mottershead, D.N., 1997: A morphological study of greenschist weathering on dated coastal structures, South Devon, UK. *Earth Surface Processes and Landforms*, 22: 491–506.

Peterson, J.A., 1982: Limestone pedestals and denudation estimates from Mt Jaya, Irian Jaya. *Australian Geographer*, 15: 170–173.

Philippon, J., Jeannette D. and Lefevre, R.A., (eds): 1992: La conservation de la pierre monumentale en France. Presses du CNRS. Paris. 270 p.

Rapp, A., 1992: Kärkevagge revisited. Field excursions on geomorphology and environmental history in the Abisko mountains, Sweden. *Sveriges Geologiska Undersökning*, Ser. Ca 81: 269–276.

Rudberg, S., 1970: Naturgeografiska seminarieuppsatser vid Göteborgs universitet höstterminen 1959–vårterminen 1969. *Meddelanden från Geografiska Föreningen i Göteborg, Gothia*, 10: 1–172.

Sellier, D., 1998: Significations de quelques marqueurs des rythmes de la météorisation des granites en milieu tempéré océanique. *Cahiers Nantais*, 49: 87–110.

Sonesson, M., 1974: Late Quaternary forest development of the Torneträsk area, North Sweden: 2. Pollen analytical evidence. *Oikos*, 25: 288–307.

Swantesson, J.O.H., 1989: Weathering phenomena in a cool temperate climate. PhD thesis., University of Göteborg, UNGI Rapport 28. 193 p.

— 1992: Recent microweathering phenomena in southern and Central Sweden. *Permafrost and Periglacial Processes*, 3: 275–292.

Trudgill, S.T., Viles, H.A., Inkpen, R.J. and Cooke, R.U., 1989: Remeasurement of weathering rates, St Paul's cathedral, London. *Earth Surface Processes and Landforms*, 14: 175–196.

Ursing, B., 1964: *Svenska växter i text och bild–Kryptogamer*. Nordisk Rotogravyr. 530 p.

Vicente-Hernandez, M.A., Molina Ballesteros, E. and Rives Arnau, V., (eds): 1993: Alteracion de granitos y rocas afines–Deterioro de monumentos historicos. Actas del workshop, Avila, 5–7 November 1991. Consejo superior de investigaciones cientificas. Madrid. 190 p.

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