Rock Weathering in Central Spitsbergen and in Northern Victoria Land (Antarctica)

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Abstract

Field studies carried out at Longyearbyen (Spitsbergen, 78º 13' N, 15º 36' E) and at Terra Nova Bay (Antarctica, 74° 41' S, 164° 07' E) question the role of frost action as an efficient rock weathering agent. By carrying out measurements of rock temperature, rock moisture content and Young's modulus variations in both locations, differences between these environments are explained in terms of climate, rock properties and the implications of these properties on the weathering processes involved. The large variability of polar environments, and its repercussions on particular geomorphological processes like rock decay, are highlighted.

1 INTRODUCTION

In periglacial research, the expression *cryogenic weathering* is used to refer to the "combination of mechanico-chemical processes which cause the *in situ* breakdown of rock under cold-climate conditions" [1: p. 40]. Strong evidence indicates that frost action is not the only weathering process leading to rock decay in polar regions [1]. Other processes , such as pressure release, salt weathering, chemical weathering, biological activity or thermal shocks (i.e., temperature variations of at least 2ºC/minute whose repetition leads to thermal fatigue) may play a determinant role. The efficiency of frost as a rock decay agent and the type of damage induced depend indeed on rock properties, temperature conditions (freezing intensity, rate and duration; number of freeze-thaw cycles) and rock moisture content [2]. The lack of field data on rock temperature and moisture conditions has been for a long time an obstacle to better understanding weathering processes and conducting realistic laboratory simulations. Studies presenting rock temperature data in polar [3][4][5][6] or alpine [7] environments remain rare, particularly when considering all-year high-frequency monitoring. Rock moisture content has a major control on frost shattering [8], but it is the least monitored parameter in field studies. Rock moisture monitoring has been carried out in Greenland [9], in the maritime Antarctic [10] and in southern Canada [11], but most of the published research concerns punctual or short-term measurements.

The present study emphasises the complexity of rock weathering in two particular polar environments: the area of Longyearbyen, in central Spitsbergen (78º 13' 38" N, 15º 36' 00" E) and the area of Terra Nova Bay, in Northern Victoria Land, Antarctica (74° 41' 42" S, 164° 07' 23" E). These two locations present different characteristics in terms of geology, glacial history and climate (Table 1), although both field sites are subjected to arid conditions and are located on continuous permafrost. Previous work considered both areas as characterised by low shattering rates [1]. The present study assesses the impact of different polar environments on the type and intensity of weathering processes involved by carrying out similar measurements of rock temperature and moisture content and by estimating rock weathering rates through non-destructive determination of the dynamic Young's modulus variations of exposed rock tablets. The modulus of elasticity (or Young's modulus) expresses the rock stiffness and has been used successfully as a weathering evolution indicator [8][12].

	Longyearbyen	Terra Nova
Mean annual air temperature	-5.8 ºC	-14.7 ºC
Mean temperature of the coldest month	-15.2 ºC	-22 to -25 ºC
Mean temperature of the warmest month	+6.2 ºC	+3 to +5 ºC
Annual precipitation (in water equivalent)	about 200 mm	270 mm

Table 1. Climate data from Longyearbyen and Terra Nova Bay. Refer to text for explanations.

2 CENTRAL SPITSBERGEN

2.1 Temperature and rock moisture conditions

In Longyearbyen, the mean annual air temperature is -5.8 ºC for the period 1975 – 2000, as measured at the airport weather station located 3 km away from the field site (Table 1). The coldest month is February (-15.2 ºC), while July is the warmest month (+6.2 ºC). The precipitation measured at sea level is low (Table 1). Snow is the dominant type of precipitation. At sea level, a persistent snow cover is usually registered from late September to late May.

Rock temperature is measured on boulders and on a NNE-facing rockwall, both close to sea level. This 25 m high rockwall is characterised by a tectonically undisturbed succession of sandstones and laminated shales (Carolinefjellet Formation, Lower Cretaceous). These rocks contain some salts linked to their marine origin. Salt outbursts can locally cover some rock beds during dry summer periods and lead to local rock surface induration and/or desquamation.

The sandstone temperature is monitored at depths of 40 cm, 10 cm and just below the rock surface. The rock experiences numerous and sometimes considerable temperature fluctuations, even during the polar winter. Rock surface temperature (Fig. 1) crosses the 0 ºC threshold in the autumn and in the spring (as also reported from north-facing rockwalls in the Alps [7]). Temperature came very close to 0 ºC several times during the polar winter, due to milder weather conditions, and even was positive in December 2002 while Spitsbergen experienced exceptionally warm conditions with positive air temperatures for several days in a row. The freezing of the rock surface in the autumn and its melting in the spring bring along several freeze-thaw cycles close to the rock surface, particularly in the spring (8 cycles in autumn 2001 and 9 cycles in autumn 2002; 29 cycles in spring 2002). The amplitude of temperature variations decreases from the surface downwards due to thermal dampening. At 40 cm depth, the rock freezes once in the autumn and remains frozen for the whole winter. During the Arctic summer, rock surface temperature is continuously positive, as reported also from Ellesmere Island [4].

When the sky is clear, the sun shining directly on the rock in the early morning causes an abrupt temperature rise close to the surface, where the rock can be as warm as 30 ºC. Such sharp rock temperature variations have been reported in other cold environments, such as the French Alps [7] and the Karakoram [13]. Nevertheless, these short events generally do not constitute thermal shocks, as they do not reach a temperature variation rate of 2 ºC/minute. Only a very few thermal shocks (as defined by this threshold) are observed; most of them occurred at negative temperatures, for example in March, and were not connected to an insolation effect (i.e., the rock face was not hit by direct sunshine at the time of these recordings). We cannot conclude that thermal shocks cause any weathering in these dry polar conditions.

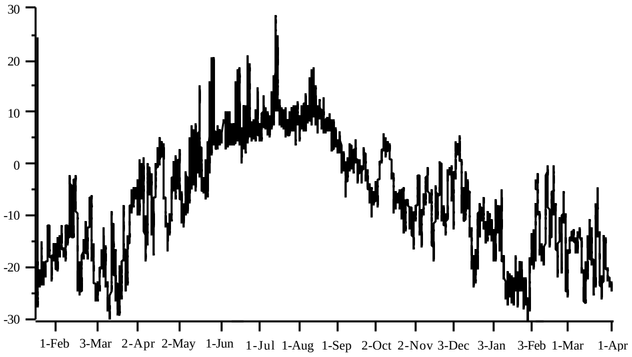

Fig. 1. Rockwall temperature (°C) at 0.5 cm depth at the Spitsbergen site, measured every minute from January 18, 2002 to April 1, 2003.

The amplitude and seasonal distribution of rock moisture content variations are monitored by daily weighing of sandstone tablets exposed in the natural environment (Fig. 2). Results are expressed in percentage of the total saturation of the porous media, which was measured in the laboratory by progressive immersion in water under atmospheric pressure. Large and quick variations of rock moisture content happen particularly during the summer (in rainy or foggy weather conditions), but also during the autumn and spring.

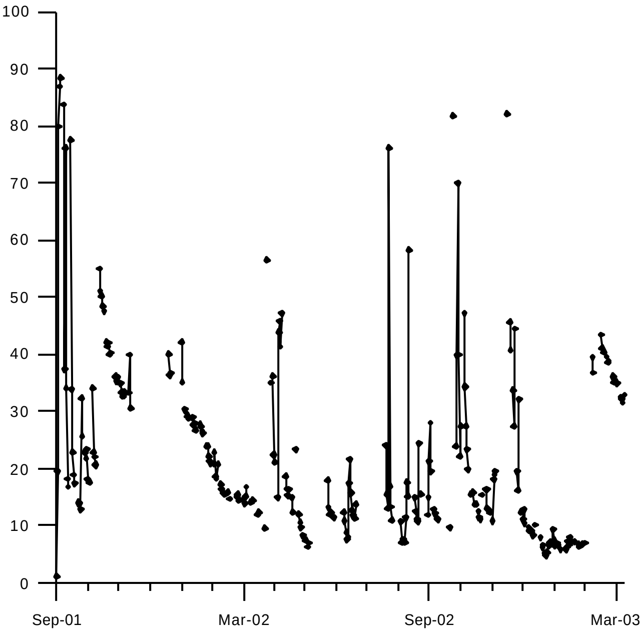

Fig. 2. Variation of moisture content (expressed in % of the total saturation) of a parallelepiped sandstone sample (74 cm^3) measured daily from September 10, 2001 to March 21, 2003.

The winter is characterised by a progressive drying of the rock linked to sublimation (comparable observations were reported from Greenland [9]). Snowfall does not necessarily induce a moisture uptake and weight losses have been observed when samples are covered by a cold snow layer, as monitored several times during both winters. Rocks rarely reach high saturation values (as described in other studies [11]), and when it is the case, this happens in the autumn and in the spring.

2.2 Implications for rock weathering

Conditions favourable to frost weathering (i.e., freezing of the rock when its moisture content is high [8][14]) are met only rarely, in the autumn and in the spring. However, when these conditions are met, frost action can be very aggressive, because of high rock moisture contents (e.g., frost occurring after a rainy period, or after snowmelt), the quick cooling caused by the quick weather changes in this part of the Arctic, or the extended duration of freezing periods, whose efficiency has been underlined by Coutard and Francou [7]. Rock decay evolution, indicated by Young’s modulus values, confirms this interpretation (Table 2).

Sandstone samples exposed at the study site did not show any visual decay after the first five months of exposure and very limited decrease of Young’s modulus values after one year (-3.7 %). Conditions favourable to frost weathering did not occur often enough during the first five months of exposure to initiate weathering within this sandstone.

Moreover, the sandstone porosity, measured by immersion under atmospheric pressure of non-fractured blocks, is only about 5.2 to 5.6 %. The slow water uptake of the rock, which was still going on 208 hours after the beginning of a progressive immersion, indicates predominant microporosity (pores with access radius of less than 1 µm) and poor permeability.

It is well known that rocks with a very low porosity are not frost sensitive. Lautridou and Ozouf [15] proposed a threshold porosity of 6 %. According to this empirical rule, the local sandstone is not sensitive to microgelivation, i.e. frost weathering acting through the rock porous media and producing small size fragments [2]. Yet, considering the crack density of the outcropping sandstone beds, the rock outcrop as a whole is sensitive to macrogelivation, i.e. the “opening (wedging) of pre-existing macrofractures (joints) that tend to produce pebble-size or coarser material (cm-to-m scale)” [2: p. 300]. Ice filling rockwall cracks have been observed at the field site during the winter and spring. A similar determinant action of wedging on poorly porous limestones and granites has been reported in the French Alps by Coutard and Francou [7].

Samples of porous French limestones (characterised by a porosity of 9.1 % for the Vilhonneur, 31.4 % for the Caen and 31.5 % for the Sireuil) used in previous weathering experimentation [8][14], underwent the same exposure as the sandstone (Table 2). The efficiency of the Spitsbergen climate for rock weathering is proven by the decrease in Young's modulus of these porous limestone tablets, even after the first five months of exposure at the study site. This indicates that conditions leading to microgelivation can indeed be episodically obtained on Spitsbergen, but that the local sandstone is resistant to these conditions because of its poor permeability and its low porosity dominated by micropores.

a. Longyearbyen. Spitsbergen				
	#	Vol.	Sept. 2001 – Jan. 02	Sept. 2001 – Aug. 02
Local sandstone	5	73.8	0	3.7
Limestones:				
mean value			6.6	8.5
Caen	*2*	*68.2*	*1.1*	*4.6*
Vilhonneur	*2*	*84.5*	*7.4*	*7.8*
Sireuil	*2*	*70.2*	*11.1*	*13.2*

b. Terra Nova Bay, Antarctica			
	#	Vol.	Dec. 2002 – Jan. 2003
Local granite	3	71.4	13.3
Sandstone imported from Longyearbyen	1	78	0.3
Limestones:			
mean value			4.6
Caen	*2*	*71.2*	*0*
Vilhonneur	*2*	*66.5*	*2.6*
Sireuil	*2*	*72.2*	*11.1*

#: number of samples
Vol.: average volume of samples, in cm^3

Table 2. Decrease of Young’s modulus (in % of the modulus of fresh samples, before exposure) for rock parallelepipeds exposed to the natural environment. On Spitsbergen, samples were exposed from September 3, 2001 and measurements were carried out on January 30, 2002 and on August 19, 2003. In Antarctica, samples were exposed from December 6, 2002 and measurements were carried out on January 12, 2003.

The three limestones responded differently to the same exposure conditions. The Caen limestone showed a very limited response to the first five months of exposure (-1.1 %) and is still the less weathered after one year (-4.6 %, compared to an average of -8.5 % for all the limestones).

This can be easily explained by previous laboratory experimentation [8][14], during which the same rocks underwent one freeze-thaw cycle in a saturated state, with a cooling rate of 2 ºC/hour, and at 75 % of the total saturation with cooling rates of 0.5, 2 and 10 ºC/hour. The Sireuil deteriorated under all conditions, except at 0.5 ºC/h freezing. The Vilhonneur was sensitive to freezing under saturated conditions. Only the Caen limestone was not sensitive to any tested conditions. A similar ranking of relative resistance to frost action is obtained after exposure to atmospheric conditions on Spitsbergen.

3 NORTHERN VICTORIA LAND

3.1 Temperature and rock moisture conditions

The ice-free areas of the Northern Foothills, where this research was carried out, constitute one of the more extensive on the Antarctic continent outside the McMurdo Dry Valleys and the Antarctic Peninsula. The bedrock in the area consists of monzogranite of the Granite Harbour Formation (Ordovician). The granite's porosity, measured by immersion under atmospheric pressure of non-fractured blocks, is about 1.5 %.

The freezing point of pore water generally decreases with decreasing porosity, particularly when only fine pores constitute the porous media, like in granite [1][2][14]. Moreover, the high salt content (in particular sulphate) of the local granite also lowers the freezing temperature in the rock pores [16], raising "the possibility that saline-moderated freeze-thaw cycles (i.e., freeze-thaw cycles that occur at subzero temperatures) exploit micro-fractures either already present in quartz minerals or formed as the result of thermal stresses and the increasing brittleness of quartz at low temperatures" [16: p. 312]. This depression of the freezing temperature has been experimentally established by measuring the temperature at which the exothermic effect of water turning into ice within the porous media is visible on the high-frequency temperature monitoring of a saturated block undergoing quick cooling [14]. Results indicate a freezing temperature of –1.6 ºC. This is consistent with results presented in the literature [17].

The mean annual temperature at the Italian Station of Terra Nova Bay (i.e., at the field site) is –14.7 ºC ([18]: PNRA station records 1990-1996) with an annual range of more than 25 ºC (maximum +3/+5 ºC in January and minimum –22/–25 ºC from May to August). Precipitation, almost entirely in the form of snow, averages 270 mm/year water equivalent [19]. Chinn [20] estimates an annual moisture deficit of approximately 180 mm/year for the area. These climatic parameters clearly differentiate Terra Nova Bay from Longyearbyen (Table 1). The area is characterised by a higher aridity than Spitsbergen, where there is no moisture deficit. Its summer temperatures remain much closer to the freezing point and suggest the occurrence of numerous freeze-thaw cycles.

Ground temperature at a depth of 2 cm (Fig. 3) indicates about 15-20 freeze-thaw cycles per year (10 cycles in 2001; exceptionally high value of 40 cycles in 2002). When taking into account the –1.6 ºC threshold, the number of cycles is 29 in 2001 and 60 in 2002. The occurrence of freeze-thaw cycles is concentrated over a short period in the year (Fig. 3), and not split into two distinct periods of about two months length in the autumn and in the spring, like on Spitsbergen (Fig. 1). For about 9 months of the year, it is very unlikely that rock surface temperatures can ever be positive at the Antarctic site, considering the lower average temperatures and the more stable winter meteorological situation in comparison with Spitsbergen.

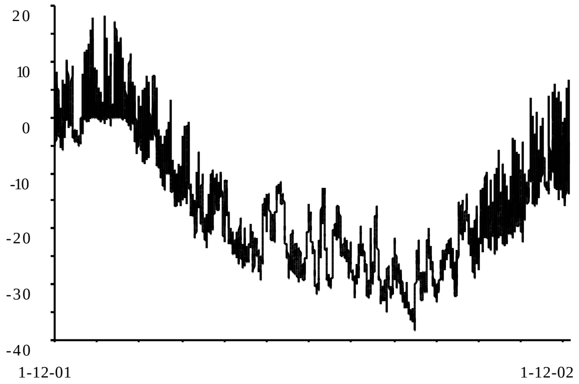

Fig. 3. Ground temperature at a depth of 2 cm at Boulder Clay, close to the Antarctic site, measured hourly over a one-year period beginning on December 1, 2001.

Figure 4 shows an example of rock temperature fluctuations, as measured during the field campaign 2002-2003. Even at a depth of 7 cm within the rock (Fig. 4), cycles crossing the critical threshold of –1.6 ºC can occur on a daily basis in the summer. The daily temperature amplitudes are considerable and reach about 20 ºC. Nevertheless, the monitored sharp temperature changes visible on Fig. 4 were not quick enough to constitute thermal shocks.

Rock moisture data have been systematically collected twice daily over a period of 6 weeks, in the summer 2002-2003, from 3 exposed tablets of the local granite and from one sample of the Longyearbyen sandstone (Fig. 5). Like in Longyearbyen (Fig. 2), rocks rarely reach high saturation values. Large and quick variations of rock moisture content are linked to snowfall and snow accumulation on the rocks, particularly if snowy weather lasts for several days. For example, the 3 days of intermittent snow from December 19 caused high rock moisture contents, but that was not the case for the less than 24 hours long snow event beginning on January 5. As snowmelt events are limited to the short Antarctic summer, high moisture content is not expected for other periods of the year. After snowmelt, the granites dry out quickly and rapidly return to the generally very low moisture content (less

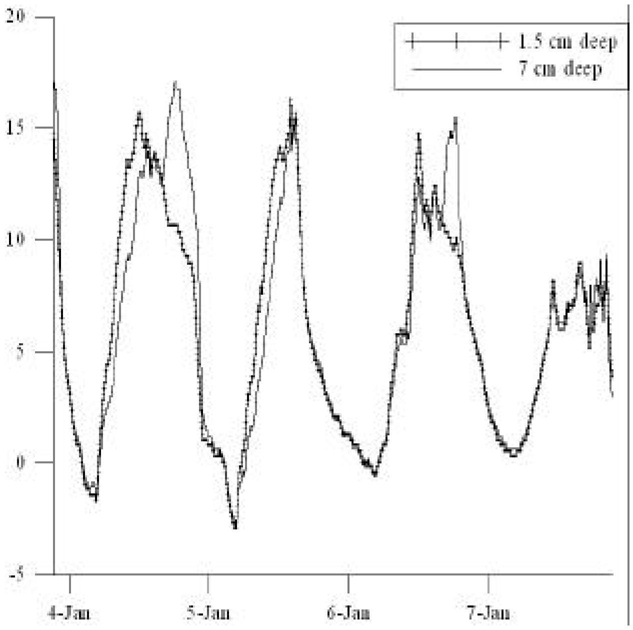

Fig. 4. Rock temperature (°C) at 1.5 cm and at 7 cm depth at the Antarctic site, measured in a granite boulder every minute from January 3 to 7, 2003.

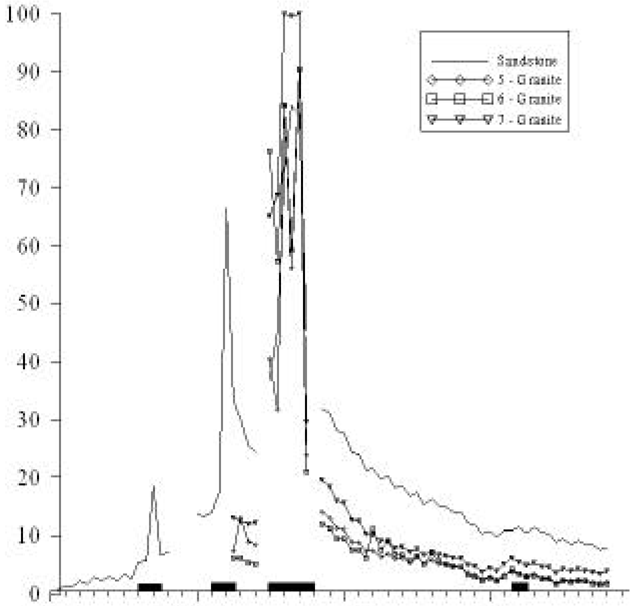

Fig. 5. Evolution of the moisture content (expressed in % of the total saturation measured by progressive immersion) of three granite parallelepipeds (denoted as 5-Granite, 6-Granite and 7-Granite) and one sandstone measured twice daily from December 5, 2002 to January 12, 2003. Thick lines along the x-axis indicate periods with snowfall occurrence.

than 8 %) that characterise them (Fig. 5). The sandstone tablet, which is characterised by a low permeability, dries much more slowly. In the arid Antarctic climate, extended periods of drying allow the sandstone to reach moisture content values of less than 10 %, which are exceptionally reached during the much wetter Spitsbergen summer (Fig. 2).

3.2 Implications for rock weathering

The studied granite displays very widespread and striking weathering features like taffonis (Fig. 6), tors, pseudo-karrens and weathering pits [16]. These features are linked primarily to microweathering, by granular disintegration of the granite, leading to the accumulation on the ground of small angular rock fragments ('grus') [16]. Granite is sensitive to salt weathering [21][22] and the origin and evolution of the observed weathering features is at least partly linked to salt action [16].

Fig. 6. Taffonis developed in a 145 cm high granite block, close to the Italian Research Station of Terra Nova Bay.

Table 2 indicates preliminary results of the Young's modulus variation of rock tablets exposed at Terra Nova Bay from December 2002. The important decrease of Young's modulus of the three local granite samples after only 37 days (-13.3 %) is attributed to the weathering effect of the salt contained in the rock. Even if many freeze-thaw cycles occurred during the measurement period, the very limited occurrence of high rock moisture content (Fig. 5) is unlikely to have been characterised by major microgelivation. Indeed, the limestone response to exposure during the Antarctic summer is much more limited than what was observed on Spitsbergen for the period from September 3, 2001 to January 30, 2002, during which only 8 freeze-thaw cycles occurred in much higher rock moisture content conditions (Fig. 2). Among the limestones, the Caen did not show any Young's modulus decrease, and the sandstone response was insignificant (-0.3 %). These results stress the lack of conditions favourable to frost weathering in Terra Nova Bay, neither by microgelivation (the overall granite porosity of 1.5 % ranks it among the rocks not sensitive to this process [15]), nor by macrogelivation (because of the poor degree of fracturing, the lack of open cracks in the granite outcrops, and the limited availability of meltwater able to saturate these cracks). Other processes must be taken into account in order to explain the granite disintegration, such as salt action [16], cryogenic fracturation of quartz minerals [16], chemical and biological processes [23] and possibly thermal fatigue.

4 CONCLUSIONS

The comparison between field results obtained at Terra Nova Bay (Antarctica) and Longyearbyen (Spitsbergen) stresses the differences between these polar environments in terms of climatic conditions and the implications of climate and rock properties on the weathering processes involved. At both locations, conditions favourable to frost weathering (i.e., freezing of the rock when its moisture content is high) are met only rarely: only in the autumn and in the spring in Longyearbyen, and only during the summer at Terra Nova Bay. The Antarctic site is characterised by much colder and drier conditions than the Spitsbergen site. The studied sandstone on Spitsbergen and the Terra Nova Bay granite are both characterised by the presence of salt and by a very low porosity that makes them naturally resistant to microgelivation. In Longyearbyen, the highly fractured sandstone outcrops are sensitive to macrogelivation (wedging effects) and salt weathering has limited effects. At Terra Nova Bay, the presence of salt within the granite porous media contributes to its granular disintegration to a much larger extent.

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