OPTICAL ROCK PROPERTIES AND WEATHERING PROCESSES IN POLAR ENVIRONMENTS (WITH SPECIAL REFERENCE TO ANTARCTICA)[1]

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Abstract: As a result of the "freeze-thaw dogma," the polar scientific community has, for a long time, emphasized the importance of physical properties of rocks (porosity, jointing, etc) as a primary control on rock weathering. More recently, due to growing interest in chemically driven processes operating in cold areas, attention has been drawn to the chemical rock properties. Surprisingly, the optical properties of rocks have either been ignored or only alluded to in most rock weathering studies. Based on the available Antarctic biological and geomorphological literature, it is now appropriate to consider these optical properties as exerting a potentially significant influence and to promote a Manichean view in which the light-colored and translucent rocks (e.g., the emblematic Beacon sandstones) are considered from the perspective of biogenic weathering, whereas the dark rocks (e.g., the dolerites of the Dry Valleys) are viewed as being influenced by thermal weathering. Field observations and monitoring carried out from Labrador to Antarctica, lead, however, to a much more subtle appreciation, for it appears necessary to: (1) integrate the optical properties within a *corpus* of rock properties (within which some operate synergistically and others antagonistically with those optical properties); (2) to take into account the impact of scale (e.g., macro vs. micro); and (3) to consider the nature and role of lithophytic communities involved in bioweathering.

INTRODUCTION

Until recently, the fact that freeze-thaw weathering was considered as "the cold region panacea" (Hall, 1995) led the scientific community to consider rock control on

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weathering from the almost unique perspective of the mechanical properties of rocks. Particular attention was systematically drawn to porosity and jointing data, both in field studies carried out in cold areas and in associated laboratory experiments (e.g., Souchez, 1971; Söderman, 1980; André, 1982; Lautridou and Ozouf, 1982). In the last two decades, growing interest in (bio)chemically driven processes operating in cold areas has drawn attention to the chemical properties of rocks (e.g., Dixon et al., 1984, 2001; Whalley et al., 1984; André, 1996; Thorn et al., 2001; Etienne, 2002; Etienne adn Dupont, 2002).

Surprisingly, the optical properties of rocks have either been ignored or only alluded to in most rock weathering studies, except for research conducted by polar geomorphologists in dry environments such as at Oobloyah Bay, in northern Ellesmere Island (Eichler, 1981a). At Oobloyah Bay, the lack of moisture led Eichler (1981a) to attribute rock disintegration to thermal rather than freeze-thaw weathering and to take rock color into account. Rock color was also studied by Miotke (1982) in Antarctica, where contrasting thermal behaviors of variously colored outcrops had been described earlier by Kelly and Zumberge (1961). The interest of biologists in the endolithic communities colonizing the Beacon sandstones of the Dry Valleys in Antarctica led them, in the 1970s and 1980s, to take into account the role played by rock translucence in weathering phenomena and to collect high-resolution nanoclimate data of interest to polar geomorphologists (Friedmann et al., 1987; Nienow et al., 1988). In the 1990s, work by Hall (1997, 1999) supported the hypothesis that thermal weathering is a potentially important process in cold areas. Hall also carried out microclimate monitoring studies on rock surfaces of varying colors both in Antarctica and in northern Canada, and found that the influence of rock albedo may not be as straight forward as is generally assumed (Hall et al., submitted).

In the present scientific context that tends to abandon the "freeze-thaw dogma" and to emphasize the complexity of combinations and successions of weathering processes in cold areas (with particular focus on thermal and biogenic processes; e.g., Hall & André, 2001, 2003; Etienne, 2002; Etienne and André, 2003; Hall, 2003; Comte, 2004), it appears of particular interest to investigate the optical properties of rocks. Based on the previous literature and on the authors' field observations and monitoring studies in various polar environments, this article explores the potential role played by the optical properties in rock weathering and questions their real role, with special attention to the following.

1. *The color of the rock (dark or light)*: What are the data in favor of the influence of rock color on rock susceptibility to thermal weathering? Is the albedo effect a good indicator of the "thermoclastic potential" of a rock type?

2. *The translucence of the rock*: Is its role crucial in biogenic weathering or is it important only in specific conditions rarely realized in polar environments (and only when particular lithobiontic microbial communities are involved)?

3. *The applicability of the Antarctic "model"*: In the Dry Valleys, is the contrast observed between light-colored and translucent rocks (favorable to biogenic weathering) and dark rocks (favorable to thermal weathering) incidental, or is it applicable to polar environments?

4. *The interplay of optical attributes with other rock properties*: Do optical attributes (color, translucence, etc.) play a role as a control on rock weathering by themselves or only when operating synergistically with other rock properties (e.g.,

microstructure)? Do mechanical properties operate antagonistically with those optical properties that they neutralize? Are optical properties a major control on rock weathering or do they only express a potential that is rarely exploited?

5. *The impact of scale*: Do optical properties play a role in rock weathering at the micro- and/or macro-scale? How extensive and scale-specific is this role?

ROCK COLOR AND THERMOCLASTIC POTENTIAL

The light regime in the first centimeter of a rock outcrop depends on the incident light flux (varying with season, time of day, and surface orientation), rock properties (color, translucence, porosity, size of the framework grains) and the water content of the rock (Nienow & Friedmann, 1993). Among these controlling factors, the color of the rock is known to depend on three main parameters: (1) the original mineralogical composition of the rock (e.g., light-colored acidic rocks versus dark basic rocks); (2) the vegetal colonization of the rock, which alters the thermal regime of the rock surface; and (3) the chemical and biochemical weathering processes operating at the rock surface and/or the addition to the original substrate of coatings from external origin (aeolian, organic, etc.). For example, in West Antarctica, the whitening of rock surfaces can derive either from leaching or from the deposition of organic substances such as the phosphate coatings formed on andesite outcrops through the decomposition of penguin guano (Arocena and Hall, 2003). In inland Antarctica (Thiel Mountains), ferro-manganic varnishes contribute to the darkening of granitoid rocks (Ishimaru and Yoshikawa, 2000). Sandstones of Alexander Island in West Antarctica provide a good example of this color diversity (Fig. 1), which is assumed to influence the thermal behavior of rocks *via* the albedo effect.

The Albedo Effect and the Thermoclastic Potential of Dark Rocks

Absolute surface temperatures are controlled by rock color (i.e., albedo) and thermal conductivity. A dark surface is thought to induce a low albedo and therefore, a propensity for high surface temperatures (Dirmhirn, 1958). However, those temperatures will remain high only if the thermal conductivity of the rock is low (Kerr et al., 1984). If both conditions are realized (low albedo and low conductivity), steep thermal gradients between the rock surface and subsurface will offer favorable conditions for rock weathering phenomena such as spalling, flaking, or cracking to develop. This has been shown based on rock mechanics studies (e.g., Thirumalai, 1970) and on field observations in arid regions such as Central Australia and the Canary Islands (Ollier, 1984; Jenkins and Smith, 1990).

Regarding the influence of albedo on the radiative budget and the resulting thermal regime of rock outcrops in hot deserts, of particular interest are the monitoring studies performed by Warke and Smith (1998) and Warke (2000) in Death Valley, California on various rock types including a white Portland limestone and a very dark grey Antrim basalt (which has a lower thermal conductivity: 0.96 $Wm^{-1}K^{-1}$ compared to 1.53 $Wm^{-1}K^{-1}$ for the limestone). As shown in Figure 2, the rock surface temperatures remain 7°C lower than the air temperature in the Portland limestone, whereas it is up to 7°C higher than the air temperature in the Antrim basalt. Although the maximum temperature is 57.6°C on limestones, it reaches 72.6°C on basalt that is subject

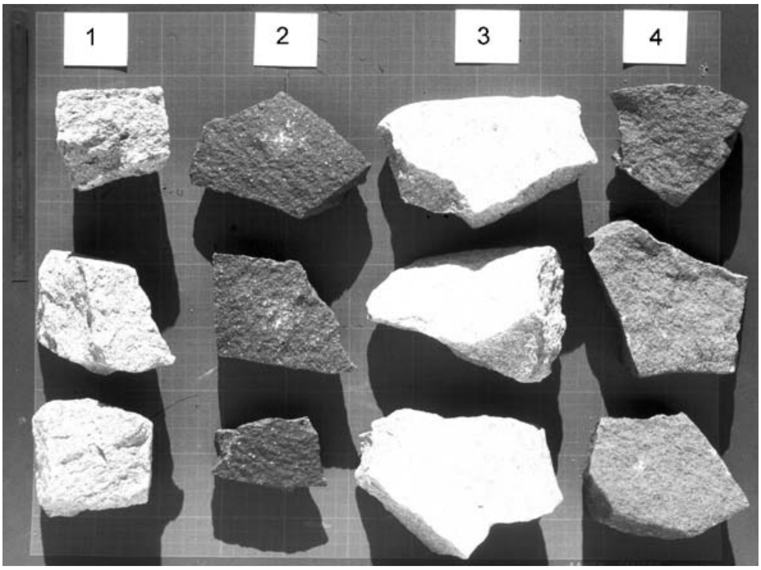

Fig. 1. Sandstone samples of various colors from Two Step Cliffs, Alexander Island (West Antarctica). From left to right: 1 = sound pale sandstone; 2 = sound dark sandstone; 3 = chemically whitened pale sandstone; 4 = reddish-brown Fe-rich coating due to oxidation on dark sandstone. Photo by M. F. André.

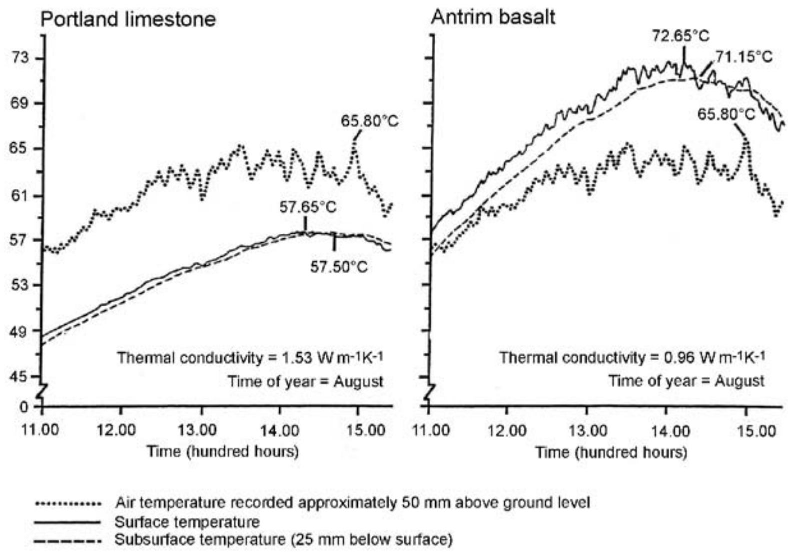

Fig. 2. Air temperature and simultaneous surface and subsurface temperatures of white Portland limestone and dark Antrim basalt recorded in August 1992 at Badwater, Death Valley, California (Warke, 2000, Fig. 2, p. 90).

to higher thermal variability and steeper thermal gradients between the rock surface and subsurface than limestone (Warke and Smith, 1998).

The heating capacity of dark rocks was also demonstrated in Antarctica, where the reflexivities of rock surfaces (in percent of incident light) range from 25% for orange-brownish sandstone with well-developed iron-oxide crusts to 53% for pure quartz sandstone in the Antarctic Ross Desert (Nienow et al., 1988). In this region of the Antarctic Dry Valleys, instantaneous temperature observations on dark- and light-colored rocks were made by Kelly and Zumberge (1961), who emphasized the role of rock albedo, with a black schist being 65% warmer than a nearby white marble. Similar temperature data were further provided for Ellesmere Island and Spitsbergen (Eichler, 1981a; André, 1993). Based on these data (Table 1), it appears that the thermal response of dark rocks to sun radiation is on average twice as high as that of light-colored rocks (but see below), with rock temperatures exceeding the air temperatures by 20°C (instead of 10°C for pale rocks). The same conclusion arises from the microclimatological data collected by Miotke (1982) and Miotke and Hodenberg (1983) in the Darwin Mountains (80°S), where dark dolerite outcrops reached up to ~25°C at –1 cm depth, whereas light-colored sandstone outcrops remained at 10°C or even less (Fig. 3).

If the dark rocks do indeed change thermal state more quickly this may have implications for thermal stress/fatigue/shock weathering responses (Hall, 1997). The question, though, is whether this thermoclastic potential of dark rocks is real and, if so, whether it plays a role? There are some scarce observations that suggest that dark rocks have a propensity for cracking.[2] On the nunataks of Alexander Island (71°52'S), in the Two Step Cliffs area, two of the authors (Hall and André) have observed a different weathering response in the pale and dark sandstones occurring there. The light-colored sandstones display wide, rounded forms and associated rock debris (Fig. 4), while the dark sandstones show angular forms with fractures frequently cutting across the bedding planes. The fracture patterns on the dark sandstones (with fractures at right angles to each other) are similar to crack patterns previously observed in high-altitude Andean deserts by Hall (1999), who emphasized the convergence of these with fracture patterns reported from hot deserts (Ollier and Tuddenham, 1962; Ollier, 1984; Selby, 1985) and from thermal experiments on basaltic rocks and on ceramics (Marovelli et al., 1966; Bahr et al., 1986). However, in the case of the Alexander Island sandstones, it remains to be investigated what role the microstructures of the sandstones play in the resulting weathering forms. Elsewhere, the mechanical breakdown of big boulders of dark dolerite in the Antarctic Dry Valleys of Victoria Land (Fig. 5) are difficult to attribute to frost shattering because of the low porosity of the bedrock and the lack of moisture in the area.

Open Questions

There are some data that indicate that the albedo effect is not as important as is commonly anticipated. For instance, in the Tibesti Mountains, Peel (1974) recorded very similar surface temperatures for rock types of different colors: 78.5°C for basalt,

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[2]But see the discussion in Hall et al. (submitted) regarding the role that rock properties other than albedo may play in causing this.

TABLE 1

Air Temperatures and Simultaneous Surface Temperatures Recorded on Dark- and Light-Colored Rocks in Polar Environments

Lithology and rock color	Air temp, °C	Surface rock temperature, °C		Maximum Δt, °C, air/rock	Location	Source
		Shadow	Sun			
Dark rocks						
Black schist	3.8	12.2	21.1	17.3	McMurdo, Antarctica, 77°S	Kelly and Zumberge, 1961
Dark gabbro	3.3	8.3	19.4	16.1	McMurdo, Antarctica, 77°S	Kelly and Zumberge, 1961
Dark diorite	13.4	18.2	36.1	22.7	N Ellesmere, 80° N	Eichler, 1981a
Dark schist	12.1	—	27.3	15.2	NW Spitsbergen, 79° N	André, 1993
Dark schist	1.5	—	25.0	23.5	NW Spitsbergen, 79° N	André, 1993
Pale rocks						
White marble	3.3	9.4	12.7	9.4	McMurdo, Antarctica, 77° S	Kelly and Zumberge, 1961
Quartzic diorite	3.8	11.6	15.0	11.2	McMurdo, Antarctica, 77° S	Kelly and Zumberge, 1961
Pale sandstone	13.5	16.1	21.3	7.8	N Ellesmere, 80° N	Eichler, 1981a
Pale limestone	13.0	14.6	24.6	11.6	N Ellesmere, 80° N	Eichler, 1981a
White limestone	8.9	—	18.5	9.6	NW Spitsbergen, 79° N	André, 1993

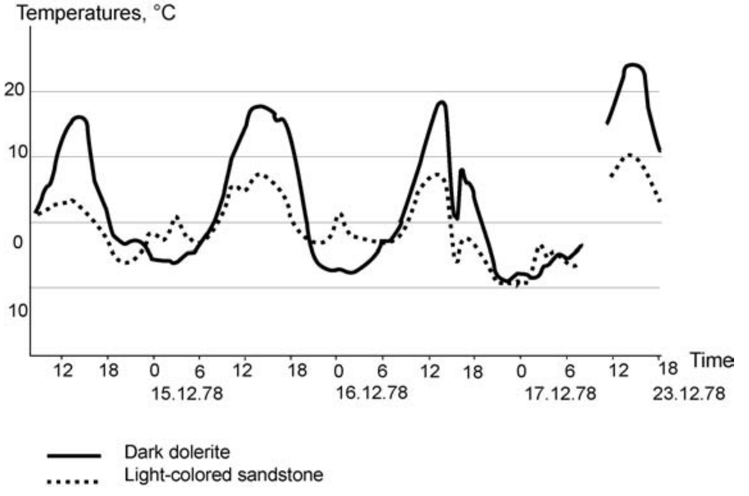

Fig. 3. Subsurface temperatures recorded at –1 cm on rock surfaces facing north in the Darwin Mountains, Antarctica, 80° S: dark dolerite vs. pale sandstone (after Miotke and Hodenberg, 1983, Fig. 17, p. 116, modified).

Fig. 4. Contrasted weathering patterns in pale and dark sandstones on a nunatak at Two Step Cliffs (Alexander Island, 71°52' S). Fracture patterns at right angles in dark sandstone are due to mechanical weathering, and round shapes and widely opened joints in light-colored sandstone due to chemical processes (20 cm ruler for scale). Photo by M.F. André.

79.3°C for dark sandstone, 78.8°C for pale sandstone. Similarly, in West Antarctica, Hall (1997) found insignificant differences in rock temperatures between the dark- and the light-colored sandstones, with maximum temperatures at +22.3°C for the pale rocks and +23.0°C for the dark ones (for an air temperature at +6.0°C). Indeed, in recent experiments considering the impact of albedo on rock temperatures (Hall et al.,

Fig. 5. Dark dolerite boulder of which mechanical breakdown was possibly caused by thermal weathering; this hypothesis is supported by the lack of moisture and the windiness of the site, located in the Dry Valleys of Victoria Land (Antarctica). Photo by R. S. Sletten.

submitted), dark rocks were, under specific circumstances, the same temperature or even cooler than the white ones. In these experiments, the rock exposures were identical as were the rock properties (manufactured paving bricks were used as the "rocks"); only the albedo differed. Nevertheless, it was clear that the light-colored rock could be hotter than the dark (Hall, et al., submitted). Similarly, light-colored lichens have been found to be warmer than dark-colored lichens (see Arocena and Hall, this volume).

Importantly, even when albedo does influence the temperature maxima at the rock surface, this may not always be the prime control on rock weathering. Based on thermal crack patterns formed during laboratory experiments and similarities with fracture patterns observed in the field, the occurrence of multiple short-term but large-magnitude $\Delta T/\Delta t$ events at the rock surface that exceed the 2°C min^{-1} threshold for thermal shock appear to be more important for weathering under some circumstances (Richter and Simmons, 1974; Bahr et al., 1986; Yatsu, 1988; Hall and Hall, 1991). From this point of view, available Antarctic data suggest that large-magnitude $\Delta T/\Delta t$ events occur whatever the rock color is (Hall and André, 2003). The impressive *corpus* of high-frequency rock temperature data collected in West Antarctica by Hall (1997, 1999, 2003; Hall and André, 2001, 2003) indicate that rates of temperature change in excess of > 2°C min^{-1} are commonly experienced even by light-colored rocks. For instance, at Two Step Cliffs (Alexander Island, 71°52'S), pale sandstones commonly provide values >6° min^{-1}, and extremes of >12° min^{-1} are not exceptional (Fig. 6A). At Rothera Point, on Adelaide Island (67°34'S), an extreme of 22.7°C min^{-1} was recorded on November 8, 2001, on a north-facing outcrop consisting of light gray granodiorite (Fig. 6B). Rock heterogeneity apparently prevails over rock color as a controlling factor of rock thermal behavior.

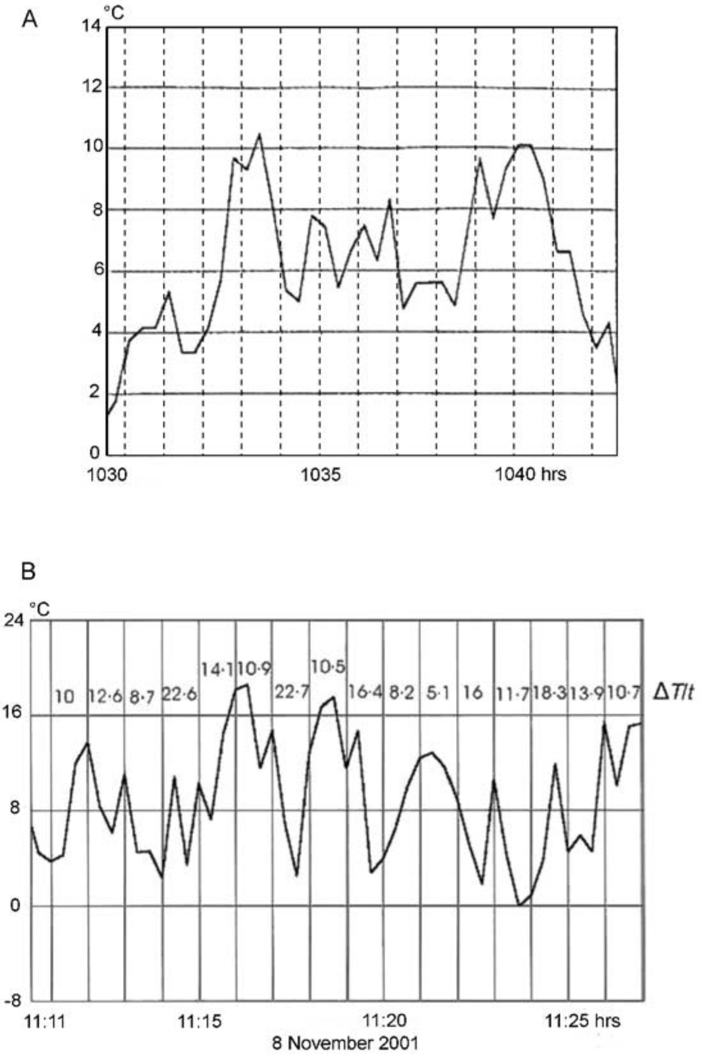

Fig. 6. Short-term and large-magnitude ΔT/Δt events at the surface of pale rock types in the Antarctic Peninsula region. A. Light-colored arkosic sandstone at Two Step Cliffs, Alexander Island (from Hall, 2003, Fig. 4, p. 351). B. Light grey granodiorite at Rothera Point, Adelaide Island (from Hall and André, 2003, Fig. 5A, p. 833).

However, it should be kept in mind that the rock temperature changes cited above were recorded using ultra-thin microtransducers, and are significant only at the grain scale (i.e., regarding granular disintegration) and not from the perspective of macro-cracking. At this micro-scale, some authors working in Antarctica attribute the primary role in granular disintegration to thermal properties that are not associated with the color of the rock, but with their mineralogical composition and texture. For example, in the Thiel Mountains (continental Antarctica, 85°S), Ishimaru and Yoshikawa (2000, p. 53) suggest that the granular disintegration of granodiorite porphyry is due to the differential thermal expansion of two light-colored minerals, quartz and plagioclase: "the differential thermal properties of quartz and plagioclase create strain along the mineral boundaries. Their differential thermal conductivity intensifies it. This strain cracks the marginal part of plagioclase and breaks it along the mineral boundaries and along the cleavages, which are mineralogical weaknesses," creating a pitted pattern of prism-shaped holes due to the loss of weathered-free plagioclase phenocrysts. When the rock albedo is mentioned, it is only as a possible additional effect. The microclimatological data collected in the light-colored sandstones of Alexander Island (West Antarctica) "suggest that the surface grains experience rapidly changing stress fields that may, with time, effect fatigue at the grain boundaries; albedo differences between grains and the resulting thermal variations are thought to exacerbate this" (Hall and André, 2003, p. 823).

On the whole, the new microclimatological data provided by ultra-thin, ultra-responsive thermocouples change our perspectives on rock weathering in polar areas. In particular, through information on the occurrence of multiple short-term but large-magnitude $\Delta T/\Delta t$ events at the rock surface, they support the thermal hypothesis of granular disintegration and flaking (which was also suggested in high-altitude dry areas such as Karakoram, see Whalley et al., 1984; Waragai, 1998). However, this sophisticated equipment fails to account for cracking operating at a macro-scale (Figs. 4–5, see above). According to Rice (1976, p. 61-62), "differential volume changes due to temperature variations within a rock, that induce stresses that can lead to failure, are more likely in large boulders than in small ones." From this point of view, the more responsive the instrumentation, the less it can account for the thermal behavior of large pieces of rock. Whereas the recent high-frequency microclimatological data from Antarctica support the thermal hypothesis of granular disintegration (e.g., Hall, 1997, 2003; Ishimaru and Yoshikawa, 2000) and tends to downplay the albedo effect, it does not negate the influence of rock color at the macro-scale (which requires adapted monitoring protocols).

ROCK TRANSPARENCY AND BIOGENIC POTENTIAL

Among the controlling factors of the light regime of an outcrop, rock translucence—which is optimal in quartzic lithologies—can play a significant role in the settlement of light-demanding lithophytic communities that are involved in rock weathering. In polar environments, two major biota are involved: (1) cryptoendolithic lichen communities that live in a subsurface position, i.e. in the internal airspaces between rock crystals (Friedmann, 1982; Vincent, 1988); and (2) algal and cyanobacterial sublithic microbiota that colonize the undersurface of stones embedded on the soil surface in polar environments (Smith et al., 2000).

The Antarctic "Evidence"

Pioneering studies of the impact of microorganisms on rock weathering were conducted in the Dry Valleys of Antarctica (e.g., Friedmann, 1977, 1982; Friedmann et al., 1981). The Beacon sandstone of the Ross Desert consists of >99% silica and is remarkably translucent. In dry rock, the light transmissivity of this pure quartz sandstone is twice as high as that found in the orange-brownish iron-oxide crusts that can coat the sandstone, and which reduces transmission to about 20% of the surface value

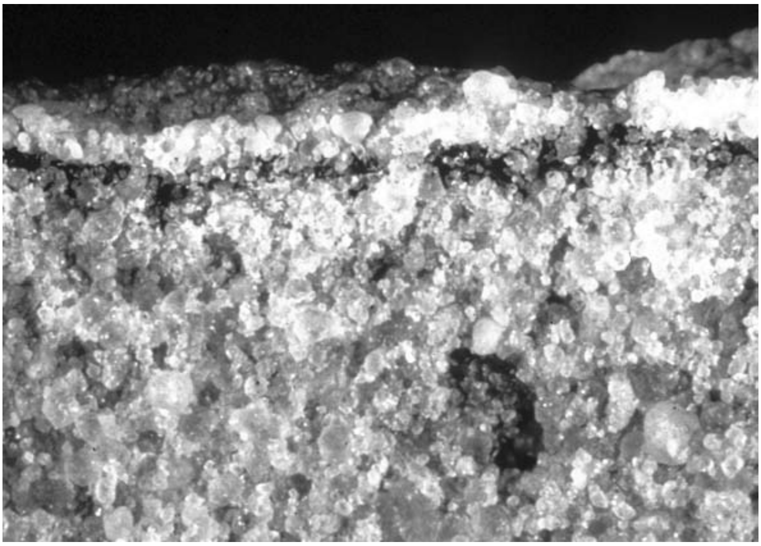

Fig 7. Well-developed microbial cryptoendolithic community colonizing the translucent siliceous Beacon sandstone at Linnaeus Terrace, Asgard Range, Antarctica. Quartz grains range between 0.2 and 0.5 mm in diameter and a vertical sequence of the so-called black, white, and green zones can be seen. Photo E. I. Friedmann (from Friedmann, 1982, Fig. 4, p. 1047).

for the total photon flux in the space of a few micrometers (Nienow et al., 1988). In the Antarctic Beacon sandstone, the 0.2–0.5 mm quartz grains form "windows" or "greenhouses" that allow the settlement of endolithic communities such as the classical lichen-dominated community described by Friedmann (1982). This community, which is responsible for sandstone exfoliation, displays three zones of various colors (black, white, green) (see Fig. 7) and is visible to a depth of 10 mm, due to the light transmissivity through the translucent quartz grains. The greenhouse effect, resulting from heat trapped subsurface due to the light transmission, is particularly strong on north-facing rock faces exposed to the midday sun (Kappen et al., 1981; Kappen, 1993).

In contrast, the apparent lack of endoliths in the sandstones of the Antarctic Peninsula region is striking. For example, two of the present authors (Hall and André) systematically searched the light-colored "cannonball sandstones" of Alexander Island (Fig. 8) for endoliths without result. Analyses of rock samples in progress (in collaboration with Charles Cockell, microbiologist, British Antarctic Survey), and Hall and André (submitted) already suggest that the rapidity of mechanical weathering possibly precludes endolithic colonization. However, an additional, if not a major, reason for the absence of endoliths, might be the opacity of the Alexander cannonball sandstones (mainly due to the feldspar content [plagioclase and microcline] of this arkosic sandstone and to its calcitic cement). This, however, requires further investigation.

Open Questions

As much as the cryptoendolithic communities colonizing the translucent Beacon sandstone of Antarctica have become emblematic of the importance of biogenic

Fig. 8. Sandstone pavement devoid of microorganisms on a nunatak at Two Step Cliffs, Alexander Island, West Antarctica. Although it is light in color, the rock type is opaque due to its arkosic composition and its calcitic cement.

weathering in cold environments, so lithophytic communities were also found to be efficient weathering agents in polar environments on various substrates, including both translucent and opaque rocks. In the Canadian High Arctic (North Ellesmere), cryptoendolithic lichenized microbiota were found by Eichler (1981b) to induce sandstone exfoliation, and in the Ross Desert (McMurdo Dry Valleys), cryptoendolithic and/or chasmoendolithic lichens were shown to be responsible for granite flaking (Friedmann, 1982; Longton, 1988). As a result of its mineralogical composition (feldspars and ferro-magnesian minerals), the granite was much more opaque (and less porous, see below) than the Beacon sandstone, which consists of almost pure silica. Endolithic communities—including both euendoliths and cryptoendoliths—have also been shown to be very efficient in weathering of basalt in South Iceland (Etienne, 2002 ; Etienne and Dupont, 2002). However, the endoliths associated with the basalts belong to fungal communities that do not need light, such that they can develop even in dark-colored and opaque volcanic rocks, as has also been found for Antarctic fungal and bacterial communities that are widepread in dolerite (Hirsch et al., 1995).

Among the microorganisms that need light for photosynthesis (microlichens and algae), chasmoendoliths are apparently much more ubiquitous than cryptoendoliths in polar environments. Chasmoendolith colonization is dependent upon the available cracks, and has been observed in various Arctic and Antarctic environments on the following substrates that include both transparent and opaque rock types: (1) marble outcrops on Victoria Land, Antarctica (Friedmann, 1977, 1982); (2) charnockite, gneiss, and quartz pebbles at Mawson Rock and in the Vestfold Hills, Antarctica (Broady, 1981); (3) granite nunataks of the Edward VII Peninsula in Antarctica and the Juneau icefield in Alaska (Broady, 1989; Hall and Otte, 1990), with, in the last case, a clear implication of chasmolithic algae in granite flaking.

Fig. 9. Epilithic lichens such as *Parmelia centrifuga*, here in Kärkevagge (Swedish Lapland), are widespread in most Arctic areas, and many of them are involved in the granular disintegration of crystalline rocks through the disruptive action of their rhizinae and/or the chemical agressivity of their acids. Photo by M. F. André.

Epilithic communities are also widespread in polar environments, provided that the dryness and windiness do not prevent surface colonization as they do in the Antarctic Dry Valleys (Friedmann, 1982). For instance, the role played by saxicolous lichens in rock weathering was demonstrated in: (1) maritime Antarctica, where crustose lichen species contribute significantly to both mechanical disruption and chemical weathering of minerals forming metamorphics and volcanics (Walton, 1985; Ascaso et al., 1990); (2) Spitsbergen, where biogenic weathering of amphibolitic substrates is induced by lichens (André, 1997); (3) continental Scandinavia, where granular disintegration of glacially scoured outcrops and morainic boulders in various lithologies (granite, quartzophyllite, amphibolite, gabbro) was found to be partly caused by saxicolous lichen communities (André, 1995, 1996; McCarroll and Viles, 1995). In the Caledonides, crustose and foliose lichens like *Lecidea auriculata* and *Parmelia centrifuga* (Fig. 9) were found to penetrate the rock surface, incorporate within their thallus, and probably expel, flakes of rocks (mainly ferro-magnesian minerals such as biotite and possibly feldspars). In some cases, the decay of lichen thalli has resulted in a plurimillimetric post-glacial lowering of the rock surface.

On the whole, it seems that the cryptoendolithic communities of the Antarctic Dry Valleys, which benefit from the translucence of the Beacon sandstone, are very peculiar microbiota associated with particularly harsh conditions inducing severe physiological stresses rarely found in polar environments. In most of the Canadian and Scandinavian Arctic and Subarctic areas, temperature changes at the rock surface are less extreme and snowmelt water availability is higher, offering more suitable conditions for epilithic communities to colonize the outcrops. It is noticeable that when Friedmann searched for analogues of the Antarctic endoliths, he found them essentially in hot deserts such as the Negev and the Sinai (Friedmann and Ocampo-Friedmann, 1984). This means that if rock transparency does play a significant role in cold areas, it does so only in space-restricted areas associated with specific climatic contexts that preclude the settlement of other lithobiontic communities. In contrast, biogenic weathering is ubiquitous in polar areas where it is mainly induced by chasmoendolithic and epilithic communities that do not need a translucent substrate. The key is that, although mineral transparency may play a role in rock weathering it does so only in association with other rock properties (such as the porosity, see below). Therefore, this factor should be taken into account, but not overestimated, in polar weathering studies.

THE OPTICAL ROCK PROPERTIES: A KEY TO THE UNDERSTANDING OF WEATHERING PHENOMENA IN POLAR ENVIRONMENTS?

On the whole, the optical properties of rocks (color, translucence) are of interest for weathering studies in cold areas as they can enhance biogenic or thermal weathering in certain rock types. However, whether this potential is exploited or not depends on both the characteristics of the study site (e.g., moist or dry) and on the interplay of these optical properties with other rock attributes. For example, the rock exfoliation caused by cryptoendolithic communities in the Antarctic Dry Valleys is due to the combination of the mineral translucence and the porosity of the Beacon sandstones. The impact of the translucence is enhanced by the porosity (15%), which provides space for endoliths to settle and water to penetrate the rock; the porosity can also enhance light penetration. Rocks with large framework grains and high porosity behave as micro-aquifers (Kappen et al., 1981) and have been shown to have a lower decrease in the flux of incident light than the other rocks (Nienow et al., 1988; Nienow and Friedmann, 1993).

In the Canadian Arctic, the albedo effect has been suggested to confer a higher thermoclastic potential to dark rocks like dolerite (Eichler, 1981a, see above, Table 1), and yet in the field (North Ellesmere, 80°N) no weathering evidence of this could be found. Rather, Eichler (1981a) observed the microfracture pattern of light-colored sandstones, which he interpreted as due to thermal cracking. This fracturing is probably due to the brittle behavior of quartz, which is related to the mechanical properties of this mineral, and possibly to its tectonic and even magmatic history (frequent fluid or gaseous inclusions that make the quartz grains easily microfissured when submitted to tectonic and/or thermal stresses). In this context, the mechanical properties of minerals prevail over the optical properties. Similarly, in North Labrador (on Killinek Island, see André, 1982), the comparison of the post-glacial weathering of dark and light-colored erratic blocks (Fig. 10) shows that the thermoclastic potential of dark rocks (if any) has no geomorphic expression. The reason is that the light-colored limestones have a high porosity (up to ~10%), which is of importance in this moist subarctic study site (both at the regional scale, with annual precipitation of ~500 mm, and at the local scale, with hollows concentrating water such as the one visible in Fig. 10B) such that they have been completely destroyed by mechanical breakdown. By comparison, the dark dolerite boulders have remained intact since ~7000 BP because of their low porosity (~1%) and thus limited weathering. In this subarctic context, the moisture availability allows frost shattering to be more active than thermal weathering, and freeze-thaw preferentially affects the porous rocks, whatever their color.

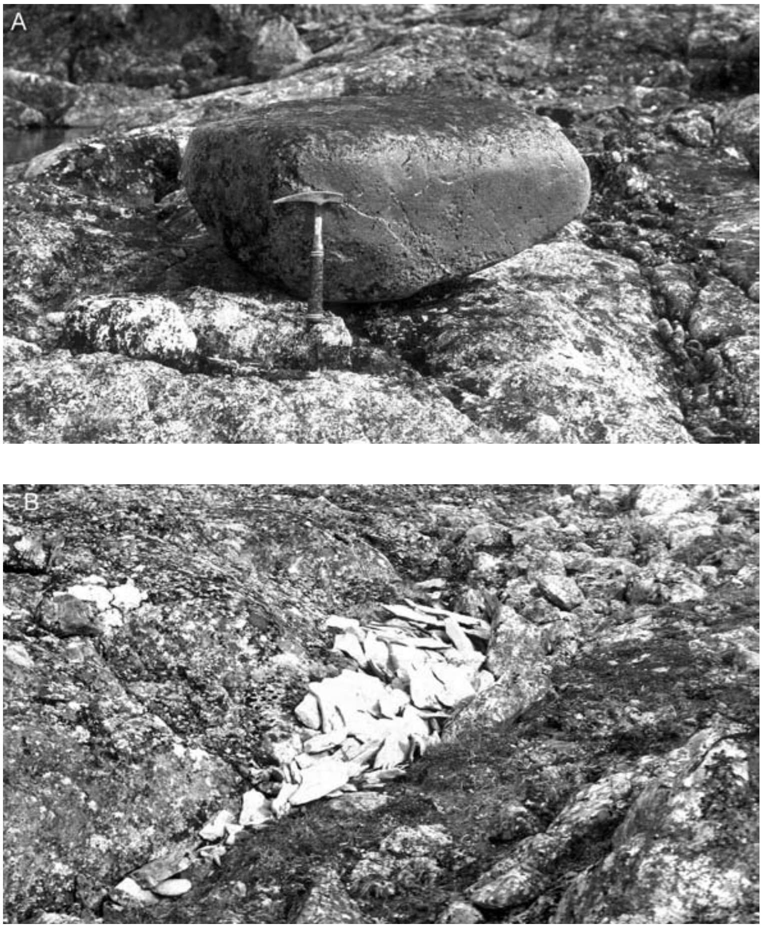

Fig. 10. Ca. 7000 yr old erratic blocks on Killinek Island (Nord Labrador). A. Well-preserved dark and non-porous dolerite erratic. B. Light-colored, porous limestone erratic subject to mechanical breakdown. Photos by M. F. André.

From the studies noted above, a tentative general conclusion can be drawn concerning the optical rock properties. On the whole, the rock color and translucence seem to play a role that is mainly "additive" (in that it amplifies rock behaviour associated with other rock properties) and/or of local importance in association with very specific conditions (e.g., very dry polar environments). In this respect, the contrast between the translucent Beacon sandstones (prone to biogenic flaking) and the dark dolerites (prone to thermal weathering) might be more of a misdirection than of a "model" widely applicable to the polar environments due to the extremely unusual nature of the Antarctic Dry Valleys within the present polar context.

It is of interest that new insight into the thermoclastic potential of rocks provided by the application of microthermocouples (<0.15 mm diameter) and high frequency logging (20 s intervals) leads one to downplay, if not discount, the albedo effect (Hall and André, 2003). It is tempting to disregard rock color in weathering studies by stressing the fact that the wind prevails over radiation in polar environments as a controlling factor of large-magnitude $\Delta T/\Delta t$ event temperature changes at the rock surface. However, there is an urgent need to fill the gap between monitoring protocols and instrumentation that will improve our knowledge of rock thermal behavior at the grain scale, and the field observations of fracture patterns and products at the macroscale. The influence of optical rock properties on rock weathering might vary tremendously according to scale, and much more work needs to be done in this regard.

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