Rock Moisture Data from the Juneau Icefield (Alaska) and Its Significance for Mechanical Weathering Studies

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ABSTRACT

Information was obtained regarding rock moisture content from nunataks along a west to east transect across the Juneau Icefield in Alaska. The data, together with rock temperatures and general climatic information, were collected for east-, west-, north- and south-facing samples. For one day data were collected every hour. The resulting information indicates the spatial and temporal variability that can exist over both short distances and short time-spans. It is suggested that this variability can have important repercussions with respect to weathering processes. The number of wetting and drying cycles monitored greatly depends upon the level of sample saturation that is considered significant. Available information suggests that wetting and drying can be operating at more than one level within the rock and that this will result in different weathering products. Wetting and drying may be more important than has been previously thought, both in terms of a weathering agent in its own right and as one that interacts with other processes, thereby speeding up their effect upon the rock.

RESUME

Des informations ont été recueillies concernant le contenu en eau des nunataks selon un transect ouest-est au travers de l'Icefield Juneau en Alaska. Les données concernant l'humidité ont été notées en même temps que des observations concernant les températures des roches et les composantes climatiques, et cela pour des échantillons recoltés en des lieux exposés à l'est, à l'ouest, au nord et au sud. L'information rassemblée indique une grande variabilité spatiale et temporelle des observations aussi bien sur des distances courtes que sur des périods de temps réduites. Il est suggéré que cette variabilité peut avoir des répercussions importantes en ce qui concerne les processus d'altération. Le nombre de cycles de séchage et d'humidification observé dépend pour beaucoup du degré de saturation des echantillons qui est, de ce fait, un facteur considéré comme significatif. L'information disponible suggère que l'humidification et le séchage peuvent se produire à plus d'un niveau dans la roche et que cela détermine des productions différentes de débris. Ces processus d'humidification et de séchage peuvent être plus importants que ce qui a été supposé précédemment, aussi bien comme agent d'altération simple que comme processus se combinant avec d'autres.

KEY WORDS: Rock moisture Weathering Wetting and drying Alaska

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INTRODUCTION

Although chemical and biological weathering have been recognized as operative on the Juneau Icefield (Dixon *et al.*, 1984; Hall and Otte, 1990), the bulk of studies have emphasized the role of mechanical processes, with gelifraction, in particular, being stressed (Hamelin, 1964; Shenker, 1979; Klipfel, 1981; Linder, 1981). Central to any consideration of these weathering processes are data on rock moisture content and temperature (McGreevy and Whalley, 1982, 1985). Although in recent years there has been an increasing attempt to monitor actual rock temperatures (e.g. Francou, 1988), field-based data regarding rock moisture content, and its variability in both time and space, have received little attention.

While freeze–thaw is relatively rare on the Juneau Icefield during the summer months and no data are available regarding the presence and character of salts, it would appear that climatic conditions, particularly in the west, are conducive to weathering by wetting and drying. Periods of hot, bright weather alternate with times of low cloud, high humidity and heavy precipitation that produce a number of wet–dry cycles. The process of wetting and drying is, however, poorly understood (Ollier, 1984) and little is known regarding its mode of operation (Hall, 1988a). In some rocks water uptake causes rock expansion, while drying results in contraction (Nepper-Christensen, 1965), but as the rocks may not return to their original length, this may ultimately cause breakdown (Venter, 1981; Hames *et al.*, 1987). In addition, the bonding strength of the component minerals can also be diminished such that with many wetting and drying cycles there can be a decrease in rock strength that may ultimately lead to failure (Pissart and Lautridou, 1984; Hall, 1988a). Wetting and drying also operates synergistically with other weathering processes (e.g. within freeze–thaw: Hall, 1991), but its role and contribution are, as yet, unknown, although Hall and Otte (1990) showed that it played a major role in enhancing biological weathering.

Fundamental to any consideration of weathering due to wetting and drying, as with other mechanical weathering processes, is the acquisition of data pertaining to actual rock moisture content and its temporal and spatial variability. However, essential as such data may be, very little are actually available. Subsequent to the pioneering work of Ritchie and Davison (1968), who monitored moisture changes in masonry materials exposed to each of the cardinal points, the only known studies are those of Trenhaile and Mercan (1984) and Hall (1986). In an attempt to add to this meagre supply of information, rock moisture data are presented for a summer period on the Juneau Icefield in Alaska and an assessment is made of its significance with respect to weathering.

STUDY AREA

The Juneau Icefield (Figure 1) is a relict of the great Cordilleran ice sheet and covers an area of approximately 4000 km^2 along the Alaska–Canada Boundary Coast Range (Marston, 1983). The Icefield is situated within a maritime environment along the southern and western edges of the Coast Range but becomes more continental with distance inland towards the east. While no specifics regarding the climate have been published, details regarding the general climatic conditions as well as the mountains and glaciers of this region can be found in Miller (1964). The present studies were undertaken at four sites along a west to east transect across the Icefield (Figure 1). C17 (Camp 17) is situated at the western margin of the icefield on a ridge above a small cirque glacier. C10 is on a nunatak that rises to *c.* 426 m above the surrounding ice, while C18 is located on a nunatak just to the south of the Alaska–Canada border, in the region of the Gilkey Glacier at an altitutde of *c.*1700 m a.s.l. C26 is close to the western extremity of the icefield and is located on a nunatak approximately 30 m above the ice.

METHODOLOGY

Twelve visually comparable specimens of granodiorite were collected at C17, and, of these, three pieces were set out facing each of the cardinal points. The rocks were marked so that at each study site they could be placed facing the same aspect as at the experiment start. They were positioned in such a way that they were open through a 180° arc centred on their cardinal orientation (i.e. an east-facing stone would be open in an arc from north through east to south). These stones were then each weighed three (at 0800, 1300 and 1800 hours) or four times each day (as above and 2200 hours) by means of a portable electronic balance accurate to 0.1 g. The rock samples having been dried and weighed and then saturated and again weighed, it was possible to convert the daily rock

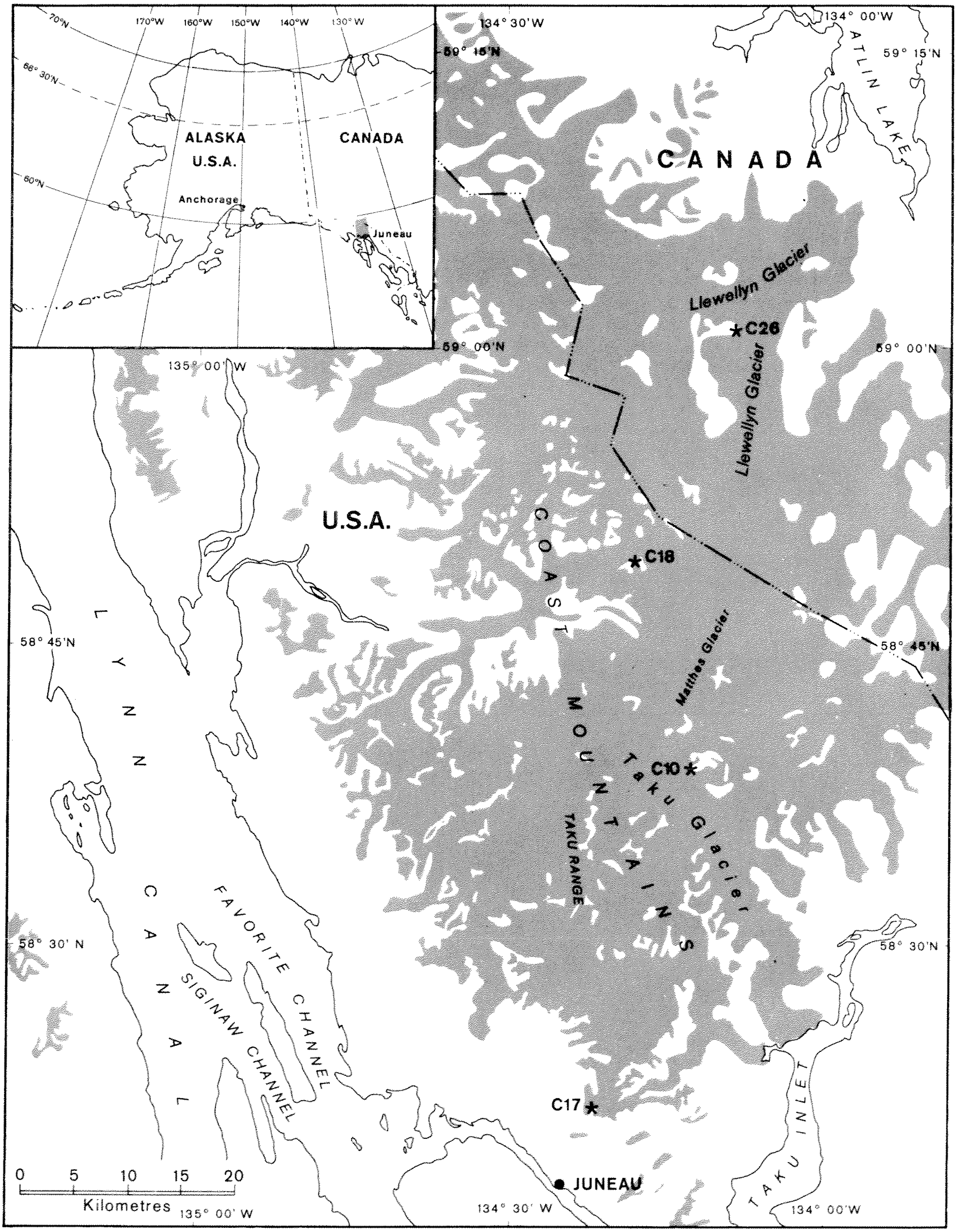

Figure 1 Simplified map of the Juneau Icefield (shaded area) to show the location of the four study sites.

mass to a measure of percentage saturation. The rock samples (Table 1) varied in thickness between *c*.2 cm and 5 cm, and so, being set on the ground surface, equated to the outer shell of the bedrock.

Air temperature in a Stevenson Screen was recorded together with the unscreened ambient temperature at the rock surface, taken by means of a meteorological thermometer at an open (360° exposure) site. For a short period rock surface temperatures were also measured at each of the four aspects. Wind direction and speed, cloud cover and whether it was sunny, overcast or raining were also recorded. For one day, measurements were taken hourly of temperature and rock mass for each of the rock samples.

RESULTS AND DISCUSSION

The daily record for the period 11 July through to 18 August is shown in Figure 2. From 11 July until 18 July the record is for Camp 17 at the western (maritime) extremity of the Icefield. From 18 July data acquisition is at Camp 10, where it remains until 28 July, when it moves eastward to Camp 18 until 6 August. From 10 August until 18 August the record is from Camp 26 at the eastern (continental) extremity of the Icefield. Data shown include wind speed and direction, rain or sun, cloud cover, air and rock temperature (for a 360° exposed site), and the average percentage saturation for the three blocks exposed at each of the four aspects.

From Figure 2 it can be seen that daytime rock temperatures are higher than air temperatures, reflecting the effect of incoming solar radiation in warming the rock. Conversely, night-time radiative cooling sometimes produces rock temperatures lower than those of the air. On days with clear skies, low wind speeds and large radiation receipts the rock temperatures were substantially higher than those of the air (cf. 12 July, when a 117% difference was recorded), indicating the inadequacy of using air temperatures as a surrogate for rock conditions. Unfortunately, rock temperature data from this study are still not adequate for any detailed discussion regarding their spatial and temporal variability and their effect upon moisture changes and weathering in general, as the time between readings is simply so large that it can hide many variations that could have taken place.

Consideration of rock moisture conditions (Figure 2) indicates that levels on the continental side of the Icefield (C26) were very low and correspond to the sunny conditions and high rock temperatures

Table 1 Sizes and shapes of the samples used in the experiments.

	Axes (cm)						Shapes			
Sample	*a*	*b*	*c*	d^1	D^2	$\bar{x}$size	F^3	R^4	OP	S^5
N1	10.6	5.6	4.9	0.1	2.7	7.03	165.3	0.04	8.16	0.74
N2	15.2	6.6	2.4	0.5	3.1	8.07	454.2	0.16	10.9	0.39
N3	10.2	7.0	2.6	0.1	3.0	6.6	330.8	0.03	−3.1	0.46
S1	10.9	6.3	4.6	0.3	3.2	7.27	187.0	0.09	5.45	0.68
S2	12.0	5.5	3.3	0.5	2.4	6.93	265.2	0.21	8.99	0.55
S3	10.0	6.4	4.1	0.3	2.9	6.83	200.0	0.1	2.69	0.64
E1	9.5	5.4	2.5	0.1	2.6	5.8	298.0	0.04	3.26	0.5
E2	9.3	7.4	3.2	0.2	3.2	6.63	260.9	0.06	−5.5	0.53
E3	12.1	5.0	4.0	0.2	2.4	7.03	213.8	0.08	11.4	0.64
W1	10.4	4.0	2.5	0.3	1.9	5.63	288.0	0.16	12.9	0.53
W2	8.1	6.0	2.2	0.6	3.0	5.43	320.5	0.2	−5.3	0.46
W3	9.2	8.4	2.3	0.1	4.0	6.63	382.6	0.03	−15.4	0.41

Axis Measurements:

[1] Diameter of the sharpest corner of the *a*/*b* plane.

[2] Diameter of the largest inscribed circle of the *a*/*b* plane.

Shape Indices:

[3] Cailleux's Flatness Index.

[4] Modified Wentworth Roundness.

[5] Maximum Projection Sphericity.

OP = oblate/prolate index.

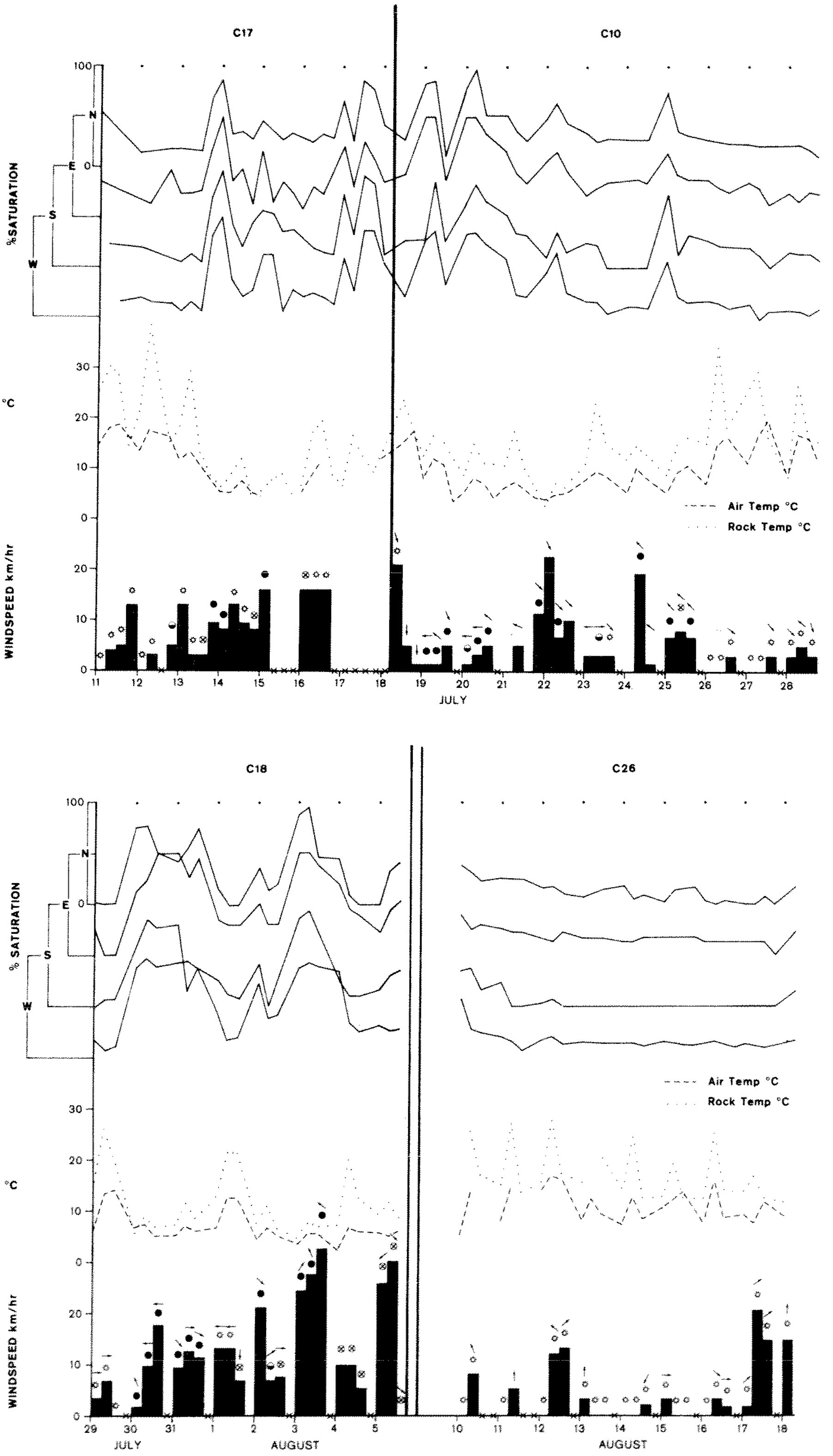

Figure 2 Graphs depicting the variation in moisture content for the four aspects together with rock surface and air temperatures plus a generalized picture of climatic conditions (vertical bars indicate wind speed; arrows indicate wind direction; × is no data available; ● = precipitation; sun symbol = sunshine; and circled × = overcast).

experienced there. At the three other sites there were periods of wet weather (e.g. 13 and 14 July) which produced high degrees of saturation. However, while the basic trends in moisture content for the four aspects are often similar, important variations do occur. For example, on 31 July there was rain and a westerly wind that resulted in those samples on the western side having a high ($\leq 95\%$) moisture content. The samples to the south, however, showed an initial *drying* phase followed by a small peak indicative of wetting, but the moisture content was still less than 50%. The north-facing samples showed a wetting response greater than those of the east or south, owing to the frequency of prevailing northwesterly winds. On the other hand, a northwesterly wind on a day with sun (27 July) resulted in a low, flat response from the north and west aspect samples, while those for the south and east showed small peaks indicative of slight moisture increases.

The responses are not always so obvious or simple. For instance, on 3 August there was a strong southeasterly wind accompanied by intermittent precipitation, and yet the north, south and eastern aspects show a *decrease* in moisture content due to the drying effect of the wind predominating over the wetting by intermittent rain. At the same time the leeward, western aspect maintained a high level of rock moisture content due to the absence of wind to promote drying. For times of high radiation inputs, with consequent high rock temperatures (e.g. 12 August), it is the southerly aspect that exhibits the lowest rock moisture content. Overall, the rock response with respect to its moisture content will be a funtion of moisture type (i.e. rain, mist, snow, etc.), wind direction and speed, the time of day and the radiation input (here shown indirectly by rock surface temperature). Short-term changes in any of these factors (e.g. fluctuations in wind direction) can rapidly alter the moisture status of the rock. In spite of the greater insight into rock moisture content that these data offer, a clearer understanding of temporal and spatial variability requires much more detailed rock and climatic data than are available here. However, for one day (12 August) measurements were taken every hour (Figure 3) and these start to show some of the complexity and variability that can occur.

Figure 3 clearly shows that the rock surface temperatures follow the progression of the sun through the day. The east-facing rocks heat up first, followed sequentially by those of southerly, westerly and northerly aspects. The eastern and southern aspects experience the highest temperatures, while the north has the lowest. The loss of heating due to direct radiation is shown by the sharp drop in temperature as exhibited by the south-facing rocks after 1700 hours. After initially calm conditions, a southeasterly wind probably caused the slight drop in the temperatures of the eastern aspect, while a shift to the southwest a little later is reflected by the slight rise prior to afternoon cooling. As the temperatures show a marked variability, so too does the rock moisture content despite this being a day *without* any form of precipitation. For example, the eastern samples show an *increase* in moisture content from 16% to 24% at 0900 hours as the sun warms the rock, followed by a decrease to 14% by 1200 hours, a plateau and then an increase from 1500 hours to 26% at 1600 hours, after which it remained constant. The south-facing samples start in an almost dry state but then exhibit a sudden rise to 17% by 0900 hours, a return to almost dry by 1000 hours and then back to 7% by 1100 hours. This is followed by a gradual rise to 10% at 1300 hours and then back to an almost dry state at 1600 hours, where it remains until 2000 hours, after which it suddenly rises to 12%. The south-facing samples appear to slightly mirror the changes in the eastern samples but with a different magnitude of change and the timing generally several hours later. The west-facing samples show a gradual *decrease* through to 1100 hours followed by a slight rise to 1300 hours and a subsequent decrease. Finally, the north-facing samples show an initial drop from 25% to 17%, followed by a rise and a fall that parallel the changes in the eastern samples (and are 1 h later than those of the south).

There are three main attributes apparent from Figure 3.

First, the north-, east- and west-facing samples all have moisture contents substantially higher than that of the south ($N > W > E \gg S$).

Second, moisture contents can *rise* subsequent to initial heating of the rock. This phenomenon, not yet clearly understood, has also been found by Meiklejohn (personal communication, 1991) from work on sandstones heated by early morning sun during winter in the Drakensberg Mountains of southern Africa. It may be that the heating of the cool rock sets up a water vapour transfer due to the temperature gradient in the rock. Moist air moves into the rock, where it cools and the moisture condenses. Later, as the rock continues to heat up, this temperature gradient disappears and the moisture is driven off.

Third, there are significant temporal and spatial variations in moisture content that could have

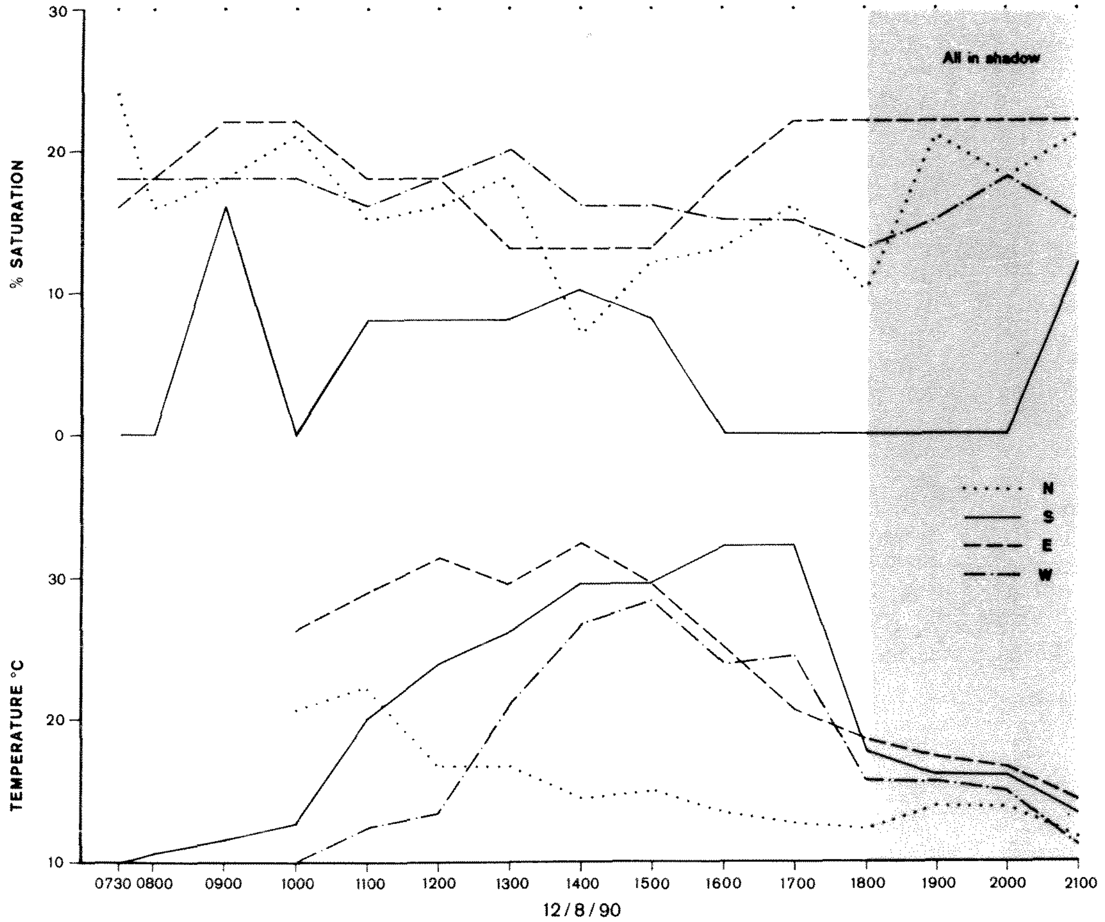

Figure 3 Readings of rock moisture content and rock temperature for each of the four aspects taken at hourly intervals on 12 August.

significant repercussions with respect to weathering.

In terms of weathering it was noticeable that during the record period, even recognizing that it was during a summer, no freeze-thaw events were recorded at any sites. Had any taken place then, as would be the case later in the year when they do occur, rocks of different aspects would have been affected in different ways as a result of the combination of varying moisture regimes and temperature conditions. Thus, it is suggested that great care should be taken in appropriating the freeze-thaw process to any location in the absence of *detailed* rock temperature and moisture information. The small-scale variability in both these factors can be so great (see Hall, 1992, for more details) that it may be found that rocks of differing aspects may or may not freeze in the presence of freezing air temperatures. Equally, the recording of subzero rock surface temperatures is no indicator that the freezing conditions were of any significance, as there may be little or no water available to freeze. Small-scale, aspect-controlled, variability in rock moisture could result in one aspect suffering freeze-thaw weathering, while another a short distance away (< 2 m) does not. Conversely, it could be that the wetter rocks do *not* suffer temperatures conducive to the freezing of available moisture, while the drier rocks of another aspect do. Finally, the amount of water present, and the magnitude, duration and rate of freeze combine to determine the nature of the freeze-thaw mechanism (see Hall, 1991). Without such data, it is impossible to understand the manner in which the rock is being broken and how this varies temporally for any one given location.

Although freeze–thaw did not take place during the study period, wetting and drying events certainly occurred at the more maritime locations. Again, the information from this study, despite being more detailed than in other weathering studies, is still not sufficient to give an accurate picture of the number of wetting and drying cycles, as it was possible for changes to take place within the time between readings. However, from the data that are available it would appear that the actual number of events experienced by any aspect is constrained by the threshold of moisture content that is adopted. Consideration of Table 2 indicates that, on the basis of information presented in Figure 2, the number of events for any given aspect can vary significantly, dependent upon what level of saturation is chosen. However, a lowering of the threshold does not always imply a greater number of cycles (cf. E for C17), as it may be that the moisture level will remain *above* the lower limit but cycle back and forth across a higher level. The problem is really one of the meaning of the threshold adopted. In other words, is the more readily accepted higher level actually of any greater significance? It must be recognized that the moisture levels cited here *refer to the whole block*, although, in reality, water is concentrated within the outer shell of the rock rather than being disseminated throughout the block. Thus, the only real distinction between a 10% saturated rock and a 75% saturated rock is the *depth* to which the rock is wetted. This, then, implies that cycling through, say, a 10% or 25% threshold relates to the outermost margin of the rock and may result in granular disintegration or very thin flaking of that rock. On the other hand, cycling through a 50% or 75% (or higher) level may actually be causing the wetting and drying effect to be taking place *below the surface layer* and result in the production of a thicker weathered skin. In reality, both will be operating at most sites during any one year but it may help to explain, as was found on the nunataks of the Juneau Icefield, how flakes produced from the bedrock (i.e. due to higher moisture levels) subsequently broke down to material of sand grain size (due to the lower moisture levels).

Table 2 Wetting and drying cycles for different degrees of saturation monitored at the four study sites.

Site	10%	25%	50%	75%
C17				
N	0	2	3	2
E	1	7	4	2
S	2	3	4	3
W	3	5	4	2
$\bar{x}$	1.5	4.25	3.75	2.25
C10				
N	1	2	4	2
E	0	4	4	2
S	2	5	3	2
W	2	3	4	0
$\bar{x}$	1.25	3.5	3.75	1.5
C18				
N	2	5	3	1
E	1	2	3	2
S	1	4	2	2
W	0	2	3	3
$\bar{x}$	1.0	3.25	2.75	2.0
C26				
N	4	0	0	0
E	1	0	0	0
S	2	0	0	0
W	3	0	0	0
$\bar{x}$	2.5	0.0	0.0	0.0

Thus, consideration of moisture level variations within rock are much more complex than has been suggested previously. Not only are the variations spatially and temporally controlled such that significant variability can occur over short distances and small time-scales, but also the effects upon weathering processes might be more important than has been hitherto thought. In addition to being a controlling factor upon the nature and effect of freeze–thaw weathering, the degree of saturation and *its* variability may control the nature and extent of weathering due to wetting and drying. Wetting and drying can also work synergistically with freeze–thaw, the former being operative during wetter, milder conditions and accentuating the effects of freeze–thaw, which operates during colder periods, owing to the resulting fatigue. Wetting and drying also exerts a control upon, and must interoperate with, biological weathering. Hall and Otte (1990) found that chasmoendolithic algae were a major cause of flaking in granitic rocks on some of the nunataks of the Juneau Icefield. Expansion and contraction of the mucilage of algae living parallel to the rock surface but at a depth of several millimetres was as a direct result of wetting and drying. The resulting flakes were found to break down to sand-sized grains and it may be that low-amplitude wetting and drying cycles aided in this process.

From available studies it would appear that weathering as a direct result of wetting and drying is likely to be slow (Pissart and Lautridou, 1984; Hames *et al.*, 1987; Hall, 1988b). However, the number of cycles that might occur in any one year may well be very large indeed at some locations and so, through fatigue, could still be effective in causing breakdown, both by their own direct action and also by weakening the rock, thereby lessening the extent of activity required for other processes. What is required, apart from more detailed field data on rock moisture content itself, is information on how wetting and drying actually operates, what the effect of different moisture levels are, and how wetting and drying interoperates with other weathering mechanisms.

CONCLUSIONS

The data presented here, albeit from only a short summer period, give some insight into the complexity and variability of rock moisture content that can occur in cold regions. Significant differences are seen to occur between rocks of different aspects, even though the samples were physically only a short distance apart, and this may have important ramifications with respect to the resulting weathering. The more detailed data for a single day show that this variability can be very large and thus indicate the need for a shorter sampling period if a true picture of wetting and drying is to be obtained. With respect to wetting and drying, it is apparent that the saturation level adopted will greatly affect the perceived number of wetting and drying cycles thought to affect the rock. However, it may well be that rather than a single threshold a range of different levels should be examined in order to evaluate the zones within which the respective cycles are effective, as this may have some bearing on the nature of the resulting breakdown.

Ultimately it will be necessary to obtain information on rock temperatures, radiation input, wind speed and direction, together with precipitation type and amount, in order to explain the temporal and spatial variations in rock moisture content that are measured. However, this level of information is needed to fully investigate not just wetting and drying but also the role of *all* mechanical weathering processes, as well as those of chemical and biological weathering. With respect to wetting and drying itself, there is clearly still a need for extensive laboratory investigation into the manner in which this process operates such that the field data can then be properly evaluated.

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