APPENDIX:

THERMAL ATTRIBUTES OF ROCK WEATHERING: ZONAL OR AZONAL?

A COMPARISON OF ROCK TEMPERATURES IN DIFFERENT ENVIRONMENTS

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Published in: *Polar Geography,* 2004, vol. 28, 79-92

ABSTRACT

Recent investigations into mechanical weathering in cold environments have highlighted products similarities to those of hot deserts. Although general temperature conditions between these two settings are obviously different on the basis of absolute air temperatures, the zonality with respect to thermal changes affecting the rock is less apparent. Data are presented here from four diverse environmental settings with particular emphasis on the fluctuating temperature regime as applicable to rock thermal stress fatigue and thermal shock. The data focus on diurnal oscillations and short-duration rapid changes on rock surfaces at sites in the Antarctic, sub-Antarctic, and at two southern African sites. Comparisons show that different climatic regimes may not be distinctive with respect to rock thermal changes. The azonality is strongly apparent when contrasting the two African sites, a hot desert and cooler alpine setting, in terms of diurnal fluctuations where very similar values are recorded. Overall temperature ranges measured at the Antarctic site approach the magnitude of those in southern Africa and all sites show a high potential for thermal shock under rapid temperature changes. These findings highlight potential azonality with respect to thermally-induced rock weathering and shift the emphasis in cross-climate comparisons to detailed considerations of the moisture regime.

INTRODUCTION

In deserts, weathering processes appear distinctive due to assumed unique temperature conditions (Cooke *et al*., 1982; Smith, 1994) and thermally induced weathering, involving the expansion and contraction of rock under oscillating temperatures, has traditionally been considered to be a major component of hot desert weathering processes. An increasing body of literature (see Hall *et al.*, 2002), however, suggests that thermally-induced processes are also highly effective under cold alpine and high latitude settings. Hall *et al.* (2002) emphasise the neglected role of thermal stress in mechanical breakdown under cold conditions where frost action has traditionally been regarded as the dominant process. An argument for similar thermally-driven processes in cold and hot settings is supported by the presence of angular products, the result of mechanical rock breakdown, and near-identical thermally-induced hierarchical fracture patterns. Notably, both Hall *et al*. (2002) and Smith (1994) cite similar research problems pertaining to the study of rock weathering in cold climates and hot deserts; primarily the absence of appropriate field data on temperature and moisture conditions.

The concept of zonality of process is fundamental to the traditional approach of ‘climatic geomorphology’ (see Thorn, 1988). For example, Weinert (1961, 1965) separated southern Africa into two climatic-weathering regimes, namely a dominant chemical weathering environment in the temperate-wet east extending into dominant mechanical weathering in the hot and arid west. A climatic zone classification is also used to define the periglacial realm (e.g. Peltier, 1950; Karte, 1983; French, 1996) and cold environments suffer from the preconception that freeze-thaw weathering is the dominant mechanical weathering process with limited chemical weathering. Ironically, however, freeze-thaw is recognised to occur in both hot deserts *and* cold high altitude and high latitude settings (Abrahams and Parsons, 1994; Thomas, 1997; Hall *et al.*, 2002). An apparent similarity in products and the potential for similar thermal regimes with respect mainly to *thermal changes* thus challenges the accepted zonality of weathering processes. Clearly, the specific attributes of thermal conditions need further investigation which poses the question: are the rock thermal conditions, with respect to mechanical disintegration, unique to specific environments?

In this paper, summary rock and air temperature data are presented from four sites (Figure 1): from the desert of southern Namibia and a mountain in South Africa (both on similar latitudes near the tropic of Capricorn but on opposite extremes of the African sub-Continent), from the periglacial environment of the sub-Antarctic in the "Roaring Forties", and finally the permafrost regime of the Antarctic Peninsular near the Antarctic circle. It is shown that although the settings differ greatly in terms of absolute air temperatures, they experience many similarities in terms of rock temperature changes; thereby nullifying the notion of zonality with regards to rock weathering.

THE ROLE OF TEMPERATURE CHANGE IN MECHANICAL ROCK WEATHERING

Thermal stress fatigue is a process where rock experiences a series of thermal events that may not cause immediate rock failure, but through repetition on a diurnal or seasonal scale, can ultimately result in granular disintegration or the propagation of new fractures (Yatsu, 1988). Where temperature changes are rapid, thermal shock occurs when the stress temperature change is sufficient to cause rock failure (Yatsu, 1988). The processes and effect of thermal changes on rock are reviewed in detail by Hall (1999; 2003) and Hall *et al*. (2002). Although the emphasis in those papers lies within cold environments, repeated comparisons are made with hot conditions in deserts. A brief summary follows and readers are referred to the above papers for a more extensive discussion.

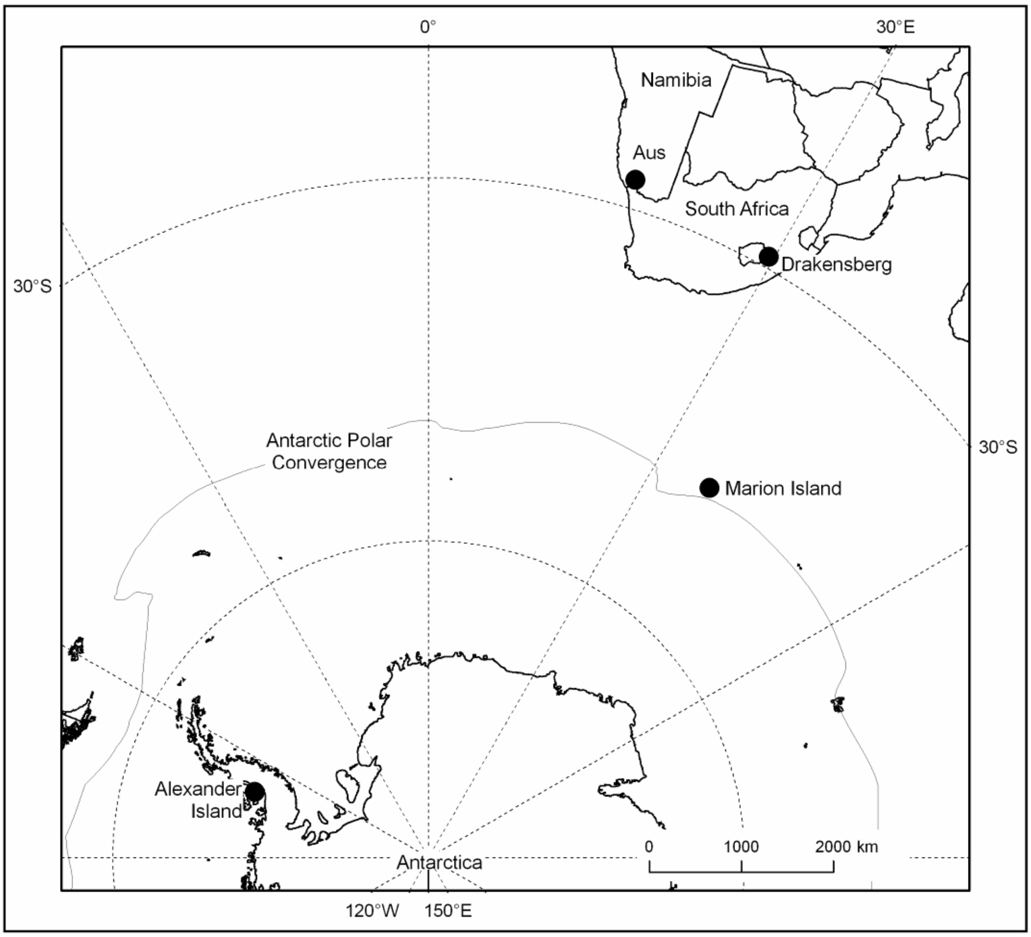

Figure 1: Logger site general locations.

Thermal shock is induced where the rock fails to accommodate rapid changes in temperature and subsequent fracturing occurs. The process can be envisaged in the case of vegetation burning or lightning strikes on rock, but rapid rock temperature changes are also noted under partly cloudy or windy conditions, or where shading occurs (Hall *et al*., 2002). A boundary rate of change of temperature of 2°C/min was ascertained by Richter and Simmons (1974; in Yatsu, 1988) for the occurrence of fracturing along grain boundaries. On large rock bodies, where uneven heating and buttressing increases tensile and compressive forces, the value may be lower. High frequency rock temperature measurements in the order of one-minute duration are thus required to recognise thermal shock (Hall, 2003). Although some data are available on general rock temperature in deserts and stemming from freeze-thaw investigations in cold environments, very few high frequency data are available for discerning thermal shock in different environments.

In hot deserts, the role of thermally-induced breakdown is readily envisaged due to high insolation receipts by day and low rock temperatures from radiative cooling at night. In contrast, thermal stress in cold climates has been largely neglected due to the assumption of dominant freeze-thaw weathering (Hall, 1999). However, relatively high rock temperatures due to insolation heating, particularly on vertical rock surfaces at high latitudes, causes steep temperature gradients between air and rock surfaces. As a result, removal of the heat source, or wind blowing on the surface, can cause rapid cooling. Heating and cooling cycles establish compressive and tensile stress within the rock, the most potentially destructive of which are the tensile stresses under cooling (Marovelli *et al*., 1966). Under cold conditions, the contrasting low air temperatures and heated rock surfaces imply that cooling stresses are probably frequent. Hierarchical fracture patterns, similar to those found in ceramics (Bahr *et al*., 1986), that cross bedding planes and obvious lines of weakness may develop and have been observed in both hot and cold environments (Hall *et al*., 2002). Unfortunately, both desert and cold environments suffer from a general lack of appropriate field data for thermal stress calculations, or from which rock thermal regimes can be compared.

MEASURING ROCK TEMPERATURES

Published literature highlights the range in approaches to measuring rock temperatures. Manual measurements taken by placing thermometers or probe thermometer sensors against bedrock characterised the early literature and have also been used more recently (e.g. Boelhouwers *et al*., 2003). An advantage of this approach is that there is no disturbance to the rock surface in the form of sensor attachment, although the contact when measuring may not be reliable and repeatable and thus the method is impractical for frequent readings. Thermistors (e.g. Smith, 1977; Meiklejohn, 1994b; Hall, 1997) and thermocouples (e.g. Peel, 1974; Hall and André, 2003) have both been used as permanent attachments to rock, particularly where frequent measurement in the order of one minute or shorter are taken. Seldom are all logger and sensor specifications detailed by researchers; e.g. sensor size and casing composition, accuracy and response times.

Attached sensors suffer from the ability to alter surface conditions and thus the possibility that data reflect sensor and not true rock temperatures. The problem has been rectified somewhat with the use of small thermistors where shading effects, heat sink and heat inertia (mass) are minimal (e.g. Hall, 1998). The typically larger thermocouples, some protected in stainless steel and measuring up to 5 mm in diameter, can be inserted from beneath or behind the rock surface (e.g. Hall, 1997). Smaller bead-type thermistors have also been used on rock surfaces (Hall, 1998). A reduction in sensor size is accompanied by the difficulty in attachment, more frequent visitation for maintenance and a greater risk of data loss (e.g. Hall and André, 2003 p. 828).

Notwithstanding potential sensors problems, few specific details on sensor locations are provided in studies. Although aspect orientations are generally noted, sometimes for specific comparative reasons, detail is lacking. For example, ‘upward facing’ or equator orientations fail to fully consider the effect of the angle of incidence on the rock surface. At high latitudes, horizontal surfaces are less orientated towards incoming solar radiation than vertical faces. A failure to document precise dip and orientation may make a comparison between sites problematic. In addition, frequency of measurement varies considerably. Measurement intervals range from diurnal minima and maxima, based on actual values or derived from interval data, to 20 second intervals (Hall and André, 2003; Hall, 2003). High-frequency recordings on a number of channels rapidly generate large data sets, which can create on-site logger storage problems and increase visitation frequency. Seldom can all collected data be presented in detail making direct comparisons between published field information from different sites difficult.

SITE DESCRIPTIONS AND DATA COLLECTION

Four data sets collected by the authors from field investigations initiated in the 1990's, but not running consecutively or simultaneously, are presented here. The data focus on diurnal cycles, intended to illustrate the conditions conducive to thermal fatigue, and maximum short-term (one minute) rock temperature changes as representative of the potential for thermal shock. As is typical for isolated, site-specific studies a direct comparison of data was not intended from the outset and different equipment were used at the sites. A Campbell Scientific® logger and a Grant Squirrel® were used in the Antarctic for air and rock temperature measurements respectively. MCS® data recorders were used at the three other sites. A brief site description and specific methodology is detailed as follows:

In southern Namibia (26° 42' S; 16° 12' E), a logger station was set on the summit of a granite gneiss outcrop on the farm Klein Aus Vista, 2 km west of the village Aus and 115 km inland from the coastal town of Luderitz. Granite gneiss outcrops, part of the Namaqua Metamorphic complex, are conspicuous in the area and rise to a few hundred metres above the sandy plains. The logger was situated on the eastern fringe of the coastal Namib desert, at 1278 m a.s.l. The environment is arid to hyper-arid with precipitation approximately 150 mm p.a. and a mean annual air temperature (MAAT) of ~20°C. Rock surface temperatures were measured using Type-T thermocouples (2mm x 5mm; 2 second response time; resolution 0.4°C over the range -200 to +400°C) bonded with contact adhesive to the northern, upper and southern-facing surfaces of a granite block measuring 2m x 2m x 1m, long axis orientated to the north. At a latitude of 26°S the upper surface was deemed most appropriate for maximum thermal fluctuations and only those data are considered here. Monitoring covered a six month period until logger failure in January 2003 (Table 1). Daily minimum and maximum were recorded for both rock surfaces and shaded air temperatures at 1m height. Another logger was installed to assess short-term temperature changes over a nine month period ending September 2003. The single thermistor sensor, measuring 5mm in diameter (resolution 0.2°C over the range -35 to +95°C) and cased in stainless steel, was inserted into a pre-drilled clast (~3kg) to 2mm depth from the opposite surface and placed such that the undisturbed surface faced upwards. These commonly used thermocouples have a response time of less than 30 sec, sufficient for one minute resolution readings (Hall, 2003). The logger was programmed to only record events where temperature changes exceeded 1°C in any minute period.

The second site was located on a similar latitude to Aus but on the eastern region of South Africa in the Drakensberg range. The site, located adjacent to the Injisuthi Cottage outpost at 1920 m a.s.l. (29° 08' S; 29° 26' E), represents a mid-latitude cool alpine environment with an estimated mean annual precipitation (MAP) of 1050 mm and a MAAT of 14°C. Maximum altitude near the site is 3450 m on the escarpment and valleys incise to below 1400 m a.s.l. Located on a valley interfluve the site is on the contact between the Lower Jurassic Drakensberg Group basalt lavas and Clarens Formation sandstones (Eriksson, 1983; Eales *et al.*, 1984). To measure rock temperatures, a basalt clast (~3kg) was drilled, the thermistor (identical to the Aus thermistor-type) inserted to 2 mm from the opposite surface and positioned with the undisturbed surface facing upwards (see Hall, 1997). Daily minimum and maximum were recorded for both rock surface and shaded air temperatures at 1m height. Records began in November 2001 and ended in August 2002 due to cable damage in a runaway fire. No short-term data are available from the site, although one of the authors monitored rock temperatures at one-minute intervals in sandstone using a LM 35DZ thermistor connected to a calibrated digital display at 1700 m in 1994 from nearby site (see Meiklejohn, 1994b). These are the only known short-interval data available from the Drakensberg.

The third site is located in the sub-Antarctic. Marion Island, one of two constituting the Prince Edwards islands (46°S 38°E), reaches 1240 m a.s.l. and is a hyper-maritime periglacial environment (Boelhouwers *et al.*, 2003). Precipitation at the coast is in the region of 2000 mm p.a. and the MAAT ~6.5°C (Smith, 2002). Precipitation falls on approximately 25 days each month (Schulze, 1971) which implies cloudy conditions and consequent low insolation receipts. In the higher interior of the island, discontinuous permafrost exists above approximately 1000m and MAAT is estimated at 0°C (Boelhouwers *et al*., 2003). Temperatures were measured in 1999-2000, using the same logger and thermocouples as later used at Aus, on a grey lava block measuring approximately 1m x 1m x 0.6m. Rock surface temperatures were monitored on the northern and southern-facing aspect. While the southern aspect of the block has a vertical face, the northern surface dipped at approximately 40°. Given the latitude of the site (46°S), this would imply more near-direct insolation than an upward-facing surface during the year. One shaded sensor measured air temperature at 0.5m above the ground. Readings were taken as hourly instantaneous for one year (Table 1) and the results, in terms of frost cycles and overall means are presented by Boelhouwers *et al*. (2003). Here the northern surface data are re-analysed in part to determine diurnal fluctuations as indicative of conditions conducive to thermal fatigue. On a separate occasion, subsequent to this period near sea level, thermocouples were also used on rock surfaces to monitor short-duration temperature fluctuation on grey lava clast surfaces. Finally, an Antarctic site was monitored in Viking Valley on Alexander Island (71° 50’ S, 68° 21’ W), which is an east-west-orientated tributary of the Mars Glacier that is part of the Two-Step Cliffs massif. The area comprises a belt of Jurassic and Cretaceous marine sandstones (Horne, 1968; Taylor *et al*., 1979); a detailed description of the site is provided by Hall (1997). The monitoring site was located at an altitude of 200 m a.s.l. in the base of Viking Valley, where MAP is estimated at less than 200 mm and MAAT at -8°C. Viking Valley has continuous permafrost with a shallow active layer (ca. 5 to 20 cm) (Meikeljohn, 1994a; Meiklejohn & Hall, 1997). Sandstone air temperatures and rock temperatures were recorded using a Campbell micrologger and Grant Squirrel logger respectively both with Campbell Scientific® 108 temperature sensors that utilise BetaTherm 100K6A1 thermistors (Hall, 1997).

ROCK TEMPERATURES

Summary data from the four sites are presented in Table 1, and Figure 2 provides the basis for visual comparison of data. At the two southern African sites, estimated MAAT is approximately 6°C warmer in the arid west. The difference is matched by the mean rock temperatures with the western site 6.2°C warmer than the recorded values in the east (28.6°C *vs* 22.4°C). Notwithstanding the differences in mean temperatures, the data illustrate remarkably similar thermal conditions with regard to temperature ranges. Absolute ranges in rock temperatures are 64.4°C measured at Aus in the west and 62.7°C from the Drakensberg in the east. Maximum daily ranges of 44.4°C and 48.7°C, and average daily ranges of 31.3°C and 31.0°C are noted in the west and east respectively over the monitored periods. Although the total measured air temperature range at Aus was greater than that recorded in the Drakensberg (41.6°C and 33.9°C) the maximum diurnal range (27.0°C and 25.7°C) and average daily ranges (13.9°C and 12.2°C) are similar.

At the higher latitude sites, site mean annual air temperatures are estimated at 1°C and -8°C on Marion Island and Viking Valley respectively. At both sites, total ranges in rock temperatures are smaller than the southern African sites, although the Antarctic rock range of 54.9°C (43.3°C for sub-Antarctic) still compares remarkably well to the lower latitude data. The maximum daily range decreases from values in the mid-40 Celsius for the African sub-continent to 34.2°C on Marion Island to 21.0°C on Antarctica. Average daily range is also smaller at 8.9°C and 5.8°C respectively in contrast to ranges of 30 degree Celsius at the southern African sites. The highest and lowest absolute air temperature ranges for the four sites were recorded at these higher latitude settings: a low range of 26.6°C on sub-Antarctic Marion Island and a high range of 46.3°C on the Antarctic Peninsular, some 5°C greater than the Namibia site. Both the Marion Island and the Antarctic data show similar daily ranges in air temperature (e.g. a mean daily range of 6.1°C and 5.2° respectively), although these are approximately half the corresponding range of the sub-continent sites.

Location and attributes	**Aus, southern Namibia**	**Drakensberg, South Africa**	**Sub-Antarctic, Marion Island**	**Viking Valley, Antarctica**
Lithology	Granite gneiss	Basalt	Basalt	Sandstone
Latitude, altitude (a.s.l.),	26°S, 1278m	28°S, 1920m	46°S, 1000m	71°S, 200m
MAAT (est)	20 °C	14 °C	1 °C	-8 °C
MAP (est)	150mm	1050mm	2000mm	<200mm
Climate description *[and Koppen classification]*	Hyper-arid, sand desert margin	Mid-latitude alpine	Periglacial, discontinuous permafrost	Arid to hyper-arid, polar, continuous permafrost
Monitoring period	July 2002 to Jan 2003	Nov 2001 to Aug 2002	April 1999 to March 2000	Dec 1992 to Aug 1993
Sensor type	Thermocouple	Thermistor	Thermocouple	Thermistor
Sensor location	Horizontal block surface	Horizontal block surface, 2mm depth	North-facing block surface (dip 40°)	Horizontal block surface, 2mm depth
Logger record interval	Daily min max	Daily min max	Hourly instantaneous	Hourly instantaneous
Rock T: Absolute range from min to max [range]	-1.6 to 62.8 °C [64.4 °C]	-6.7 to 56.0 °C [62.7 °C]	-8.8 to 34.5 °C [43.3 °C]	-33.3 to 21.6 °C [54.9]
Rock T: Max daily range min to max [range]	7.6 to 52.0 °C [44.4 °C]	4.3 to 53.0 °C [48.7 °C]	-4.1 to 30.1 [34.2 °C]	0.0 to 21.0 °C [21.0 °C]
Rock T: Mean daily range min to max [range]	13.0 to 44.3 °C [31.3 °C]	7.0 to 38.0 °C [31.0 °C]	1.7 to 7.2 °C [8.9 °C]	-9.6 to -3.8 °C [5.8 °C]
Rock T: Mean	28.6 °C*	22.4 °C*	1.8 °C	-7.2 °C
Air T: Mean	22.1 °C*	15.3 °C*	0.8 °C	-8.0 °C
Air T: Absolute range from min to max [range]	1.3 to 42.9 °C [41.6 °C]	-3.3 to 30.6 °C [33.9 °C]	-10.8 to 15.8 °C [26.6 °C]	-34.8 to 11.5 °C [46.3 °C]
Air T: Max daily range	27.0 °C	25.7 °C	17.8 °C	16.8 °C
Air T: Mean daily range	13.9 °C	12.2 °C	6.1 °C	5.2 °C
Max short-term (♠T/t) recorded at or near site	1.7 °C/min (2mm depth) (1 min intervals)	2.0 °C/min (surface) (1 min intervals)	>2.0 °C/min (surface) (1 min intervals)	>2.0 °C/min (surface) (1 min intervals)
* derived from (min + max)/2 (following Smith, 2002)				

Table 1: Summary of environmental conditions and recorded temperature data at the four logger sites.

Short-term rock surface temperature fluctuations were recorded at all four locations, although the measurements may not have coincided with the longer-term data or at the actual site. Temperature changes in the order of 2°C/min, the value for thermal shock, were recorded for three of the sites with a maximum value of 1.7°C/min during a cooling cycle noted at the Namibia site.

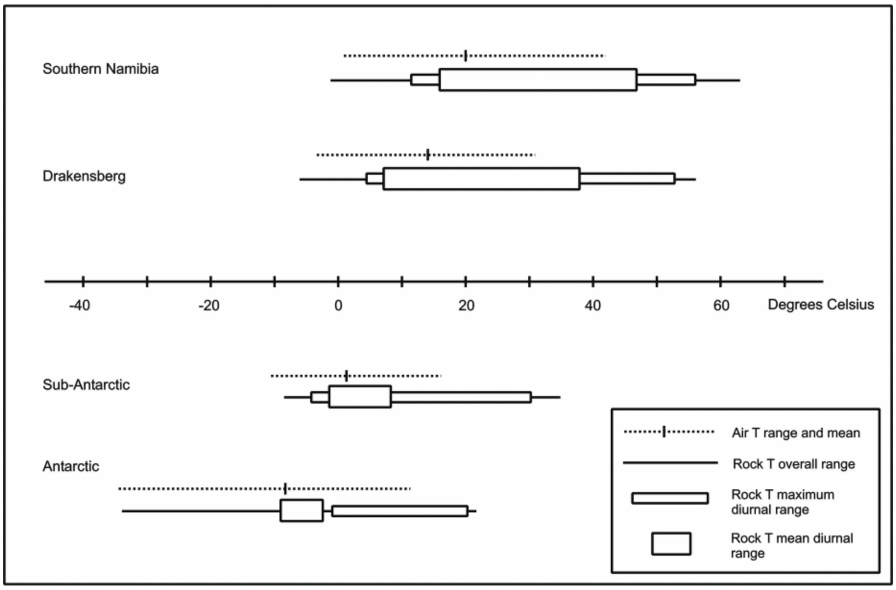

Figure 2: Air and rock temperature ranges as recorded at the four sites.

DISCUSSION

As expected, air and rock temperature means are at a maximum at the southern African desert site, decline to the alpine setting in the east of the sub-Continent at a similar latitude, and then decrease at higher latitudes towards the pole. At the two southern African sites, the similarities in temperature oscillations for both the overall range and at the diurnal scale are notable. Although the absolute temperatures are approximately 6 to 7°C warmer in the desert in the west, ranges in both air and rock surfaces are very similar as evident on Figure 2. Thus, the potential for thermal stress fatigue appears <u>not</u> to differ between the alpine and desert setting. As described by Weinert (1965), Aus falls into the zone of maximum propensity for mechanical disintegration and the Drakensberg site falls into the zone for maximum chemical decomposition. The products, as noted for dolerites across southern Africa (Weinert, 1965) should, therefore, be primarily due to prevalent moisture conditions.

At the higher latitude sites, a decrease in diurnal rock temperature range is observed. The maximum daily range in the sub-Antarctic is approximately 75% that of the desert, and on the Peninsular approximately 50% of the desert range (Table 1; Figure 2); average daily ranges are proportionally even smaller. Some similarities between sites can, however, be highlighted. Although the Antarctic site has mean temperatures roughly 8°C lower than the sub-Antarctic site, the ranges in air temperature are similar and the average daily ranges are in the same order of magnitude. Of particular interest is the similarity in the magnitude of rock temperature range between the Antarctic site and the southern Namibia site, although somewhat smaller on the sub-Antarctic island. Smaller ranges on Marion Island can in part be attributed to the cloudy conditions on the island where high mean monthly cloud cover averaging 6.2 oktas are experienced (Holness, 2001). On Antarctica, ranges on near-vertical surfaces with more direct insolation may provide a greater range in temperatures. For example, on vertical rock surfaces, Hall (1998) shows a diurnal range of 28.5°C, somewhat higher than the range values presented here. Notwithstanding the lower range values recorded (in contrast to the lower latitude sites), an issue arises in terms of the effectiveness of temperature oscillations and hence the duration required for rock breakdown. Since the overall range at the Antarctic site approaches that of the sub-Continent, and the maximum daily range of the sub-Antarctic site exceeds the average diurnal ranges of the higher latitude sites, given sufficiently long periods of time the process types may be similar even if the durations required for effective breakdown differ. Duration of exposure and efficiency of process operation thus requires further consideration.

All sites show a potential for thermal shock. Rates of temperature change in the order of at least 2°C/min were measured at three of the sites. Since the sensor at the Namibia site was placed 2 mm beneath the surface, a more dynamic temperature environment could be expected at the surface and changes exceeding the 1.7°C/min are likely to be frequent. Under the colder air temperatures of the high latitude settings, temperature gradients between heated rock and air should be higher than those experienced in hot desert conditions. This contrast can potentially provide a more dynamic environment for rapid temperature changes on cooling even if overall ranges, as envisaged on a diurnal basis, appear to be smaller at the colder sites. Given that stresses are greater under cooling (Marovelli *et al*., 1966) the possibility exists that thermal shock is underestimated as an effective contributor to fracturing in cold environments. More data are, however, required to contrast high-frequency thermal changes under different environmental conditions than presented here. On the basis of the above, several questions are considered as being essential to furthering our understanding of the mechanical weathering process and its spatial distribution:

1) *How different are environments with respect to rock thermal conditions?* Clearly, moisture and air temperature conditions can distinguish environments as climatic zones and the concept of climatic geomorphology is well entrenched in the geomorphic literature (see Thorn, 1988). However, based on the data presented here, it is possible that certain processes or process suites dependant on thermal changes are not zonal in geographic distribution. The climatic contrast across southern Africa, from a desert to a wet, cooler alpine setting clearly shows the similarity in thermal oscillations conducive to stress fatigue. In addition, the potential for thermal shock appears to be ubiquitous across a large latitudinal gradient covering diverse environments. However, more comparable data from different climates are still required to further test for zonality or azonality between different settings. Specific issues pertaining to field methodologies for such studies also require attention in future. Techniques for rock temperature measurement, both in terms of equipment and approach (for example recording durations) vary from study to study. Recently, approaches

to standardise monitoring programmes have gained in popularity, such as the permafrost monitoring of PACE (Harris *et al*., 2001), the CALM (Circumpolar Active-Layer Monitoring) initiative of the International Permafrost Association, and proposals for geomorphic monitoring of periglacial slopes (Matsuoka, 2004). For direct comparative purposes a standard approach is required in rock weathering assessments that includes methodologies for rock temperature and rock moisture analysis; this leads to the following important considerations:

2) *Do we know* what *to measure, where to measure it and how?* Air temperatures alone are inappropriate when considering rock conditions; detailed rock temperature data are crucial. Traditionally, rock temperature data collection in cold environments has been directed towards the identification of freeze-thaw cycles on a seasonal or diurnal scale (Hall *et al*., 2002). While these data may provide some indication of thermal fatigue regimes, they are not applicable to identifying thermal shock. Advances in sensor technology, logger memory capacity and battery life expectations has improved the ability to collect high resolution data up to the grain scale in the field (Hall and André, 2003; Hall, 2003). Grain-scale, high-frequency (less than one minute) data appear incomparable to longer-interval data specifically directed towards frost-weathering cycle identification (Hall, 2003). Sensor size and measurement frequency does have a lower (or smaller) limit as pertaining to rock measurement. Hall (2003) postulates that measurement at a 10 second interval is the shortest realistic duration for measurement given the thermal response time of rock crystals. Similarly, using sensors smaller than the grain scale may improve the understanding of individual crystal breakdown, or perhaps inter-granular interactions, but will probably have little bearing on new fracture propagation in the rock mass (Hall, 2003). Evidently, more attention needs to be directed towards the issue of appropriate field measurements that are pertinent not only to the spatial and temporal scale(s) of the thermal regime, but also to other related processes such as salt weathering, wetting and drying, freeze-thaw and chemical weathering.

3) *If thermal conditions tend towards azonality, why are different products observed in the field?* Thermal fracture patterns are observed in both hot deserts and in cold climates, angular weathered material is equally as ubiquitous and granular-scale mechanical weathering also produces an array of rounded forms (Hall *et al*., 2002). Where thermal regimes are comparable, the difference in products must, therefore, be attributed to rock properties and/or the moisture regime. The relevance of moisture conditions is apparent in the contrasting products observed by Weinert (1961; 1965) grading from disintegrated in the west of southern Africa to decomposed in the east. Given the similarities in the rock thermal regimes, the absolute moisture content, moisture fluctuations and the state of water (frozen vs unfrozen) appear to be increasingly important factors in determining process and product. Unfortunately, even less is known of moisture conditions in the field, in part due to the failure to recognise the importance of chemical weathering in apparently dry settings, the assumption of moisture presence where freeze-thaw is considered as *the* mechanical weathering process, and the logistical difficulty in actually monitoring rock moisture conditions in the field. Until a clearer picture is presented on both thermal conditions *and* moisture content little progress will be made in understanding weathering processes at *any* location. In summation thus the following:

4) *What are the future research issues?* The zonality approach to temperature conditions still requires extensive testing. Data presented here suggest that conditions pertaining to rock thermal fluctuations may be azonal. Absolute temperatures can still be applicable to specific processes, but this needs to be considered not from the perspective of temperatures alone, but also from the perspective of moisture conditions (specifically state and fluctuations) before more clarity can be obtained on process. The efficiency of thermal stress fatigue under different temperature ranges still requires extensive laboratory testing, as does the effectiveness of rapid temperature changes on producing fracturing at both the granular scale and to the rock mass. Much effort must also be directed towards measurement

techniques with clearly defined questions or hypotheses that require testing.

CONCLUSION

Rock temperature data collected from two localities in southern Africa, a hyper-arid hot desert and a cooler, wet alpine setting in the Drakensberg in the east highlight the similarity in rock thermal regimes under different climatic settings. Although absolute temperatures in the desert are higher, the ranges and fluctuations of air and rock temperature on a diurnal basis and in total over the monitoring periods highlight a remarkable similarity in thermal oscillations experienced by rock in both settings. It is expected, therefore, that the climatic conditions, although different, are conducive to near identical thermal stress fatigue regimes. A similar argument can be made for the role of thermal shock since rapid changes in temperature can be expected in either location. It follows that the concept of zonality or climatic distinction between obviously different environments may not apply to the mechanical weathering suite of processes reliant on rock temperature changes.

In contrast, a gradient of decreasing thermal oscillations is found with increasing latitude. Although the data may not be entirely representative of maximum possible thermal oscillations at high latitudes, some similarities that again question the concept of zonality emerge. Temperature fluctuations at high latitudes *can* be in the same orders of magnitude as those found in a hot desert. The efficiency of occasional diurnal fluctuations as opposed to frequent fluctuations in the context of long-term stress fatigue still needs further quantification. In addition, rapid changes conducive to thermal shock appear to be ubiquitous, and may even be more effective in terms of rock breakdown on cooling under cold conditions where air-rock temperature gradients are steeper. As noted for thermal fatigue, more data on the efficiency of rapid changes in rock fracturing at the grain scale and to the rock mass are required.

Finally, if a degree of azonality applies to rock thermal conditions, this would highlight the importance of rock moisture in determining process operation and effectiveness under different settings. Although several directions for research into rock temperatures are noted above, a substantial list can also be made for improving the understanding of the rock moisture regime. These data will need to be reconciled with the diverse rock physical properties and changing physical properties inherent in field conditions. Until an adequate understanding is made of all three aspects, determining process operation will remain elusive.

ACKNOWLEDGEMENTS

The authors are indebted to: Pieter, Johan and Willem Swiegers on the farm Klein Aus Vista and Ezemvelo KZN Wildlife for permitting logger installations in southern Namibia and the Drakensberg, South Africa, respectively. Data from the sub-Antarctic were collected during South African National Antarctic Programme (SANAP) Marion Island expeditions to Marion Island under the auspices of the South African Department of Environmental Affairs and Tourism. The University of Pretoria partially funded logger equipment at some sites. Data from the Alexander Island site were obtained from a logger installed by the British Antarctic Survey, from Kevin Hall.

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