THE UTILIZATION OF THE STRESS INTENSITY FACTOR (K_{IC}) IN A MODEL FOR ROCK FRACTURE DURING FREEZING: AN EXAMPLE FROM SIGNY ISLAND, THE MARITIME ANTARCTIC

KEVIN HALL

Geography Department, University of Natal, Pietermaritzburg, South Africa

ABSTRACT. A recent theoretical model to explain rock fracture during freezing (Hallet, 1983) offers a potentially valuable means for explaining weathering in the field. The model utilizes the stress intensity factor (K_{IC}), and a value for this is derived for quartz-micaschist, the main rock on Signy Island. It is shown that the main problem of the model for field applications is the attainment of a saturated state. However, it does offer a theoretical framework against which field data can be evaluated, and it provides a mechanism to explain why the cliff faces are mainly unweathered whilst loose talus blocks show extensive breakdown.

INTRODUCTION

Freeze–thaw weathering is a process usually cited (e.g. Washburn, 1980) as a major weathering agent in polar and high-altitude locations. Despite the apparent ease with which it is quoted it is, nevertheless, a mechanism which is as yet little understood and for which there are few quantitative field observations (McGreevy, 1981). In broad terms there are three major controls: temperature, moisture and rock properties. Although especially germane to the mechanism, data on temperatures are few (see McGreevy, 1981 for a review) and those on moisture even rarer (Trenhaile and Mercan, 1984; Hall, in press *a*; McGreevy and Whalley, in press). When considering moisture it is apparent that its chemical composition is important (Williams and Robinson, 1981; McGreevy, 1982; Fahey, 1985) and yet information on solutes of rock moisture *in situ* is limited to one sample from chalk (Kinniburgh and Miles, 1983) and the recent analysis of four samples from this current study (Hall and others, 1986). The properties of the rock have been considered to varying extents in different studies with porosity, water absorption capacity, saturation coefficient and microporosity being the most common ones cited (e.g. Fahey, 1985; Hall, in press *a*). There are, however, other parameters such as compressive strength, specific energy index (Szlavin, 1974) and fracture toughness which play an important role. Here it is the use of the fracture toughness index (K_{IC}) which is to be considered.

Gunsallus and Kulhawy (1984) have stated clearly that the development of fracture mechanics is based on the precept that a single parameter, K, the stress intensity factor, can be used to represent the stress field ahead of a crack. The value of K is mainly a function of the level of applied stress and crack size. The fracture toughness of a rock is thus its critical stress intensity factor value. With knowledge of the value of K_{IC} (critical intensity factor mode I: the opening mode (Schmidt and Rossmanith, 1983)) for the particular rock under study and measurements of the crack length it is possible, by means of a model suggested by Hallet (1983), to calculate the pressure inside the crack for propagation to take place, and the temperature required to generate that pressure.

The moisture content of the rock, and its chemical composition, affect both the strength of that rock (Broch, 1979) and the operation of the model (Hallet, 1983), and therefore data on interstitial rock water is of vital importance. In addition, if the rock is saturated or nearly so, then temperature is the major control on the tensile

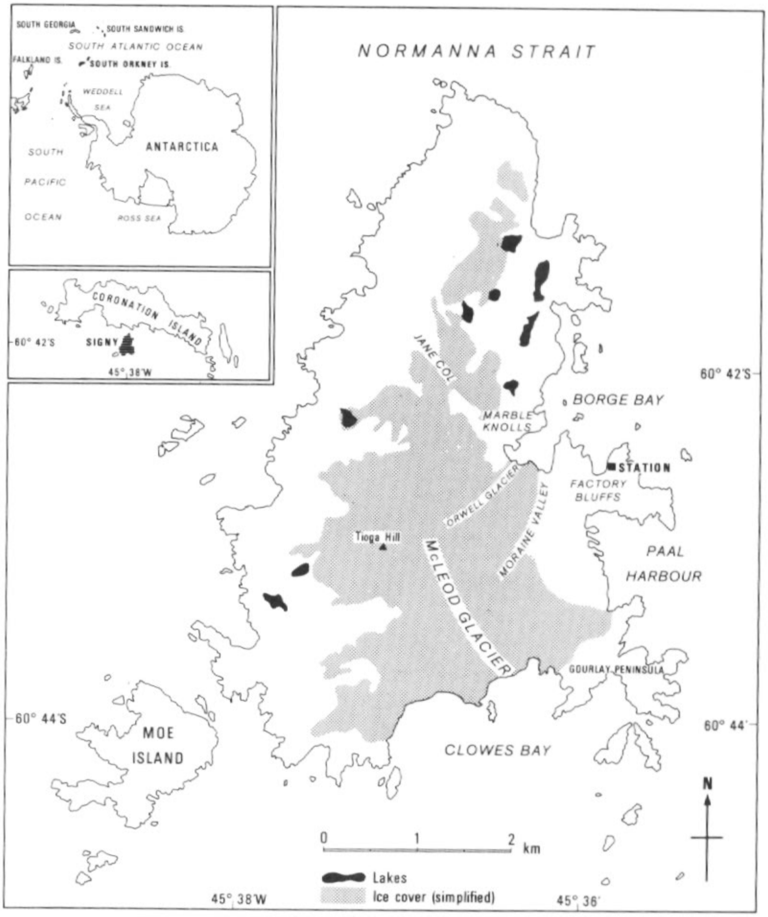

Fig. 1. Location map of Signy Island.

stress exerted by the growth of ice within the rock. So, for a valid utilization of K_{IC}, moisture and temperature data are required. In this study information has been obtained, for the first time in a polar environment, on both of these parameters and so the application of K_{IC} can be attempted. However, the details on temperature (Walton, 1982), moisture (Hall, in press *a*) and rock properties (Hall, in press *a* and *b*) are given elsewhere and it is only the derivation and application of K_{IC} to freeze–thaw studies within a maritime Antarctic environment which are presented here.

STUDY AREA

Data and rock samples were collected from Signy Island (Lat. 60° 43′ S, Long. 45° 38′ W), one of the smaller islands in the South Orkneys group (Fig. 1). Signy is *c.* 8 km north to south, *c.* 4.8 km east to west, has an area of 19.94 km^2 and rises to a height of 279 m. Approximately one-third of the island is covered by an ice cap, but much of the rest of the island is subject to long-term snow cover and the whole is an area of discontinuous permafrost. Running water is limited and mainly confined to a few small streams along the margins of the ice cover.

Geologically the island comprises metamorphosed sediments, primarily quartz-micaschist with smaller outcrops of amphibolites, quartzites and marbles (Mathews and Maling, 1967; Storey and Meneilly, 1985). Climatically it is a typical cold, oceanic island with a mean monthly temperature of $-4°C$ but with the summer three months slightly above freezing (Collins and others, 1975). The precipitation is 0.4 m yr^{-1} and is mainly in the form of snow, except for January and February when rain can predominate. The mean amount of sunshine is only around 1.5 hr day^{-1} with average wind speeds of about 26 km hr^{-1}. The vegetation is typical of the maritime Antarctic and is comprised of fructicose lichens, cushion mosses and occasional areas of the grass *Deschampsia antarctica* (Smith, 1972). There are extensive areas of patterned ground (Chambers, 1967).

TECHNIQUES AND APPROACH

Samples of quartz-micaschist were collected from various positions on rock outcrops and the ground surface for a variety of altitudes and aspects. In addition, sampling was undertaken in different environmental conditions during spring and summer, i.e. from under snow cover, during snowmelt, in a meltwater rivulet, during thawing of frozen ground, etc. The field moisture content of all samples was obtained (Hall, in press *a*) and the rocks subjected to the irregular lump point-load test in order to find their compressive strength (Broch and Franklin, 1972). As quartz-micaschist is anisotropic tests were carried out both parallel and transverse to schistosity (Hall, in press *b*). Data on temperature conditions on Signy at two vegetated sites are already available (Walton, 1977 and 1982) but year-round micro-meteorological data logging, by means of 'Datacapture' 16-channel recorders, is currently in progress at the three reference Fellfield sites (Factory Bluffs, Moraine Valley and Jane Col: Fig. 1). Finally, information on the solutes available *inside* the rock has been obtained (Hall and others, in press) as these may play a role in inhibiting (Mcgreevy, 1982) or abetting (Williams and Robinson, 1981) frost action. Thus, measures of rock moisture content *in situ*, and its chemical composition, together with point-load strength and a range of temperatures to which the rock may be subject, have been obtained.

To obtain the fracture toughness (K_{IC}) of the rock, the regression equation of Gunsallus and Kulhawy (1984) was used, where

$$K_{IC} = 0.0995 I_{S_{50}} + 1.11 \tag{1}$$

All point-load readings were index referenced to a standard 50 mm size (designated $I_{S_{50}}$) following Broch and Franklin (1972, fig. 25). Although the regression equation of Gunsallus and Kulhawy (1984) was not derived from quartz-micaschist it was utilized here because no data are available for this rock type (see Atkinson, 1984). Thus it was possible to obtain a value of K_{IC} which could be incorporated into the model for the breakdown of rock due to freezing produced by Hallet (1983):

$$K_{IC} = \left(\frac{\pi l}{2}\right)^{\frac{1}{2}} (P + \sigma) \tag{2}$$

where Hallet (1983) defines l as the length of a 2-dimensional crack, P as the pressure inside the crack, and σ as the 'applied' normal stress perpendicular to the crack plane (tensile stresses being positive). Hallet's equation could then be rewritten as

$$P = K_{IC} \left(\frac{2}{\pi l}\right)^{\frac{1}{2}} - \sigma \tag{3}$$

so as to obtain the value of P required in the crack for propagation to take place.

Table I. Values of P (MPa m^{-2}) found for cracks of different lengths with a variety of overburdens.

Overburden thickness (m)	*Crack lengths (m)*					
	0.0001	0.0005	0.001	0.005	0.01	0.1
1	105.53	47.13	33.34	14.92	10.56	3.36
2	105.37	47.15	33.36	14.94	10.58	3.38
5	105.46	47.24	33.45	15.02	10.67	3.46
10	105.59	47.37	33.52	15.10	10.80	3.60
50	106.67	48.45	34.66	16.24	11.88	4.68
100	108.03	49.81	36.02	17.60	13.24	6.04
150	109.38	51.16	37.37	18.95	14.59	7.39

As overburden pressure plays a role in determining the value of P, the mean density of the rock was determined and so the compressive pressure was then calculated for various thicknesses of overburden and entered into equation 3. Finally, accepting that internal ice pressure increases with negative temperatures at a rate of 1.14 MPa deg (Hallet, 1983) for any saturated rock, it was possible to calculate what temperatures would theoretically be required to generate these pressures and then to compare them with the island temperature records.

RESULTS AND DISCUSSION

The mean of 50 K_I values derived from point-load tests via equation 1 was found to be 1.32 MN m$^{-\frac{3}{2}}$. The range of K_I values was low, varying between 1.4891 (for $I_{S_{50}}$ normal to schistosity 3.81 MN/m^2) and 1.2000 (for $I_{S_{50}}$ parallel to schistosity 0.1 MN/m^2) despite taking values both transverse and parallel to schistosity. Therefore, utilizing this value of K_I together with crack lengths (l) of 0.0001, 0.0005, 0.001, 0.005, 0.01 and 0.1 m, together with σ set for overburdens of 1, 2, 5, 10, 50, 100 and 150 m, it was possible to generate a variety of results for P (Table I). The value of σ was derived from the density of the quartz-micaschist ($\bar{x}$ of 20 samples = 2.76 g/cm^3) multiplied by h (the height of a column of uniform cross-section) times acceleration due to gravity.

The values of P shown in Table I are based upon a saturated state. If this presumption is accepted then, knowing the rate of pressure increase with decrease in temperature (1.14 MPa deg^{-1}) it is possible to calculate the theoretical temperatures required to achieve these pressures (Table II). If the rock is not saturated then this model (equation 2) is said not to give adequate results (Hallet, 1983) but, nevertheles it does provide a hypothesis for comparison against observed temperatures.

The theoretical values shown in Table I are constrained by the degree of saturation of the rock and temperatures from actually achieving the required levels. Results of moisture determinations (Hall, in press *a*) show that most samples were less than 50% saturated. However, of a sample of 47, eight showed > 90% saturation, with four fully saturated, and a further 10 had > 50% moisture content. Those samples with the higher moisture contents all comprised small blocks residing on the ground either in melt rivulets or from under melting snow. Samples taken from the wetter, outer faces of vertical cliffs and from small rock outcrops all showed low (15–30%) moisture values. Consequently, on Signy Island it would appear that the model of Hallet (1983) can only be practically applied to blocks that have been released from the cliffs.

Qualitative observations and the results of engineering geology tests (Hall, in press *b*) all indicate that the cliffs have been subject to very little weathering. Further, the

Table II. The calculated temperatures required to generate P (as given in Table I) for different crack lengths and overburden pressures.

Overburden thickness (*m*)	*Crack lengths* (*m*) 0.0001	0.0005	0.001	0.005	0.01	0.1
1	−92.41	−41.34	−29.25	−13.09	−9.26	−2.95
2	−92.43	−41.36	−29.27	−13.11	−9.28	−2.96
5	−92.51	−41.44	−29.34	−13.18	−9.36	−3.04
10	−92.62	−41.55	−29.40	−13.25	−9.47	−3.16
50	−93.57	−42.50	−30.40	−14.25	−10.42	−4.11
100	−94.76	−43.69	−31.60	−15.44	−11.61	−5.30
150	−95.95	−44.88	−16.62	−12.80	−12.80	−6.48

analysis of solutes from inside rocks taken from a cliff face (Hall and others, 1986) also shows that minimal chemical weathering has occurred. What weathering has [illegible]en place on the cliffs appears to be associated with large blocks bounded or associated with discontinuities (lithologic, structural, etc.). Certainly these discontinuities may be preferential sites for moisture and, with the larger crack size, require less severe temperatures for crack propagation. However, the model of Hallet may not be applicable to this situation.

What is apparent is that it is the small released blocks and the undersides of overhangs that show the greatest amount of weathering. The overhangs are certainly subject to gravity on the unconstrained lower edge where schistosity is parallel to the ground, and this must abet any weathering agent. The small blocks on the ground, which are most vulnerable to weathering along the planes of schistosity, appear to show the greatest amount of damage. This may be for a number of reasons: greater moisture content, damage during fall, a greater number of effective temperature events, freezing from several faces and the possible additional effects of hydrofracturing (Powers, 1945; Hallet, 1983).

If, as was found to be the case, some of the blocks had a high moisture status then the main control on rock destruction by crack propagation is that of temperature. Temperatures measured at the ground surface show values as low as −25°C, with events between 0°C and −15°C fairly common at sites with little snow cover. However, these are surface temperatures, whereas the crack-wall temperature and the rate of cooling (slower rates being preferential) are the actual controlling factors. Walder and Hallet (1985, p. 342) state 'Clearly, crack growth for a fixed *final [illegible]mperature* is greater, the lower the cooling rate' but experiments currently in progress on the quartz-micaschist show (Fig. 2) that the rate of fall towards a final temperature is faster for a large-amplitude freeze than for a small-amplitude freeze. This is the case even where the small-amplitude freeze has a faster environmental rate of fall of temperature (4.2 deg h^{-1} as against 3.0 deg h^{-1}). Inside the rock the rate of fall is some three times faster, over the same range, when the final temperature is −6°C as opposed to −3°C and both rates (*c.* 1.6 deg h^{-1} and 0.45 deg h^{-1}) are in ranges suggested to be too fast to be efficient by Walder and Hallet (1985, p. 342).

However, an unconstrained block sitting on the ground is subject to cooling from the surrounding air on five faces, and not one as on a cliff face. In this case, water may be forced ahead of the freezing fronts towards the centre of the block and produce a closed system. The effect of this water pressure could be to cause hydrofracture during freezing and such a situation would be most likely '... during rapid freezing in rocks that are saturated, or nearly so, when slow crack growth due to ice segregation

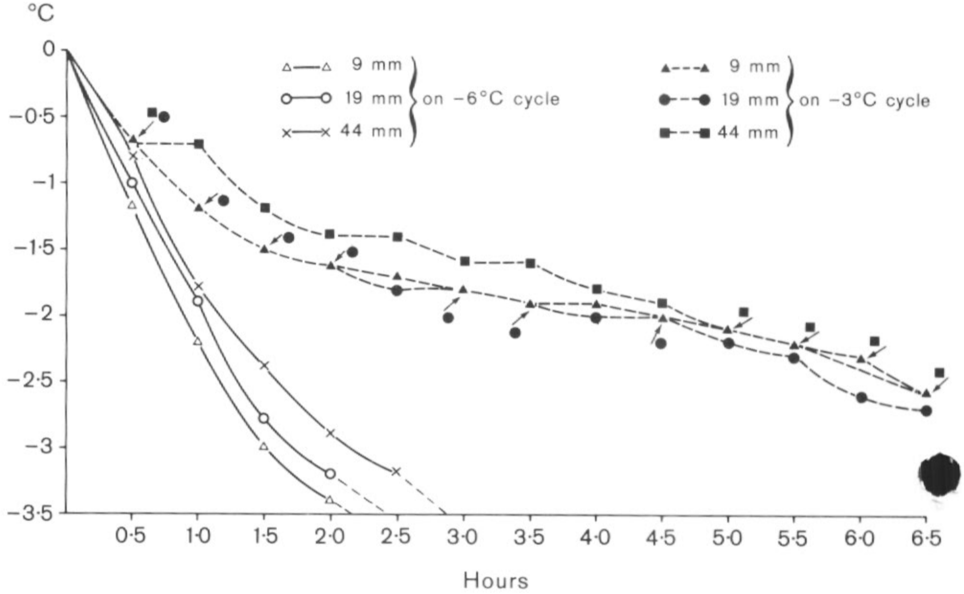

Fig. 2. Plots of temperatures at various depths within a quartz-micaschist block. The environmental rate of fall of temperature for the −6°C cycle was 3 deg h^{-1} and for the −3°C cycle 4.2 h^{-1}.

is unable to accommodate the volumetric increase associated with the H_2O-phase transition' (Walder and Hallet, p. 343). Thus, whilst slow rates of fall of temperature are required for the cliffs, but are not apparently found above a depth of *c*.0.6 m where the rock is almost dry (Hall, submitted), it is the faster rate which would be most destructive for the loose blocks. It is suggested that hydrofracturing is the cause of rock destruction for the loose block, when saturated (or nearly so) and experiencing a relatively rapid rate of fall of temperature inside the rock from several faces, thereby producing a closed system. This hypothesis, based on the utilization of the stress intensity factor and its application to cliff-faces and talus blocks, appears justified both upon the basis of field observation and on empirically derived data.

The above discussion appears to fit the field evidence and, as such, offers an explanation for the pattern of rock breakdown found. However, the role of other mechanisms such as salt or insolation weathering in aiding breakdown cannot [illegible] ignored. Further field and laboratory studies are currently in progress and determine the role of these other agents and how they interact with freeze–thaw. In addition, the role of events at levels below apparent threshold levels must be considered, for as Mura (1981, p. 268) states 'It is well known that materials fail under repeated (cyclic) loading and unloading at stresses smaller than the static fracture stresses. The magnitude of the stress required to produce failure decreases as the number of cycles increases.' Thus, whilst the stress intensity factor and its application in models is a great step forward in our theoretical understanding of 'freeze–thaw', great care must be taken in its application to a field situation. Indeed, Walder and Hallet (1985) have pointed out that thaw is not a prerequisite for continued crack growth.

Conclusion

The use of the stress intensity factor (K_{IC}) via such models as that suggested by Hallet (1983) appears to offer a good theoretical framework for more sophisticated investigation of freeze–thaw weathering. The greatest difficulty in the application of the model to the real world is its requirement for a saturated state. To date the utilization of the stress intensity factor has been towards explaining open system, bedrock breakdown (Walder and Hallet, 1985) where abundant water supply is said to be 'quite plausible'. However evidence from the maritime Antarctic would suggest that this saturated condition is definitely not the case in bedrock and so its applicability for bedrock may be limited in this environment. Nevertheless, it does offer a means of explaining why small, unconstrained blocks do show breakdown when cliffs do not and, importantly, it offers a means of deriving important theoretical data against which to test field data. At present, the testing and application of both K_{IC} and the models utilizing it is limited by insufficient field data on temperature, moisture and moisture solutes. Once we obtain extensive information on these controls it will be possible to better determine the applicability of the models to the real world.

Acknowledgements

Sincere thanks go to Dr R. M. Laws, Director of British Antarctic Survey, and Dr D. W. H. Walton for allowing me to participate in the Signy Island Fellfield Programme. Funding for the fieldwork was provided by the University of Natal and the laboratory work constitutes part of a programme currently in progress funded by an FRD grant from the CSIR, both of which are gratefully acknowledged.

Received 30 October 1985; accepted in revised form 7 February 1986

References

Atkinson, B. K. 1984. Subcritical crack growth in geological materials. *Journal of Geophysical Research*, **89**, 4077–114.

Broch, E. 1979. Changes in rock strength caused by water. *Proceedings of the 4th International Congress on Rock Mechanics*. Balkema, Rotterdam, 71–5.

Broch, E. *and* Franklin, J. A. 1972. Point-load strength test. *International Journal of Rock Mechanics and Mining Science*, **9**, 669–97.

Chambers, M. J. G. 1967. Investigations of patterned ground at Signy Island, South Orkney Islands. III. Miniature patterns, frost heaving and general conclusions. *British Antarctic Survey Bulletin*, No. 12, 1–22.

[illegible]llins, N. J., Baker, J. H. *and* Tilbrook, P. J. 1975. Signy Island, Maritime Antarctic. (*In* Rosswall, J. *and* Heal, O. W. *eds. Structure and function of tundra ecosystems. Ecological Bulletin* (Stockholm), **20**, 345–74.)

Fahey, B. D. 1985. Salt weathering as a mechanism of rock breakup in cold climates: an experimental approach. *Zeitschrift für Geomorphologie*, **29**, 99–111.

Gunsallus, K. L. *and* Kulhawy, F. H. 1984. A comparative evaluation of rock strength measures. *International Journal of Rock Mechanics and Mining Science and Geomechanical Abstracts*, **21**, 233–48.

Hall, K. J. In press *a*. Rock moisture content in the field and the laboratory and its relationship to mechanical weathering studies. *Earth Surface Processes and Landforms*.

Hall, K. J. In press *b*. The physical properties of quartz-micaschist and their application to freeze–thaw weathering in the maritime Antarctic. *Earth Surface Processes and Landforms*.

Hall, K. J. Submitted. A laboratory simulation of rock breakdown due to freeze–thaw action in a maritime Antarctic situation: I. Large blocks. *Earth Surface Processes and Landforms*.

Hall, K. J., Verbeek, A. A. *and* Meiklejohn, K. I. 1986. A method for the extraction and analysis of solutes from rock samples with some comments on their implication for weathering studies: an example from Signy Island. *British Antarctic Survey Bulletin*, No. 70, 79–84.

Hallet, B. 1983. The breakdown of rock due to freezing: a theoretical model. *Proceedings of the 4th International Conference on Permafrost*. National Academy Press, Washington D.C., 433–8.

Kinniburgh, D. G. *and* Miles, D. L. 1983. Extraction and chemical analysis of interstitial water from soils and rocks. *Environmental Science and Technology*, **17**, 362–8.

McGreevy, J. P. 1981. Some perspectives on frost shattering. *Progress in Physical Geography*, **5**, 56–75.

McGreevy, J. P. *and* Whalley, W. B. In press. Rock moisture content and frost weathering under natural and experimental conditions: a comparative discussion. *Arctic and Alpine Research*.

Mathews, D. H. *and* Maling, D. H. 1967. The geology of the South Orkney Islands. I. Signy Island. *Falkland Islands Dependencies Survey Scientific Reports*, No. 25, 32 pp.

Mura, T. 1981. *Micromechanics of defects in solids*. M. Nijhoff, The Hague.

Powers, T. C. 1945. A working hypothesis for further studies of frost resistance of concrete. *Journal of American Concrete Institute*, **16**, 245–72.

Schmidt, R. A. *and* Rossmanith, H. P. 1983. Basics of rock fracture mechanics. (*In* Rossmanith, H. P. *ed. Rock Fracture Mechanics*. Springer Verlag, New York, pp. 1–30.)

Smith, R. I. L. 1972. Vegetation of the South Orkney Islands with particular reference to Signy Island. *British Antarctic Survey Scientific Reports*, No. 68, 1–124.

Storey, B. C. *and* Meneilly, A. W. 1985. Petrogenesis of metamorphic rocks within a subduction–accretion terrane, Signy Island, South Orkney Islands. *Journal of Metamorphic Geology*, **3**, 21–42.

Szlavin, J. 1974. Relationships between some physical properties of rocks determined by laboratory tests. *International Journal of Rock Mechanics and Mining Science*, **11**, 57–66.

Trenhaile, A. S. *and* Mercan, D. W. 1984. Frost weathering and the saturation of coastal rocks. *Ea[illegible] Surface Processes and Landforms*, **9**, 321–31.

Walder, J. *and* Hallet, B. 1985. A theoretical model of the fracture of rock during freezing. *Geological Society of America Bulletin*, **96**, 336–46.

Walton, D. W. H. 1977. Radiation and soil temperatures 1972–74: Signy Island Terrestrial Reference Site. *British Antarctic Survey Data*, No. 1.

Walton, D. W. H. 1982. The Signy Island Terrestrial Reference Sites. XV. Micro-climate monitoring, 1972–74. *British Antarctic Survey Bulletin*, No. 55, 111–26.

Washburn, A. L. 1980. *Geocryology*. Halstead Press, New York, 406 pp.

Williams, R. B. G. *and* Robinson, D. A. 1981. Weathering of sandstone by the combined action of frost and salt. *Earth Surface Processes and Landforms*, **6**, 1–9.