FREEZE-THAW SIMULATIONS ON QUARTZ-MICASCHIST AND THEIR IMPLICATIONS FOR WEATHERING STUDIES ON SIGNY ISLAND, ANTARCTICA

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ABSTRACT. Results of two series of freeze-thaw simulations on quartz-micaschist indicate that there is a significant difference in the rate of freeze penetrating depending upon whether the plane of schistosity is normal or parallel to the advancing freezing front. Rate of fall of temperature is up to five times faster when schistosity is parallel to the freeze advance. In these stimulations it was found that the rate of fall of temperature within the rock was controlled primarily by the amplitude of the freeze event rather than the environmental rate of fall of temperature. A distinction is made between open systems (e.g. cliffs) and closed systems (e.g. loose blocks) with respect to processes and rate of breakdown. It is suggested that, with the very low porosity of this rock, there is a difference in the freeze mechanism based upon schistosity orientation but that, overall, moisture content plays a crucial role in determining whether any frost weathering will occur.

INTRODUCTION

A series of laboratory simulations of freeze-thaw cycles were undertaken, as part of the investigation of the mechanisms and rate of weathering of quartz-micashist in the maritime Antarctic environment of Signy Island. To date, the results of many simulations have been more reflections of experimental design and procedures rather than the environmental conditions which rocks might experience in nature (McGreevy, 1982). However, in the present instance the study of freeze-thaw weathering comprises part of a larger study, the Fellfield programme (Walton and Hall, submitted), and consequently, for the first time, a large data base was available to relate the simulations to the field situation.

A number of early freeze-thaw studies utilized schists (e.g. Wiman, 1963; Martini, 1967; Brockie, 1972) but no data were presented on either the properties of the rocks themselves or the environments that were being simulated. Thus, the results of these early experiments could not be related to any particular environment. Recent studies have shown the importance of information on such factors as rock water content (e.g. McGreevy and Whalley, 1985), rock thermal properties (McGreevy, 1985), interstitial rock water chemistry (Williams and Robinson, 1981; McGreevy, 1982; Fahey, 1983), and the engineering properties of rock (McGreevy and Whalley, 1984). In this study most of the necessary background data were either already available or produced as part of this study, e.g. field micrometeorological conditions (Walton, 1982), rock moisture content and properties controlling this (Hall, 1986*a*), the chemistry of the interstitial rock water (Hall and others, 1986), the physical properties of the rock (Hall, in press) and the application of rock fracture mechanics (Hall, 1986*b*). Thus the planned simulations could be closely related to the physical and environmental constraints characteristic of quartz-micaschist on Signy Island. The data presented here relate to two sets of simulations, and are concerned with the rate of fall of temperature within the rocks and the effects of schistosity orientation upon this and subsequent processes.

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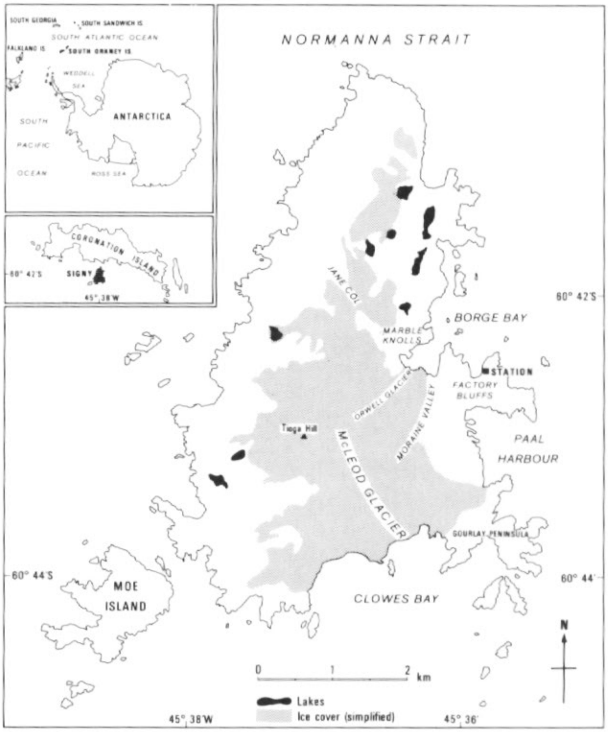

Fig. 1. Location map for Signy Island.

Field Situation

Rock samples and field data were collected from Signy Island (60° 43′ S, 45° 58′ W), one of the smaller islands in the South Orkneys (Fig. 1). As the bulk of the island's metamorphosed sediments comprise quartz-micaschist (Mathews and Maling, 1967; Storey and Meneilly, 1985), this rock was chosen for the initial simulations. In the field, all cliffs and rock outcrops observed had the plane of schistosity normal to the cliff face and parallel to the ground (Fig. 2), with minor variations due to localized folding. Thus, over the face of the cliff schistosity was normal to freezing plane penetration. On blocks that were weathered – free from the cliffs, and at the very cliff top, schistosity was sometimes parallel to the direction of freeze penetration. On the cliffs, once some material has been removed, gravity aids weathering (Hall, in press), and the orientation of the schistosity abets this. This effect of gravity is recognized but is not considered in any detail in the following text.

Climatically, there is a typical cold, oceanic regime with a mean monthly temperature of *c*. −4°C, but the summer three months have means slightly above freezing (Watson, 1975; Collins and others, 1975). Rain predominates in the summer but during the rest of the year the precipitation is in the form of snow. Wind speeds average 26 km h^{-1} and mean sunshine levels are less than 1.5 h per day.

Fig. 2. Example of a typical quartz-micaschist cliff. Note the exploitation along the lines of schistosity that are parallel to the ground and normal to the face. In addition, a number of vertical cracks can be seen that define the edges of large blocks in the process of being weathered-free.

Methods

Samples of quartz-micaschist were collected from different environmental positions at a number of locations of Signy Island (Hall, 1986*a*). For the bulk of the samples the collected (i.e. 'wet') weight was found and then subsamples were subjected to the irregular lump point load test (Broch and Franklin, 1972) in order to gain a measure of the strength of the rock at field moisture content (details of rock strength tests are presented in Hall, in press). The rocks were then dried at the island laboratory so that it was possible to calculate the actual field moisture content (Hall, 1986*a*). Later, the rocks were tested for porosity, microscopy, saturation coefficient and water absorption capacity following the procedures described by Cooke (1979). In addition, a new technique, was used to obtain information about the interstitial rock water chemistry (Hall and others, 1986). Thus, for the rocks that were to be used in the simulations there was a data base pertaining to the field properties of the rock concerned.

Data on the climate and microclimate at various selected reference sites were available (Walton, 1977, 1982). However, in 1983–84 'Datacapture' micro-meteorological data loggers (Walton and Hall, submitted) were installed at the main study areas (Factory Bluffs, Moraine Valley and Jane Col; Fig. 1). These data were used in planning the temperature cycles to be used in the simulations. The temperature of the environment chamber is controlled via a microcomputer that continually monitors the chamber, compares the measured and programmed temperatures and initiates corrective action when required. The same microcomputer, via additional hardware, monitors, logs (on disk) and prints out the sensor data (cabinet and 6 rock temperature sensors, and cabinet humidity) at pre-programmed intervals; details of the equipment are presented in Walton and Hall (submitted).

Simulation I was carried out on a 12.0145 kg block of quartz-micaschist with sensors on the rock surface and at depths of 9, 19, 44 and 92 mm. The rock was encased in polystyrene such that only one a/b plane, with schistosity parallel to the cooling front, was exposed, and wetted to a typical field moisture content (0.11% by weight). In Simulations II a 9.5836 kg block, at field moisture (0.14% by weight), was encased in polyurethane foam such that only one face (the b/c plane) was exposed. In this instance schistosity was normal to the freezing plane, a situation found on most of the cliff exposures observed in the field. Thin film platinum resistance temperature sensors were placed at the rock surface and at 5, 10, 20 and 60 mm depths behind the exposed face. In addition, a small sample of this rock (dry wt = 91.9 g) was 'saturated' by immersion in water for 48 h (i.e. the rock absorbed the maximum amount of water possible under non-vacuum conditions) and was then placed in a tray of water to half its depth as a means of comparison with earlier experiments (e.g. Wiman, 1963). The two samples were very similar with respect to their composition, both having thin silica laminae with the occasional small silica pod.

Both simulations, comprised the same temperature sequence, as shown diagrammatically in Fig. 3, which was considered to approximate to conditions occurring in the spring to autumn poeriod. Simulation I ran for 12 full cycles (600 h) and generated 349 368 data readings whilst Simulation II ran for 10.5 cycles (528 h) with 196 376 data recordings. The frequency of data collection during Simulation I is presented in Fig. 2; data read rates remained the same in Simulation II except during the long, warm phases when fewer readings were obtained in order to conserve disk space.

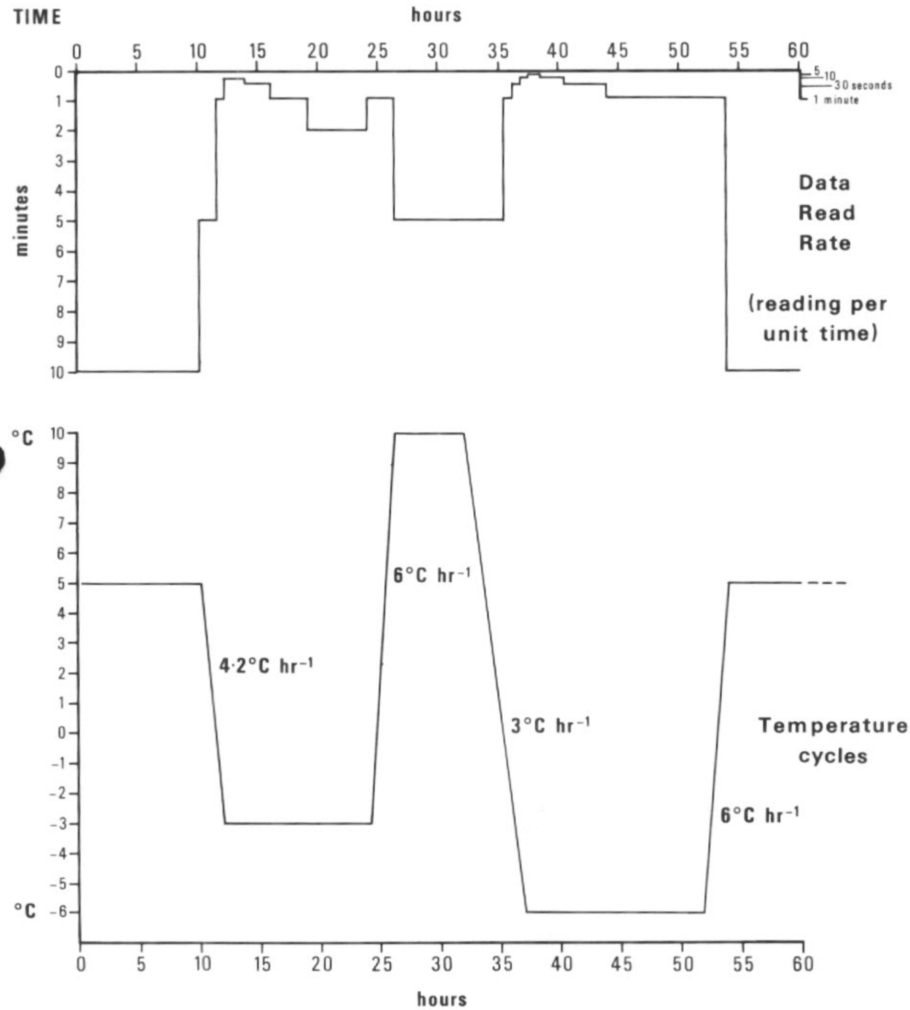

Fig. 3. Graphs to show the temperature sequence, including rate of change of temperature, to which the samples were subjected and the rates at which the computer monitored data during those cycles.

Results and Discussion

In Simulation I sudden temperature rises during cooling phases occurred at 44 mm depth in rock when the temperature was between −1.2° and −1.4°C. The rises varied between 0.7° and 0.9°C, and are thought to reflect the release of latent heat during the water-to-ice phase change (Fig. 4). It was noticeable that no signs of this latent heat release were detected in the early cycles, only after four complete cycle sequences were the first peaks recorded, but they were consistent thereafter. During the −3°C cycle the chamber temperature at the time when the exotherm was produced averaged −2.6°C, a level it had held during the preceding two hours. The high during the −6°C cycle occurred at a cabinet temperature of approximately −5.3°C during the continual fall towards −6°C. Some small, apparent peaks were recorded for other depths,

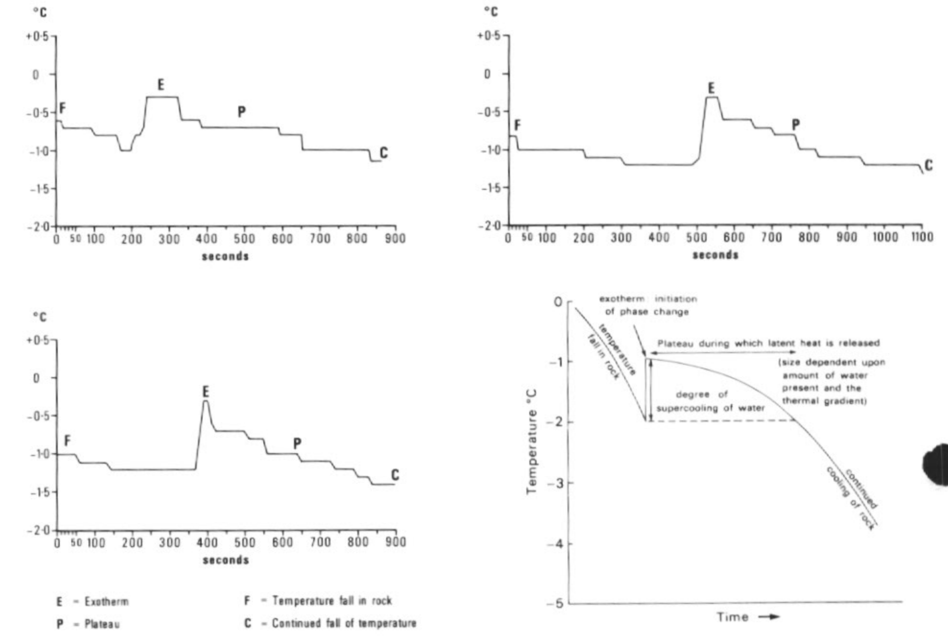

Fig. 4. Examples of some exotherms monitored at 44 mm depth during Simulation I together with a simplified graph detailing the various parts of the temperature curve.

notably a 0.3°C rise at −1.1°C for the 19 mm depth sensor, but none like those observed at 44 mm depth.

Whilst it might be thought that the temperature peaks were due to water freezing in the drill holes, rather than in the rock itself, this is not considered to be the case for four reasons: Firstly, the presence of a tight-fitting sensor covered with a coating of thermal grease would allow very little moisture to enter into the drill hole. Secondly, Douglas and others (1983) show that freezing was initiated in a 5 mm hole (the width of the present drill holes) at −0.6°C, a temperature somewhat higher than the −1.1° to −1.4°C found in this experiment; thirdly, if the freezing points were related to water in the drill holes then it would be expected to be noticeable in all holes and most likely at the first freeze after wetting, when the holes would still contain some moisture. However, four full cycles were required before thermal peaks were observed. Finally, whilst it is possible that some water from within the rock was, after a number of cycles, forced into the drill holes under hydraulic pressure in front of the advancing freezing plane (Powers, 1945), this is thought to be minimal due to the presence of the tighly fitting sensor tube and its covering of thermal grease.

Consideration of the resultant temperature data allowed the rate of fall of temperature to be calculated for different depths during both freezing cycles (Table I). What is apparent is that the rate of fall of temperature *within* the rock is partly controlled by the final temperature to which the freeze is going. For instance, for all sensor depths, the rate of fall of temperature over the range 0–3°C is faster, up to 5.5 times faster, during the −6°C cycle than during the −3°C cycle. This more rapid fall of internal rock temperature found for the −6°C sequence occurs despite the environmental rate of fall of temperature being slower (3°C h^{-1}) than during the −3°C cycle (4.2°C h^{-1}). The marginally faster cooling rate observed at the 19 mm depth may be due to the presence of quartz which allows for a faster passage of heat,

Table I. Typical cooling rates observed at various depths in the rock for Simulation I

Range	*Chamber rate*	*Cooling rate (°C h⁻¹)* At surface	9 mm	19 mm	44 mm
0 to −6°C cycle					
0 to −3	3°C	1.1	1.7	1.7	1.4
−3 to −6	3°C	0.3	0.3	0.4	0.4
0 to −3°C cycle					
0 to −3	4.2°C	0.4	0.3	0.4	0.4

Properties: Rock weight, 12.045 kg; Porosity, 0.83%; Saturation coefficient, 0.6; Moisture content, 0.11%; Water absorption capacity, 0.38%; Compressive strength, 1.98 MN/m² normal to schistosity, 0.4 MN/m² parallel to schistosity.

Table II. Some thermal peaks observed during freeze phases

Experiment no.	*Sensor depth (mm)*	*Temperature exotherm (°C)* From	To
I	44	−1.2	−0.3
I	44	−1.0	−0.3
I	44	−1.0	−0.3
I	44	−1.2	−0.3
I	92	−1.0	−0.7
I	92	−1.1	−0.8
II	60	−3.1	−2.9
II	5	−4.0	−3.7
II	10	−4.0	−3.5
II	10	−3.9	−3.3
II	20	−3.7	−3.2
II	60	−3.6	−3.4
II	10	−3.0	−2.7
II	20	−2.6	−1.6
II	60	−2.4	−2.1
II	60	−2.2	−1.9

Note: for all peaks shown the time taken to return to original pre-exotherm temperature varied from 8 to 34 min.

due to its thermal conductivity being higher than that of the mica. Although this is by no means certain, quartz is distributed throughout the rock with numerous localized concentrations, and so it could well be that a drill hole coincided with one of these.

In Simulation II thermal peaks during freezing were found at various times, for all depths (5, 10, 20 and 60 mm). However, unlike Simulation I, the temperatures at which peaks occurred were much lower and the degree of water supercooling was not as great (Table II). Although the exotherms were much smaller they are not 'instrument errors' insofar as the time taken to return *gradually* to the pre-exotherm value varied between 8 and 34 min. Rates of fall of temperature (Table III) again show that, despite the faster environmental decline, the rate of fall of temperature within the rock was faster (*c.* 3.5 times) for the lower end temperature (−6°C).

Comparison of Tables I and III clearly show that the rate of fall of temperature within the rock is slower in Simulation II. For the 0° to −3°C range (of the −6°C freeze), rates for the smaller block were about half those found in the larger block.

Table III. Typical cooling rates observed at various depths in the rock for Simulation II

Range	*Chamber rate*	*Cooling rate (°C h⁻¹)* 5 *mm*	10 *mm*	20 *mm*	60 *mm*
0 to −6°C cycle					
0 to −3	3°C	0.84	0.90	0.83	0.85
−3 to −6	3°C	0.23	0.24	0.22	0.24
0 to −3°C cycle					
0 to −3	4.2°C	0.24	0.25	0.24	0.26

Properties: Rock weight, 9.5836 kg; Porosity, 0.54%; Saturation coefficient, 0.71; Moisture content, 0.14% Water absorption capacity, 0.39%; Compressive strength (normal to schistosity), 1.89 MN/m^2.

For the −3° to −6°C range they were only reduced by about one-third. The main distinction between the two simulations, both rocks being similar in comparison, is that of the relationship of freezing plane penetration to schistosity orientation. In Simulation I schistosity was parallel to the freezing plane whilst in II it was normal to it. As the rate of fall of temperature in the rock can be crucial to both the type and rate of destruction (Walder and Hallet, 1985), it is apparent that the orientation of schistosity in relation to freezing plane penetration could exert a significant influence. On Signy Island all cliffs and rock outcrops observed were comparable to that of Simulation II. However, for loose blocks on the ground and for rock near the top of cliffs, penetration would be both parallel and normal to schistosity.

The reason for the effect of schistosity orientation upon the rate of fall of temperature is not clear. However, it may be related to the presence of air/water along the mineral interfaces of the laminae. When the plane of schistosity is parallel to freeze penetration the air/water 'layers' are very thin and are possibly 'bridged' at many places by the quartz particles. This, then, would allow for a relatively rapid transfer of heat. When penetration is normal to schistosity then the gain/loss of heat in the air/water *along* the laminae, as the freezing plane progresses inward, would be slower since the air/water is a poorer conductor than the rock and the 'bridging' by quartz particles would not help in this instance. However, the importance of schistosity orientation with respect to freeze penetration extends beyond its effects upon the rate of fall of temperature.

Where the laminae are parallel to the direction of freeze penetration then there is a closed (i.e. water migration is confined) rather than an open (where water is free to migrate) (Fig. 5) system, even in the situation of a cliff which would otherwise be recognised as an open state (Walder and Hallet, 1985). Due to its low permeability and the presence of silicate laminae, migration of moisture between layers is highly improbable. Thus, the combination, particularly in cliffs, of low rock moisture content (Hall, 1986*a*), negligible between laminae water movement, and the relatively simultaneous freeze along each plane of schistosity, means that little destruction will occur as the ice will fill the dry sections rather than exert a tensile force (Fig. 5). Water migration along laminae to freezing points is almost non-existent due to simultaneous freezing. Only in situations of high moisture content could tensile forces be developed (i.e. saturation of ⩾ 91%). Conversely, where schistosity is normal to freeze there is a greater potential for frost weathering, despite the frequent low moisture contents. In this instance freeze penetration is progressive rather than simultaneous and so it may be possible to have water migration to the point of freezing or the forcing away of moisture in front of the advancing ice front (Powers, 1945), both of which could cause damage to the rock (Fig. 5). Essentially it will be the amount of moisture which

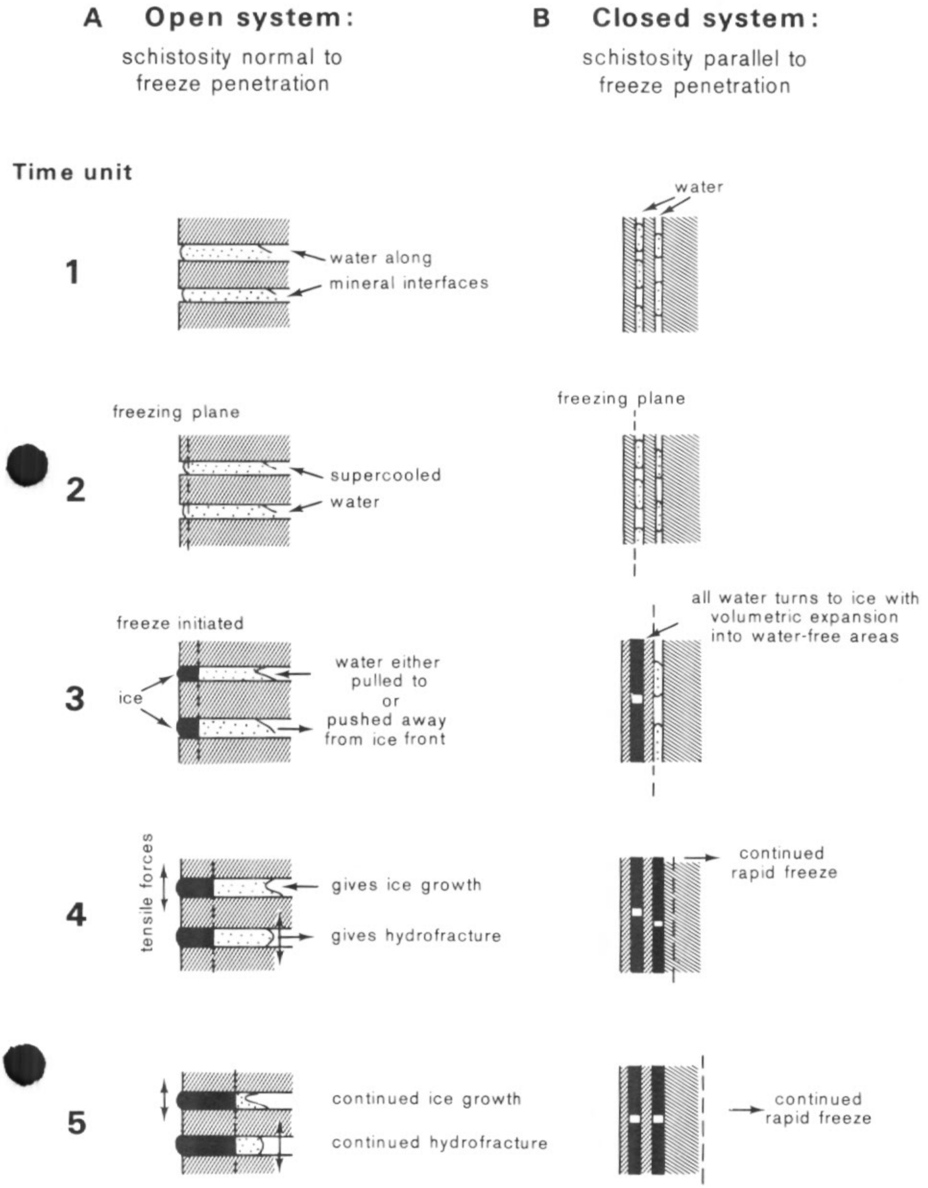

Fig. 5. Diagrammatic representation of the types of freezing envisaged for schistosity normal to, and parallel to, the freezing plane (not to any scale).

is the primary control of the degree of damage produced: the greater the moisture content the greater the potential for tensile forces. In a sample with adequate moisture the slow rates of fall of temperature associated with this schistosity orientation would be conducive to the mechanism of frost shattering suggested by Walder and Hallet (1985).

A further factor mitigating against extensive damage to the rock, particularly in the case of freeze penetration parallel to schistosity, is that of 'opposing forces'. Hallet (1983), in his model of rock breakdown due to freezing states that there is expulsion of water ahead of the freezing front, in a saturated rock, as long as crack expansion is insufficient to accommodate the volume increase due to the ice-water transition. In a laminated rock, like quartz-micaschist, where moisture is concentrated along the lines of mineral interfaces, this would mean that upon freezing the ice in one laminate would be exerting pressure against ice in another (Fig. 5*b*). Thus, with schistosity parallel to freeze penetration it is only the outer layer and the edges of the laminae that might be subject to damage, even in a saturated rock.

During Simulation II a small sub-sample of the large block was first saturated and then placed in a tray of water to half its depth. At the end of the experiment, despite only experiencing seven full cycles, as opposed to the 10.5 cycles of the large block, the sample had lost 0.76% (by weight) material whilst the block lost only 0.013%. Two factors help to explain the greater loss from the small sample: a higher moisture content and omnidirectional freezing. The simultaneous freezing from all sides would produce a closed system and hence the potential for hydrofacturing (Walder and Hallet, 1985), and the greater moisture content would abet this process. This would help explain why loose blocks in the field with relatively high moisture contents exhibited a greater degree of breakdown than did the cliffs. Theoretically, with the asymmetric freeze penetration of small blocks there should be the greatest potential for frost damage towards the base of the block. There water would freeze last and so lateral water migration would take place over a longer period.

The anisotropic response of quartz-micaschist and schist to freezing is something not previously recognized and, as such therefore, has not been taken into account in earlier studies (e.g. Fahey, 1983). The evidence available here suggests that, with unsaturated small blocks subject to rapid freezing little damage will occur, as was found by Fahey (1983, p. 541). This is because the volumetric increase at the water to ice phase change is taken up by the available free space along the laminae. With small samples that experience rapid falls of temperature, giving freeze penetration parallel to schistosity, there is no mechanism available to cause localized tensile stress. Thus, in any future study which encompasses laminated rocks it would be necessary to consider the asymmetric nature of freeze penetration.

Conclusions

The orientation of the plane of schistosity to the freezing front appears to affect both the rate of fall of rock temperature and the actual process operating. In addition the rate of fall of temperature within the rock is seen to be more a function of freeze amplitude than the rate of environmental temperature decline. A clear distinction, with respect to freeze mechanisms and potential for rock damage, can then be made between the 'open' system of a cliff and the 'closed' system of a loose block. It is suggested from the simulation data, that loose blocks should undergo greater and faster weathering than cliff faces and this is borne out by the author's field observations. Due to anistropy of the rock, loose blocks, which are subject to simultaneous freezing from all sides, are frozen 'asymmetrically', since freeze penetration is faster when entering parallel to schistosity, and as a consequence it is possible that the greatest damage may be towards the base of a block. Generally it is concluded that weathering rates, particularly for non-saturated cliff situations, are likely to be slow. It is suggested that a major control on the degree of weathering is moisture content. The simulation results appear to agree with field observations. This underlines the importance in weathering studies of using field data to plan laboratory simulations.

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