FROST WEATHERING IN A MOUNTAIN PERMAFROST AREA
(PLATEAU MOUNTAIN, ALBERTA, CANADA)

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Abstract

The slopes of the mountains on and around Plateau Mountain (Canada) show very well developed block
slopes, in contrast to the rocky mountain sides seen elsewhere in the adjacent Rockies. This study of the frost
sensitivity of the limestones forming outcrops on the Plateau Mountain slopes combines field and laboratory
experimentation. The distribution of water in blocks in the field and the weathering undergone by samples put
on the block slope for one winter are measured. The first results indicate that bursting or scaling caused by frost
action are not the main causes of the formation of these block slopes in this cold alpine environment, although
frost weathering is often considered as an important process in periglacial environments.

Introduction

Frost weathering is considered to be an important
process in periglacial environments (Mugridge and
Young, 1983; Fahey and Lefebure, 1987), but some geo-
morphologists (White, 1976; McGreevy, 1981; Hall,
1995) have stressed the lack of field and laboratory evi-
dence to show that the transformation of water into ice
is indeed the origin of the accumulation of shattered
rock fragments found in alpine and arctic environ-
ments. Other processes should be involved to explain
frost action, like hydration shattering (White, 1976), or a
combination of physical, chemical and biological
processes, which probably corresponds to the most
common situation (Hall, 1995).

Moreover, when frost action itself is considered, it is
striking to see how little is known about the processes
involved. New laboratory techniques developed in geo-
morphology during the last few years allow a better
understanding of what are the relative influences of the
individual physical processes, e.g. the use of acoustic
emissions (Hallet et al., 1991), of pulsed nuclear mag-
netic resonance (Akagawa & Fukuda, 1991), of Young’s
modulus (Weiss, 1992; Prick, 1997) and of dilatometry
(Matsuoka, 1990; Weiss, 1992; Pissart et al., 1993; Prick,
1995). These new techniques are all non-destructive.

Another problem is that a major part of the early labo-
atory experimental work did not use thermal or mois-
ture conditions approximating those experienced in
nature (Hall, 1986). This is an important point which
has not been considered carefully enough in the past, as
some of the early studies generated breakdown pres-
sures that are unlikely to appear during freezing in the
field. Nowadays, it is becoming usual to view field and
laboratory studies as complementary (Hall, 1986), and
so to simulate “natural” temperature variations and
moisture content. The current state of knowledge
regarding frost action could be improved by combining
several laboratory tests with a field study of an area
characterized by a rapid decay of rock, thereby testing
the question of the effectiveness of frost as a weathering
agent in cold environments. The block slopes of Plateau
Mountain (Alberta, Canada) are a particularly good
place to carry out such a study.

Study area

Plateau Mountain is a flat-topped mountain lying
approximately 80 km southwest of Calgary (Figure 1)
with a summit elevation of 2519 m. The mountain top
was not glaciated during the Late Pleistocene and is
characterized by relict permafrost which has already
been studied (Harris and Brown, 1978; Harris and
Prick, 1997).

The mountain is formed from the core of an anticline
which is tilted gently downwards to the north and
west. The surface anticline of Plateau Mountain is
bounded by the McConnell Thrust to the west and the
Livingstone Thrust to the east. This area (including the
Savanna Creek at the south side of the mountain, where
the block slopes are located) is heavily affected by tec-
tonics and forms a transfer zone between these two
faults (Dahlstrom, 1970; Norris, 1993).
Debris slopes are far more developed in this area than elsewhere in the Rocky Mountains of Southwestern Alberta where outcrops of limestones of the same age occur. This frost sensitivity study appears to be the first such in North America.

The rocks studied belong to the Mount Head Formation and were collected in the Savanna Creek valley (50°11′17″ N and 114°31′12″ W), south of the top of Plateau Mountain. These limestones and dolomites are arenaceous and cryptocrystalline. The rocks show significant evidence of solution processes. Some blocks show elongated cavities up to a few centimeters long whose internal surfaces are covered with well crystallized calcite (J. Cl. Ozouf, personal communication, 1997). Nevertheless, the mechanical behavior of these limestones is very good: their dynamic Young’s modulus is 80 GPa and their shear modulus is 18 GPa. It is very likely that the solution process takes place through the numerous cracks (whose spacing varies between a few centimeters and 30 centimeters) which are characteristic of the outcrops.

The porosity of these limestones is extremely low (0.38 to 1.22 %). According to frost sensitivity scales established previously (Letavernier and Ozouf, 1987; Prick, 1997), limestones with such a low porosity are not frost sensitive. The availability of limestones for this study was important since most of the methods to measure frost sensitivity have only been adapted to the study of limestones (e.g. Letavernier and Ozouf, 1987).

The water distribution in blocks in the field

The degree of saturation of rocks in the field is an important concern for some authors (White, 1976; Hall, 1986) because it largely determines the effectiveness of the frost action on the rock. An interesting component of the study was to find out the water distribution in the blocks on the block slope and on the adjacent soil. On May 15, 1997, one block was picked up in the lower part of the block slope, where it was in contact with snow, and broken into pieces with a hammer. Nineteen small pieces were collected, weighed in their natural state and in a dry state, in order to determine their water content, knowing their porosity under vacuum. The same operation was conducted with a block collected on the soil, where the snow had already disappeared. Both blocks were 10 to 15 cm in diameter.

The block on the soil has a lower degree of saturation throughout. The first three outer millimeters of the block lying on the soil had a moisture content representing 73 % of the maximum water content (3 samples), but the value for the outer 3 mm of the block collected on the block slope was always higher than 100 %: we had to brush off snow and ice from the block surface before hammering it. More than 10 mm into the blocks, the water content on the block slope was still more than 82 % of the full saturation (6 samples), whilst it was only 49 % for the block lying on the soil (2 samples).

This indicates that high water contents can be observed in the external part of the blocks where they are in contact with a water source (such as a snowpatch). At the same time, the rocks exposed to the open air on the soil surface are fairly dry. These general remarks have already been stressed in former works (e.g. White, 1976), but the present study emphasizes the important influence of the rock porosity. The poor porosity of this limestone does not allow water to migrate easily into the centre of the block. For example, the block collected on the block slope was saturated in the first few outer millimeters, then the water content dropped dramatically at the centre of the block: 55.6 % at 15 mm; 49.3 % at 30 mm and 47.4 % in the centre.

Behaviour of the rock in the field

Four shaped samples and two unshaped ones were put out in the field on the block slope of Savanna Creek valley in September 1996 and collected in early June 1997. Their dry weight, density, porosity (measured under vacuum) and their Young’s Modulus (for the shaped samples only) were measured before putting them in the field and after bringing them back to the

Figure 1: Location of Plateau Mountain
laboratory. The dynamic Young’s modulus was determined using the Grindosonic apparatus, which allows measurements of the fundamental vibration frequency of a rectangular block of rock, and therefore, the determination of its Young’s modulus.

On June 3, the only sample which was no longer snow covered, lay at the margin of a snow patch and had a water content of 61%. The five other samples, collected under the snow and mainly covered with ice, had a water content close to saturation.

The weight losses are nil for the shaped samples and insignificant for the unshaped ones (-0.02 g/cm$^3$ is the maximum value obtained). Usually, frost weathering is characterized by an increase in porosity (Weiss, 1992), but no porosity increase (evaluated by immersion under vacuum) was observed in the present study. The rock density did not vary either. Only one sample out of the four shaped ones showed a decrease in its mechanical strength (dynamic Young’s modulus), but this decrease is quite limited (the modulus value after the winter is equal to 97% of its value before being put in the field) and does not reflect a significant weathering effect.

In conclusion, these samples have not been significantly weathered during a single winter in the field in the cold alpine environment of Plateau Mountain. These samples have been put back in the field for the summer 1997, and will be tested again in September 1997 and in June 1998, in order to be able to compare the relative weathering efficiency of various climatic conditions. It is possible that the more or less daily night frost during the summer could be more damaging to these rocks than the long winter freezing, during which samples are often covered by snow. It is hoped to increase the number of samples in the field and to set them in various locations, with varying winter snow cover, including sites where the snow blows off the slope completely.

The critical degree of saturation

The moisture content has an important impact on the behavior of a rock undergoing frost action. The degree of saturation depends not only on the way the sample is hydrated and on the duration of the immersion, but also on the porosimetry of the rock. Each type of rock studied previously has a degree of critical saturation $S_{cr}$ which is dependent on the lithology. With degrees of saturation greater or equal to $S_{cr}$, a rock will be damaged by frost (Fagerlund, 1971; Weiss, 1992; Prick, 1997). The damage is evaluated by determining the Young’s modulus for the fresh rock samples, and on the same samples after they have undergone eight freezing and thawing cycles at diverse specific water contents.

Figure 2. Results of the determination of the degree of critical saturation $S_{cr}$ of the limestone of the Mount Head Formation, on Plateau Mountain. For some samples, two measurements of the Young’s modulus could be obtained in different directions on the sample and are shown on this figure. For the explanations, see text.

$S_{cr}$ values are specific for each material. It is the degree of critical saturation that accounts for the rock dilatometrical behaviour observed during a freeze / thaw cycle (Prick, 1997).

In the present case (Figure 2), it will be seen that frost action generates physical weathering regardless of the moisture content. This is the case for a sample whose degree of saturation (100%) has been reached under vacuum, for one dried in the open air (down to 55% of maximum saturation) after saturation under atmospheric pressure and for the other samples, which have been saturated by immersion under atmospheric pressure for 4 weeks or more. It is important to notice that the saturation level reached in the last case is always far below 100% and can even be as low as 71%. This can be explained by the porosimetry of the rock: the combination of larger cavities (connected to the solution process), cracks and fine micropores tends to make the water migration through the pores more complex and results in the trapping of air bubbles in the porous media during wetting.

The other interesting point is that the observed loss of mechanical strength ($E/E_0$) is no greater for samples with high degrees of saturation, including the samples saturated under vacuum. In all previous studies, a saturation under vacuum has always been very effective in causing significant weathering of limestones. The most logical explanation is that the weathering effect (independent to the degree of saturation) was not due to the presence of water and was simply a consequence of thermal contraction and dilation. However, this is not the case, since when the same samples were submitted to the same freezing and thawing cycles, but in a dry state, two of the three samples did not show any loss of...
mechanical strength at all. The third one showed an average $E/E_0$ value of 0.98, which is a very limited weathering effect when compared with the 0.91 and 0.92 $E/E_0$ values observed when the same sample is submitted to the same frost action with a degree of saturation of 84% (Figure 2).

The second possibility is that the loss of mechanical strength observed in Figure 2 is indeed related to the freezing of the water contained in the rock. All the limestones previously studied had a porosity mainly composed of pores rather than cracks. In the present case, we think that the cracks contained in the rock play a more important role than its fine pores. The duration and mode of immersion do not fully determine the saturation of these cracks which can get filled with water far more quickly than pores, and that is why, in Figure 2, the same amount of weathering is induced regardless of the degree of saturation (above 55%).

**Dilatometrical results**

Dilation measurements of rock subjected to freezing and thawing have rarely been carried out (Matsuoka, 1990; Weiss, 1992). Dilatometrical variations are measured in several locations: in the central point of the circular base, near the border of the same base, and also on two points which are facing each other on the sides of the cylinder. With these four measurements, it is possible to register not only the variations in length of the cylinder, but also its variations in diameter. The measurements were made with linear electronic displacement transducers giving dilation variations with an accuracy of about 5 micrometers. These measurements and rock temperature measurements are automatically carried out during one freeze/thaw cycle performed in a climatic simulator.

For the experiment presented on Figure 3, a limestone sample saturated under atmospheric pressure underwent a freezing and thawing cycle between +20 °C to -20 °C, with a rate of change of temperature of 2°C/h. The dilation response is very limited when compared to what can be observed when freezing a porous limestone sample in the same conditions (Pissart et al., 1993; Prick, 1995). Instead of the 190 micrometers dilation observed in the latter, there is only a 15 micrometers dilation during the freezing of the water in the porous media. The amount of water contained in such a slightly porous rock is very small, the rock mechanical strength is quite good, and this is why the dilation observed is small, but nevertheless able to exceed the thermal contraction. When the sample remains at -20 °C for 24 hours, no dilatometric variation is observed, although a porous limestone would show a small shrinkage in length correlated to the drying out of small pores as unfrozen water tends to migrate towards the ice crystals formed in bigger pores. This is correlated with the low porosity and permeability of the rock. During the warming, the changes in dimensions reverse.
Conclusions

All the results obtained up to now seem to stress the non-effectiveness of frost as a weathering agent of these strong and only slightly porous rocks. It is suspected that other processes such as pressure release could have quite an important effect on these rocks whose geological history has been marked by the thrust faulting of the Rocky Mountains.

We must here emphasize that our experimental technique and the size of our samples allow us only to observe the bursting and scaling types of weathering. There is another type of frost weathering: the wedging effect, when water widens and propagates the cracks in which it freezes (Letavernier and Ozouf, 1987). This process is probably a very widespread component of frost weathering in natural conditions. It has been studied and modeled in the laboratory (Davidson and Nye, 1985; Tharp, 1987; Matsuoka, 1995). Currently, it is technically impossible for us to test the importance of this process and to compare it with the results of bursting and scaling simulations, but we realize that this effect could play an important role in the liberation of rock fragments in the field, particularly in the case of a hard limestone with a low porosity (Matsuoka, 1995). The potential important role of the rock cracks has already been underlined while analyzing the lack of a critical degree of saturation for these limestones.

If this work confirms these preliminary results indicating the limited effect of frost on the weathering of these limestones, the next job will be to try to find out which other process, or combination of processes, could explain it. It is hoped that this work will bring some new elements to the important question of whether frost weathering has been too often used in former geomorphological works as a “cold region panacea” (Hall, 1995).

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