# PRESSURE RELEASE AND GLACIAL EROSION

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ABSTRACT. Two tunnels were dug through a small cirque glacier to the rock wall behind (*a*) the *névé*, and (*b*) the lower glacier. The upper tunnel revealed shattering of the rock wall due to the freezing of melt water. The bedrock at the end of the lower tunnel was both smoothed and fractured. The problem is to account for the fracturing of the resistant gneiss where the temperature remains at 0° C. throughout the year. The solution offered is that the release of pressure beneath a thick glacier immediately downstream from a *roche moutonnée*, or from a small steep step, enables the stresses locked within the gneiss to crack the rock. These stresses result from the gradual removal of the overburden, since the gneiss consolidated under the pressure of thousands of metres of rock strata. The glacier can later remove the jointed and broken rock.

ZUSAMMENFASSUNG. Zwei Tunnels wurden durch einen schmalen Kargletscher zur Felsenwand hinter (*a*) dem Firn und (*b*) dem unteren Gletscher gegraben. In dem oberen Tunnel wurde auf Grund des Gefrierens von Schmelzwasser Zerstörung der Felsenwand aufgewiesen. Das Felsenbett am Ende des unteren Tunnels war sowohl ausgeglättet als auch zerspalten. Es handelt sich darum, eine Erklärung für das Brechen des widerstandsfähigen Gneises da zu finden, wo die Temperatur das ganze Jahr hindurch 0° C beträgt. Als Lösung wird vorgeschlagen, dass durch den Druckabfall unter einem dicken Gletscher unmittelbar stromabwärts von einem Rundhöcker oder von einer schmalen, steilen Stufe die Drucke, die innerhalb des Gneises eingeschlossen sind, den Felsen zu zerspalten vermögen. Diese Drucke rühren von der allmählichen Behebung der Überlast des unter einem Druck von tausende von Metern in der Felsenstrata erstarrten Gneises her. Der Gletscher vermag später den zergliederten und zerspaltenen Felsen wegzuschaffen.

## INTRODUCTION

A new phase in our understanding of glacial erosion resulted from Willard Johnson's account of his descent into a bergschrund.[1] My own preference is still for the melt-water variation of Johnson's hypothesis[2]; but recent work of Battle,[3] in demonstrating the relatively small changes of temperature which occur in bergschrunds, has shown that rock shattering by thaw-freeze processes is probably confined to the surface zone of a glacier. It was partly to help in resolving the remaining problem of deeper glacial erosion that our tunnelling project in Vesl-Skautbreen, Jotunheimen, was conceived.[4]

## BERGSCHRUND EROSION

The most suitable bergschrund that Battle found in the neighbourhood of Vesl-Skautbreen was at the head of Tverraabreein (see 1 : 50,000 map Midt-Jotunheimen) at an altitude of 2130 m. Here the outside temperature varied between 14° C. and —3° C., but some days it varied less than 1° C. Between 7 and 21 August it fell below —1° C. only twice, both times reaching —3° C., and it fell below 0° C. nine times. Within the bergschrund the temperature varied between 1° C. and —2° C. and seldom varied 2° C. in one day.

The August–September 1951 records which Battle obtained in a bergschrund at the Jungfraujoch, Switzerland, showed even less variation, from 0° C. to —1° C., in spite of outside temperatures varying between 11·5° C. and —12° C. The very much lower air temperatures in March 1951 which Battle recorded at the same bergschrund varied from —5° C. to —21° C., corresponding with a maximum bergschrund temperature of —2° C., presumably that of the surrounding ice, and a minimum of —4·4° C.

Battle also completed a very large number of laboratory freezing tests down to temperatures varying from —1° C. to —10° C. He used thoroughly saturated sedimentary and igneous rocks, including samples comparable with those occurring in Jotunheimen. In this he has amplified the findings of Thomas,[5] who wrote that good rock with no clear joints or cracks, and particularly if of low porosity, suffers little damage from frosts unaccompanied by other agents of disintegration, unless the falls of temperature are sudden and substantial. Lastly Battle also considered the case of frost shatter in cracks, but this work was cut short by his tragic death in Baffin Island.

On 14 August, when melting had widened the entrance, it was possible for us to penetrate 10 or 12 m. down, and 30 or 40 m. along, the Tverraabreein bergschrund. Everywhere the rock surface appeared fresh and angular, and in places great angular blocks were being removed from the headwall. Lower down icicles hung from the rocks and from slender snow bridges over our heads, and the rock was mostly draped with transparent ice 2–10 cm. thick. The impermanence of this mantle was demonstrated by its being melted away at points where water dripped and trickled down from above. More spectacular was the way in which many square metres of this ice mantle were being cleaved away from bedrock by the movement of the glacier to which it was also firmly attached.

Bergschrunds of any size do not form at the head of Vesl-Skautbreen, which moves only about 1 cm. a day. The most that seems to happen, especially during years of excessive melting such as 1947, is for a crack or randkluft to develop between the rock wall and the *névé*. The rock some metres down this randkluft had its mantle of glazed ice, but there was a gap between it and the rock of about 1 cm. where the ice had been melted away. There had been little or no sun for several days beforehand, but innumerable downpours of rain had occurred.

Thus at the headwall there was the usual evidence of rock shatter, but evidence that this occurred far below on any real scale was not immediately apparent. However, the upper tunnel, dug 20 m. through the *névé*, presented us with some very revealing evidence. It opened into an extensive cavern system between the headwall and the semi-consolidated firn. After scrambling downwards perhaps 12–15 m. an extensive cavern was reached in which the unsupported span of the roof must have been fully 30 m. The roof sloped steeply at an angle of 57 degrees and was very straight, showing no tendency to sag in spite of the span and the fact that the lower portions had been unsupported for fully ten years. The cavern widened wherever the rock wall sloped steeply. The angle of the roof, which marked the direction of ice movement, presumably followed the average slope of the neighbouring headwall. Nearly 50 m. below the tunnel the cavern was blocked by water, the level of which fluctuated.

There was abundant evidence within the cavern that frost action was proceeding with vigour. Considerable areas of rock were covered by the usual ice mantle, and the countless icicles added their testimony. The grey lustre of the rock which was draped with ice was interrupted here and there by black patches and streaks where drips and runnels of melt water had removed the coating of ice and revealed the bare, black, wet rock beneath. Large exposures of the tough gneiss showed cracks many yards long, and many great and small blocks lay almost clear of the parent rock. It all suggested active prizing and sapping of the headwall by the repeated freezing of melt water.

A mass of white, lightly consolidated firn at one point within the cave showed that the wind had, on occasion, sufficient access to drift in fresh snow. Such air circulation could lower the temperature within, leaving a pocket of cold which could then be sealed off. Radiant heat would be excluded even more effectively than from an open bergschrund, but dripping water could enter such a cold pocket, penetrate thin cracks and then, on freezing, damage the rock.

The presence of such a cave system in a glacier moving as little as 1 cm. a day tempts one to speculate on the possibility of such features occurring fairly widely. They may occur below the bottom of the bergschrund and randkluft or may merge into them, as Battle often found in his subglacial perambulations. Such caverns may change in position somewhat over a period of centuries and so allow frost shatter to be fairly widely distributed over the headwall. Any local steepening of this wall, by giving rise to such a cavern, could increase the incidence of frost shatter. This, in turn, would accentuate such steep portions of the headwall perhaps a 100 m. or more below the bottom of a bergschrund or randkluft, and in this way headward erosion could proceed.

Fundamental to this whole question of frost damage is the presence of minute cracks in the rock, which a thin film of water can enter. Physical weathering cannot really begin—and chemical weathering is severely restricted—unless such cracks are present beforehand.

## DEEP GLACIAL EROSION

The rock wall at the end of the lower tunnel posed a very different problem. Here, 80 m. below the bottom of the cavern system, the temperature remained unchanged at 0° C. throughout the year. McCall and his party were disturbed by floods from within at Christmas 1951 when "camping" in the tunnel entrance. Melt water certainly penetrated to this depth, but its downward course seemed to be a halting one which did not permit a through draught of cold air to affect the prevailingly uniform temperature. Yet the rock wall was angular with totally unweathered faces. Projecting slabs of rock were smoothed and striated, but elsewhere the surfaces were rough, due to the protrusion of the harder crystals, and appeared freshly fractured when the all-pervading coating of rock flour was removed. Thus, in addition to the evidence of the more readily understood mechanism of smoothing and grinding, we were confronted with undoubted evidence of sapping or prizing by an unknown process. It is certainly necessary to look elsewhere than to thaw-freeze for an explanation of the removal of this good hard rock from near the base of the headwall.

The answer to this problem is, I suggest, given by a remarkable demonstration of the bursting up of layers of this massive gneissic rock which I noted at the snout of the neighbouring Svellnosbreein. In 1939 ice covered the area of rock shown in Fig. 1 (p. 416), which was photographed in July 1946. This great mass of gneiss was smoothed, grooved and chipped by glacial erosion on its more projecting convex surfaces, as shown in the foreground and on the top of the uppermost slab. But a 20 cm. thick layer had arched upwards fully 5 cm. although it was still joined to the parent rock at either end. Beneath this a much thicker layer had risen and separated along the full width shown in the photograph, and beneath that a further layer had lifted forming jagged step faults with a maximum upthrow of several centimetres. Some of the rock fragments broken free during the process are shown *in situ*, and the edges of the fractures are so sharp that the whole action must have occurred after the glacier had retreated from the site. It is reasonable to assume that the gneiss burst up soon after the release of the pressure of the over-lying ice. A neat illustration of this action occurred in the walls of the lower tunnel. The digging of the tunnel caused the immediately adjacent ice, which was subject to the considerable pressure of about 100 m. of ice, to be relieved of this pressure on the free face. A series of cracks then formed parallel with the walls and roof of the tunnel and layers of ice about 2 or 3 cm. thick could be pealed off.[6]

The gneiss had been consolidated under the pressure of several thousand metres of overlying strata. The gradual removal of these confining strata had been completed by the glacier in lowering its bed. The strength of the gneiss presumably enabled it to resist bursting up until the final release of all superincumbent load on the last reatreat of the glacier. Then the internal stresses exceeded the yield stress of the gneiss and the topmost layer arched up as it expanded. This reduced the pressure on the layer below which also burst up, followed in turn by the layer still further below.

This formation of joints roughly parallel with the surface by pressure release has been suggested previously in other contexts. Gilbert[7] cautiously favoured such an explanation for the parallel sheets "which wrapped around the topographic forms" in the granite domes of Yosemite in the High Sierra of California. Matthes,[8] in his fine account of this magnificent area, was well aware of the importance of sheet structure, estimating that nearly half of the landscape features were modelled by exfoliation. He considered, however, that exfoliation occurred in inter-glacial times and not when glacial erosion was active. Little or nothing was said of the mechanism of exfoliation in this cool, temperate climate, and he ignored Gilbert's pertinent suggestion.

The most spectacular manifestation of pressure release cited is the bursting of marble during quarrying in Vermont, referred to by Bain.[9] Expansion of the marble was so rapid that the stone frequently closed in on the drill steel while working. Violent bursts occurred at depths of about 10 m. and machines were thrown from their tracks. The damage was so serious that the quarries had to be closed. Measurements showed that the rock expanded spontaneously and one of Bain's photographs shows the tendency for the arch to develop in a face as a result of the bursting up of the layers of rock.

This general behaviour has been induced in rock in Bridgman's High Pressure Laboratory.[10] Limestone was enclosed in a cylinder and subjected to axial pressure sufficient to cause plastic deformation, presumably equivalent in nature to mild metamorphism. On the release of pressure the specimen ruptured into discs perpendicular to the axis of the cylinder. In fact Bridgman complained that all through his high-pressure experiments he had been bothered by fractures that occurred during release of pressure. He wrote prophetically that the field, *par excellence*, in which to look for effects of this sort was geology, although it might not always be easy to tell from observation that the fractures have been produced in this way.

Full credit must be given to certain American geologists for their recognition of the geomorphological importance of this form of exfoliation, but more detailed in his minerological investigation, though perhaps over-cautious in his conclusions, is Cameron[11] in his study of the newer Grey Granite of Aberdeen. He examined the jointing and microstructure of the granite in the Kemnay Quarry to a depth of 165 m. below the surface. Horizontal joints are much more common near the surface and are comparatively rare in the deepest parts of the quarry. These joints never have any mineral associated with them nor did microscopic examination reveal any reason for their occurrence, and yet they represent the plane along which the granite splits most readily—the "easy way" of the quarrymen. At Kemnay there is a very great difference in the ease of splitting between the easy way and the hard way, and this difference is as great 150 m. down as at the top. Cameron concludes that there is nothing at Kemnay which directly disproves the suggestion that the flat-lying joints, and the potential horizontal planes of easy parting, are due to a combination of such factors as the expansion of felspars on weathering and the removal of the load of superincumbent rocks by erosion.

It is surprising that Cameron, who has presented us with such excellent evidence of the lack of relationship between the horizontal joints—or pseudo-bedding—and microstructure, did not set aside weathering as an explanation. The scale, both in thickness and depth of occurrence, of such jointing, continuing in Yosemite National Park to 150 m. below the surface, is such that chemical weathering can hardly provide an adequate answer. The onion scaling of boulders of gabbro lying in the turf at the foot of the Cuillins of Skye clearly reveals chemical exfoliation, and Professor Linton showed me a section near Tideswell in the Peak District which exhibited rectangularly jointed basalts, *in situ* in a soil section nearly 10 m. deep, in all stages of transformation by chemical weathering to rounded boulders. The shells in such instances are usually less than a centimetre in thickness.

My first view of the gneiss at the end of the lower Vesl-Skautbreen tunnel led me to mistake the roughened rock surface, smeared with rock flour, for a chemically weathered surface. So I arranged for Dr. M. H. Battey, then a research student in the Department of Mineralogy and Petrology, Cambridge, to visit the tunnel in the summer of 1952 to examine these rock surfaces, and to ascertain the pattern of jointing in relation to the form of the cirques. Battey[12] is quite definite that the rock surfaces in question are entirely unweathered. In addition he showed that the jointing of the gneiss follows closely the cliff faces of the cirques as these change direction through 180 degrees. Such observations in particular led me to look into this matter of pressure release closely. The question had also been brought to my attention by Mr. W. B. Harland, who noted the very close parallelism between joints and the sides of certain Alpine glaciated valleys in granite, and by Dr. C. F. A. Pantin, who described the remarkable exfoliation features on the sugar loaves of Brazil.

In a small quarry about 5 km. from La Souterraine *en route* for Gueret in the Central Massif of France, I again photographed up-arching of granite. On the north side of the road from Coniston to the Old Copper Mines, in the Lake District, many acres of nearly bare Borrowdale Volcanic rocks show pseudo-bedding parallel with the surface even when the gradient changes considerably. Small, roadside quarries show no obvious planes of weakness which would account for this bedding. The way in which this pseudo-bedding followed faithfully the contour of the ground was recognized many years ago on Dartmoor by Hansford Worth,[13] but he mistakenly attributed the jointing to the cooling surfaces of the granite. More recently Waters[14] made a strong case for the Dartmoor pseudo-bedding having succeeded the moulding of the present surface relief, and he attributes this jointing to pressure release.

Granites seem particularly prone to develop such joints. But great was my surprise when I obtained evidence that many sedimentary rocks also seem to be in a state of stress and to expand when quarried. The foreman of the Craig-yr-Hesg Quarries, Pontypridd, informed me that the hard Blue Pennant Grit of the Carboniferous Series in this quarry could be split far more readily when freshly quarried than if it were left for a few months before being worked. Mr. E. Williams, one of the owners of the quarry, kindly forwarded me blocks of Blue Pennant Grit for testing in Cambridge, one which had been freshly quarried and another which had been quarried several months previously. Mr. Masson-Smith, a research student in the Department of Geology, Cambridge, was working on the density and allied properties of rocks. He had already noted that samples of rock which he cut from the centre of large blocks were denser than ones cut from the outside, and also that the density of the heavier specimens decreased with the lapse of time. He kindly agreed to test the Blue Pennant specimens for expansion. Preliminary measurements showed that a specimen cut from within the relatively freshly quarried block expanded in several directions, but that in some directions it contracted markedly.

These large blocks were cut into slabs by the foreman of Messrs. Rattee and Kett, Cambridge. He tested, in my presence, the relative ease with which these two blocks could be split and showed that the newer specimen broke rather more easily than the older one although a further six weeks had now elapsed since quarrying. He also volunteered the remark that most of the rocks he received split more readily if worked on arrival from the quarries than if left for some time. It therefore seems likely that, in the absence of an alternative explanation, a considerable variety of rocks have stresses within them when first quarried.

## Conclusion

How, then, may pressure release function under a glacier? Fig. 1 shows an example of the arching up of rock slabs after the glacier had receded from the immediate site—the ice can just be seen in the top right-hand corner of the photograph. If the glacier advanced again it could readily remove the loosened layers of rock; a repetition of retreat and advance could enable further erosion to occur. Whilst admitting the importance of such action I should certainly not limit effective glacial erosion to this form of rock removal.

The one widely recognized mark left on the landscape by glacial erosion is the family of related features from the small steep valley step to the lesser *roche moutonnée.* In accounting for these features the assumption ordinarily made is that rock has been removed by plucking or sapping from the downstream side, leaving that face steep and irregular. Fig. 2 (p. 416) shows a *roche moutonnée* of step-like form within a few hundred metres of the rock shown in Fig. 1. The contrast between the smoothed upper tread and the irregular "plucked" riser can be seen. The literature helps us little in our search for the mechanism of "plucking" in such circumstances. It cannot be a simple tug-of-war between the glacier ice and unjointed bedrock as the tensile strength of the rock is so very much the greater that the ice and not the rock would always break. It was for this reason that I previously suggested that the motive action was thaw-freeze shattering.[15] Professor Hollingworth has expressed to me the view that the bedrock with which a glacier has to deal is rarely if ever unjointed, and so the rock, because it is jointed, can be considered to be weaker than the ice in such a tug-of-war.

The question as to whether or not certain of the more massive igneous, metamorphic and sedimentary rocks are in fact well jointed before they come within the zone of pressure release or of weathering agents needs thorough investigation. My present conviction is that whether or not such rocks are initially jointed, joints commonly form by pressure release when the pressure of the overburden is reduced to little or nothing. The question then arises as to whether or not pressure beneath a thick glacier can be low enough for this initial cracking of the rock to occur. I think it can for the following reasons.

Carol[16] gained access to caves formed on the downstream sides of *roches moutonnées* in the Upper Grindelwald Glacier under 50 m. of ice. The tunnel dug through the base of the 1000 m.

Mt. Collon ice fall of the Lower Arolla Glacier opened into an extensive cavern system between the steep rock-bed and the glacier at the foot of the ice fall.[17] The caves are due to the rigidity of the ice which, provided the movement is relatively quick and the weight of the overlying ice is not too great, passes the obstacle a short distance before being pressed down to make contact again with the bed.

In Fig. 2 pseudo-bedding is shown in the gneiss below the *roche moutonnée*, and also to some extent in the *roche moutonnée* itself. A decrease in the thickness of the glacier may have resulted in the release of pressure immediately downstream from the *roche moutonnée* leading to the formation of the joints. A subsequent increase in glacial thickness may have once more brought the ice into contact with the broken rock and led to its removal. The very great pressure of the ice on the crest may also have encouraged the *roche moutonnée* to "exfoliate" along vertical joints parallel with the "plucked" face, a suggestion made to me by Professor Orowan. Substantial variations of pressure both in time and place may well occur beneath glaciers with markedly irregular beds.

Such a theory of pressure release would seem to have the double advantage of accounting for the initiation of cracks in which thaw-freeze can then act, and of explaining deep glacial erosion in sparsely jointed rocks by "plucking" at depths where temperature changes rarely or never occur.

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## REFERENCES

1. Johnson, W. D. An unrecognised process in glacial erosion. *Science*, N.S., Vol. 9, 1899, p. 106.
—— The profile of maturity in Alpine glacial erosion. *Journal of Geology*, Vol. 12, 1904, p. 569–78.
2. Lewis, W. V. A melt-water hypothesis of cirque formation. *Geological Magazine*, Vol. 75, 1938, p. 249–65.
—— The function of melt-water in cirque formation: a reply. *Geographical Review*, Vol. 39, No. 1, 1949, p. 110–28.
3. Battle, W. R. B., *and* Lewis, W. V. Temperature observations in bergschrunds and their relationship to cirque erosion. *Journal of Geology*, Vol. 59, No. 6, 1951, p. 537–45.
4. McCall, J. G. The internal structure of a cirque glacier. *Journal of Glaciology*, Vol. 2, No. 12, 1952, p. 122–30.
5. Thomas, W. N. Experiments on the freezing of certain building materials. *Department of Scientific and Industrial Research. Building Research Board, Technical Paper*, No. 17, 1938.
6. Lewis, W. V. Tunnel through a glacier. *The Times Science Review*, No. 9, 1953, p. 10–13.
7. Gilbert, G. K. Domes and dome structure of the High Sierra. *Bulletin of the Geological Society of America*, Vol. 15, 1904, p. 29–36.
8. Matthes, F. E. Geologic history of the Yosemite valley. *U.S. Geological Survey. Professional Paper*, No. 160, 1930.
9. Bain, G. W. Spontaneous rock expansion. *Journal of Geology*, Vol. 39, 1931, p. 715–35.
10. Bridgman, P. W. Reflections on rupture. *Journal of Applied Physics*, Vol. 9, 1938, p. 517–28.
11. Cameron, J. Structural features in the grey granite of Aberdeenshire. *Geological Magazine*, Vol. 82, 1945, p. 189–204.
12. Battey, M. H. Geological factors in the development of Veslgjuvbotn and Vesl-Skautbotn. *R.G.S. Research Series*, No. 3. [In course of publication.]
13. Worth, R. Hansford. *Dartmoor*. Plymouth, R. H. Worth's Executors, 1953.
14. Waters, R. S. Pseudo-bedding in the Dartmoor granite. *Transactions of the Royal Geological Society of Cornwall*, Vol. 18, 1952 [pub. Jan. 1954], p. 456–62.
15. Lewis, W. V. Valley steps and glacial valley erosion. *Transactions. Institute of British Geographers*, Vol. 13, 1947 [pub. 1948], p. 19–44.
—— The formation of *roches moutonnées*. *Journal of Glaciology*, Vol. 1, No. 2, 1947, p. 60–63.
16. Carol, H. The formation of *roches moutonnées*. *Journal of Glaciology*, Vol. 1, No. 2, 1947, p. 57–59.
17. Haefeli, R. Some observations on glacier flow. *Journal of Glaciology*, Vol. 1, No. 9, 1951, p. 496–500.
18. Clark, J. M., *and* Lewis, W. V. Rotational movement in cirque and valley glaciers. *Journal of Geology*, Vol. 59, No. 6, 1951, p. 546–66.