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DEPARTMENT OF ENERGY, MINES AND RESOURCES

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NIVATION LANDFORMS

(Report and 6 figures)

D. A. St-Onge

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ABSTRACT

The numerous rock types on Ellef Ringnes Island in the Queen Elizabeth Islands, N. W. T. makes it possible to study the influence of lithology on landforms resulting from the activity of a given process. Nivation, a combination of frost shattering, gelifluction and sheet wash, carves a series of landforms which vary according to the type of rock in which they occur. Lithology, in determining debris size, controls the agents of removal and consequently the nature of the nivation landform.

NIVATION LANDFORMS

INTRODUCTION

This paper results from field work carried out on Ellef Ringnes Island, Queen Elizabeth Islands, N.W.T. as part of the Polar Continental Shelf project in the summers of 1959-60-61. During a brief visit in August 1967, nivation landforms, developed on gabbro ridges northeast of Isachsen, were measured and photographed.

Until a few years ago periglacial features, particularly patterned ground, felsenmeer and mass movement were explained in relation to the 'freeze-thaw cycle' concept. Mechanical weathering was assumed to be both extensive and intensive because of the number of freeze-thaw cycles during the summer months.

In this paper the nivation landforms on three rock types - gabbro, sandstone and shale, are examined in the light of present-day knowledge of frost-shattering mechanisms and on the nature of resulting materials.

Previous studies

The historical sequence of major studies on nivation landforms has been outlined in previous publications and will not be repeated here (Henderson, 1956; St-Onge, 1964, pp. 287-289; 1965, p. 11; Bird, 1967, p. 227).

In recent years, views held on the mechanisms of frost shattering have changed. Ground temperature measurements made at regular intervals from the surface to a depth below the permafrost table have shown that "there are no cycles, apart from the annual cycle, at depths below a few centimetres and it follows that assumptions still widely held ... that frost cycles are a vigorous process producing frost splitting at depth in arctic countries are not valid." (Cook and Raiche, 1962a, p. 76, See also Cook, 1955; Czeppe, 1961, p. 61 and diagrams VIa-b-c; St-Onge, 1965, p. 7 and Fig. 4).

Another assumption widely held was that heating and cooling of rocks could generate stresses sufficient to disintegrate them; this process was believed to be particularly effective in deserts. Tricart however, concluded from experimental work that heating and cooling a dry rock is ineffective, but stated that granites seem to behave differently: "leur fort coefficeint de dilatation les rend sensibles à la désagrégation granulaire par thermoclastisme, tandis que leur gélivité est faible." (Tricart, 1956, p. 294).

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Ottawa, Canada.

More recent studies place less emphasis on the importance of thermal variations in rock disintegration: "Several experimental studies, made under conditions more severe than those imposed by nature, indicate that stresses generated by natural temperature variations are significantly smaller than the rupture strength of rocks ... it is possible, however, that small effects are cumulative over long periods". (Leopold, Wolman and Miller, 1964, p. 114). It is also possible that rock deterioration may be the "result of ordering and disordering of the highly polar water molecules on mineral surfaces (largely clay) with cooling and warming". (Dunn and Hudec, 1966, p. 20).

Thus, both field observations and laboratory studies indicate that frost is not very effective in the mechanical weathering of dry rock. To be important in landscape evolution, both mechanical weathering and chemical weathering require the presence of water.

FROST SHATTERING

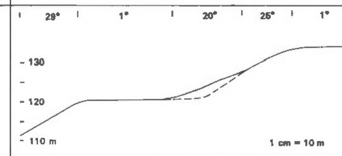
Whether or not frost shattering will take place, and its effectiveness, are related to three variables: rock porosity, moisture supply and frost intensity.

Porosity, which "is a measure of the interstices contained in any particular volume of rock", varies widely from one rock type to another. Leggett (1962, p. 137) gives the following average values for porosity: crystalline rocks generally up to 0.5 per cent, slate and shale 4 per cent, sandstone 10 to 15 per cent. Porosity controls the amount of moisture available and the space for crystal growth. The shear stress generated by freezing water depends in part, on the amount of water available, and thus, in a given rock unit this is a function of porosity.

Miller (1945, p. 65) defined the critical moisture content as "the maximum amount of interstitial water which, when converted into ice, will fill all the available pore space ...". Until recently it was assumed that this condition had to be fulfilled before frost shattering could take place (St-Onge, 1965). In a cooling rock, ice crystals form first in the larger pores and water migrates from the finer pores towards the growing crystals. This phenomena, called cryo-osmosis by Lliboutry (1965, t2, p. 951), makes the growth of comparatively large crystals possible, and may be the most important aspect of frost action. Ice crystals grow normal to the surface, in the direction of heat conduction, and it is the pressures thus generated that cause flaking and spalling of rock particles.

In saturated rock enormous stresses are generated through the increase in volume of freezing water (9 per cent at 0° C). In high arctic regions these pressures are confined between frost layers progressing downward from the surface and upward from the permafrost. Conditions best suited to rock disintegration are those of slow cooling, which creates large crystals, followed by long periods of intense frost which can generate pressures up to 2200 kg/cm^2.

It is now obvious that physical weathering related to frost is more intense in rocks where abundant moisture is available. In low precipitation regions of the Arctic, intense physical weathering is thus limited to the vicinity of snowbanks. It also follows that the depth of frost weathering is controlled by the depth of annual thaw.

<table>
<tr><th>LITHOLOGY</th><th>AGENT</th><th>NAME</th><th>FORM</th></tr>
<tr><td>Gabbro</td><td>Sheetwash
Gelifluction</td><td>Nivation terrace</td><td>
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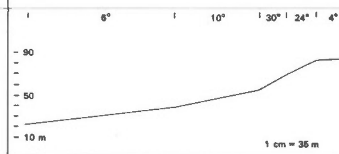
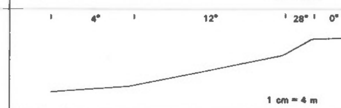
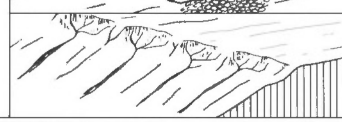
<tr><td>Sandstone</td><td>Gelifluction
Sheetwash</td><td>Nivation bench</td><td>
</td></tr>
<tr><td rowspan="3">Shale</td><td rowspan="3">Sheetwash
Rill erosion
Creep</td><td>Nivation hemicircle</td><td>
</td></tr>
<tr><td>Nivation hollow</td><td></td></tr>
<tr><td>Nivation ledge</td><td></td></tr>
</table>

Figure 1. Relationship between lithology, agent and landform carved by nivation processes.

NIVATION LANDFORMS

Field work carried out on Ellef Ringnes Island showed that the size of material produced by frost action varies greatly from one rock type to another. Thus fine grain gabbro yields large blocks and boulders and few fines, whereas coarse grain gabbro is frost shattered to comparatively fine material (25 cm in diameter or less); sandstone disintegrates into sand and occasionally into slabs; shale produces thin flakes up to 3 cm across and silt. If this variety of material is produced by frost action, landforms resulting from nivation are also likely to differ from one rock type to another (Fig. 1).

Nivation Landforms in Gabbro

Terraces are common near the summit of gabbro ridges, 250 to 300 metres high. They occur either as a series of giant steps leading to the crest or as isolated features on either side of the ridge top (Fig. 2). They vary in length from 10 metres to over 2 kilometres, averaging between 200 and 300 metres. The distance between the terrace edge and the backwall can reach 150 metres but is more frequently between 10 and 15 metres. The backwall, with slopes ranging from 25 to 35 degrees, is seldom more than 5 metres high.

Figure 2. Nivation terraces near the top of the southwest extremity of the horseshoe-shaped gabbro ridge north of Isachsen, Ellef Ringnes Island, N.W.T. View looking north. G.S.C. 200736.

A typical terrace consists of a steep backwall 3 to 10 metres high, and a flat or gently inclined 'floor'.

The backwall scarp is made up either of craggy, roughly columnar outcrops of gabbro or of large angular boulders, 50 to over a 100 cm across. Granular snow or ice covers most of the backwall all year round, but unusually warm summers as in 1959, make detailed studies possible. Bedrock outcrops and boulders are lichen free and commonly display unweathered facets outlined by sharp edges, obviously the result of comparatively recent splitting.

The floor dips away from the backwall usually between zero and two degrees. Materials on this surface form two distinct bands. The inner band contains a high enough percentage of fines to make geliturbation possible, and is characterized by small-sized patterned ground one metre or less in diameter, with frequent sorted circles and mud boils. The outer band is covered by coarser material which grades into an open-work block field (felsenmeer) near the outer edge of the terrace. Patterned ground is rare except for occasional poorly developed gelifluction lobes (Fig. 2). On terraces, the floor of which is 10 metres or less in width, the inner zone is poorly developed or entirely missing (Fig. 3). Total thickness of unconsolidated material on a terrace floor is not thought to exceed 1 metre.

In the area studied, terraces cut into gabbro show no preferred orientation. Their long axis (a line parallel to the backwall) is either parallel with, or lies at a very small angle to the ridge crest line. The same relationship exists between the long axis of the terraces and the outside edge

Figure 3. Nivation bench in glauconitic sandstone northeast of Deer Bay, Ellef Ringnes Island, N.W.T. View looking east.

of a mesa. Thus, it seems that the dominant northeast wind is not a controlling factor in determining the orientation of terraces carved near the summits of high gabbro ridges and mesas.

In most cases it is very nearly impossible to determine whether these terraces have been created by nivation alone or whether they are inherited forms presently being modified by nivation. For example, from the top of the southwest extremity of the horseshoe-shaped gabbro dyke north of Isachsen, two west-facing terraces lead down into a flat trough 15 metres wide, bounded by scarps 2 to 4 metres high (Fig. 2). This trough, open at both ends, has all the appearances of a channel segment isolated during stages of downcutting. Its origin was unlikely to be from nivation although this is difficult to ascertain; it is more likely to have been a segment of a meltwater channel of unknown age. Whatever its origin, the channel is being actively modified by nivation processes as shown by recent frost shattering of some gabbro boulders.

The evolution of a nivation terrace in gabbro or in rocks of similar hardness can be summarized thus:

- Snow accumulates in an area oriented to the wind or in an initial irregularity in the slope.
- Conditions favourable to frost shattering are created.
- This process yields large quantities of coarse fragments and few fines.
- The fines are removed by water percolating through the boulders.
- The backwall recedes leaving an apron of coarse fragments.
- These boulders act as the base level of the terrace since they can no longer be saturated.
- As the terrace widens, the effects of percolating water and sheet wash are greatly reduced.
- Away from the outer edge, the open-work boulder field is gradually clogged with a matrix of fine material.

- The moisture retention capacity increases with a corresponding increase in frost shattering.
- Eventually the percentage of fine material is sufficiently high to render geliturbation possible.

The evolution of nivation terraces in gabbro is slow in comparison to their formation in softer rocks. Gabbro is a hard, compact rock with a low porosity, and frost shattering takes place only under the most favourable conditions.

Nivation Landforms in Sandstone

Northeast of Deer Bay lies a low plateau of glauconitic sandstone which has been deeply dissected by tributaries of Sandstone River. Large snowbanks accumulate on south-facing slopes and nivation processes are particularly effective in this comparatively soft porous rock (Fig. 3).

The disintegration of sandstone by frost produces silt, sand and small sandstone aggregates. The frost-shattered material containing a large percentage of fines, moves downslope either by gelifluction, sheet and rill wash or by a combination of these.

Figure 3 illustrates a typical profile of an active nivation bench in a sandstone area. The steep backwall carved in unweathered bedrock is undergoing intense shattering. The floor is an inclined surface (6 to 8 degrees) in abrupt contact with the backwall. The material on this surface is covered by mosses and lichens, and at the time of the author's visit, consisted of an oozy mass. Walking across it meant sinking 10 to 15 cm and footmarks were quickly obliterated by material flowing downslope. In spring, when only a thin film has melted, material is transported by sheet wash on this surface. As downward melting progresses, laminar gelifluction becomes predominant. Similar features are found in the area of Resolute on Cornwallis Island (Cook and Raiche, 1962b).

If, due to climatic conditions, nivation were to become an effective process in an area of steep valley slopes, debris would be deposited at the foot of the slope. In cross-section, bedding would alternate between coarse and fine, depending on the importance of the role played by gelifluction in depositing each bed. Stratified slope deposits of this type are common in Europe and are described in detail in the French literature where they are called 'grèzes litées' (Guillien 1953, Souchez, 1964).

Nivation Landforms in Shale

In shale and minor siltstone of the Kanguk Formation (Upper Cretaceous) nivation processes have carved a series of landforms notable for their number and variety.

Frost shattering quickly reduces soft shale to fine sand and silt. This material is easily moved by sheet wash and rivulets on slopes steeper than 4 degrees and, as a result, bedrock outcrops on the floor as well as the backwall. The resulting landforms display a wide range of shape and size: (1) nivation hemicircles – amphitheatre-like features 50 to 200 metres across

Figure 4. Nivation hemicircle in shale and minor siltstone; southeastern part of Meteorologist Peninsula, Ellef Ringnes Island, N. W. T. View eastward.

Figure 5. Nivation hollow in shale, northwest coast of Louise Fjord, Ellef Ringnes Island, N.W.T. View northwestward.

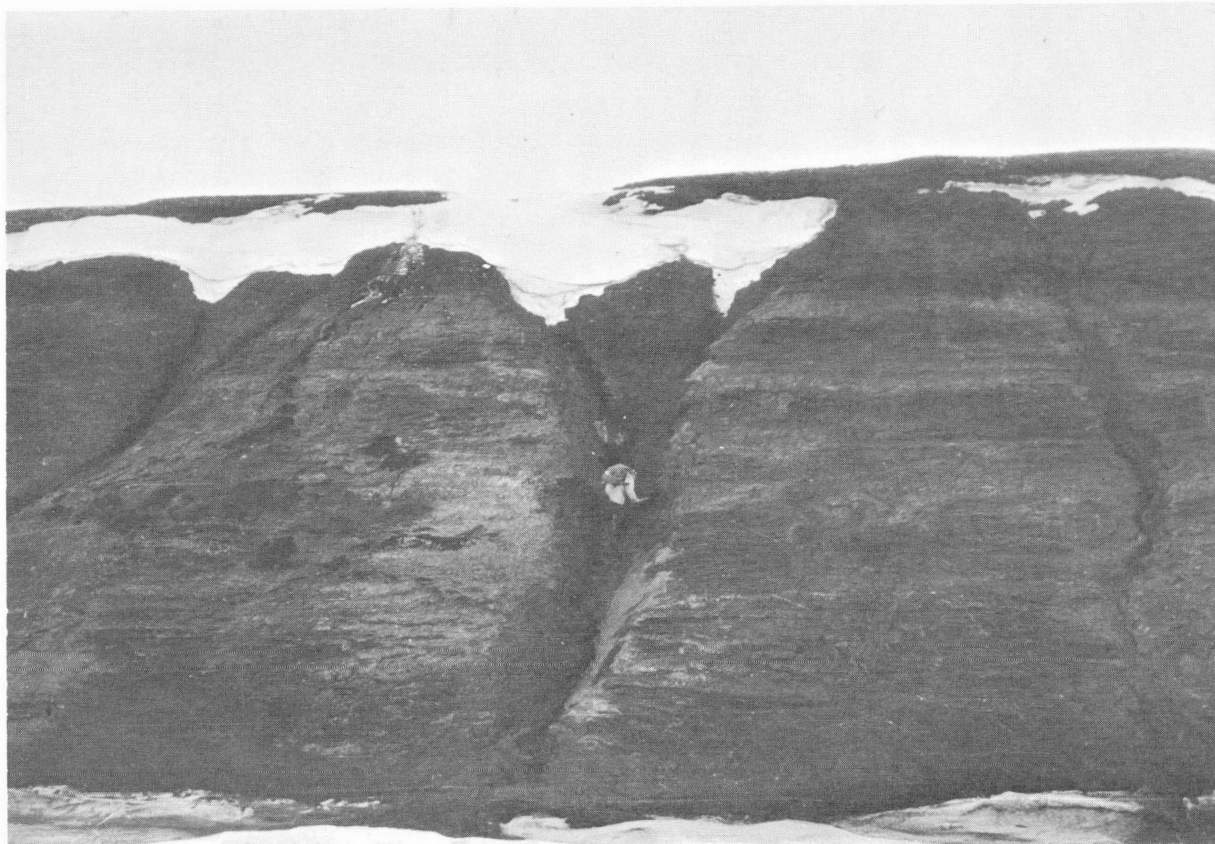


Figure 6. Nivation ledge on a valley wall of a small tributary of the Brant River, Ellef Ringnes Island, N.W.T. View looking west.

(Fig. 4); (2) nivation hollows -- "U" shaped widenings at the head of small gullies (Fig. 5); and (3) nivation ledges – breaks in slope or narrow ledges in the upper part of steep slopes (Fig. 6).

A typical nivation hemicircle has a steep cuspated backwall of 22 to 28 degrees. This steep, complex slope is in sharp contact with the moderately steep floor inclined at 8 to 12 degrees. Snow patches, clinging to the backwall, last through most summers. From them water flows as a thin sheet over a smooth surface 1 to 10 metres wide, but quickly forms rivulets and small streams which carve small gullies as they flow across the inclined floor. As the backwall recedes, incision of the floor becomes more pronounced and the more indurated bedrock gives rise to small hillocks (Fig. 4).

DISCUSSION

Frost shattering is most effective in relatively soft, very porous rocks such as sandstone, saturated by water from melting snowbanks and frozen during the winter months. In rocks with lower porosity be they hard rocks such as gabbro or soft rocks such as gypsum, frost shattering is far less effective.

Assuming the rock to be saturated, the size of material resulting from frost action also depends on porosity and on the intensity and duration of frost. Fine grain gabbro produces large blocks because, provided a large enough volume of low porosity rock is involved, enough stress can be generated to overcome rupture strength. Further reduction in size is a considerably slower process. On the other hand, as pointed out by Souchez (1964), intense frost over prolonged periods may produce finer debris than shorter periods and/or less severe conditions. Under the latter conditions supercooled water in micropores does not freeze and stresses are less than the rupture strength of the rock.

On Ellef Ringnes Island, since frost intensity and saturation conditions are presumed to be similar under the perennial snowbanks, the differences in debris sizes must be related to lithology, and to the variation in the rupture strength and porosity of each rock type. Nivation combines the frost shattering of rocks in areas where saturation conditions are optimal, and the removal of debris by gelifluction, sheet wash and rill erosion. Which of these three will be dominant is determined by the granulometric characteristics of the frost-shattered material; this in turn determines the shape of the resulting landform.

From the evidence on the rate of evolution of nivation processes on gabbro, the author concludes that the numerous terraces found on the sides of gabbro ridges and mesas were not carved during 'Post Glacial Time', between 8,000 and 10,000 yrs. B.P. Either nivation processes have been active on Ellef Ringnes Island during most of the Pleistocene or nivation is merely modifying landforms originally created by other processes.

However, the effectiveness of nivation in softer more porous rocks clearly indicates that, if given sufficient time, it will sculpture large terraces such as those found on the gabbro hills of Ellef Ringnes Island.

Similar features have been described in other regions and a variety of names applied to them; altiplanation terraces, nivation terraces, goletz terraces (St-Onge, 1964, p. 292, 1965, pp. 11-12; Bird, 1967, pp. 227-228, 247-248). It is unlikely that all these forms are identical or that they have the same origin. The origin postulated here is one of possibly several likely explanations.

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