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INTENSITY VERSUS DURATION OF BEDROCK WEATHERING UNDER PERIGLACIAL CONDITIONS IN HIGH ARCTIC CANADA

Abstract

A distinction is drawn between intensity and duration of bedrock weathering with reference to field observations compiled at widely scattered localities in the Canadian high Arctic. The influence of bedrock mineralogy, texture, porosity and structure on microfracturing and subsequent bedrock disintegration is discussed using examples. Preservation of periglacial features including felsenmeer beneath glacial ice is suggested. Other factors influencing both the development and preservation of weathering forms including tors and weathering pits are summarized based on observations compiled during the past four summers.

INTRODUCTION

Much of high Arctic Canada is today covered by, or in close proximity to, upland icecaps (Fig.1). Aproximately 60 percent of the total land area of Ellesmere Island, for example, is covered by glaciers while large ice masses also occur on both eastern Devon and Axel Heiberg Islands. Similar remnant icecaps may have existed much further south during the Late Wisconsin as, for example, in upland portions of the Adirondacks and eastern Appalachians. By examining upland glacial/periglacial conditions existing today in the high Arctic a better understanding of subaerial processes under periglacial conditions in general may be gained.

A preponderance of erosional features has been reported from high Arctic Canada leaving the impression that the typical landscape is glacially scoured. Pim Island off the east-central coast of Ellesmere Island, for example, affords an intensely ice sculptured upland topography typified by grooves, striations and polished granite surfaces (Blake, 1977; Blake, 1978a). Similarly, along the northeastern coast of Devon Island, east of Truelove Inlet, exposures of Precambrian charnockites and gneisses are typically ice-eroded revealing low rounded outcrops.

In contrast, widely scattered examples of highly weathered bedrock terrain have also been reported from this region. Hodgson (1973) working on the Fosheim Peninsula of western Ellesmere Island pointed out that while the area has

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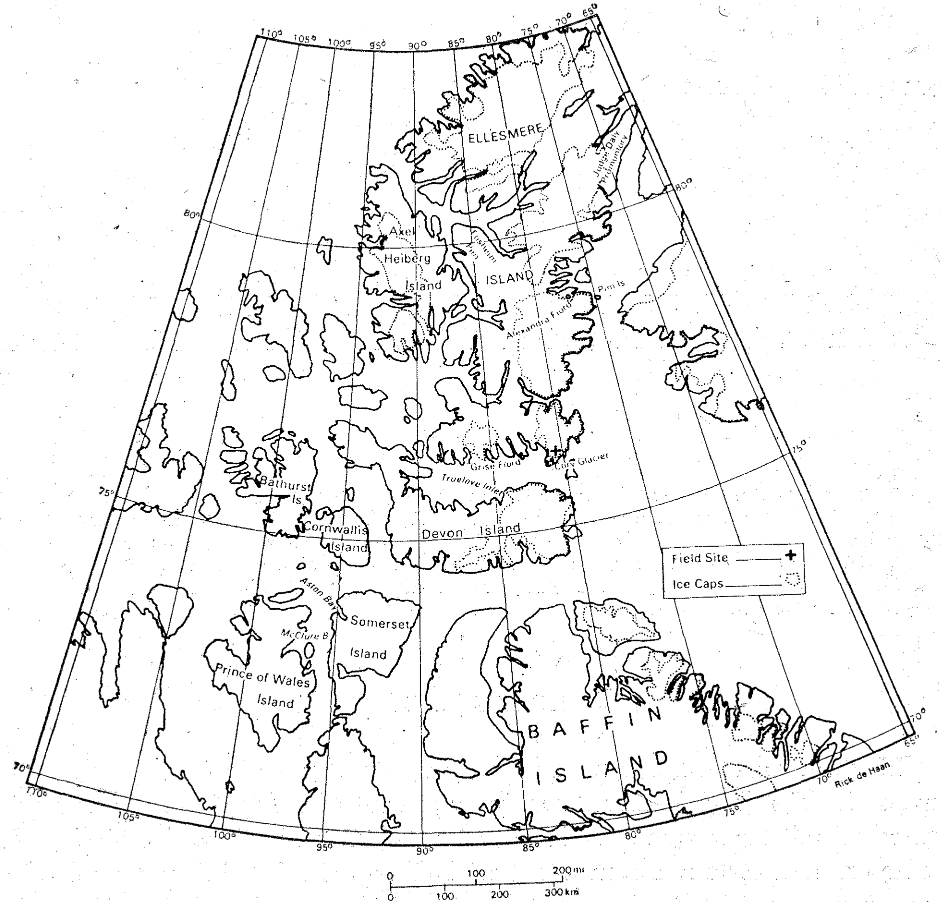


Fig. 1. Field study areas

been glaciated, bedrock weathered to various degrees is the dominant surface material and exercises most control over the form of the landscape. ENGLAND (1974) (*cf.* also ENGLAND and BRADLEY, 1978) observed highly weathered surfaces in sandstone along Judge Daly Promontory on the northeastern coast of Ellesmere Island. DYKE (1976) reported that surficial materials over much of Somerset Island comprise in situ weathered bedrock and went on to describe tors and associated weathering phenomena from a variety of lithologies there. BLAKE (1978b) (cf. WATTS, 1984) has described rock weathering forms on a ridge overlooking a subsidiary tongue of the Cory Glacier on southeastern Ellesmere Island. WATTS (1981a, 1981b) has identified similar terrain along the south coast of Alexandra Fiord (eastern Ellesmere Island) both near sealevel and in upland summit areas.

Highly weathered outcrop terrain is produced by subaerial weathering processes acting on bedrock over a period of time. SUGDEN and WATTS (1977) have suggested that such features could survive, preserved beneath cold based ice and could therefore pre-date one or more glaciations as discussed later. Subaerial weathering processes would largely stop during such glaciations rendering it difficult — probably impossible — to ascertain the true age of such terrain. Intensity of subaerial weathering of bedrock depends on several variables particularly including: bedrock lithology, climate and topography.

Field and laboratory observations made in this study point to the role of microfracturing in bedrock disintegration (*cf.* BISDOM, 1967). Microfracturing occurs in a progressive way from the surface downward and is apparently related to penetration of moisture into the bedrock. In this regard, lithological characteristics influence the ease with which water penetration can occur. The role of salt crystallization in this microfracturing process will be examined in a later paper.

WEATHERING INTENSITY AND BEDROCK MINERALOGY

Under cold arid conditions four lithologic factors including mineralogical composition, texture, microporosity and structure determine the weathering potential of outcrop surfaces.

Numerous authors have noted a correlation between rates of mechanical breakdown in rock and the presence of such minerals as biotite, hornblende and even plagioclase. During studies on weathering of biotite-hornblende rich rocks near Rehiran in Invernesshire, Scotland, WILSON (1970) established that the initial weathering of biotite in lower parts of soil profiles is to hydrobiotite. BASHAM (1974) studied the distribution, profiles morphology and mineralogy of deeply weathered gabbroic rocks in Aberdeenshire, Scotland and also noted that biotite typically weathers to hydrobiotite and vermiculite. Moreover, his petrographic observations confirmed that biotite does not weather uniformly throughout the rock mass and that the degree of weathering is strongly influenced by the microcrack system present. During studies on the Precambrian Boulder Creek granodiorite west of Boulder, Colorado, ISHERWOOD and STREET (1976) reported that grus formation had resulted from biotite expansion along basal cleavages and used modal analyses to show that the greater the biotite percentage, the greater the susceptibility to granular disintegration.

ISHERWOOD (1975) during her doctoral studies found that on the northern coast of Cumberland Peninsula of Baffin Island where biotite is only an accessory mineral in granites, granular breakdown and formation of woolsac tors through microfracturing is largely influenced by the presence of hornblende which in yielding Mg^{+2} ions contributes to the formation of vermiculites from illite with an inherent increase in volume of up to 40 percent. BUSTIN and MATHEWS (1979) studied weathering of clasts in glacial and glaciofluvial deposits in southwestern British Columbia and noted that degree of disintegration is highly variable even in the same lithologies of adjacent clasts. They recognized that this disintegration is associated with biotite content observing numerous microfractures radiating from expanded biotite crystals. The present author has observed similar relationships in the Late Wisconsin tills of southeastern Ontario deposited by the Lake Simcoe ice lobe (*cf.* WINKLER, 1980).

Along the south coast of Alexandra Fiord east of the R.C.M.P. post on east central Ellesmere Island a number of intensely weathered outcrops have been examined both within 50 m of sea level and on upland surfaces at up to 800 m a.s.l. (*cf.* WATTS, 1981a; 1981b). The most intensely weathered lithologies present are quartz-feldspar biotite hornblende gneisses. Results of geochemistry and petrographic work point to a close correlation between the abundance of hornblende in the outcrops and the degree of bedrock weathering (*cf.* Pl. 1) as discussed elsewhere (WATTS, 1981b) (*cf.* also WATTS, 1979, p. 979).

WEATHERING INTENSITY AND BEDROCK TEXTURE

Textural characteristics of bedrock will also markedly influence the ease with which surface disintegration can take place. While a rhyolite and a granite may have virturally identical mineral composition, textural differences can favour much more intense weathering of the phaneritic granite even under arid climatic conditions. Microfracturing tends to be concentrated about the peripheries of individual grains where moisture is able to concentrate. Numerous authors have noted a link between coarseness of texture and physical weathering potential of bedrock. CARROLL (1970) emphasized that a coarsely granular rock will disintegrate more rapidly than one of finer grain and maintained that this is due to thermal expansion of individual minerals. HUDEC (1973) pointed out that under all climatic conditions weathering commences with interaction of water molecules at the mineral surface. He further stated that through adsorption and thus rock saturation, at low relative vapour pressures, the water is able to exert expansive forces even without freezing. He thus concluded that effective internal surface area (influenced largely by texture) is a major factor in rock weathering. BAYNES and DEARMAN (1978a, *cf.* 1978b) in studies on changes in the engineering properties of granites induced by weathering showed that this microfracturing is concentrated along open grain boundaries leading to development of intergranular porosity. DUMANOWSKI (1968) studied granite weathering forms in a variety of climatic zones and found that they reveal many common features independent of climatic conditions. His observations seem to indicate that for porphyritic granites a more rapid weathering depends on grain size assuming uniform mineral composition. The present author confirms this in field observations presented to follow based on field work on southeastern Ellesmere Island and on western Somerset Island.

Highly weathered terrain occurs on a Precambrian bedrock ridge at 500 m a.s.l. immediately west of the Cory Glacier (76°16′N, 80°8′W) on the southeast coast of Ellesmere Island, some 75 km east southeast of Grise Fiord, the most northerly community in North America (*cf.* Fig.1). Preliminary bedrock mapping of this region has been done by CHRISTIE (1962, 1969) with more recent reconnaissance in progress (*cf.* FRISCH *et, al.*, 1978). The most interesting, highly weathered nature of this site has been noted and illustrated by W. BLAKE (1978b) and by WATTS (1983a, 1983b).

The outcrop ridge itself measures 250 m long by up to 100 m wide and is located on an upland surface (Pl. 2). On the west flank, the exposed valley wall bedrock reveals intense weathering down to 250 m.a.s.l. in cliffs and steep-sided valley slopes above the side valley glacier tongue. To the north end of the ridge, weathered outcrops can be traced down to within 20 m vertically of the glacier. To the east, a gently sloping upland surface exists on which solifluction is active in removing residuum derived through outcrop disintegration.

The ridge comprises massive, coarse grained, locally porphyritic granite. Mineralogically, orthoclase and quartz predominate with less than 4% mafic minerals including only minor biotite and hornblende yielding a coarsely foliated, gneissic texture. Individual potassic feldspar phenocrysts up to 2 cm across are present. The granite is very massive with rectilinear joint sets developed parallel to, and cutting across, regional foliation. Joint cracks 0.5 m or more across are common but thin markedly with depth (Pl. 2). Accumulations of grus derived from *in situ* disintegration of porphyritic granite form aprons up to 40 cm thick (average depth less than 15 cm) in sheltered joints and about individual outcrops. The grus consists of polycrystalline fragments of quartz, feldspar and biotite averaging 1.5 cm across.

In conjunction with grus development and removal, residual rounded joint blocks or tors have been produced in the massive, resistant granites. The tors measure up to 3 m high by 5 m wide and are separated by widely spaced joint sets. They reveal considerable rounding. Surface stripping has yielded exposures in which two or more blocks remain stacked vertically in place on flat, exposed summit surfaces of tors along the entire ridge weathering pits have developed. The pits are typically circular in plan measuring from 14 cm to 90 cm in diameter and up to 15 cm deep (*cf.* WATTS, 1983). The porphyritic texture exhibited at this locality has clearly influenced weathering intensity.

Several days were also spent at a second site situated 3 km east of McClure Bay near the west coast of Somerset Island (latitude 73°38′N; longitude 95°32′W) (*cf.* Fig. 1). Here about the periphery of a hill some 150 m high, numerous examples of tors were discovered. The hill also reveals outcrops of extremely coarse grained massive granite porphyry. Microfracturing and grussification at this locality can be directly attributed to this coarse texture. On the hill summit where individual feldspar phenocrysts reach up to 2.5 cm across, grus development is pronounced with accumulations commonly up to 1 metre thick. Where a more equigranular finer texture is evident on the upland surface, weathering although evident is less intense with individual blocks of granite cropping out.

Texture has clearly influenced intensity of outcrop disintegration at this site but how long has subaerial weathering gone on? Some field observations may be noteworthy in this regard. A well defined raised beach system flanks this hill to the south and east at elevations between 80 and 90 m. a. s. l. Both shell and bone material have been collected from the beaches but no dates are available. Nevertheless, DYKE's work (DYKE, 1979; 1980; *cf.* LOWDON and BLAKE, 1979) has provided emergence curves which show that 80 to 90 m beaches both in the Stanwell—Fletcher Lake area of southern Somerset Island date to between 8000 and 9000 years before present. Exposures on the southeast side of this hill occur below, at and above the raised beaches marking the highest level of post-glacial marine emergence recognized. A significant difference in the granites was observed on transects run up the hill. At and below the strandlines, exposures reveal overall tor forms but lack accumulation of grus. Outcrop surfaces while not fresh and lacking evidence of glacial abrasion, tend to be regular with less than 1 mm of microrelief due to differential erosion of minerals with minimal iron oxide staining (*cf.* Pl. 3). In complete contrast, exposures extending up onto the crest of the hill exhibit much more intense microfracturing, grus accumulations and tor development in virtually identical lithologies to those below the beach level (Pl. 4). The conclusion is inescapable. Subaerial disintegration encountered, commenced prior to 9000 years ago and resulting residuum on lower hillsides was largely removed during a brief period of postglacial marine submergence. A number of other observations were made at this locality. Examples of corestone-like forms were noted partially exposed about the hill indicating that, for this lithology at least, disintegration may commence beneath groundlevel within the outcrop (Pl. 5; cf. LINTON, 1955; WANG, ROSS and REES, 1981; *cf.* also WANG, this volume). Diabase dykes were noted cutting the hill and grus accumulations up to 1 meter thick were sampled. Although the diabase is finer textured than the granite porphyry, it contains plagioclase and pyroxene both of which have higher weathering potentials than orthoclasse and quartz comprising the main granite body.

WEATHERING INTENSITY AND BEDROCK MICROPOROSITY

The microporosity of a bedrock lithology will also influence ease with which moisture is able to penetrate and thus can influence the rocks' microfracturing potential. Literature in this regard is scanty. Porosity characterisitics of rocks including such measures as percent porosity, water absorption capacity, saturation coefficient and microporosity do vary substantially from one rock type to the next and, indeed, within rocks possessing the same mineralogical composition but with textural differences (*cf.* COOK, 1979; SPERLING and COOK, 1981a, 1981b). Field work in the present study has focused primarily on highly weathered terrain at scattered localities within the Precambrian Shield of the eastern high Arctic. Lithologies considered mainly include igneous and metasedimentary types of low microporosity and thus porosity characteristics and their overall impact on weathering rates while acknowledged as important in certain lithologies (e. g. clastic sediments) are not considered within the scope of this study.

To further understand how lithology directly influences rates and processes of subaerial disintegration under arid Arctic conditions observations were also made in terrain underlain by number of lithologies south of Aston Bay on Somerset Island. DYKE (1976) has pointed out that tors and other in situ weathering features are developed in all major bedrock lithologies on Somerset Island including in both mafic and felsic gneisses, in quartzites, in metasediments interbedded carbonates, cherts and quartzites, in carbonates, in conglomerate and in sandstones. Along the upper tributaries of the Hunting River system (latitute 73°31'N; longitude 94°40'W) four distinct lithologies are present (*cf.* Fig. 1). Proterozoic carbonates with interbedded chert and quartzites in the northern part of the area stand out as resistant ridges with peripheral debris slopes comprising small, angular blocks derived from active frost shattering of otherwise fine grained, massive resistant rocks of low micro-fracturing potential. Immediately to the east flat-lying interbedded, Lower Paleozoic limestones, sandstones and dolomites occur as extensive surfaces of residuum derived from subaerial breakdown of immediately underlying bedrock. This material has also apparently resulted from frost action influenced by horizontal bedding structures within the sedimentary rocks yielding blocks up to 30 cm thick (averaging 15 cm thick) by up to 150 cm across (averaging 80 cm across). While some local displacement has occurred, the lack of relief or fines in this bedrock-controlled topography has yielded mininal solifluction. Actual outcrops are restricted to small, partially covered exposures at slight breaks in topography as along upper gully sides. The presence or absence of rock structures such as bedding planes can thus influence both the nature and degree of physical weathering.

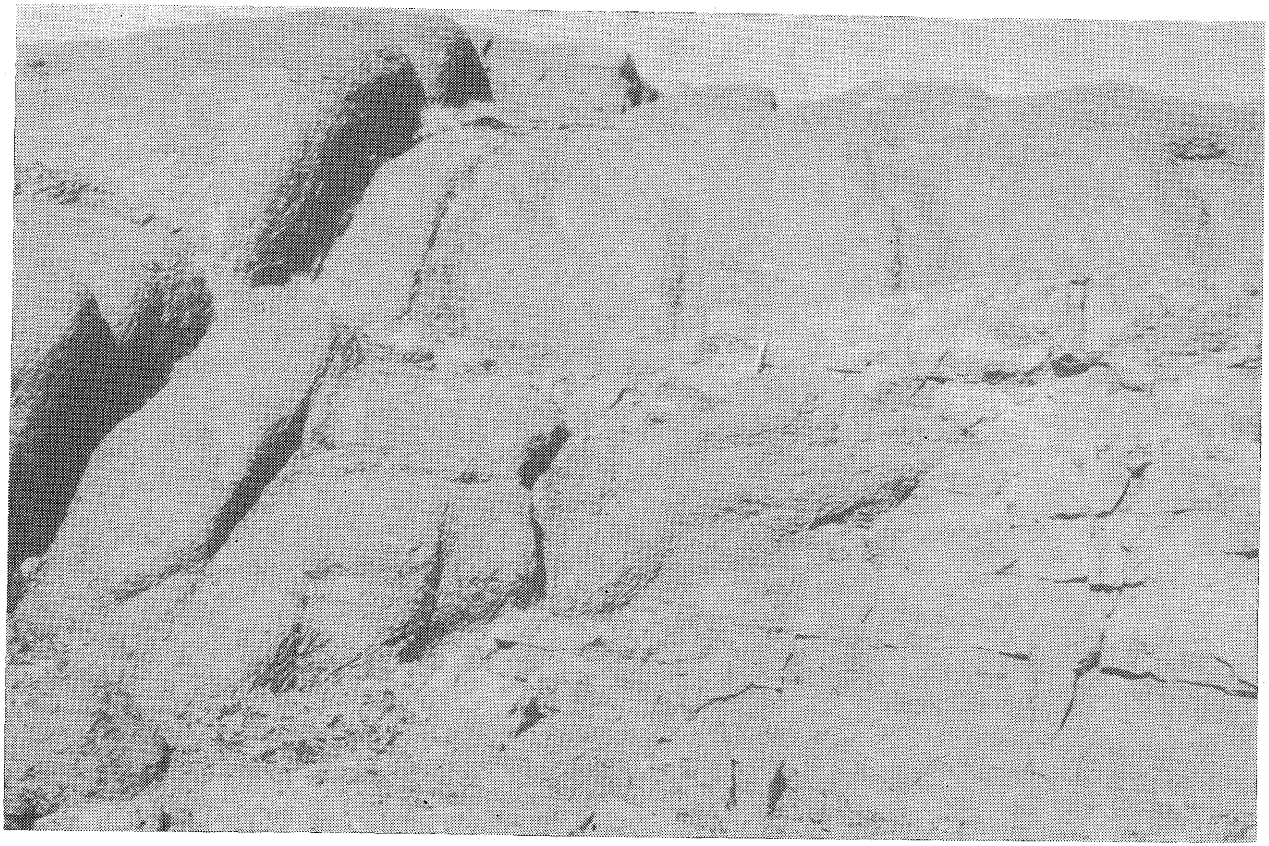
Most of the area studied south of the Hunting River comprises low ridges affording extensive exposures of Precambrian gneisses parallel to regional foliation associated with the Boothia uplift- a north-south trending arch running up the Boothia Peninsula, along western Somerset Island and northward between Cornwallis and Bathurst Island. Colluvium present on these ridges is largely a mixture of blocks and sandy debris (DYKE, 1976). In places active solifluction has occurred on the gneisses. DYKE (op. cit.) described the occurrence of abundant tors on these surfaces and suggested that continued mass movement has favoured backwasting resulting in isolated masses of outcrops as tors. This author concours and was impressed by the importance of frost shattering in the backwearing process. A variety of mafic intrusions including diabase dykes cut the gneisses and also affors tor-like forms. Where active back wasting of outcrops has been limited and removal of material through solifluction hindered by lack of relief as on flat upper ridge surfaces, accumulations of grus up to 50 cm thick occur along edges of isolated gneissic exposures.

FELSENMEER

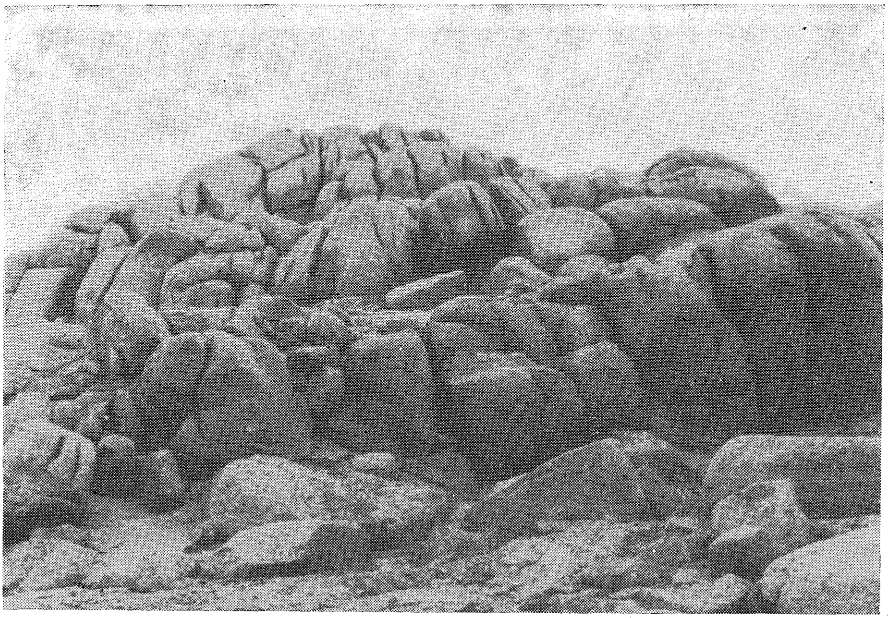
The distribution of mature felsenmeer and upland detritus has similarly been used as a criterion in evaluating the relative age of upland weathering surfaces (e. g. PHEASANT and ANDREWS, 1972; BOYER and PHEASANT, 1974) (*cf.* IVES, 1975; DYKE, 1976; GRANT, 1977; BROOKES, 1977). Inherent in this interpretation is the view that upland plateau surfaces have remained essentially ice-free since Late Wisconsin — and for possibly much longer — time. Sugden and Watts (1977) have suggested, however, that tors and felsenmeer along the Cumberland Peninsula of Baffin Island are not necessarily diagnostic of areas that escaped glaciation. They pointed to the presence of unweathered erratics and the roche moutonnée shape of some tors in implying that the features have survived inundation by an ice sheet in approximately their present form. Other authors have suggested that weathering processes acting since the end of the Wisconsin could yield mature felsenmeer. DAHL (1966) in studies on block fields, weathering pits and tor-like forms in the Narvik Mountains of Norway examined the distribution of block-fields in relation to bedrock lithology, snow supply, slope, drainage and vegetation and found that the largest areas of block fields occur in higher parts of the mountains. He added "the lower limit zone of the block fields in north-western Scandinavia may to a certain extent be related to a glacial evacuation below this zone during the period after the initial sinking of the ice surface but it is in no sense whatever a gauge of the maximum extent of the last glaciation". Thus according to DAHL (1966) block fields cannot be used to indicate areas that were ice free during the last glaciation.

Observations made in this study about the periphery of ice caps on eastern and southeastern Ellesmere Island suggest that upland plateau areas are typically of low surface relief and carry remnant icecaps or are, at least, covered by snow which may persist through much of the brief summer season (e. g. Pim Island). Active flow is restricted to outlet glaciers which extend from the plateau ice caps through valleys down to the coast. The first areas to emerge from beneath the ice during overall stagnation may not be either the plateau or the valley floors but valley flanks particularly along the narrow coastal fringe.

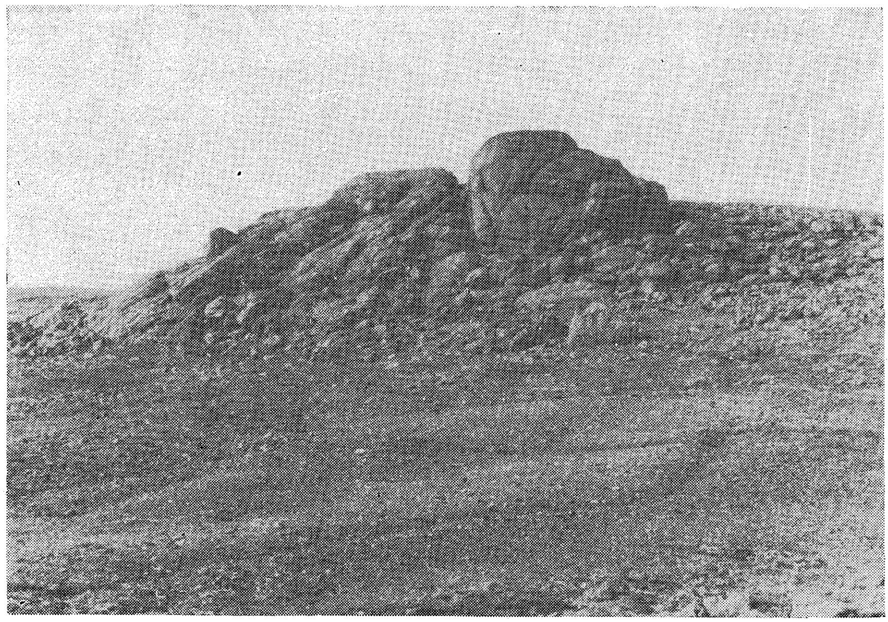
BIRD (1966) pointed out that felsenmeer development is favoured under maritime polar conditions with rock type influencing its formation. He concluded that felsenmeer in some areas may very well be pre-glacial having escaped serious glacial modification (*cf.* IVES, 1958). Indeed, RAPP and RUDBERG (1960) in noting definitive evidence of glacial erosion associated with block fields in Scandinavia concluded that block fields can form in postglacial time and may be preserved beneath an overriding ice sheet. Again, the role of lithology here may markedly influence the intensity of rock fracturing and felsenmeer development. The concentration of moisture as in sight topographic depressions on upland surfaces further favours felsenmeer development even though the ground frost action would be limited to few freeze-thaw cycles per year. Thus felsenmeer can be preserved beneath cold based ice and can even develop rapidly under cold Arctic and alpine



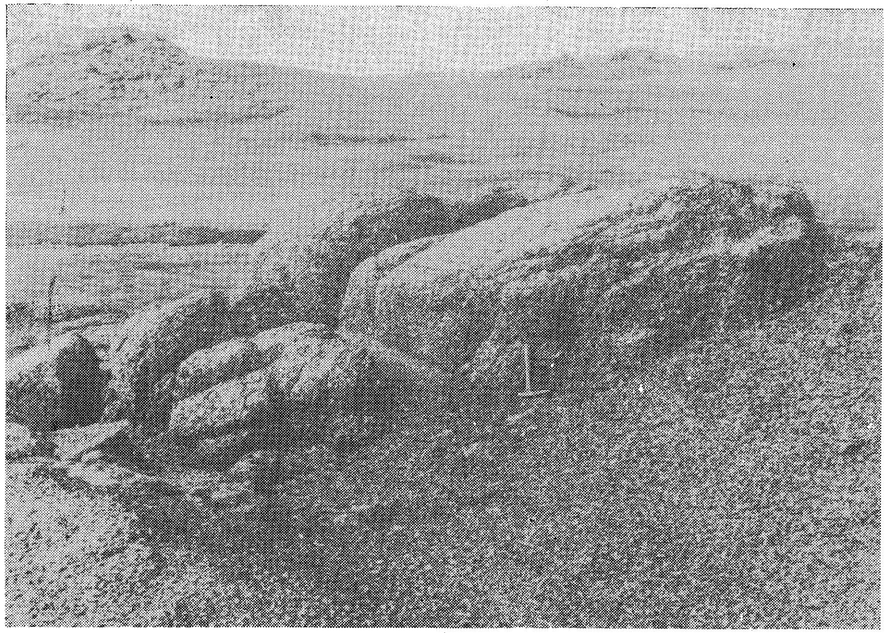
Pl. 1. Contact between granite intrusion (right) and host quartz feldspar biotite hornblende gneiss. South coast, Alexandra Fiord, Ellesmere Island. Note the difference in overall weat hering appearances of the tro lithologies. The granite is typified by unaltered angular joint blocks while the paragneiss reveals highly altered rounded joint blocks. Field view is 6 m across



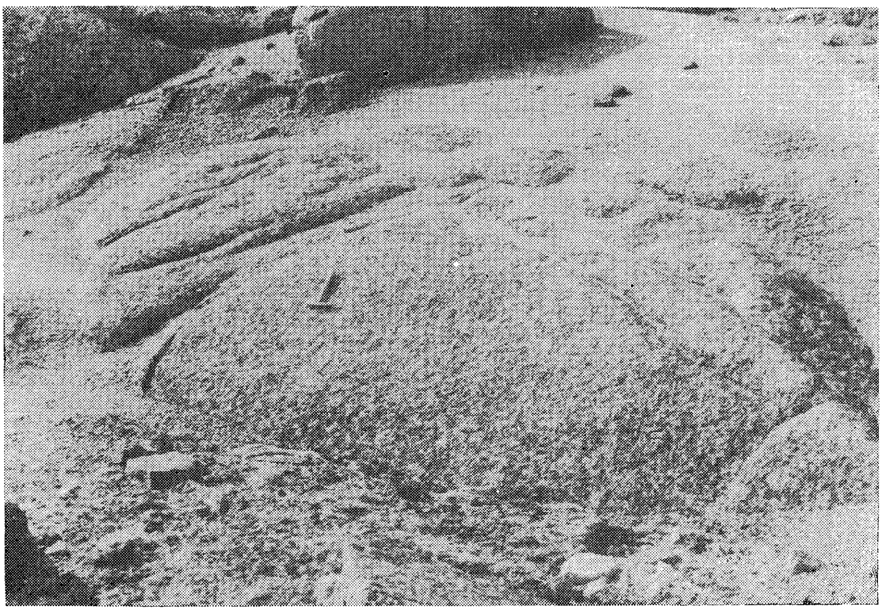
Pl. 2. Pronounced vertical jointing superimposed in otherwise massive granite porphyry. Cory Glacier site, southeastern Ellesmere Island



Pl. 3. Tors developed in massive granite porphyry, McClure Bay, Somerset Island. Note the overall fresh appearance of the outcrops and the lack of grus accumulation. Note also the remnant beach surfaces in the foreground and to the right of the tors



Pl. 4. Intensely weathered granite porphyry in upper hillside position east of McClure Bay, Somerset Island. Note the grus accumulations partially burying the outcrop joint blocks. Compare with Pl. 5



Pl. 5. Partially exposed massive joint blocks, or proto-tors formed in massive granite prophyry near McClure Bay, western Somerset Island. Note residual grus accumulations about the periphery of the exposure

conditions in postglacial time given the conditions of suitable lithology and available moisture i.e. non through drainage (dependent on topographic position). Its overall value in correlating ages of morphostratigraphic zones (unless used in conjunction with other age dating techniques as provided in moraine sequences and marine limits (e. g. DYKE, 1979) may thus be limited to relative comparisons.

SUMMARY

Field data collected during four field seasons working on scattered examples of high weathered bedrock terrain on Ellesmere, Coburg, Devon and Somerset Islands has permitted the following observations:

1. Similar yet not identical assemblages of weathering forms occur at or near sealevel and in upland summit areas at widely scattered localities in the Precambrian Shield of high Arctic Canada.

2. Lithology and, more specifically, mineral composition, texture and rock structure markedly influence the degree of development of these weathering forms.

3. Water plays a major role in the physical disintegration processes. Although not yet studied quantitatively, there is good evidence that salt crystallization along coastal areas both at sealevel and on summit plateau may influence the microfracturing process believed to be largely responsible for these forms.

4. Backwearing through microfracturing of joint block surfaces and subsequent removal of debris particularly through solifluction continues to further the process of tor formation. Thus immediate topographic relief also influences weathering production and preservation.

5. In the absence of well defined moraine sequences the actual age of these features is extremely difficult to ascertain. Moreover, visual impressions are confused by what appears to be relatively intense modern weathering.

6. Nevertheless, the presence of erratics resting on these forms is consistent with the view that the upland features predate at least one glaciation.

7. Terrain described in this study lies immediately adjacent to upland ice caps and the assumption that tors, etc. in themselves define ice-free areas is not valid.

8. Preservation of these features without destruction either by actively eroding ice or by continental subaerial disintegration is attributed to lengthy preservation beneath cold-based ice. Subaerial weathering would cease at such times.

9. Degree of weathering is, at best, of only secondary value in chronology studies in high Arctic Canada.

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