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Precambrian gneisses and intrusive anorthosite of Smithson Bjerge, Thule district, North-West Greenland

by

Allen P. Nutman

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Abstract

Smithson Bjerge is part of the Precambrian crystalline complex of North-West Greenland. The area comprises the Qaqujârssuaq anorthosite, the Heilprin Gletscher complex, paragneisses, multiphase orthogneisses and diverse minor granitic and basic intrusions. The Heilprin Gletscher complex comprises intimately associated granite, ferrogabbro and ferrodiorite. The Heilprin Gletscher complex and the Qaqujârssuaq anorthosite were intruded into the paragneisses and the multiphase orthogneisses, and may form an anorthosite-granite-ferrodiorite association. All lithological groups apart from the minor intrusions have been affected by large-scale overturned folding and regional medium-pressure granulite facies metamorphism.

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Fig. 1. The head of Inglefield Bredning, looking east towards the Inland Ice, with Smithson Bjerge in the background to the right. The northern (pale) half of Smithson Bjerge is underlain by the Qaqujârssuaq anorthosite, the southern half predominantly by multiphase orthogneisses and supracrustal rocks. The best preserved parts of the Heilprin Gletscher complex form the headland projecting into Inglefield Bredning. Basic dykes cutting the anorthosite are visible.

INTRODUCTION

Area and accessibility

This report describes the bedrock geology of Smithson Bjerge, a semi-nunatak of approximately 250 km^2 at the head of Inglefield Bredning, North-West Greenland (figs 1 and 2) and follows a preliminary report on the area (Nutman, 1979). It is mainly based on field observations, but also includes follow-up structural studies, petrographic observations and also reconnaissance geochemical studies. The area was mapped on aerial photographs at a scale of approximately 1:25 000 during seven weeks of the summer of 1978. For this report the results of mapping are condensed to 1:50 000 (Plate 1). The work on Smithson Bjerge was affiliated to the geological investigations of North-West Greenland by the Geological Survey of Greenland, conducted principally by Dawes (Dawes 1972, 1975, 1976a, 1979) and aimed primarily at the production of a 1:500 000 map.

Smithson Bjerge is a semi-nunatak of undulating high ground (up to 1000 m) elongated east–west and bounded by large, active glaciers to the north and south, the Inland Ice to the east and Inglefield Bredning to the west. The area is dissected by a wide east–west valley containing a braided river and chains of lakes. The undulating high ground falls away as unscalable cliffs or very steep slopes to the glaciers and the large valley. Apart from these restrictions, the area can be easily traversed on foot.

The most continuous rock exposures occur in the cliffs and steep slopes. The undulating high ground comprises a mixture of more-or-less *in situ* frost-shattered debris, blankets of morainic material and isolated areas of good outcrop. There is virtually no exposure in the large valley, which is floored with diverse glacial and fluvial-glacial deposits. A terrace of marine clay and silt containing ice-rafted boulders obscures the bedrock along much of the coastal strip that faces Inglefield Bredning.

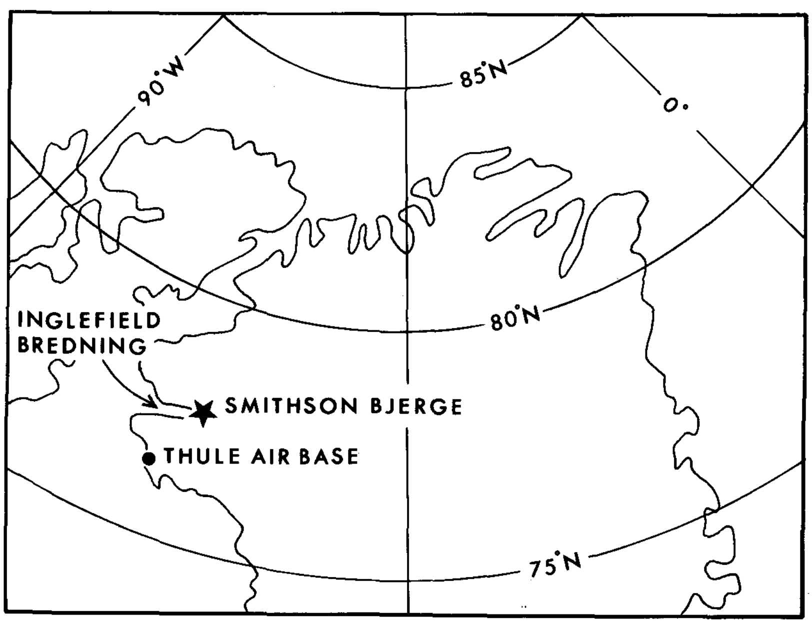

Fig. 2. Location of Smithson Bjerge.

Previous geological work

The first methodical geological investigations in North-West Greenland were carried out on two expeditions between 1916 and 1923 by the late L. Koch. A geological map resulting from this work has recently been incorporated into the first part of an account of the history of early geological work in North Greenland (Dawes & Haller, 1979). Koch's map of the Thule district correctly designates Smithson Bjerge as part of the 'Archaean-Algonkain' basement (see also Koch, 1926, Fig. 1). Smithson Bjerge was briefly visited during reconnaissance work in 1971 and 1975 by P. R. Dawes, during which the *Qaqujârssuaq anorthosite* was identified and the main geological divisions were made (Dawes, 1972, 1976b).

The regional study of the crystalline basement of North-West Greenland (75–79°N) predominantly by P. R. Dawes, has largely been based on reconnaissance mapping using boat transport with limited helicopter support; detailed investigations have been limited to a few widely-scattered localities. Thus only the general outline of the regional tectonometamorphic history of the basement rocks is known (Dawes, 1976b).

Preliminary geochronological work suggests that the basement in North-West Greenland contains a large component of, or has been derived from Archaean rocks (Kalsbeek & Dawes, 1980; Kalsbeek, 1981) and was subsequently affected by a Proterozoic tectonometamorphic event at *c.* 1900–1600 Ma (Larsen & Dawes, 1974; Kalsbeek, 1981), which is correlated with the Hudsonian orogeny of North America.

Regional setting and lithological divisions

The 1978 mapping confirmed and further subdivided the geological divisions recognised during the reconnaissance work by P. R. Dawes in 1971 and 1975 (Table 1). Many of the lithologies on Smithson Bjerge occur throughout the Precambrian crystalline basement complex of North-West Greenland. However, the northern part of the area comprises the Qaqujârssuaq anorthosite, which is the only anorthosite known in the complex. It was the presence of this large body of anorthosite whose contact with the adjacent rocks is exposed that led to the choice of Smithson Bjerge as a target for a more detailed study than is normally carried out during the systematic 1:500 000 mapping mentioned above.

Smithson Bjerge comprises two main groups of rocks that have been highly deformed and metamorphosed under granulite facies conditions. In addition there are minor intrusions that are less deformed and have only been metamorphosed under amphibolite facies conditions or less. The lithological groups and their subdivisions are as follows:

(A) *Old complex*
Multiphase orthogneisses.
Supracrustal sequence: interlayered semipelitic gneisses and ferruginous quartzites.

(B) *Intrusive meta-igneous rocks*
The Qaqujârssuaq anorthosite: anorthosite-leucogabbro, gabbro, mafic amphibolite dykes and dioritic dykes.
The Heilprin Gletscher complex: granites, ferrodiorites and dioritic dykes.

(C) *Minor intrusions*
Garnet-amphibolite dykes.
Undeformed microgranite sheets.
Pegmatites.
Unmetamorphosed dolerite dykes.

Table 1. Principal geological events of Smithson Bjerge

(1)	Intrusion of east-west trending dolerite dykes *(youngest)*
(2)	Faulting
(3)	Intrusion of pegmatite and microgranite sheets
(4)	Deformation producing minor upright warps (D_2)
(5)	Granulite facies metamorphism and deformation D_1 that produced overturned folds (*c.* 1900–1600 Ma). Intrusion of garnet amphibolite dykes
(6)	Intrusion of the Qaqujârssuaq anorthosite and the Heilprin Gletscher complex. They may have been intruded at approximately the same time, forming an anorthosite-ferrodiorite-granite association
(7)	Formation of old complex, consisting of multiphase orthogneisses and a supracrustal sequence

In the following sections the field characters of these rocks and preliminary whole-rock geochemical results are discussed. Description and discussion of the petrography of rocks of groups A and B are largely dealt with under the heading of metamorphism.

OLD COMPLEX

Multiphase orthogneisses

There are a northern and a southern belt of multiphase orthogneisses. The southern one forms the scarp of the ridge between the east–west valley and Heilprin Gletscher and the northern one outcrops close to the margin of the Qaqujârssuaq anorthosite (Plate 1).

The southern orthogneiss belt is bounded to the north and south by the supracrustal sequence. This belt could only be examined at close hand along the top of the ridge, as the rest is exposed in a precipitous cliff. The orthogneisses have a brownish-red crumbly weathering with exfoliation, a coarse-grained flecked texture and when fresh are buff-coloured. These characters are all typical of granulite facies orthogneisses. Mineralogically they comprise quartz, anti-perthitic plagioclase, hornblende and orthopyroxene with subordinate garnet, clinopyroxene, K-feldspar, ilmenite-magnetite and biotite. Along the top of the ridge the orthogneisses have a compositional layering on a 1 to 5 m scale, which coincides with powerful, syn-granulite facies penetrative *LS* fabric, which is axial planar to rare, small, recumbent folds. The gneisses in the cliff, forming the southern side of the ridge seen from the top, seem to be less deformed, cross-cutting relations between phases being more

Table 2. Representative chemical analyses of the multiphase orthogneisses

	235312	235316	235721	235709	235710	235723	235744
SiO_2	59.99	61.52	61.63	65.07	65.37	65.92	68.84
TiO_2	0.91	0.88	0.83	0.80	0.87	0.61	0.51
Al_2O_3	18.77	16.84	17.68	16.43	16.55	16.74	15.45
FeO^{tot}	7.23	6.85	6.60	6.00	6.52	5.08	3.79
MgO	2.81	2.47	3.65	1.53	1.71	2.65	0.86
CaO	3.58	4.73	5.71	3.55	3.97	4.25	2.28
Na_2O	4.36	3.91	4.41	4.29	3.69	3.73	3.47
K_2O	0.93	1.31	1.35	2.31	2.23	1.18	4.81
H_2O	1.97	0.83	0.11	0.52	0.21	0.11	0.21
P_2O_5	0.27	0.23	0.30	0.26	0.33	0.15	0.21
Total	100.82	99.51	102.27	100.76	101.45	100.42	100.43
Rb	9	28	21	66	61	15	119
Sr	454	491	487	358	358	388	360
Y	16	22	37	25	29	16	17
Zr	159	145	158	281	327	139	448

Chemical analyses given in Tables 2 to 5 were carried out by the geochemical laboratory of the University of Exeter. Major elements were determined using X-ray fluorescence analysis on sodiumtetraborate glass discs and a flame photometric procedure for Na_2O and MgO. Trace elements were determined on powder tablets using X-ray fluorescence. International standards were used as controls.

common. The dominant phases are mafic tonalites, with subordinate units of pinkish-brown granite. In local areas of lower deformation on the top of the ridge some of the granite units are intimately associated with basic material and may be satellite units of the younger Heilprin Gletscher complex (see below).

The belt of orthogneisses close to the southern margin of the Qaqujârssuaq anorthosite consists of intersheeted tonalites and granodiorites, and is up to 100 m wide and 15 km long. The belt lies in the partially mobilised contact zone of the anorthosite and is extensively veined by granitic material and also locally by basic rocks associated with the anorthosite. Thus the relation between this belt of orthogneisses and the supracrustal rocks at its borders is obscured.

It is likely that the composition of the multiphase orthogneisses has been somewhat modified during the granulite facies metamorphism. From a reconnaissance study of the geochemistry of the orthogneisses, based on seven samples (Table 2), it is clear that they do not form a coherent variation trend. Some samples (e.g. 235723) lie on the calc-alkali trend (fig. 3). Other samples (e.g. 235710) are distinctly more iron-enriched and have the highest P_2O_5 and Zr content of the gneisses analysed. These variations suggest that the multiphase orthogneisses are polygenetic.

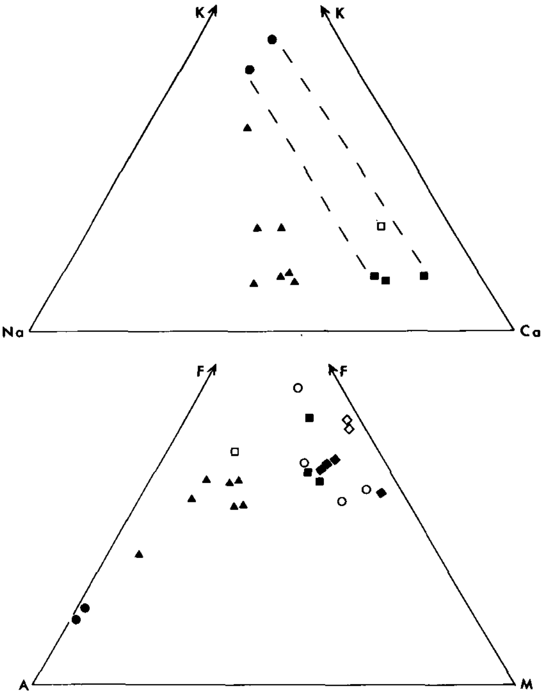

Fig. 3. Ca-Na-K and A-F-M (wt%) diagrams. Only multiphase gneisses and Heilprin Gletscher complex lithologies are shown on the Ca-Na-K diagram. Heilprin Gletscher complex: ● granite, □ intermediate lithology and ■ ferrodiorite and ferrogabbro. ○ Diorite sheets of the Heilprin Gletscher complex and the Qaqujârssuaq anorthosite. ◇ Mafic amphibolite dyke, ◆ garnet amphibolite dyke and ▲ multiphase orthogneisses. The dashed lines represent limiting mixing lines between granitic and basic compositions.

Supracrustal sequence

The supracrustal sequence comprises diverse layered rusty-weathering quartzofeldspathic paragneisses interlayered with subordinate units of ferruginous meta-quartzite. These rocks form approximately half of the outcrop south of the Qaqujârssuaq anorthosite (Plate 1). The layering of these rocks is commonly on a 10 to 100 cm scale and is a useful marker for the position of recumbent isoclinal folds. There are no discernable facies variations in the sequence either laterally or vertically and the different lithologies seem to be interlayered in an entirely random manner. In the quartzofeldspathic gneisses there are no original features such as graded bedding preserved.

Typical assemblages of quartzofeldspathic paragneisses are quartz, biotite, garnet, plagioclase, hornblende, orthopyroxene or sillimanite, with accessory magnetite, ilmenite, graphite and zircon. These rocks are interpreted as derived from impure feldspathic sandstones with subordinate pelite. The ferruginuous quartzites are quartz, orthopyroxene, clinopyroxene, amphibole, magnetite, garnet and sulphide rocks. On the basis of similar, somewhat better preserved granulite facies, quartz-rich metasediments from the early Archaean of West Greenland and Labrador (Nutman, 1980; Bridgwater *et al.*, in press), they are interpreted as chemical sediments, perhaps akin to silicate facies banded iron formation.

The supracrustal sequence is interpreted as a succession of interbedded detrial and chemical sediments. The sequence contains no rocks of igneous or clearly volcanogenic origin, and its predominantly quartzofeldspathic nature suggests that it is of sialic provenance.

The nature of contacts between units of supracrustal rocks and multiphase orthogneisses is not clear. Where contacts are not obscured by granitic and pegmatitic sheets they are sharp and interdigitation of the units is minimal. It is not possible to state whether the orthogneisses and supracrustal rocks occur in a basement-cover relation or whether they were juxtaposed by thrusting.

INTRUSIVE META-IGNEOUS ROCKS

Relations between the Qaqujârssuaq anorthosite and the Heilprin Gletscher complex

The Heilprin Gletscher complex and the Qaqujârssuaq anorthosite are igneous rocks that were emplaced in the same chronological interval; that is, they both intrude lithologies of the old complex (see below) and are also strongly deformed and have been metamorphosed up to granulite facies. Furthermore, a late, minor phase in both of them are compositionally similar dioritic bodies that show evidence of a low ductility contrast between them and their hosts when they were emplaced. On the other hand similar dioritic rocks that locally intrude the old complex are normal tabular dykes. This suggests that the Qaqujârssuaq anorthosite and the Heilprin Gletscher complex may have been intruded at approximately the same time, and could form an anorthosite-ferrodiorite-granite association perhaps similar to ones documented elsewhere (Bridgwater & Windley, 1973; Emslie, 1978).

Qaqujârssuaq anorthosite

The Qaqujârssuaq anorthosite (Dawes, 1976b) underlies approximately 100 km^2 of Smithson Bjerge and consists predominantly of anorthosite (more than 90% modal plagioclase; Streckeisen, 1976). South of the main outcrop there are some thin units of anorthosite interlayered with supracrustal rocks. Leucogabbro forms less than 10% of the present outcrop and is most abundant as thick, discontinuous layers near the southern margin of the body (Plate 1). Gabbro forms less than 1% of the outcrop and ultramafic rocks and rocks rich in oxides (e.g. chromite) have not been found. Deformation throughout most of the body is strong. It is only in augen of low deformation that original features such as instrusive relations are preserved. Compositional layering on a 1 cm and upwards scale is common. It is interpreted as a tectonically modified igneous structure because it is concordant to the margins of the thick leucogabbro layers in the southern part of the body.

The main outcrop of the Qaqujârssuaq anorthosite is divided into three east–west trending zones (fig. 4). From north to south these are:

(a) *Northern anorthosite zone with minor leucogabbro.* This comprises approximately 70% of the outcrop of the body. In this zone the regional foliation and the compositional banding are coincident and dip gently northwards. There are some small, recumbent folds in the compositional layering with the sense of being parasitic on an antiformal closure to the south. The foliation is axial planar to these folds.

(b) *Central leucogabbro and anorthosite zone.* This forms approximately 15% of the outcrop of the body. In this zone anorthosite and leucogabbro are interlayered on a scale ranging

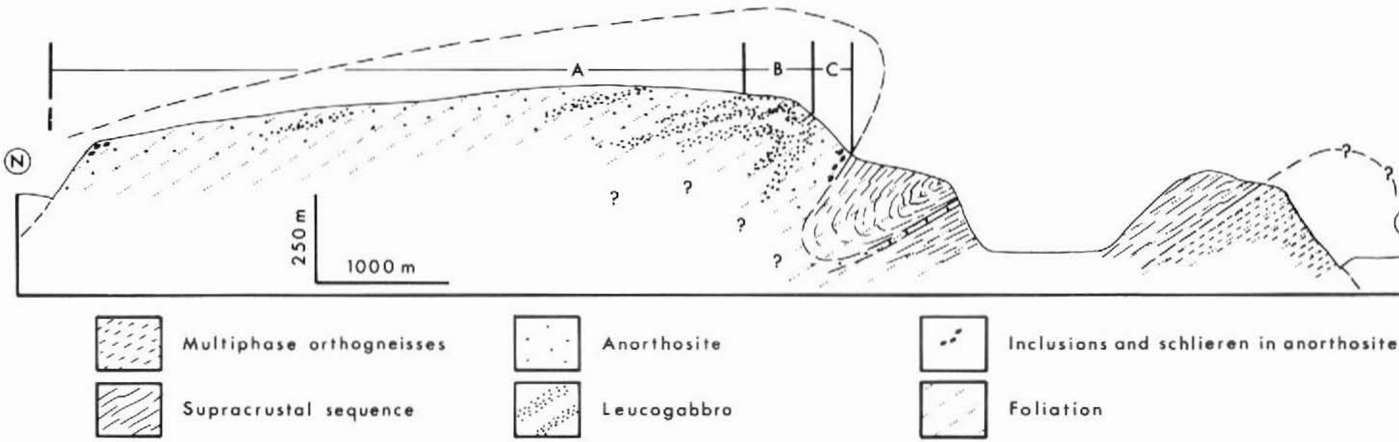

Fig. 4. North–south schematic section across central Smithson Bjerge. A, northern anorthosite zone; B, leucogabbro anorthosite zone; C, southern anorthosite zone.

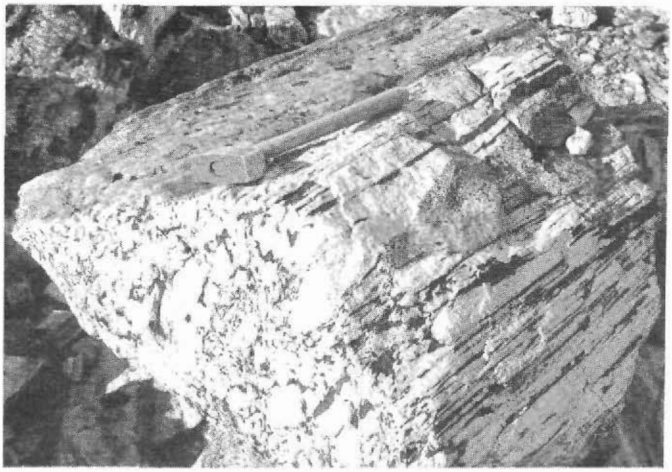

Fig. 5. 'Tennis ball' leucogabbro. Note the strong *L* fabric, which is axial planar to D_1 folds.

from 25 cm to 100 m. The foliation dips gently northwards and is axial planar to 'M' folds overturned to the south in the compositional layering. Despite the strong fold axial rodding that is common in this zone, igneous textures such as 'tennis ball' texture in leucogabbro are preserved (fig. 5).

(c) *Southern anorthosite zone with minor leucogabbro.* This forms approximately 15% of the outcrop of the body. The compositional layering is commonly vertical or steeply-dipping, and therefore discordant to the gently north-dipping foliation (fig. 4). Evidence of multiple intrusion within the anorthosite body plus its relation to the rocks to the south are preserved in this zone.

The compositional layering–foliation relations described show that the Qaqujârssuaq anorthosite is exposed in an overturned antiform (fig. 4). On this basis, the northern part of the northern zone and the southern edge of the southern zone are approximately equivalent, and the central leucogabbro anorthosite zone is the lowest-exposed level. It is estimated that not more than 500 m (post-deformational thickness) of the body is now exposed; the total thickness of the body is unknown. The relation between the main body of the Qaqujârssuaq anorthosite and the thin anorthosite bands to the south is uncertain.

There is considerable lithological variation in the Qaqujârssuaq anorthosite. The lowest-exposed levels (in core of the recumbent antiform) comprise interlayered leucogabbro (grading locally into gabbro) and anorthosite. Locally the layering is on a 25 cm scale, but more commonly the leucogabbro units are over 50 m thick. Individual leucogabbro units can be traced for up to several kilometres but the poor exposure, folding and lack of marker horizons make it hard to assess the continuity of the units – thin layers of leucogabbro are seen on an outcrop scale to be discontinuous, and this form is assumed for the units of mappable size. There are several lithological variants of leucogabbro which are to a certain extent intergradational:

(a) *Medium to fine-grained equigranular leucogabbro.* This is locally gradational into the megacrystic pyroxene leucogabbros described below. It has little or no compositional layering but the ferromagnesian minerals form a distinct foliation and lineation.

(b) *Megacrystic pyroxene leucogabbro.* Clots of orthopyroxene up to 10 cm diameter with clinopyroxene exsolution lamellae are distributed randomly in an anorthositic or finer-grained leucogabbroic matrix. Similar rocks with megacrysts of clinopyroxene also occur, but in this case the megacrysts rarely exceed 3 cm in diameter. The orthopyroxene and clinopyroxene clots are mantled by hornblende, locally with either fine-grained pyroxenes or disseminated garnet, partially altered to intergrowths of fine-grained plagioclase and hornblende. The megacrysts could be of igneous origin with metamorphic multi-mineralic complex coronas.

(c) *'Tennis ball' leucogabbro.* Where least deformed, this comprises ovoid plagioclase aggregates up to 10 cm long in a finer-grained groundmass that ranges from leucogabbroic to almost ultramafic in composition (fig. 5). This texture also occurs on a smaller scale with plagioclase aggregates 1×1 cm in diameter. Upon progressive deformation, the plagioclase aggregates form rods parallel to the regional mineral lineation (fig. 5) or smears coincident with the foliation, depending on the local strain history.

(d) *Leucogabbro breccia*, consisting of irregular anorthositic blocks in a leucogabbro matrix. This lithology occurs mainly in the extreme eastern part of the area, where its matrix is closest in character to the 'tennis ball' variety of leucogabbro. Leucogabbro breccia also occurs sporadically in the leucogabbro-rich zone of the body further west, where the matrix is pyroxene-phyric leucogabbro and the enclaves are anorthosite with leucogabbroic layers (fig. 6).

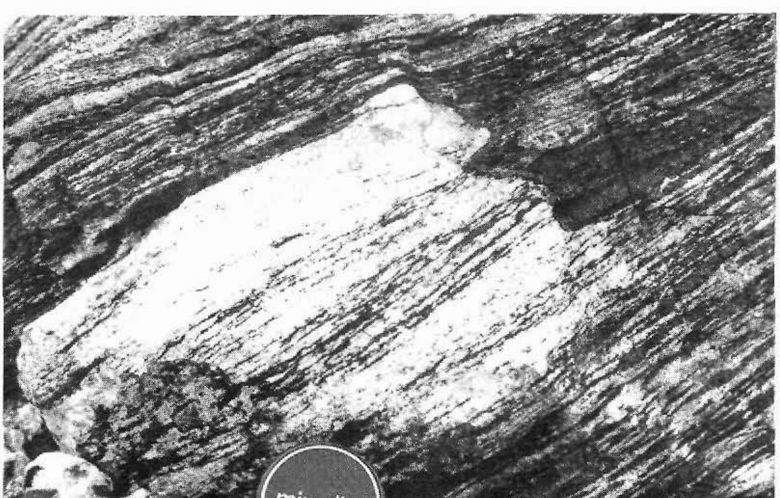

Fig. 6. Leucogabbro with anorthosite enclave.

The anorthosites that are interspersed with the leucogabbros are either weakly layered or have a flecked texture. Where least deformed the layering and the flecks are seen to be discontinuous laminae and ovoid patches rich in ferromagnesian minerals.

Upwards through the body (i.e. traversing northwards or southwards from the central leucogabbro-rich zone) there is a general increase in the proportion of anorthosite at the expense of leucogabbro, but no new lithologies or structures are found until the uppermost part of the body, where the anorthosite is commonly very leucocratic, homogeneous and finer grained and is referred to here as 'plagioclase rock'. Not only does plagioclase rock commonly form the border of the body but it locally occurs as enclaves in anorthosite and leucogabbro up to 100 m in from the edge of the body.

Throughout the compositional range plagioclase rock-anorthosite-leucogabbro-gabbro petrographic features are essentially similar. Plagioclase is calcic (~75% An, optical determinations) and forms either layers comprised of large, unzoned polygonal grains or agglomerations. Ferromagnesian layers and lenses are predominantly clinopyroxene+hornblende±orthopyroxene. Locally there is either garnet or complex metamorphic coronas.

Preserved structures of probable igneous origin are predominantly the megacrysts of plagioclase and pyroxenes in leucogabbros and planar layering. Only one clear example of graded layering has been found. This occurs in the eastern part of the central leucogabbro and anorthosite zone. As it occurs as an isolated outcrop (with no exposure in any direction for 200 m) it is not possible to put it in a regional context. It is preserved in the hinge of a fold and comprises fine-grained leucogabbro that grades northwards into anorthosite with mafic flecks (fig. 7). Only one complete cycle is exposed, and this is approximately 1.5 m thick. The layering in the body is generally uniform, but locally near the southern edge of the body it is highly irregular. Such irregularities predate the development of the recumbent folds

Fig. 7. Graded layering in leucogabbro.

because the regional foliation passes obliquely through them. These structures are interpreted as irregularities in igneous lamination near to the margin of the body. At the margin of the body evidence is locally preserved that shows that it is polyphase, suggesting the body consists of more than one pulse of magma.

The contact zone between the Qaqujârssuaq anorthosite and the old complex to the south is extremely complex with many different relations present. However, it is clear that the contact is the margin of an intrusion, albeit modified by deformation. The contact zone is poorly exposed, but as it lies near the hinge of an overturned antiform (fig. 4) it is relatively undeformed, aiding interpretation of it. The following relations demonstrate both the complexity of the contact zone and that the Qaqujârssuaq anorthosite was intruded into the old complex:

(a) *Border gabbro.* Locally the anorthosite is isolated from the old complex by a unit of medium to fine-grained homogeneous gabbro up to 50 m wide. The border gabbro is intruded by sheets of plagioclase rock and occurs as enclaves (previously veined by plagioclase rock) within the marginal part of the anorthosite body. The contact of the border gabbro with the envelope rocks to the south is not clearly exposed, but locally the border gabbro contains ghost-like inclusions of layered quartzofeldspathic rocks, suggesting an intrusive relation.

(b) *Enclaves of supracrustal rocks.* In the anorthosite body within 50 m of the contact there are rare enclaves of quartz-garnet-orthopyroxene-clinopyroxene rock and rusty weathering garnet and pyroxene-bearing schlieren (fig. 8). The former are interpreted as enclaves of altered ferruginous quartzites and the latter as restite remaining from 'digested' pieces of quartzofeldspathic gneiss incorporated into the anorthosite. A few enclaves of garnet and pyroxene-rich rock possibly derived from ferruginous quartzite occur in the anorthosite near Tracy Gletscher; this is in accordance with the interpreted shape of the anorthosite boay (fig. 4).

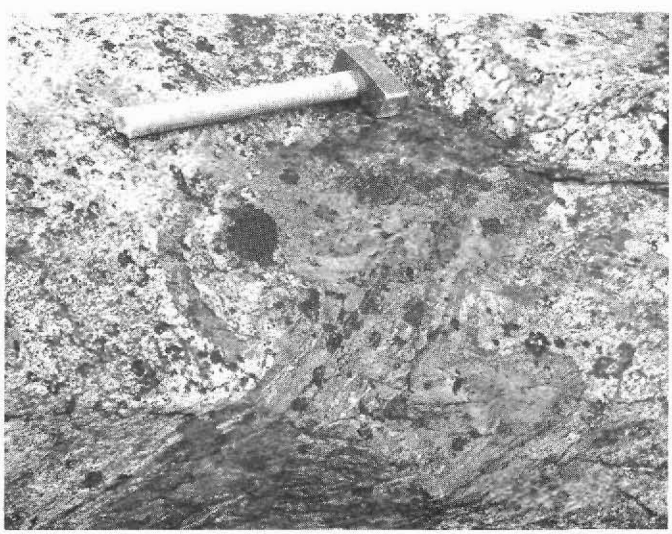

Fig. 8. Diffuse enclaves of supracrustal rocks in anorthosite.

Fig. 9. Mobilised quartzofeldspathic rocks containing anorthosite blebs.

(c) *Anatexis of old complex rocks near to the Qaqujârssuaq anorthosite.* The layered semipelitic gneisses of the supracrustal sequence are generally metatectites, apart from individual, isolated layers which probably due to their composition are diatectites (metatectite and diatectite in the sense of Winkler, 1974). However, towards the anorthosite body there is a progressive enhancement of the anatectic structure with all lithologies apart from ferruginous quartzites transformed into diatectites. Ferruginous quartzites are not so radically altered and are left as disrupted marker layers 'swimming' in a granitic matrix speckled with clots and schlieren of ferromagnesian minerals. These changes are attributed to the thermal effect of the anorthosite intrusion on its contact rocks.

Locally in the contact zone of the anorthosite there are isolated exposures of rocks comprising a schlieric quartzofeldspathic gneiss matrix crowded with blebs of anorthosite (fig. 9). This lithology is interpreted as formed where the thermal effect of the anorthosite body intrusion was sufficient to completely mobilise adjacent old complex rocks, which then back-veined into the border of the body.

(d) *'Dirty' anorthosite.* Along some sections of the contact there are diffuse, irregular units of brown-weathering biotite-bearing anorthosite, interpreted as having been contaminated by the country rocks. They are commonly intimately associated with granitic material containing garnet-rich clusters and mafic schlieren – presumably mobilised country rocks.

The Qaqujârssuaq anorthosite is cut by thin basic dykes. Two types are recognised, melanocratic amphibolite and mesocratic dioritic dykes. Dykes intermediate in composition are rare. Where least deformed the dykes show a variety of morphologies. Most commonly they form swarms of irregular dykes net-veining the anorthosite (fig. 10); but elsewhere, particularly near the margin of the anorthosite body they are broken up into strips or isolated bloks, 'swimming' in their host. The dykes commonly have irregular margins and locally flame-like apophyses and they have been affected by the overturned folding. In addition the dioritic dykes locally have diffuse margins and contain enclaves of anorthosite, and they also occur as strings of pods interconnected by very thin dykelets. Locally the

Fig. 10. Thin, deformed amphibolite dykes in anorthosite.

dioritic dyke lithology occurs as diffuse patches in the anorthosite. At the only observed intersection between the two types of dyke the dioritic dyke is younger. These dykes and related bodies are interpreted as formed during a late stage of the crystallisation of the anorthosite.

The characters of the Qaqujârssuaq anorthosite suggests that it is the border of a body emplaced as a liquid-crystal mixture. Its exposure in the hinge of an antiform suggests it could be the top of a larger pluton. As there may be as much as several hundred metres stratigraphic interval of the body exposed, two geochemical traverses were run from north to south across the body to examine its chemical variation. One of these traverses is represented in fig. 11, and representative analyses are given in Table 3. The variation of most components is regular and is mirrored about the position in the traverses of the axis of the recumbent antiform. The parametres M (FeO^t/FeO^t+MgO) and A (Na_2O/Na_2O+CaO) show no significant variation throughout the traverses (fig. 11). Thus it is suggested that variation of Sr, Cr, Ba and Ni (fig. 11) is a function of colour index of the samples rather than a cryptic variation. These geochemical characters are in accordance with the field evidence that the body was intruded as one or more pulses of magma and not a single batch of liquid which then underwent fractional crystallisation.

Geochemical data on gabbros and 'dirty' anorthosite from the southern contact zone clearly show interaction with the country rocks by higher $FeO^t/MgO+FeO^t$ values and K_2O, Ce, Ba and Sr contents than equivalent lithologies in the interior of the body (Table 3).

The dioritic sheets, pods and interstitial patches in the anorthosite have moderately high FeO^t/FeO^t+MgO values and erratic P_2O_5, Zr and Y contents (Table 4). The field and geochemical characters of these rocks suggest that they could have been late-stage liquids in the crystallisation of the anorthosite that segregated and formed intrusive bodies. Most of the melanocratic amphibolite dykes that cut the anorthosite complex have high FeO^t, TiO_2, Sr, Ba, V, Cr, Ni and low SiO_2, Zr and P_2O_5 contents (Table 4). These geochemical characters suggest the dykes may have crystallised as olivine-plagioclase-(ilmenite) rocks or as hornblendites but their origin is uncertain.

Table 3. Chemical analyses of the Qaqujârssuaq anorthosite

	235644	235613	235646	235650	235390	235391
SiO_2	47.95	49.03	48.65	49.14	51.32	55.24
TiO_2	0.05	0.14	0.18	0.24	0.81	0.37
Al_2O_3	30.92	28.89	26.39	18.76	14.39	23.53
FeO^{tot}	0.68	1.71	2.97	7.52	10.38	3.07
MnO	0.01	0.03	0.05	0.15	0.18	0.04
MgO	1.47	2.02	3.48	8.39	10.17	1.99
CaO	15.69	14.07	13.94	11.64	9.68	8.43
Na_2O	1.95	2.69	2.09	1.62	1.34	3.26
K_2O	0.08	0.13	0.07	0.30	0.07	1.17
H_2O	0.56	0.88	1.31	1.09	0.16	0.85
P_2O_5	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Total	99.36	99.59	99.13	98.85	98.50	97.15
Rb	1	1	1	4	2	32
Sr	214	169	190	128	290	391
Ba	48	39	36	45	246	424
Y	n.d.	1	8	11	29	6
La	n.d.	8	n.d.	n.d.	34	31
Pb	2	1	3	6	5	8
U	n.d.	n.d.	n.d.	n.d.	2	n.d.
Th	n.d.	n.d.	1	2	1	1
Zr	n.d.	1	4	2	62	93
V	5	18	48	135	189	37
Cr	4	37	289	428	733	53
Ni	n.d.	14	46	166	277	35
Zn	9	19	31	53	93	43
Nb	3	3	4	4	9	5
Ce	n.d.	n.d.	n.d.	n.d.	61	45

235644 plagioclase rock
235613 and 234546 anorthosite

n.d. = not detected

235650 leucogabbro
235390 border gabbro
235391 'dirty' anorthosite

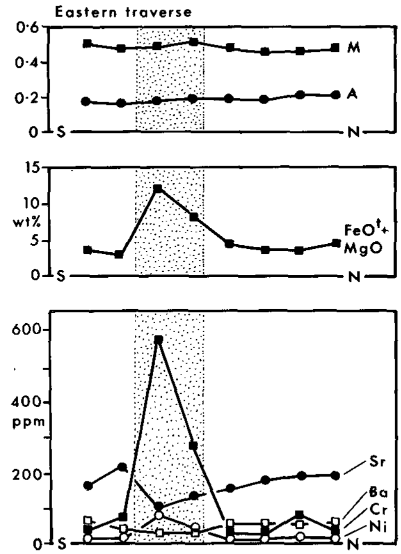

Fig. 11. North–south geochemical traverses across eastern part of the Qaqujârssuaq anorthosite. Stipled area shows location in the traverse of the leucogabbro with anorthosite zone, which lies in the core of the recumbent antiform (see fig. 4). M = $FeO^t/FeO^t + MgO$ and A = $Na_2O/Na_2O + CaO$. S and N mark the south and north ends of the traverse.

Heilprin Gletscher complex

The Heilprin Gletscher complex is defined as the body of meta-igneous rocks that occurs on the south-western point of Smithson Bjerge. It may have formed contemporaneously to other meta-igneous complexes in North-West Greenland, such as the Kap York and Etah complexes (Dawes, 1976b). The Heilprin Gletscher complex consists predominantly of intersheeted ferrodiorite (with subordinate ferrogabbro) and granite in approximately equal amounts. Phases intermediate in composition are estimated to form less than 10% of the complex. It is a lenticular, sheeted body concordant to the compositional layering of the adjacent rock units. Eastwards from the south-western point of Smithson Bjerge the complex is more deformed. This is accompanied by an original tapering of the body, as witnessed by its interdigitation eastwards with host lithologies. On the south-western point of Smithson Bjerge ferrodiorites are dominant, but eastwards they become subordinate to granite. Elsewhere there are sporadic concentrations of granitic sheets, locally associated with basic material. These are particularly abundant on the ridge south of the east–west valley, directly east of the Heilprin Gletscher complex, with which they can be correlated with confidence. Another possible concentration of granitic sheets is in a tract along the northern side of the east–west valley. This tract was only traversed at its western end (the rest is in a cliff) where the granites grade into diatectic supracrustal rocks and are found in association with the thin, southerly anorthosite band. Thus some of the prominent white sheets in the cliff to the east could be either anorthosite or granite sheets.

The ferrodiorites (and subordinate ferrogabbros) are generally homogeneous, but igneous layering manifested by colour-index banding on a 25 cm scale is preserved locally. Hornblende is commonly the only or the predominant ferromagnesian mineral, but well preserved garnet+orthopyroxene+clinopyroxene+hornblende+plagioclase assemblages occur locally. At some localities they have a biotite foliation. The presence of biotite is

Table 4. Chemical analyses of minor basic intrusions

	235389	235775	235364	235379	235637	235611	236810	235679
SiO_2	47.76	56.21	56.42	57.43	44.98	46.03	46.97	53.89
TiO_2	2.03	0.83	0.77	0.51	1.73	1.97	0.26	1.05
Al_2O_3	21.14	16.06	17.31	19.42	15.96	15.81	15.46	16.27
FeO^{tot}	13.39	8.94	8.41	6.17	16.65	16.93	10.51	10.39
MnO	0.08	0.12	0.07	n.d.	n.d.	n.d.	n.d.	n.d.
MgO	4.03	5.38	4.47	3.59	9.67	10.03	12.13	7.51
CaO	9.00	8.03	6.07	6.43	10.20	9.76	13.42	10.18
Na_2O	1.77	3.20	2.41	3.45	1.27	0.67	1.19	2.40
K_2O	0.32	0.23	1.19	1.00	0.01	0.05	0.32	0.70
H_2O	0.11	0.29	0.29	1.23	0.64	0.43	0.03	0.32
P_2O_5	0.93	n.d.	0.06	n.d.	n.d.	n.d.	n.d.	n.d.
Total	100.56	99.26	97.47	99.23	101.11	101.68	100.29	101.75
Rb	3	3	32	57	n.d.	n.d.	9	23
Sr	212	244	282	226	144	148	56	140
Ba	288	17	927					
Y	7	10	4	3	15	17	12	27
La	44	3	21					
Pb	3	n.d.	3					
U	n.d.	1	1					
Th	2	44	1					
Zr	1069	115	108	114	14	19	5	83
V	143	171	109					
Cr	22	62	263					
Ni	119	9	140					
Cu	63	106	107					
Zn	20	3	92					
Nb	11	13	6	6	2	2	2	8
Ce	101	n.d.	35					

235389 diorite cutting Qaqujârssuaq anorthosite
235775 diorite cutting Heilprin Gletscher complex
235364 diorite enclave in margin of Qaqujârssuaq anorthosite
235379 garnet amphibolite dyke
236337, 235611, 236810 and 235679 melanocratic amphibolite dykes cutting Qaqujârssuaq anorthosite

n.d. = not detected

probably due to metasomatic addition of K from the intersheeted, penecontemporaneous granites of the complex.

The granites of the Heilprin Gletscher complex range from isotropic rocks with randomly orientated megacrysts of alkali feldspar where they are least deformed, to extremely pale, flaggy acidic 'schists' where they are most deformed. They are devoid of compositional layering apart from where there is evidence of contamination by country rocks or interaction with the ferrodiorites. There are garnets up to 1 cm diameter randomly distributed through the granites; it is not known if the garnets are original phenocrysts or whether they grew during metamorphism.

Throughout the Heilprin Gletscher complex the granites and ferrodiorites are intersheeted, but in most places severe deformation has obscured the relations between the phases. At the south-western tip of Smithson Bjerge where the rocks are least deformed, the intersheeting of phases can be seen to be of intrustive origin that has elsewhere been accentuated by subsequent deformation.

The following relations between the ferrodiorites and granites occur:

(a) Irregular enclaves of ferrodiorite are found in granite (fig. 12). These enclaves commonly have biotite selvages and have locally been subjected to K-feldspar blastesis.

(b) *Ferrodiorites and granites are intersheeted in an ambiguous manner.*

(c) Inhomogeneous intermediate schlieric rocks occur between granites and ferrodiorites. These are interpreted as hybrid rocks produced by interaction between granitic and ferrodioritic magmas more or less *in situ*. Elsewhere there are units up to 20 m thick of homogeneous gneisses of intermediate composition, these are interpreted as formed by hybridisation at a site remote to where these rocks crystallised.

This range of relations indicates that the emplacement of the ferrodiorites and granites was penecontemporaneous, with emplacement of ferrodiorites starting first.

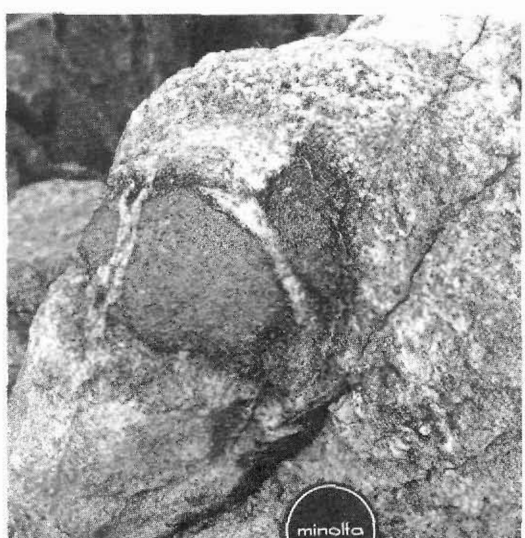

Fig. 12. Ferrodiorite enclaves in granite.

Table 5. Chemical analyses of the Heilprin Gletscher complex

	235736	235773	235774	235780	235782	235781
SiO_2	48.76	52.63	53.15	56.79	74.48	74.55
TiO_2	2.04	0.99	0.75	1.84	0.26	0.26
Al_2O_3	16.18	15.72	17.37	16.63	13.43	13.53
FeO^{tot}	13.47	10.08	8.87	10.62	1.64	1.66
MnO	0.16	0.16	0.13	0.11	0.02	0.02
MgO	5.98	7.82	6.08	2.62	n.d.	0.03
CaO	8.05	6.45	7.20	5.29	0.80	0.86
Na_2O	1.45	2.24	2.28	2.95	3.10	1.96
K_2O	1.08	1.17	1.13	2.14	6.23	6.20
H_2O	0.51	0.48	0.53	0.46	0.53	0.27
P_2O_5	1.57	0.29	0.35	1.62	0.02	0.01
Total	99.23	98.03	98.37	101.07	100.51	99.35
Rb	24	32	36	131	217	220
Sr	510	607	244	541	111	98
Ba	592	542	153	1813	553	459
Y	43	31	17	55	26	34
La	38	30	10	110	49	50
Pb	16	11	13	20	42	42
U	n.d.	3	2	10	7	5
Th	3	6	5	10	71	66
Zr	135	99	44	755	191	195
V	122	122	115	184	16	16
Cr	316	254	171	45	n.d.	n.d.
Ni	50	105	104	28	n.d.	n.d.
Cu	34	26	25	7	n.d.	n.d.
Zn	146	101	101	115	25	28
Nb	10	9	3	19	9	10
Ce	87	80	13	194	99	99

235836 ferrogabbro
235773 and 235774 ferrodiorites

235780 hybrid lithology
235782 and 235781 granites

n.d. = not detected

Thin, fine-grained dioritic dykes, commonly less than 4 m wide cut the major phases of the Heilprin Gletscher complex and also the country rocks. Dykes within the ferrodiorites or country rocks are tabular and are commonly discordant to compositional layering of their host, but are cut by the regional foliation. In contrast, where they cut granitic rocks of the complex their margins are highly irregular, with the development of lobes and cusps, demonstrating that they were emplaced into a plastic or semi-crystalline host. These contrasting relations show that the complete crystallisation of the granites post-dated that of the ferrodiorites. There is considerable variation in modal zircon, sphene, apatite and ore minerals from dyke to dyke. This is considered due to interaction at the time of their intrusion between the (thin) dioritic dykes and hot host rocks of diverse lithologies, which at the time were in a variety of physical states. These dioritic dykes are very similar to those in the Qaqujârssuaq anorthosite.

The ferrodiorites and subordinate ferrogabbros are not only iron-rich but also have high $FeO^t/FeO^t{+}MgO$ values (fig. 3) and high TiO_2, MnO, P_2O_5, Zr, Y, La, Ce contents (Table 5). In these respects they are similar to ferrodiorites of acid-basic complexes reported from elsewhere (e.g. Emslie, 1978; Nutman *et al.*, in press), which probably owe their enrichment in many incompatible elements and their high $FeO^t/FeO^t{+}MgO$ to derivation by deep-seated fractionation of mantle-derived basic magmas (Emslie, 1978).

The granites are enriched in the incompatible elements Zr, Y, Rb, Ba, La and Ce (Table 5). In the salic tetrahedron the two samples of granite analysed plot in the vicinity of the plagioclase, quartz, K-feldspar join in the water saturated system at 7 kb (fig. 13). Therefore it is possible that they are early stage, low-temperature anatectic melts of a quartzofeldspathic source. Anatectic segregations in quartzofeldspathic rocks of the old complex close to the anorthosite are lithologically similar to the granites; such rocks at depth could be the source of the granites.

The composition of a single late dioritic dyke of the Heilprin Gletscher complex is similar to that of diorites from the Qaqujârssuaq anorthosite (Table 4). Taking into account the similar morphology of these bodies, it is proposed that the diorite dykes outside the anorthosite body are genetically related to those within the anorthosite body.

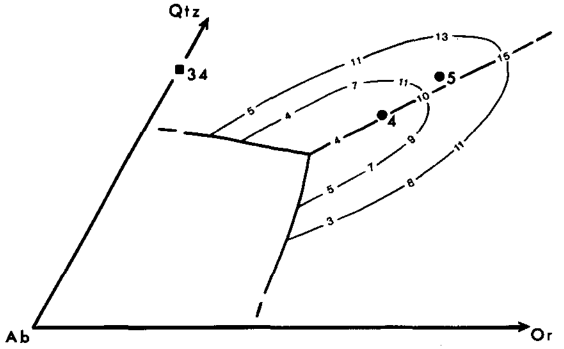

Fig. 13. Salic tetrahedron – projection from An onto Ab-Qtz-Or surface; granites and mixed composition of the Heilprin Gletscher complex. Phase boundaries are for P_{H_2O} = 7 kb. Small numerals are 100 × An/An + Ab + Qtz + Or of the phase boundaries between plagioclase, orthoclase and quartz space. Large numerals are 100 × An/An + Ab + Qtz + Or for samples.

Fig. 14. Late amphibolite dyke lying close to foliation but discordant to compositional layering in hinge of a D_1 fold.

MINOR INTRUSIONS

Garnet amphibolite dykes

Garnet amphibolite dykes up to 30 m thick of iron-rich quartz tholeiitic affinity (GGU 235379, Table 4) are concentrated in the southern part of the Qaqujârssuaq anorthosite, but a few (less than ten) badly exposed lithologically similar dykes up to 2 m thick cut the rocks to the south. Description of these dykes is based on the large, well-exposed ones. Compared with their host the dykes are relatively undeformed and their attitude is usually subconcordant to the regional foliation (fig. 14). At their contact there is locally a zone up to 10 cm wide of a schlieric mixture of the dyke material and the country rock. The centres of the larger dykes are homogeneous, isotropic to weakly foliated clinopyroxene-garnet-bearing amphibolite. Recrystallisation has led to the breakdown of garnet and clinopyroxene to give plagioclase-hornblende amphibolite; this occurs most commonly along hair-line fractures and at the edges of thin pegmatites that cut the dykes. In the borders of the dykes a prominent foliation is developed parallel to their margins.

Pink microgranite sheets and dykes

Undeformed, pink microgranite sheets and dykes that post-date ductile deformation occur sporadically throughout the area. Their principal concentrations are cutting the eastern end of the anorthosite body and also the old complex rocks south of the east–west valley. The microgranite sheets are mainly sub-horizontal, but some sections of them follow the gently north-dipping regional foliation, and locally they exploit vertical fractures. The sheets are normally homogeneous, but there are some composite bodies comprising pegmatite margins with a microgranite core. Microgranite dykes trend north–south and are normally less than 3 m wide. They are homogeneous, with a thin biotite selvage developed locally at their margins. Mica in the dykes is aligned parallel to the contact. Locally they contain pegmatite stringers and schlieren.

Pegmatites and quartz veins

Undeformed pegmatite dykes up to a few metres wide and up to 50 m long occur sporadically, they have a north–south trend and commonly occur in *en echelon* sets. They may have formed in the same phase of activity as the pink microgranites.

A few quartz veins up to 2 m wide occur south of the anorthosite body. They are vertical, trend north–south and are composed of coarse-grained clear quartz and less than 1% modal biotite flecks and pyrrhotite.

Dolerite dykes

East–west undeformed dolerite dykes account for approximately 3% north–south crustal extension across Smithson Bjerge. They are concentrated in the northern part of the anorthosite body, are up to 75 m wide and individual members of the swarm can be followed for more than 15 km. They are poorly exposed, forming elongate rubble-filled depressions with only the occasional exposure of dolerite. Dykes end in fans of dykelets or *en enchelon* relations. Locally they have exploited north–south fractures for up to 200 m. The contacts of the dykes are sharp, with a well-developed flinty chill bordered by fine-grained grey dolerite. In from the contacts the dolerites are reddish-brown, coarse grained, homogeneous and are devoid of enclaves or igneous layering. However, a single inhomogeneous dyke cuts the Heilprin Gletscher complex. The dykes are somewhat altered, as shown by their rusty-brown colour and clouded plagioclase, even on 'fresh' surfaces. Plagioclase laths are randomly orientated and they show a sub-ophitic relation with pyroxene.

STRUCTURE

D_1

Large east–west trending close folds (D_1) are the main structures present in the area (fig. 15). D_1 folds are asymmetric, with long limbs that dip gently north and shorter limbs which are near vertical. They have an axial plane foliation and a lineation parallel to the fold axes (fig. 15). Depending on the lithology, the foliation is defined by biotite or mats of either amphibole or pyroxene and the lineation by sillimanite, pyroxenes or amphiboles. Quartz aggregates form both *S* and *L* fabrics. These mineral fabrics are commonly accompanied by pre-existing fabrics that were modified and accentuated during D_1. On the long, gently north-dipping limbs the rocks are flattened, obliterating most pre-D_1 structures. For example, 'tennis ball' structures in leucogabbros are reduced to oblate smears parallel to the foliation. In contrast, in the hinges of D_1 folds and to a lesser extent on the steeply-dipping or vertical limbs the rocks are not so flattened, and pre-existing structures in the rocks are better preserved. However, in these parts of the folds the rocks have still undergone considerable stretching parallel to D_1 fold axes as demonstrated by the mineral lineation and the prolate form of 'tennis ball' textures in leucogabbros (fig. 5).

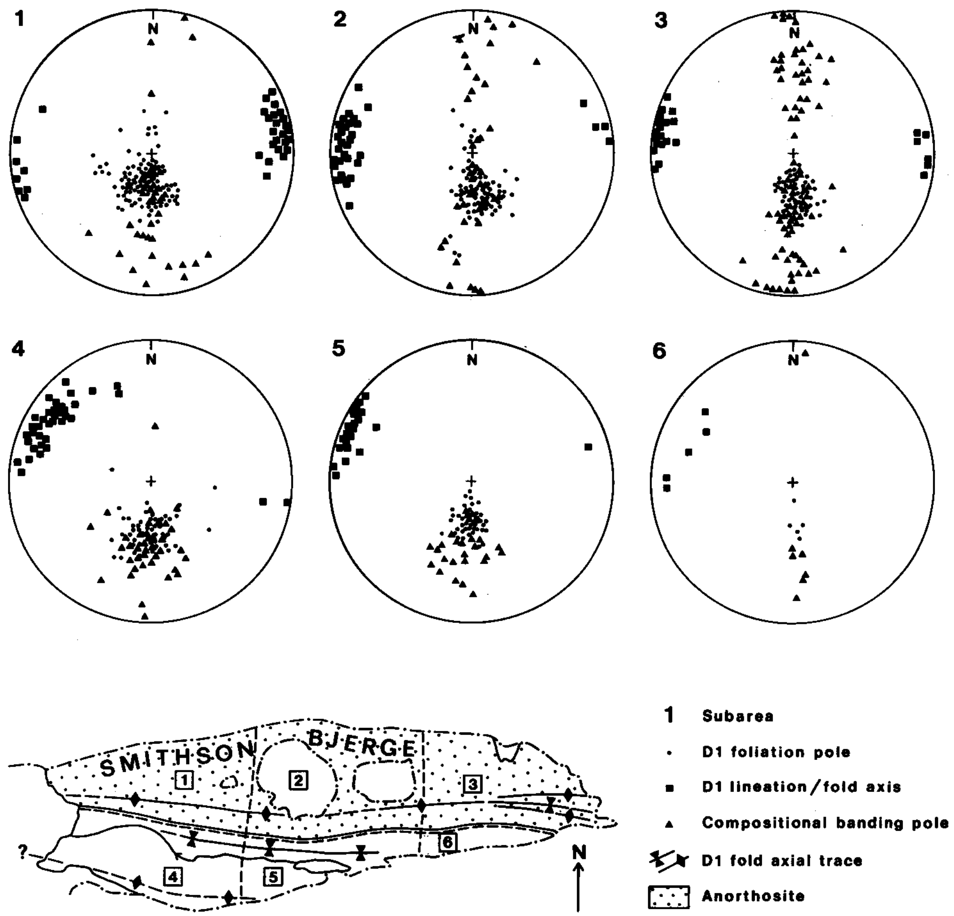

Fig. 15. Structural data from Smithson Bjerge.

The Qaqujârssuaq anorthosite outcrops in a D_1 antiform (fig. 4). This is shown by (1) the sense of parasitic folds in compositional layering, (2) compositional layering–foliation relations (Plate 1) and (3) the shape of the southern boundary of the anorthosite body. The fold is non-cylindrical, as indicated by the variable plunge of mineral lineations and minor D_1 fold axes (fig. 15). The non cylindricity could be either an original D_1 feature or it could be due to gentle refolding with north–south axes. Overall, the whole fold seems to plunge gently westwards. Its form is more complex in the east, where the outcrop pattern of leucogabbro units and layering–foliation relations suggest that it is resolved into several smaller, closely spaced folds (Plate 1).

In the supracrustal rocks north of the east–west valley synformal overturned folds marked by ferruginous quartzite units, compositional banding–foliation relations and the sense of small folds suggest that a large D_1 synform is present. This synform appears to plunge gently and tighten westwards. There is some evidence for a major D_1 structure south of the east–

west valley. Brief helicopter reconnaissance of the cliff overlooking Heilprin Gletscher showed that there is a unit of supracrustal rocks below the orthogneisses. In the western part of the cliff these rocks may close around a fold to link up with the upper supracrustal unit. This interpretation is supported by a traverse southwards to the sea in front of the snout of Heilprin Gletscher where only supracrustal rocks were encountered. Thus this outcrop pattern suggests there is a large D_1 antiform with multiphase orthogneisses in its core (Plate 1 and fig. 15). A projection westwards of the trend of measured D_1 lineations and fold axes places its inferred hinge in the western part of the Heilprin Gletscher complex; at this locality the rocks are relatively undeformed and the orientation of compositional layering is variable, as would be expected if a D_1 fold hinge passes through there.

The likely distribution of D_1 folds suggests that the thin southern anorthosite band could be a southerly lateral continuation of the main anorthosite body (fig. 3). The reason for the great contrast in thickness is uncertain; it could be due to a primary lenticular form of the body, extreme tectonic thinning, or to a combination of both of these factors.

Timing of D_1 and high-grade metamorphism

Much of the multiphase orthogneisses are hypersthene gneisses (granulites) that show only limited growth of retrograde amphibole. Orthopyroxene, clinopyroxene and *coexisting* hornblende in these rocks are constrained to the powerful *LS* fabric, with no evidence that they are pre-D_1 grains that were rotated into the fabric during deformation or that they grew epitaxially. These relations suggest that granulite facies metamorphism and D_1 deformation were synchronous. This relation is confirmed by petrographic observations of other lithologies, although at many localities relations are ambiguous due to later growth of biotite and hornblende.

The east–west garnet amphibolite dykes do not contain hypersthene and may have crystallised under amphibolite facies conditions. They were intruded subconcordantly to D_1 *S* fabrics, but they are themselves slightly deformed, as demonstrated by the foliation in their margins.

D_2

Small folds (D_2) with northerly-plunging axes post-dating the D_1 mineral lineation occur at a few localities in south-west Smithson Bjerge. The undulation of D_1 fold axes and mineral lineations (fig. 15) throughout the area could be due to very gentle D_2 flexures.

Faults and joints

The area is dissected by numerous north–south subvertical brittle fractures, ranging in size from hair-line joints to faults with minor displacements which have weathered-out to form deep gullies. Chemical alteration along the fractures is common, with feldspar turned from white to pink where they cut the anorthosite and with sporadic epidotisation along them throughout the area. These fractures clearly post-date the high-grade metamorphism and intense ductile deformation of the area, but are locally exploited by the east–west dolerite dykes. Some fractures were reactivated after these dykes were emplaced.

METAMORPHIC HISTORY

All the major lithological units were metamorphosed under granulite facies conditions, presumably at *c.* 1900 Ma, when the Rb-Sr isotopic system was last reset (Kalsbeek & Dawes, 1980; Kalsbeek, 1981). This was followed by patchy retrogression under amphibolite facies conditions. K/Ar mineral ages on hornblende and biotite from a garnet biotite pyribolite dyke (garnet amphibolite dyke of this paper) have given 1852±48 and 1610±46 Ma respectively (Larsen & Dawes, 1974).

Variation in the granulite facies mineral assemblages appears to be predominantly controlled by bulk composition. Details of the high-grade metamorphic history based on a quantitative approach are presented in Garde *et al.* (in press); an outline of this topic is given here and is dealt with on a lithological basis.

(a) *Orthogneisses.* Assemblages in these rocks are orthopyroxene + antiperthitic plagioclase + hornblende + quartz ± clinopyroxene ± garnet ± K-feldspar ± biotite. Signs of retrogression include start of replacement of pyroxenes and hornblende by pale green fibrous amphibole and biotite overgrowth on ilmenite.

(b) *Metasedimentary rocks.* In semipelitic lithologies the polymorph of Al_2SiO_5 is always sillimanite, devoid of cores or mantles of kyanite or andalusite. The granulite facies parageneses are normally garnet + biotite + quartz + antiperthitic plagioclase ± sillimanite ± orthoclase ± graphite ± orthopyroxene; sillimanite and orthopyroxene seem to be mutually exclusive. Signs of alteration include chloritisation of garnet and secondary biotite overgrowths. The ferruginous quartzites comprise orthopyroxene + garnet + quartz ± clinopyroxene ± amphibole ± magnetite ± graphite. Orthopyroxene (iron-rich) is rusty-brown and pleochroic and some grains contain wide exsolution lamellae of clinopyroxene. In some samples orthopyroxene grains have complex garnet-bearing coronas.

(c) *Ferrodiorites and ferrogabbros of the Heilprin Gletscher complex.* These contain orthopyroxene + clinopyroxene + garnet + plagioclase + magnetite-ilmenite granulite assemblages, which are commonly extremely altered, with quartz-sieved pale green amphibole that replaces pyroxenes, plagioclase-hornblende intergrowths after garnet and considerable overgrowth of biotite. Apatite and zircon are important accessory phases.

(d) *Granites of the Heilprin Gletscher complex.* These do not contain assemblages diagnostic of granulite facies metamorphism, but their intimate association with the ferrodiorites shows that they have undergone the full metamorphic history observed. Parageneses in these rocks are quartz + plagioclase + microcline + garnet + biotite. Microcline megacrysts are twinned and contain unzoned subhedral plagioclase and quartz inclusions. Boundaries of the microcline megacrysts are commonly recrystallised into mosaics of optically disorientated subgrains. Magnetite, zoned zircon and apatite are the principal accessories. In more deformed and retrogressed parts of the complex, garnets are chloritised and muscovite is developed.

(e) *Qaqujârssuaq anorthosite and leucogabbros.* These rocks show essentially the same petrographic features despite their considerable modal variation. The assemblage orthopyroxene + clinopyroxene + hornblende + plagioclase + garnet occurs but clinopyroxene + hornblende + plagioclase is more common. In some cases garnet has grown at the expense of orthopyroxene and has subsequently broken down to amphibole-plagioclase intergrowths. The anorthosite body is cut by plagioclase-orthopyroxene-amphibole veins. They are mineralogically and modally similar to their hosts and may have developed late in the crystallisation of the anorthosite or they may be of metamorphic origin.

The difference in the granulite facies assemblages (notably the presence or absence of clinopyroxene or garnet) could be due to their equilibration under different *P, T* conditions (see Fig. 3 of Wells, 1979), but as rocks with the different parageneses are found interlayered in the field this explanation in this case seems unlikely. This is supported by *P, T* estimates for the equilibration of these assemblages having only a small spread (*c.* 700°C and 7.5 kb, Garde *et al.*, in press). Instead it is favoured that bulk compositional control has caused the diversity of parageneses at constant *P, T.*

The constancy of estimated *P, T* values throughout the area shows that the granulite assemblages formed during a regional event that obliterated mineral-chemical evidence of the thermal affect of the intrusion of the Qaqujârssuaq anorthosite which is clearly shown in the field by the nature of the anorthosite's contact. The estimated *P, T* conditions are in accord with sillimanite being the only Al_2SiO_5 polymorph present (using the phase boundaries of Holdaway, 1971).

The granulite facies metamorphism is the likely cause for some of the geochemical characters of the rocks such as low Rb content, as demonstrated by high K/Rb values of tonalitic gneisses and diorite dykes (fig. 16). Furthermore it could be responsible for other changes, for example the rather mafic character of the multiphase orthogeisses. For example Wells (1979) demonstrated that extraction of components such as SiO_2, Rb and Na_2O dissolved in a hydrous pore fluid at the onset of granulite facies metamorphism leaves the granulite facies rocks more mafic than their precursors.

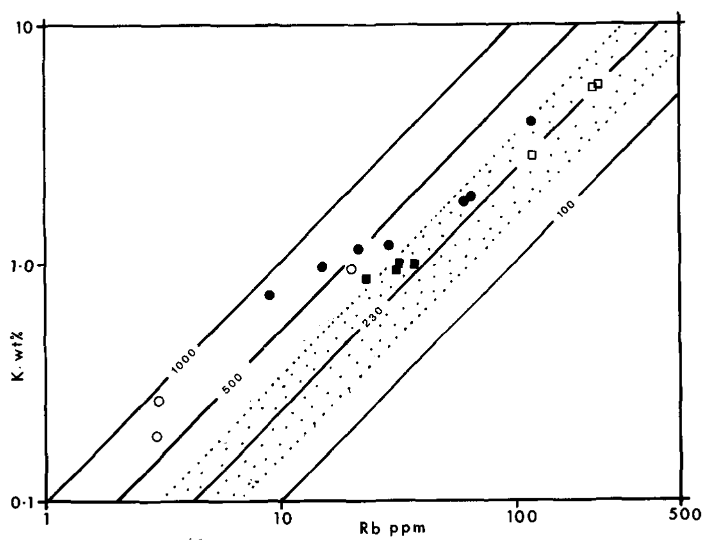

Fig. 16. K/Rb plot. Heilprin Gletscher complex, □ granites and ■ ferrodiorite. ● Multiphase orthogneisses and ○ diorite dykes. Stippled area is the 'main trend' of Shaw (1968).

Not much is known about the post-granulite facies history. The presence of sillimanite as the only Al_2SiO_5 polymorph constrains the conditions under which retrogression occurred to give raise to the observed amphibolite facies overprint. The late Proterozoic Thule Group sedimentary rocks lie unconformably on parts of the Precambrian crystalline complex in the vicinity of Smithson Bjerge. The oldest members of this unmetamorphosed group are at least 1200 Ma old (Dawes, 1976b) and estimated *P* for the granulite facies metamorphism is 8–9 kb (equivalent to up to 30 km burial) and it probably occurred at *c.* 1900 Ma. Thus the minimum average excavation rate of the metamorphic complex during the middle-upper Proterozoic was 46 m Ma^{-1}.

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REFERENCES

Bridgwater, D. & Windley, B. F. 1973: Anorthosites, post-orogenic granites, acid volcanic rocks and crustal development in the North Atlantic shield during the mid-Proterozoic. *Geol. Soc. S. Africa Spec. Publ.* **3**, 307–317.

Bridgwater, D., Nutman, A. P., Ryan, B. & Schiøtte, L. in press: Progress report on the Archean geology of the Saglek area, northern Labrador. *Pap. Can. geol. Surv.*

Dawes, P. R. 1972: Precambrian crystalline rocks and younger sediments of the Thule district, North Greenland. *Rapp. Grønlands geol. Unders.* **45**, 10–15.

Dawes, P. R. 1975: Reconnaissance of the Thule Group and underlying basement rocks between Inglefield Bredning and Melville Bugt, North Greenland. *Rapp. Grønlands geol. Unders.* **75**, 34–38.

Dawes, P. R. 1976a: 1:500 000 mapping of the Thule district, North-West Greenland. *Rapp. Grønlands geol. Unders.* **80**, 23–28.

Dawes, P. R. 1976b: Precambrian to Tertiary of northern Greenland. – *In* Escher, A. & Watt W. S. (edit.) *Geology of Greenland,* 248–303. Copenhagen: Geol. Surv. Greenland.

Dawes, P. R. 1979: Field investigations in the Precambrian terrain of the Thule district, North-West Greenland. *Rapp. Grønlands geol. Unders.* **95**, 14–22.

Dawes, P. R. & Haller, J. 1979: Historical aspects in the geological investigation of northern Greenland. Part I: New maps and photographs from the 2nd Thule expedition 1916–1918 and the Bicentenary Jubilee expedition 1920–1923. *Meddr Grønland* **200**(4), 38 pp.

Emslie, R. F. 1978: Anorthosite massifs, rapakivi granites and late Proterozoic rifting in N. America. *Precambrian Res.* **7**, 61–98.

Garde, A. A., Glassley, W. E. & Nutman, A. P. in press: Two-stage corona growth during Precambrian granulite facies metamorphism of Smithson Bjerge, North-West Greenland. *J. metamorph. Geol.*

Holdaway, M. M. 1971: Stability of andalusite and the aluminium silicate phase diagram. *Am. J. Sci.* **271**, 97–131.

Kalsbeek, F. 1981: The northward extent of the Archaean basement of Greenland – a review of Rb-Sr whole-rock ages. *Precambrian Res.* **14**, 203–219.

Kalsbeek, F. & Dawes, P. R. 1980: Rb-Sr whole-rock measurements of the Kap York meta-igneous complex, Thule district, North-West Greenland. *Rapp. Grønlands geol. Unders.* **99**, 30–33.

Koch, L. 1926: A new fault zone in northwest Greenland. *Am. J. Sci.* (5), **12**, 301–310.

Larsen, O. & Dawes, P. R. 1974: K/Ar and Rb/Sr age determinations on Precambrian crystalline rocks in the Inglefield Land – Inglefield Bredning region, Thule district, western North Greenland. *Rapp. Grønlands geol. Unders.* **66**, 4–8.

Nutman, A. P. 1979: Field work on Precambrian anorthosite and contact rocks, Smithson Bjerge, Inglefield Bredning, North-West Greenland. *Rapp. Grønlands geol. Unders.* **95**, 22–26.

Nutman, A. P. 1980: A field and laboratory study of the early Archaean rocks of the northwestern Buksefjord region, southern West Greenland. Unpubl. Ph.D. thesis, Univ. Exeter, 464 pp.

Nutman, A. P., Bridgwater, D. & Fryer, B. 1984: Early Archaean iron-rich Amitsoq gneisses from southern West Greenland: plutonic rocks of mixed crustal and mantle origin. *Contrib. Mineral. Petrol.* **87**, 24–34.

Shaw, D. M. 1968: A review of K/Rb fractionation trends by covariance analysis. *Geochim. cosmoschim. Acta,* **32**, 573–601.

Streckeisen, A. 1976: To each plutonic rock its proper name. *Earth Sci. Rev.* **12**, 1–33.

Wells, P. R. A. 1979: Chemical and thermal evolution of Archaean sialic crust, southern West Greenland. *J. Petrol.* **20**, 187–226.

Winkler, H. G. F. 1974: Petrogenesis of metamorphic rocks, 320 pp. New York: Springer-Verlag.

QAQUJÂRSSUAQ ANORTHOSITE

- Anorthosite
- Leucogabbro
- Contact zone

Heilprin Gletscher Complex

- Ferrodiorite
- Granite
- Multiphase orthogneiss
- Supracrustal rocks

MINOR INTRUSIONS

- Dolerite dyke
- Amphibolite dyke(s)
- Garnet " "

Pegmatite and thin granite sheets not shown

STRUCTURE

- Compositional banding
- " " & D1 foliation
- D1 foliation
- D1 lineation
- " & D1 fold axis
- D1 fold axis

COVER

- Moraine
- Fluvial deposits
- Marine deposits
- Talus and rock flows
- Undifferentiated cover
- Perennial ice

GEOLOGICAL MAP OF SMITHSON BJERGE, INGLEFIELD BREDNING

5 km

N

mag. N