MEDDELELSER OM GRØNLAND
UDGIVNE AF
KOMMISSIONEN FOR VIDENSKABELIGE UNDERSØGELSER I GRØNLAND
BD. 179 · NR. 9

GRØNLANDS GEOLOGISKE UNDERSØGELSE

SANERUTIAN APPINITIC ROCKS AND GARDAR DYKES AND DIATREMES, NORTH OF NARSSARSSUAQ, SOUTH GREENLAND

BY

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WITH 38 FIGURES AND 2 TABLES IN THE TEXT, AND 3 PLATES

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BIANCO LUNOS BOGTRYKKERI A/S
1965

Abstract

Precambrian (Ketilidian) foliated granites and gneisses are intruded by Kuanitic basic dykes and large bodies of noritic gabbro, diorite and hypersthene-monzonite of Sanerutian age. The latter constitute an appinitic suite, the recognition of which is new to South Greenland. Younger granites are developed around the basic masses and from the occurrence of relict basic dykes are shown to be at least partly due to recrystallization of earlier granitic rocks, though in places the granite has been clearly mobile. It is suggested that the Sanerutian plutonic episode may represent the epeirogenic uplift phase of a root-zone of the orogeny which developed in Ketilidian time rather than the expression of a separate orogenic development as has been thought previously.

The appinitic rocks are considered to belong to the normal orogenic calc-alkali suite. Hypersthene monzonite and locally syenite are thought to have developed by diffusive potassium enrichment in basic to intermediate magma. The Gardar alkali province, represented here by swarms of trachydolerites and microsyenites, together with carbonatites, is shown to occupy a characteristic post-orogenic position. Its development is related to continental disruption during the later phases of the Svecofennid chelogenic cycle. The rocks of this region are interpreted as belonging to a unified tectono-magmatic cycle.

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INTRODUCTION

This paper presents a preliminary account of the geology of a mountainous area covering nearly 400 sq. km immediately north of Narssarssuaq Air Base which lies 60 km north-east of Julianehåb in South Greenland (plate 1). The work was conducted as part of the Geological Survey of Greenland's current programme of mapping in the region. The mapping was carried out in the summer field seasons of 1962 and 1963. Aerial photographs on a scale of 1:40,000 were mainly used because suitable topographic maps were only available for part of the area.

A description of field relationships is given here, together with general petrography and a provisional discussion of petrogenesis in relation to the development of the Ketilidian-Sanerutian orogeny. Detailed petrological accounts will be deferred for further publications.

The writer wishes to thank mag. scient. K. Ellitsgaard-Rasmussen, Director of the Geological Survey of Greenland, for the facilities which he made available, and all members of the staff of G. G. U. in Copenhagen and Greenland for their continual friendly assistance. Stud. mag. Niels Kelstrup and stud. sci. Erik Kirsbo provided very welcome help and companionship in the field. Fru Rana Larsen constructed 1:40,000 topographic maps of the area from aerial photographs and the final geological maps were drawn by J. Larsen and staff under his direction.

Thanks are also due to the writer's colleagues on the survey for stimulating geological discussions. The sections in this paper comparing the development of South Greenland with other fold belts and with the Svecofennid chelogenic cycle are the result of joint work with D. Bridgwater.

Previous geological work in the area had been mainly limited to the immediate vicinity of the coast. Ussing (1912) and Wegmann (1938) sailed along the coast and recognised that the area formed part of the Julianehåb Granite complex. Bondam (1955) made a brief study of some of the Gardar dykes near Narssarssuaq, and Weidick (1963) has described the interesting glacial phenomena of the area. K. Ellitsgaard-Rasmussen on a reconnaissance flight in 1958 collected a specimen from Valhaltinde and recognised the occurrence of a large basic pluton there.

September, 1964
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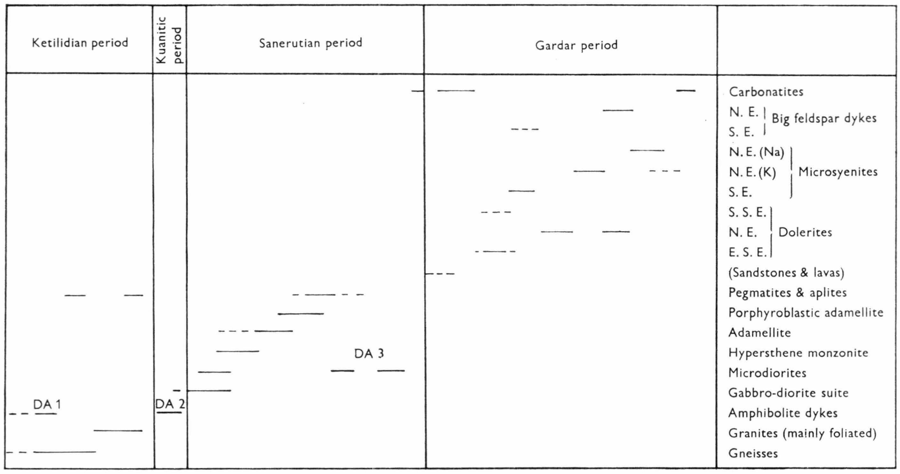

Fig. 1. Chronology of the Narssarssuaq region.

GEOLOGICAL CHRONOLOGY OF THE AREA

The chronology of the Narssarssuaq region is shown in fig. 1. The oldest rocks recognised are Ketilidian foliated granites with relict gneiss horizons. A few foliated and granitized relict amphibolite dykes may represent an early geosynclinal or inter-Ketilidian period of basaltic activity (DA1s). Following the Ketilidian plutonism a second period of basic dyking occurred during Kuanitic time (DA2s). A phase of cold shearing parallel to the Ketilidian structural trend was developed either before or just after the intrusion of DA2s. Probably closely following the DA2 intrusions there occurred the intrusion of large bodies of alkali noritic gabbros, diorites and hypersthene monzonite. These were the first expression of a return to plutonic conditions which resulted in the development of the Sanerutian granites. Microdiorite sills and dykes were intruded both contemporaneously with the main diorites and also later than the granite reactivation (DA3s). The final expression of this dioritic (appinitic) activity is represented by a lamprophyric and minor carbonatitic phase.

Probably closely following the ending of plutonic conditions Gardar sandstones were deposited. These are represented in this area only by xenoliths in carbonatite diatremes, which together with related sills and dykes, constitute the early-Gardar activity. The mid-Gardar is represented by minor E.S.E. dolerites and trachytes and a dense swarm of younger N.E. trachydolerites and microsyenites some of which are very rich in xenocrysts of anorthositic feldspar (big feldspar dykes). Late-Gardar and Tertiary igneous activity as found elsewhere in South Greenland does not appear to be represented here.

KETILIDIAN ROCKS

Foliated porphyroblastic granite

The main outcrop occurs immediately north and north-east of Narssarssuaq Air Base and continues to just beyond the end of Tunugdliarfik in the north, and to Kiagtût sermiat in the east (Plate 2). The rock is coarse-grained and generally characterized by subrectangular feldspar megacrysts up to 2 cm in length. The largest megacrysts are always microcline but plagioclase also forms quite large crystals. Nearly always the rock and the megacrysts are reddish and this is probably a result of shearing and alteration. The rock varies in mineral ogical composition between a granite *s.s.* and a granodiorite, but most commonly it is an adamellite with plagioclase in excess of microcline.

The granite occasionally grades into more gneissic zones, the clearest of which trends N.E. through Kiagtût. The foliation of the granite is subvertical and N.E. trending, and is probably mainly a relict feature inherited from gneisses which have suffered granitization. Lineation is uncommon, but where seen it is subhorizontal. Microcline porphyroblasts frequently grow across the foliation. On the other hand there has been extensive penetrative post-crystallization shearing essentially parallel to the earlier foliation. Zones of granulation are apparent in thin-section and microcline porphyroblasts frequently have granulated margins. The rocks are leucocratic and the small amount of biotite and/or hornblende is almost entirely replaced by chlorite, presumably developed during the late shearing. The shearing has locally become so intense that it has produced mylonitic banded gneisses. The best example occurs just N.E. of Núnivik where the rock is strikingly banded with alternating fine-grained bands of chloritic biotite and quartzo-feldspathic material. This banding may be due to metamorphic differentiation associated with the shearing. Relict larger crystals of quartz, feldspar etc. are present in both light and dark bands and are generally subrounded.

The penetrative cold shearing must have occurred before the diorite-gabbro intrusions and the Sanerutian granite development since these rocks are not affected by it. It is difficult to know whether this shearing should be ascribed to late-Ketilidian or early-Sanerutian time. The second period basic dykes are to a certain extent disrupted. WATTERSON (1965) has observed that the Sanerutian is characterised by belts of renewed movement parallel to the main Ketilidian structural trend. In most of South Greenland these renewed movements occurred at elevated temperature, but in the Narssarssuaq area they would seem to be mainly restricted to the early-Sanerutian and are distinctly retrogressive. Later movements during the Sanerutian in this area are extremely limited and are shown only by very minor effects in the granites and third period basic dykes. Still later shearing has developed mylonites in various directions but these form distinct localized zones without any overall penetrative effect.

Other areas of more or less foliated, porphyroblastic granite occur west of Nordbosø and in the upper part of the main Qínguata kûa valley. This granite is probably equivalent to the type Julianehåb Granite as exposed at Julianehåb, and called "big feldspar phenocryst granite" by Nesbitt (1961). The rock west of Nordbosø is more porphyroblastic and less foliated and may be equivalent to Nesbitt's "euhedral feldspar phenocryst granite". Nesbitt observed that in the Julianehåb district this granite was best developed adjacent to Sanerutian granites, and suggested that it may be due to metamorphism. This could also be true for the Nordbosø granite as it is enclosed within a region of extensive intrusion and reactivation.

The Kiagtût gneiss band

A zone of banded gneiss about 1 km wide trends E.N.E. from Kiagtût. The rocks consist of granitic, hornblendic and biotitic layers with a foliation generally striking between 60° and 80° E. of N., and dipping steeply to the north or south. Folding is only rarely seen but a few minor folds at the coast have vertical axial-plane schistosity and axes plunging at 18° on 240°.

Contacts between the gneiss and the foliated porphyroblastic granite are completely gradational, and the occurrence of this relict gneiss band is evidence in favour of a granitization origin for the granite. A very similar and parallel gneiss band was found in this granite near Julianehåb by Nesbitt (1961).

Leucocratic granite

The granite exposed over the southern half of the Mellemland plateau, and up to the contact with the Igaliko syenite is a leucocratic, medium-coarse, even-grained, nonfoliated rock. In places it is slightly porphyroblastic, and traces of foliation and folded, presumably relict banding are occasionally found.

The contact with the foliated porphyroblastic granite is gradational, but the younger diorite to the N.E. and the syenites have sharp contacts. This granite is clearly older than the Sanerutian diorite which has a chilled margin at the contact. Possibly the granite has suffered recrystallization as a result of metamorphism by the younger plutons. No amphibolite dykes have been found here. In thin-section the rock shows subhedral plagioclase crystals up to 3 mm in length. Microcline and quartz are mainly interstitial, though microcline sometimes forms small porphyroblasts. Deficiency in mafics is characteristic, generally only a little chloritic biotite is present.

Foliated aplitic granite

This rock crops out in three large areas i.e. N.W. Johan Dahl Land, N.E. Mellemlandet and near Hullet, and in a smaller area near Balder Sø. In Johan Dahl Land the aplite is surrounded, except in the N.W., by Sanerutian granite which often contains xenoliths of foliated aplite near the sharply defined contact. To the N.W. the diorite has a fine-grained margin against the aplite. Nevertheless dykes of unfoliated aplite cut the surrounding granite and diorite, and these may be due to reactivation of the aplite during Sanerutian times. On Mellemlandet the contact between diorite and aplite is generally not exposed. This is also the case near Hullet though here the contact between aplite and monzonite or diorite can be located to within a few metres. Near Balder Sø the aplite occurs as two southerly dipping sheets forming relics within Sanerutian net-veined microdiorites and granites.

The rock is medium- to fine-grained, dominantly pink but sometimes grey. It gives rise to a very characteristic outcrop surface which is covered with sharp, angular blocks and splinters. The composition is mainly adamellite. The texture is fine-grained granular with irregular to sub-lenticular porphyroclasts of plagioclase, microcline, quartz and rarely biotite and hornblende. Sometimes coarse-grained patches of these minerals occur. Also small crystals of chlorite, epidote and sericitic muscovite are characteristic. In the field a very fine and faint foliation can usually be discerned. This is subvertical and trends N.E. The foliation is entirely due to post-crystallization shearing and any original foliation the rock may have had has been obscured. There are frequently signs of post-shearing recrystallization which has resulted in the development of even-grained, non-cataclastic aplite and pegmatite veins.

In one place a relict amphibolite dyke has been strongly sheared together with the aplite, with the production of a peculiar augen structure. Granitization later than the shearing is also apparent in this rock. East of Balder Sø a foliated amphibolite is abundantly veined by foliated aplite, the two foliations being discordant. In another place an unfoliated amphibolite dyke (DA2) cuts the foliated aplite but is itself cut by reactivated aplite dykes.

This foliated aplitic granite is therefore characterized by the same development of cold shearing as is shown by the foliated porphyroblastic granite. In both cases the relationship of the shearing to second period basic dykes is not very clear which makes it impossible to decide whether the shearing is late-Ketilidian or early-Sanerutian. It seems that in parts of the area this shearing became so intense as to produce a mylonitic aplite.

First period basic dykes (DA1s).

A few examples were found of granitized basic dykes showing strong foliation. Most of the granitized basic dykes in this region are not foliated and these can be reasonably correlated with the second period basic dykes as generally recognised in South Greenland. The status of the foliated dykes is however uncertain. They might represent second period basic dykes which have been affected by very localized strong early-Sanerutian deformation. Alternatively they may have been feeders to Ketilidian geosynclinal lavas or inter-Ketilidian dykes (cf. Escher, in press, and Watterson, 1965). It is perhaps unlikely that such early dykes would survive in this area where there has been so much late-orogenic granite development. Relics of these foliated dykes are found within both the Sanerutian and the Ketilidian granites. Their relationship to the unfoliated second period basic dykes has not been observed.

KUANITIC ROCKS

Second period basic dykes (DA2s)

The occurrence of a few examples of a possibly early amphibolite dyke phase (DA1) has just been mentioned. Dykes which may be correlated with the second period of basic igneous activity generally recognised in South Greenland (DA2s), are considerably more abundant in the Narssarssuaq region. These amphibolites have been found as more or less continuous dykes (1–3 m thick) in both Ketilidian and Sanerutian granites. In both groups of rocks the DA2s are granitized. The classic example of basic dykes showing relationships of this type is that described by Sederholm (1926) in the Hangö granite. Also Goldich *et al.* (1961 p. 140) have recorded dykes with a similar position in the orogenic chronology from Minnesota.

In the Ketilidian granites the DA2s cut across the granite foliation and are not foliated themselves. They are disrupted by later movements on the granite foliation, and granitized, but folding has not been observed in them even where they have been traced for 50–100 m. Therefore the Ketilidian granites have suffered localized reactivation throughout the region subsequent to the intrusion of the DA2s. In the Sanerutian granites the degree of granitization of DA2s is higher than in the Ketilidian granites. It is concluded later in this paper that the Sanerutian granites are partly due to more thorough reactivation at the expense of Ketilidian rocks. The Ketilidian granites show features which indicate that their dominant crystallization was earlier than the intrusion of the DA2s. This may be recognised where DA2s cut across the granite foliation or where diorites, which are slightly younger than DA2s, have a chilled margin against the granitic rock. Sanerutian granites on the other hand show dominant crystallization or recrystallization later than the DA2s or diorites.

No DA2 dykes have been found in the Sanerutian diorites or monzonites, though these rocks do contain xenoliths very similar in appearance to DA2s.

Observations in other parts of South Greenland (Watterson, 1965) have shown that these DA2s were very probably intruded as dolerites

Fig. 2. Granitized second period basic dyke in Sanerutian adamellite. N.W. Johan Dahl Land.

and subsequently metamorphosed to amphibolites. Evidence from this area lends some support to this. It has been possible to recognise in thin-sections a gradual increase in degree of metamorphism from slightly granitized dykes to amphibolite xenoliths in granites and diorites. The least metamorphosed dyke was found in porphyroblastic granite west of Nordbosø. As already noted this granite is Ketilidian and has been only slightly reactivated. This dyke shows only very slight granitic veining and the thin-section shows abundant fresh augite together with plagioclase megacrysts as well as hornblende and biotite. More metamorphosed or granitized dykes contain augite relics as cores to hornblende, or hornblende aggregates with colourless (augitic) cores, or hornblendes with green cores but showing birefringence different from that of the

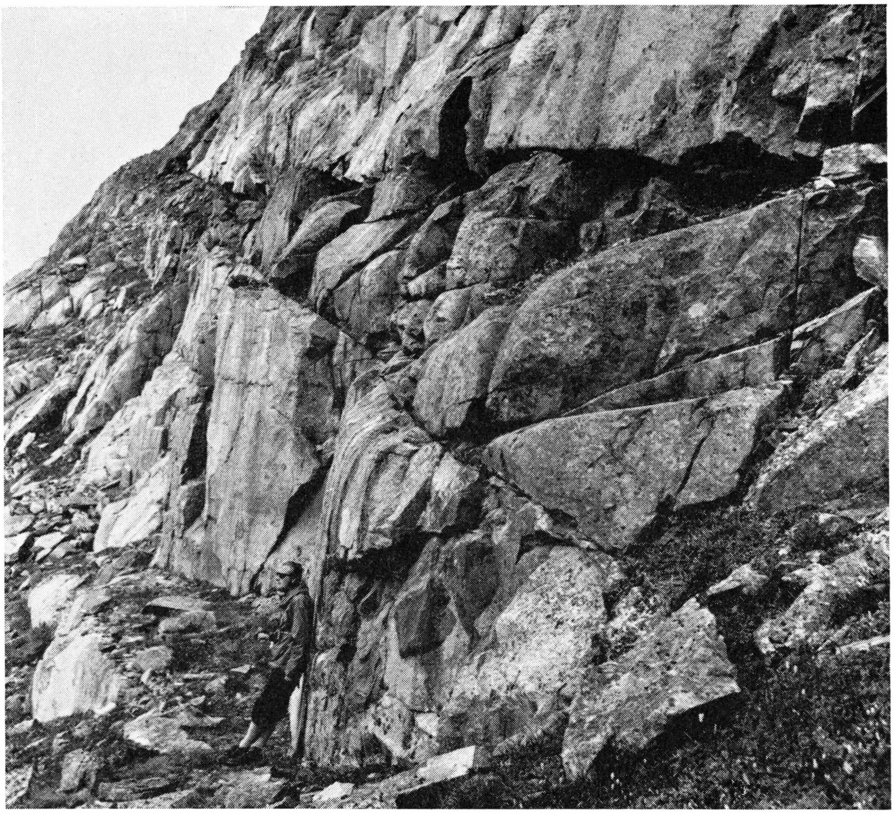

Fig. 3. Nongranitized third period basic sill cutting granitized DA2 (immediately to the right of the figure) within Sanerutian adamellite. N.W. Johan Dahl Land.

crystal margins. Plagioclase megacrysts which may be of relict igneous or metamorphic origin, are common and frequently show strong marginal zoning and rarely oscillatory zoning. Amphibolite dyke xenoliths do not contain augite but always have distinctive hornblende aggregates which, as can be seen from the less metamorphosed dykes, must be due to recrystallization from augite. These hornblende aggregates give the DA2s a spotted appearance in hand-specimen which is not found in the younger third period basic dykes of this area.

Minor amounts of biotite, quartz and microcline are usually present. The DA2s have a granular groundmass quite unlike the interstitial hypidiomorphic igneous texture of the younger first phase microdiorites. They are characteristically massive, non-foliated rocks. The dykes vary from vertical to gently inclined but are most commonly steep. Their trend is variable but a common direction seemed to be be-

Fig. 4. Detail from fig. 3.

tween north and north-west. Several examples were seen of non-granitized third period basic sills clearly cutting across granitized DA2s, (figs. 3 & 4).

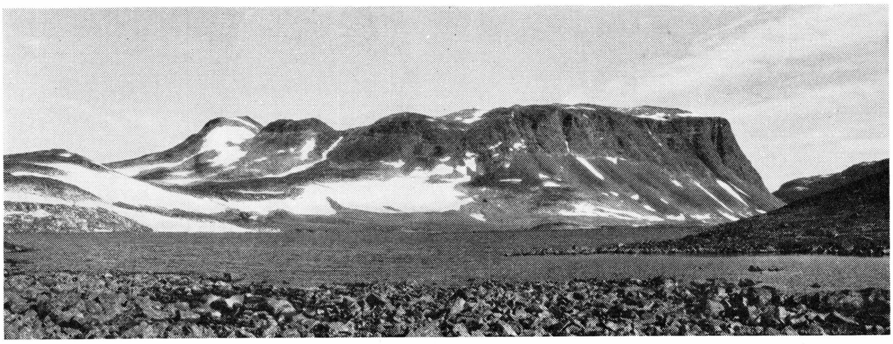

Fig. 5. The eastern part of the Johan Dahl Land intrusive complex viewed from the N.W. Diorite and monzonite forms the high ground (1400 m). The foreground is composed of Sanerutian adamellite (900 m).

SANERUTIAN ROCKS

Intrusive complexes

Two large intrusive complexes of Sanerutian age have been identified. These are centred on Johan Dahl Land (fig. 5) and Valhaltinde respectively and are comprised of a suite of basic to intermediate rocks. Smaller plutons of related rock types also occur.

Alkali noritic gabbros

The largest occurrence of these rocks is in the N.E. part of the Valhaltinde intrusive complex, but a smaller Sanerutian gabbro intrusion is found in N.W. Johan Dahl Land and certain of the rocks in the Johan Dahl Land complex approach gabbros in composition, but are perhaps more accurately described as hypersthene diorites.

The rock outcropping N.E. of Valhaltinde, adjacent to Nordgletscher, shows typical gabbroic weathering i.e. very dark rounded outcrops with a rough surface and abundant gravel-like scree. Anorthositic lenses (fig. 6) and thin discontinuous layers (fig. 7) are present striking 130° and dipping at 26° to the N.E. In thin-section the gabbro is seen to be coarse-grained, hypidiomorphic with large, subrectangular plagioclase crystals, and smaller subhedral hypersthene and augite, which tend to be enclosed within poikilitic biotite plates. Biotite also forms radiating growths round iron ore. The plagioclase is often bent and fractured, the pyroxenes are partially uralitized, and there are veins of sericite and serpentine. The anorthosite lenses and layers consist of dominant plagioclase enclosing euhedral hypersthene crystals, with interstitial augite and biotite. A chemical analysis of the gabbro is given in Table 1, p. 18.

Granite veins mainly 2–3 cm thick cut the gabbro and generally strike N.W. with a steep dip to the N.E. They have a dark hornblendic alteration zone on both sides of the vein about 5–6 cm thick. Hypersthene

Fig. 6. Anorthosite lens in noritic gabbro. Nordgletscher.

monzonite clearly cuts and dykes the gabbro. The contact is always knife-sharp and in one place was seen to be striking 124° and dipping 80° N.E., but elsewhere the contact is irregular in trend. The gabbro seems to form a belt about 700 m wide running parallel to Nordgletscher.

A similar gabbro was found nearer the centre of the Valhaltinde complex, again dyked by monzonite. This gabbro contains serpentinized olivines, but no hypersthene, and there is also a little microcline. An unusual gabbro was found on the N.W. side of the mountain, consisting mainly of augite with some hypersthene, olivine, microcline and a little biotite and plagioclase.

The gabbro in N.W. Johan Dahl Land has a lenticular outcrop about 700 m long by 300 m wide and elongated N.W.–S.E. It shows very

Fig. 7. Anorthosite layers in noritic gabbro. Nordgletscher.

characteristic gabbroic weathering, and was called a hornblendite in the field on account of the prominence of poikilitic hornblendes frequently 3–4 cm in length. In thin-section the rock is seen to consist of plagioclase, abundant fresh olivine and small amounts of augite and hypersthene all poikilitically enclosed in hornblende. A little biotite is also present. The hornblende is brown where it surrounds olivine and pyroxene but gradually changes to green towards the crystal margins. This hornblende is undoubtedly of primary magmatic origin. The gabbro is cut by a few granitic dykes and by feldspathic and hydrothermal alteration veins which cause relatively wide alteration zones. The contact of the gabbro with the surrounding Sanerutian adamellite is a leucocratic zone (2–3 m wide) of hydrothermal alteration with sericite and chlorite abundantly developed, and granitic veins sometimes showing graphic intergrowths of quartz and feldspar.

Field relations therefore show the gabbros to have been intruded before both the hypersthene monzonite and the subsequent granite reactivation. The gabbros are not foliated or thoroughly metamorphosed as would be expected if they were of Ketilidian age, and no DA2s have been found cutting them. Their petrographic features link them closely with the hypersthene diorite and monzonite. It could be argued that since these large basic to intermediate bodies pre-date the Sanerutian granite reactivation they should be regarded as Kuanitic in age. However evidence is given later in the paper to show that they are intimately

Table 1. *Chemical analyses of rocks from the Narssarssuaq appinitic suite and Sanerutian adamellites. Analyst*—B. I. Borgen.

	1	2	3	4	5	6	7
SiO_2	49.83	58.58	55.21	50.25	56.33	69.95	61.93
TiO_2	0.94	0.57	0.64	0.87	0.79	0.24	0.55
Al_2O_3	10.80	19.15	17.05	15.50	18.21	15.55	16.34
Fe_2O_3	4.10	1.80	1.95	4.36	3.62	1.11	2.16
FeO	7.95	2.26	5.05	5.88	3.58	1.05	2.64
MnO	0.19	0.05	0.12	0.18	0.12	0.05	0.07
MgO	10.38	2.07	4.36	6.31	2.13	0.55	2.20
CaO	8.53	5.70	7.33	9.22	6.67	2.20	4.24
Na_2O	2.30	4.94	3.93	3.24	4.69	4.71	4.82
K_2O	1.53	3.87	2.39	1.72	2.28	3.53	3.42
P_2O_5	0.58	0.42	0.31	0.38	0.64	0.12	0.25
H_2O+	2.98	0.46	0,70	1.66	0.90	1.02	0,94
CO_2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SrO	0.15	n.d.	0.25	n.d.	n.d.	n.d.	n.d.
Sum	99.36	99.87	99.29	99.57	99.96	100.08	99.56

No. 1. Noritic gabbro. Nordgletscher. GGU No. 55189.
No. 2. Hypersthene monzonite. Valhaltinde. GGU No. 55173.
No. 3. Hypersthene diorite. S. E. Johan Dahl Land. GGU No. 55084.
No. 4. Augite-hornblende diorite. Valhaltinde. GGU No. 55166.
No. 5. Hornblende diorite. Valhaltinde. GGU No. 55182.
No. 6. Adamellite. N.W. Johan Dahl Land. GGU No. 55113.
No. 7. Porphyroblastic adamellite. Valhaltinde. GGU No. 55165.

related to the granite reactivation. In particular it seems likely that they had not cooled completely before the younger granite activity occurred. Bridgwater (1963) has suggested that this was also the case with similar rocks at Sydprøven. Therefore it seems that they are more reasonably regarded as Sanerutian, although the writer is of the opinion that the basic igneous activity represented by the DA2s and the gabbro-diorites is a continuous event covering what we call Kuanitic and Sanerutian time.

Significant mineralogical features of these gabbros are the presence of hypersthene and of considerable quantities of primary alkali- and water-rich minerals. The hypersthene gabbro at Frederiksdal shows many similarities to the Narssarssuaq rocks (S. Watt, personal communication) and a specimen from this body has been briefly described by Bridgwater (in press, appendix part 5). The biotite from this rock has been dated by the K/Ar method at 1645 ± 50 m.yr. which is the approximate age to be expected for the Narssarssuaq Sanerutian gabbros.

Hypersthene diorite

Hypersthene diorite outcrops as a belt about 0.5–1 km wide in the inner part of the Johan Dahl Land pluton. It has a sharp contact with hypersthene monzonite which forms the core of the pluton. Towards the margin of the pluton hypersthene diorite changes gradually to augite-hornblende diorite and finally hornblende diorite at the contact with the surrounding granites. It is difficult to draw boundaries between the diorites in the field because contacts are mainly gradational and it is not easy to distinguish between the various types. Nevertheless considerable variation is seen, and from specimens collected it seems that there are quite rapid and unsystematic variations between the types in any one zone. It does not seem possible to recognise these variations as being due to dyking or inclusion of one type by another.

The other main outcrop of hypersthene diorite is near the centre of the Valhaltinde complex. It forms the steep, black outcrops of the dominant mountain peak. Here again it is associated with augite- and hornblende-bearing diorites but there was insufficient time available for separate mapping of these varieties. Relationships between the diorites are further obscured here by the cross-cutting intrusive nature of the hypersthene monzonite, and the much more thorough invasion by younger granites as compared with Johan Dahl Land (fig. 8).

The hypersthene diorite is a medium-coarse, dark-grey rock weathering to light-grey or brownish. Hypersthene and augite occur in nearly all specimens, and olivine less commonly. Plagioclase and biotite are always present, and microcline and quartz usually. Narrow hornblende rims to augite are sometimes seen. There are commonly as many as seven essential mineral phases present. Although some of the rocks closely approach gabbro in mineralogical composition the term hypersthene diorite is generally preferred for several reasons, namely: they do not show gabbroic weathering; they are associated here dominantly with diorites and monzonites; the plagioclase is generally more sodic than An_{50} and the minor constituents e.g. biotite, microcline and quartz indicate an intermediate rock. A chemical analysis (Table 1) also suggests that hypersthene diorite is the correct name for these rocks. The proportion of mafics sometimes exceeds 40 % and in that case they could be called meladiorites. In all the varieties of diorite quartz may be present up to about 10 % of the mode, so they could be called quartz diorites or tonalites, but these terms are not used here.

Plagioclase forms the largest crystals up to 6 mm in length, and is subhedral and well twinned, typically with a Carlsbad-albite combination. The crystals are often fractured or bent, usually fresh though sometimes sericitized. Patchy and normal zoning is common and deter-

Fig. 8. Granite veining hypersthene diorite. Valhaltinde.

mined compositions vary between An_{45} for the cores, to An_{23} at the margins. Mafic minerals tend to occur in clots presumably due to synneusis of early-formed crystals. Mutual relationships between the crystals indicate an order of crystallization corresponding to Bowen's discontinuous reaction series, i.e. serpentinized olivine is enclosed within hypersthene which in turn is partially enclosed by augite. Hypersthene is always more or less altered to serpentine along vein-like cracks, but augite is generally fresh. Narrow rims of hornblende are sometimes present on the augites. Biotite forms subradiating patches growing out from the margins of the mafic clots or radiating from iron ore crystals. Some plagioclase is enclosed within the mafic clots showing that it started to crystallize fairly early. Microcline occurs mainly interstitially to the plagioclase but it also frequently penetrates the plagioclase in a replacive manner. The distribution of microcline in these rocks is generally unrelated to the occurrence of younger granites and this fact, together with the textural features, suggests that the microcline is mainly of late magmatic crystallization. It may have crystallized originally as orthoclase and subsequently inverted to microcline as a result of the continued plutonic conditions associated with the younger granite development. Quartz occurs interstitially and there is sometimes a small amount of graphic micropegmatite which probably represents the final crystallization product of the magma. Myrmekite is present in small amounts. Apatite is the main accessory apart from ore, and forms euhedral crystals probably of late replacive origin.

Augite-hornblende diorites

These rocks occur in an irregular belt about 1 km wide within the Johan Dahl Land pluton between mainly hornblende diorites at the margin and hypersthene diorites towards the core. Also they form the whole of the large pluton south of Nordbosø which measures 9 km × 1 km elongated in an E.N.E. direction, as well as minor intrusions in N.W. Johan Dahl Land and much of the outer zones of the Valhaltinde complex. They are sometimes dark grey rocks and difficult to distinguish in hand-specimen from hypersthene diorites. More commonly, however, they are mottled black and white rocks and in that case difficult to distinguish from hornblende diorites. This appearance is due sometimes to a higher content of microcline but often to hydrothermal alteration which has resulted in chloritization of the mafics and sericitization of the feldspars. Amphibolite xenoliths are occasionally found (fig. 9), and in some cases these closely resemble DA2s.

In thin-section these rocks are seen to contain augite and plagioclase always, hornblende nearly always, and biotite, microcline and quartz generally. Textures are similar to the hypersthene diorites except that synneusis is not so well known. Hornblende now forms much wider rims to augites and also occurs as discrete crystals generally fairly irregular in shape, but tending to be euhedral when in contact with microcline and quartz. In one rock augite shows radial twinning and zoning and both features continue through the marginal hornblende. These green hornblendes are quite distinct from the fibrous, actinolitic amphiboles which are commonly present as uralitic alterations of augite. Hornblende occasionally forms large poikilitic crystals. These are brownish-green, very irregular in shape and considered to be primary. In contrast large, euhedral green hornblendes are found as outgrowths on brownish cores containing augite. Here the cores are primary but the margins are possibly due to recrystallization—a consequence of nearby granite activity.

Amphiboles in the Narssarssuaq basic rocks therefore show four modes of origin:

1) primary crystallization from hydrous magma e.g. ophitic brown and green hornblende in the gabbro of N.W. Johan Dahl Land.

2) autometamorphic conversion of augite to hornblende due to magmatic cooling.

3) metamorphic conversion of augite to hornblende in proximity to younger granites.

4) fibrous uralitic amphibole due to late hydrous alteration.

Fig. 9. Amphibolite and hornblende gneiss xenoliths in diorite. Johan Dahl Land W.

Types 2) and 3) are of course difficult to distinguish in thin-sections, but consideration of the texture of the rock as a whole together with field evidence may suggest which has been the main process.

Determinations of plagioclase composition indicated one core as basic as An_{54} with normal and patchy zoning to An_{30} at the margin, but compositions generally lie between these values. Plagioclase crystals often have sericitized cores but clear margins.

Chlorite frequently occurs as subrectangular fibrous patches which appear to have replaced biotite, though there is commonly no trace of biotite left, even when hornblende in the rock is still perfectly fresh. In this case chlorite probably developed as a late-magmatic hydrothermal product pseudomorphing biotite just after it was formed. Confirmation of late-magmatic hydrothermal crystallization of chlorite is given by the occurrence of interstitial, radiating, fibrous patches. Accessory minerals include iron-ore with sphene borders occurring within biotites, and euhedral apatites most often developed within mafic minerals. A chemical analysis of one of these rocks is given in Table 1. The silica percentage is somewhat lower than might be expected but apart from this the rock does not show any typical gabbroic or meta-gabbroic features. There is probably considerable variation in chemical composition of these rocks and some must be transitional to gabbro.

Fig. 10. Intrusion breccia in hornblende diorite. Mellemlandet.

Hornblende diorites

Hornblende diorites form marginal zones up to 0.5 km wide to the main diorite plutons. This is the case whether the diorites are in contact with younger or older granites. Smaller outcrops of diorite within granite or xenoliths of diorite in granite are also generally of this type. Parts of the adamellite in Johan Dahl Land have the modal composition of hornblende diorite. Faint magmatic banding is present near the northern end of the outcrop in Mellemlandet dipping at 20° towards the south. At one place in Mellemlandet an intrusion breccia is present within the hornblende diorite (fig. 10). The matrix of the breccia is fine grained and dark grey and forms only a small proportion of the disturbed mass. It is not so obviously carbonatitic as are most of the Gardar diatremes and may be an example of an appinitic intrusion breccia as described by Pitcher and Read (1952).

These rocks consist essentially of hornblende and plagioclase, and biotite, microcline and quartz are usually present. Because of the common late-magmatic hydrothermal alteration, hornblende and biotite may be completely replaced by chlorite and epidote aggregates, and plagioclase is often thoroughly sericitized. Textures are similar to the other diorites. Hornblendes often have light-coloured cores, and transitions

Fig. 11. Hydrothermal alteration veins in diorite. Johan Dahl Land W.

can be seen between these and true augites, so the cores are considered to be a relict feature from the conversion of augite to hornblende. In a few cases biotite laths occur as cores to euhedral hornblende crystals. This unusual texture has been recognised by Wells and Bishop (1955) from the appinites of Jersey. The authors describe it as hollow-shell structure and consider that it indicates crystallization under pegmatitic magmatic conditions. Crystallization starts on the outside and progresses towards the centre, the minerals formed corresponding to the order of the reaction series. As in the other diorites plagioclase shows patchy and normal zoning, though oscillatory zoning is sometimes present. For one rock a maximum compositional variation from cores to margins of An_{45-19} was obtained using several crystals. A chemical analysis of one of these rocks is given in Table 1.

Towards the margins of the dioritic plutons hydrothermal alteration veins are very abundant. These trend in all directions and vary from a few mm to several metres in width (fig. 11). They are related to joints, either actual or incipient, and they sometimes have cores of either quartz veins, aplite dykes or coarsely crystalline epidote. In one case the hydrothermal alteration has occurred in roughly spherical patches rather than veins, which are clearly older than a set of aplite dykes (fig. 12). That this alteration is mainly late-magmatic hydrothermal rather than entirely post-crystallization is shown by several facts. Firstly it is concentrated in the marginal portions of the plutons whether they

Fig. 12. Hydrothermal alteration patches in diorite, cut by aplite veins. Johan Dahl Land.

are in contact with older or younger granites, secondly alteration veins in diorite have been seen to be older than hypersthene monzonite dykes which immediately followed the diorite intrusions, and thirdly microscopic textures show interstitial growth of chlorite. WELLS and BISHOP (1955) have described similar late-magmatic hydrothermal chlorite from the appinitic rocks of Jersey.

The fact that hydrothermal alteration of the diorites occurred before the intrusion of hypersthene monzonite and the younger granite development might be taken to imply that the basic rocks cooled completely before the Sanerutian reactivation. Other evidence suggests that this was not the case and it can only be concluded that chlorite, epidote and sericite developed in veins in the basic rocks due to local very high concentrations of water, while the mass was still at a relatively high temperature, and while Sanerutian granites were developing under relatively more anhydrous conditions.

Hypersthene monzonite

Hypersthene monzonite is a distinctive rock type forming two main intrusions each about 9 km long and up to 3 km wide, their outcrops extending from Johan Dahl Land to Valhaltinde. A smaller outcrop of monzonite, though of unknown extent because of the proximity of the ice, occurs between the two main intrusions. The outcrops as a whole have an arc-like form resembling certain ring dykes. In Johan Dahl Land the hypersthene monzonite forms an intrusive core to the diorite pluton. The contact between monzonite and diorite is knife-sharp, there is no chilling, but a few dykes of hypersthene micromonzonite cut the diorite. On Valhaltinde hypersthene monzonite again intrudes diorite, monzonite dykes are common and are also seen cutting the gabbro near Nordgletscher. In one place the monzonite contains a block of hypersthene diorite about 20 m diameter and shows a chilled margin against it about 3 cm wide. Near here the monzonite also contains smaller angular, unoriented xenoliths of diorite, hornblende gneiss and amphibolite, and is cut by third period basic sills.

In thin-section it shows essentially the same mineralogy and textural relationships as the hypersthene diorite, the only difference being the considerably greater proportion of microcline and perhaps a little more biotite in this rock. Plagioclase is generally in excess of microcline except in one specimen from near the centre of the Johan Dahl Land pluton, where microcline greatly exceeds plagioclase and the rock is therefore a syenite. In N.E. Johan Dahl Land where the monzonite has been extensively invaded by reactivated granite, hypersthene has been uralitized and augite largely converted to hornblende but the rock still retains its distinctive appearance in the field. A chemical analysis of typical hypersthene monzonite from Valhaltinde is given in Table 1. Compared with the hypersthene diorite this rock is slightly richer in silica and alumina, notably richer in alkalis especially potash, and poorer in total iron, magnesia and lime. In comparison with the adamellites the monzonite is considerably poorer in silica, richer in alumina and lime, and slightly richer in alkalis.

Considering the position of the monzonite in the Johan Dahl Land pluton and its mineralogical and chemical features, it seems most reasonable to conclude that the monzonite was produced by enrichment of the central portions of the hypersthene diorite magma chamber in potassium by diffusion, consequent on the crystallization of magma at the margins and roof of the chamber. The potassium enriched magma was then intruded into the earlier rocks of the complex.

First phase microdiorites

In the Narssarssuaq region there is an older set of microdiorites which are commonly net-veined by granitic rock, and younger sets of microdiorites which cut the Sanerutian granites and are not net-veined. The early microdiorites sometimes contain xenoliths of diorite and amphibolite (possibly DA2s), and in N.E. Mellemlandet an example was

Fig. 13. Sanerutian granite dyke cutting net-veined microdiorite which is intruded into Ketilidian aplite. N.E. Mellemlandet.

seen of a net-veined microdiorite containing a diorite xenolith but cut by hornblende-rich diorite which shows a chilled margin. These early microdiorites have not been found cutting the main diorite masses. However the above relationships indicate that they are probably somewhat younger than DA2s but essentially contemporaneous with the main diorites.

The largest outcrop of these early microdiorites is at Balder Sø where they form thick sills cutting Ketilidian foliated granitic aplite. Most of the microdiorite is thoroughly net-veined by a granitic rock identical in appearance to the adamellite which is in contact with these rocks to the south. North of Balder Sø porphyroblastic adamellite clearly invades the net-veined microdiorite. There is a fairly large area about 1 km west of Balder Sø where the microdiorite is not net-veined. Areas of net-veined microdiorite, sometimes with relict dyke form occur within porphyroblastic adamellite in N.E. Johan Dahl Land. Also

Fig. 14. Net-veined microdiorite intruded into Ketilidian aplite. N.E. Mellemlandet.

similar rocks are found as xenoliths and skialiths elsewhere in the adamellite. One dyke was found cutting Ketilidian foliated porphyroblastic granite. This was not net-veined.

The granite net-veining is sometimes indistinguisable from the country-rock granite e.g. in N.E. Johan Dahl Land and south of Balder Sø. However near Balder Sø the microdiorite is still net-veined by adamellite-type granite even where it is in contact with older foliated aplite. This situation is also well shown in N.E. Mellemlandet where smaller net-veined microdiorites intrude foliated aplite (fig. 13 and 14). It seems likely that the granite reactivation closely followed the microdiorites and diorites in time and place, and in some cases granitic material was introduced along the dyke margins soon after the microdiorite intrusion. A similar conclusion has been reached by WINDLEY (in press) for bodies near Sârdloq which are apparantly younger in the chronology.

The Narssarssuaq microdiorites are medium-grained with subhedral plagioclase phenocrysts only slightly larger than the groundmass. Patchy and normal zoning is very common and oscillatory zoning is sometimes present. In one rock a maximum variation from cores to margins of An_{53-17} was determined using several crystals. Frequently cores are sericitized, but margins are clear. Small augites are occasionally present. Hornblende occurs as aggregates and larger crystals sometimes with augitic cores. Biotite is always present and sometimes forms cores to hornblende. Aggregates of biotite and sphene may represent alterations of augite or hornblende. Euhedral sphenes are very common. Microcline and quartz occur interstitially. One rock near the margin of the diorite south of Nordbosø has suffered extensive hydrothermal alteration and contains green fluorite.

The most striking thing about the microdiorites is their close similarity in mineralogy, texture and position in the chronology to the augite- and hornblende-diorites, and like these rocks they are considered to retain in large measure their original crystallization features. No typical metamorphic textures e.g. granular or porphyroblastic are present. It seems probable that they crystallized from dioritic magma and have suffered only slight recrystallization apart from in the granitized portions of the rock.

Adamellite and porphyroblastic adamellite

(Johan Dahl Land granite)

A medium-grained, homogeneous, structure-less granitic rock, dominantly having the mineralogical composition of adamellite, crops out over a large area in northern Johan Dahl Land and to the north-west. This adamellite commonly contains fairly continuous relict amphibolite dykes (DA2s) which have been more or less granitized by the adamellite. In other places however the adamellite contains a closely-mixed assortment of xenoliths of amphibolite, diorite, hornblende gneiss and foliated aplite (fig. 15).

Where the adamellite is in contact with the older foliated porphyroblastic granite e.g. south of Johan Dahl Land and near Nordbosø, the contacts are completely gradational. Over a distance of 50–100 m towards the adamellite, the foliation and feldspar megacrysts of the older granite become progressively less distinct. The contact between adamellite and foliated aplitic granite is much sharper and the adamellite contains xenoliths of aplite though it is cut by dykes of reactivated aplite. Adamellite also has a sharp contact with the dioritic plutons, the contact being marked by dykes of adamellite penetrating diorite and inclusions of diorite within adamellite. In the northern part of the area the adamellite becomes coarser grained and develops abundant microcline porphyroblasts. The contact between the two rock types is generally gradational and often takes place over a distance of 1 km or more, though locally it is much sharper. North of Balder Sø porphyroblastic adamellite cuts across microdiorite net-veined by adamellite, and in N.E. Johan Dahl Land a dyke of porphyroblastic adamellite was seen cutting an aplite

Fig. 15. Diorite and amphibolite xenoliths in Sanerutian adamellite. N.W. Johan Dahl Land.

dyke in adamellite. Therefore the porphyroblastic adamellite is clearly younger than the adamellite but there is no evidence of any significant time break. It is thought that the porphyroblastic adamellite developed from the adamellite by a continuation and intensification of the recrystallization, metasomatism and mobilization processes. The porphyroblastic adamellite is much more invasive towards the diorites and monzonite than is the adamellite, though whether the dykes are of intrusive or replacement origin cannot usually be determined. The part of the porphyroblastic adamellite shown in fig. 16 contains closely associated xenoliths of monzonite and microdiorite and was probably intrusive. The combination of these features indicates that the adamellites are at least partly a product of static recrystallization and local metasomatism, though they have clearly been mobile in places.

The adamellites consist of plagioclase generally in excess of microcline, though the reverse may be true for the porphyroblastic adamellite, quartz (10–25 %), biotite, hornblende and accessory minerals. In thin-section plagioclase is seen to form rectangular crystals with microcline and quartz occurring interstitially, though microcline also forms porphyroblasts with inclusions of rectangular plagioclase and all other

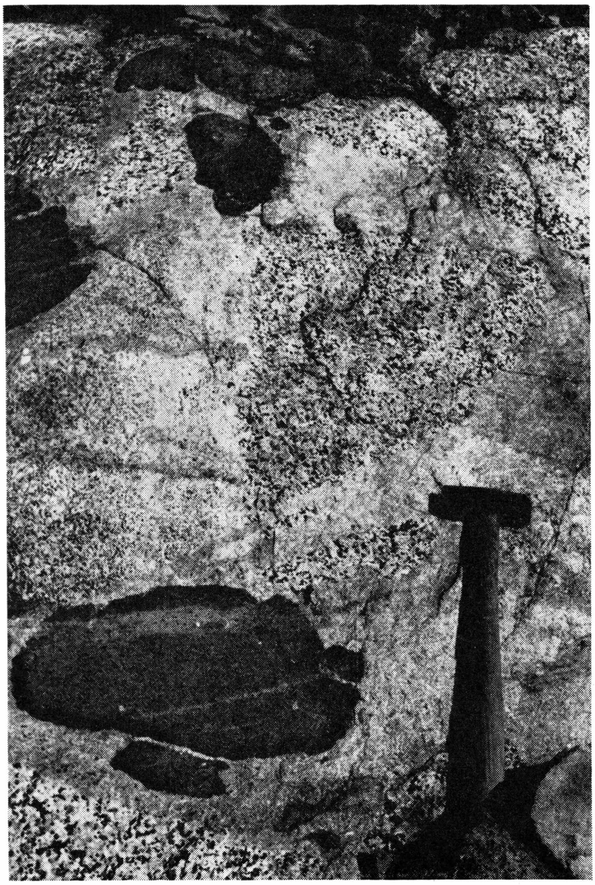

Fig. 16. Microdiorite and monzonite xenoliths in porphyroblastic adamellite. N.E. Johan Dahl Land.

minerals. Apart from the porphyroblasts this texture is identical with those more commonly regarded as typically "igneous" in origin. However, as already mentioned, the presence of relict DA2 dykes proves that a large part of these adamellites cannot have crystallized from a mobile magma. The textures must be due to recrystallization and this seems to be a case of convergence in appearance of the textures of partly mobilized metasomatic rocks with those of orthomagmatic descent such as has been described by Goodspeed (1959).

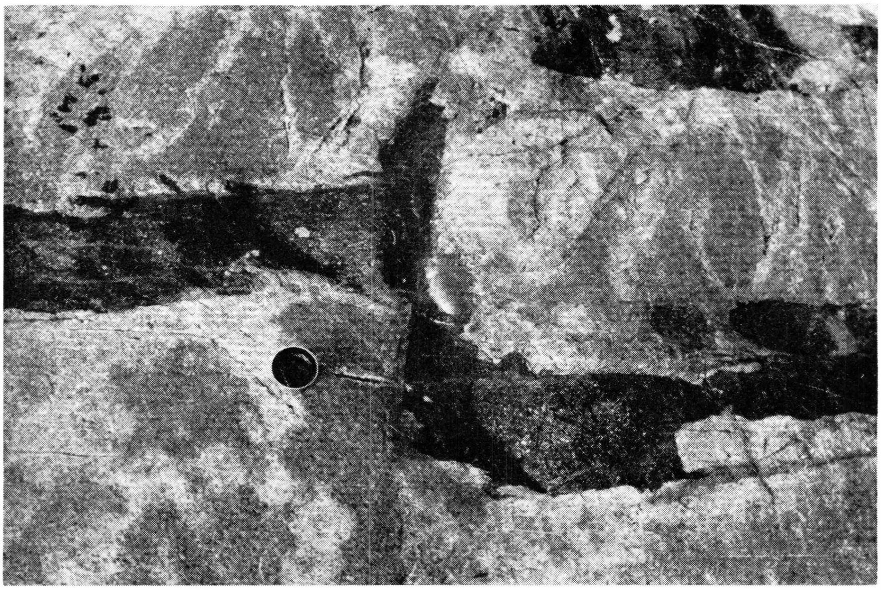

Fig. 17. Second phase microdiorite (DA3) dyke showing apophyses in longitudinal and transverse shear zones. Within Ketilidian granite. S. bank of the river at Narssarssuaq.

Plagioclase crystals show patchy and normal zoning through the range An_{45-0} from cores to margins. NESBITT (1961) suggested that zoned plagioclase in the Sanerutian granites might be relict xenocrysts from Ketilidian rocks. This may be partly true though in this area they would be relict crystals in a granitic rock which is partly of metamorphic origin. Their subhedral form might be easier to understand if they have suffered only marginal recrystallization and have exerted their force of crystallization against completely recrystallizing microcline and quartz. Hornblendes sometimes have augitic cores and rarely true relict augites are present. These features, together with the calcic cores of plagioclase, are probably due to incorporation of DA2s, diorites or other basic material into the reactivated granite. Chemical analyses of the adamellites are given in Table 1. It is apparant from the map (plate 2) that the adamellites are discordant to the Ketilidian structures, and tend to surround the basic masses, leaving relict Ketilidian rocks in between.

Pegmatites and aplites

All rocks older than the third period basic dykes are fairly abundantly cut by various generations of pegmatites and aplite dykes and veins. They are common near the margins of the basic masses, but rare towards their centres.

Third period basic dykes (DA3s)

Second phase microdiorites

Only two dykes showing features similar to the characteristic "syntectonic amphibolites" of other areas have been found. One occurs on the south bank of the Narssarssuaq river close to Kiagtût sermiat,

Fig. 18. Termination of a second phase microdiorite dyke. S. bank of the river at Narssarssuaq.

cutting mainly non-reactivated foliated granite. It is not granitized. It shows apophyses in shear zones parallel to the dyke length, and localized transverse shears associated with offsets but not cutting the apophyses (figs. 17 & 18). The rock contains euhedral dark grey feldspars and hornblendes up to 4 mm long. It is cut by carbonatite dykes which also show syntectonic intrusion features (fig. 24).

The other dyke occurs close to the glacier north of Balder Sø and is cutting porphyroblastic adamellite. The thin-section shows hornblende aggregates after augite. These rocks probably crystallized from augite dioritic magma and suffered some autometamorphism. Evidence from other areas shows them to be older than the third phase microdiorites, but this relationship has not been observed near Narssarssuaq.

Third phase microdiorites

Thin, gently inclined amphibolitic sills are of common occurrence in N.W. Johan Dahl Land and near Odin Sø. They cut Sanerutian adamellites and are never granitized and only rarely cut by thin pegmatites or aplites (figs. 3, 4, 19 & 20). Typical rocks of this group all show very similar features in the field and in thin-section. They are medium- to fine-grained and equigranular, being generally finer-grained than DA2s. In thicker sills margins are distinctly finer-grained than centres. In thin-section plagioclase shows a tendancy towards a subradiating texture. Hornblende forms small, evenly distributed crystals, the aggregates so typical of DA2s being very rarely present. There is probably less hornblende than in DA2s, but more fine-grained biotite which is usually green-brown in colour. Microcline and quartz are generally present.

These amphibolitic sills are not foliated and do not show the characteristic syntectonic intrusion features of typical DA3s in other parts of South Greenland (Watterson, 1965). Allaart (personal communication) considers them to be similar to net-veined microdiorites (Windley, in press) and they could have a similar position to some of these rocks in the chronology, though in this area they are never net-veined. It seems likely that they were intruded as mainly thin sheets (1–2 m thick) of dioritic magma into fairly cold country rocks. One sill which is intruded into porphyroblastic granite shows hornblende aggregates which were probably formed by autometamorphism from augite.

Late amphibolitic sills of the most characteristic type have not been found cutting the diorite and monzonite plutons, but probably closely related lamprophyric sills do occur. These are not foliated but sometimes show peculiar intrusive features possibly indicating some movement in the host-rock during their intrusion (figs. 21, 22 & 23). They show strongly chilled margins, banding parallel to their length which may be due to differentiation associated with movements during intrusion, and also clear evidence of multiple intrusion. Thin-sections of these lamprophyres show euhedral green hornblendes with augitic cores and frequently blue-green margins. Plagioclase, chlorite and epidote are present and calcite occurs in relatively large interstitial areas. Although suitable intersections were not found these lamprophyres are miner-

Fig. 19. Third phase microdiorite (DA 3) sill cutting Sanerutian adamellite. To the left of the hammer handle the sill is cut by a pegmatite vein. Hullet.

Fig. 20. Third phase microdiorite cutting Sanerutian adamellite. The dyke is bordered by pegmatite. Hullet.

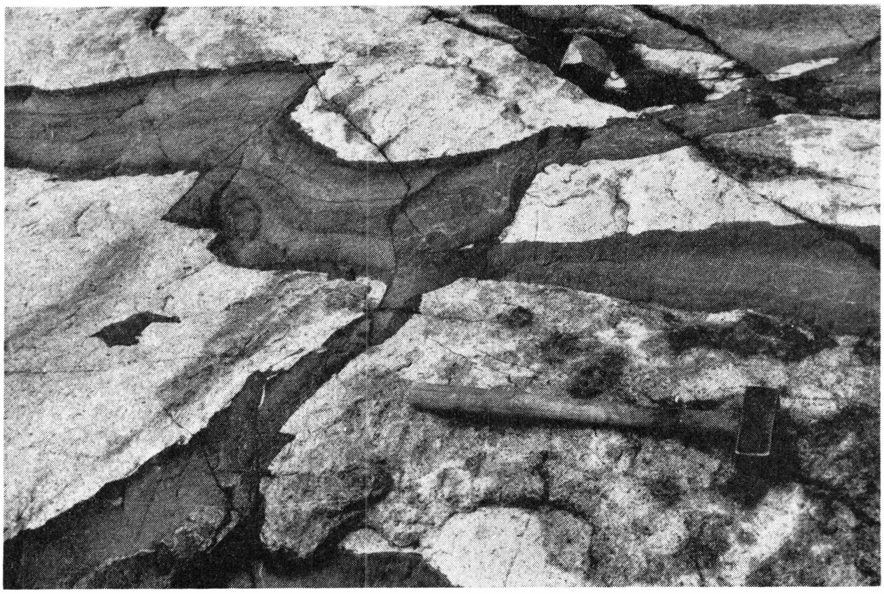

Fig. 21. Third phase microdiorite cutting diorite. Notice the chilled margins to the dyke and the irregular form of the intrusion. Valhaltinde.

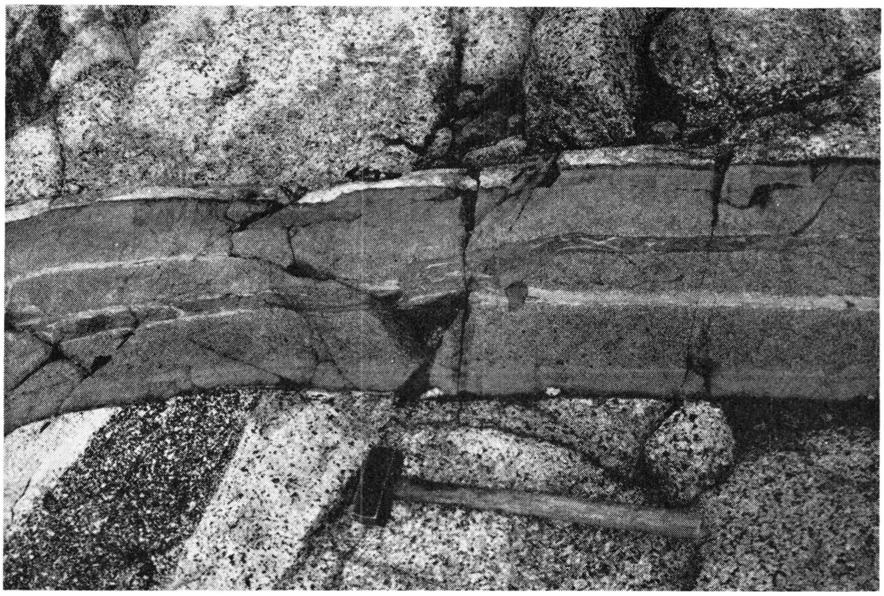

Fig. 22. Third phase microdiorite cutting monzonite. The central part of the dyke might be due to multiple intrusion. Valhaltinde.

Fig. 23. Third phase microdiorite cutting monzonite. The bands within the dyke and its irregular form are original intrusion features. Valhaltinde.

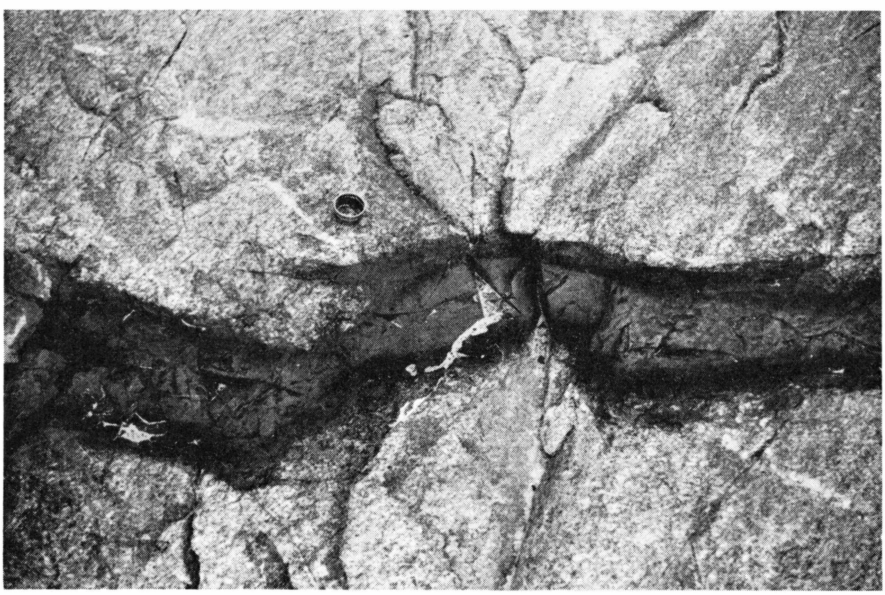

Fig. 24. Carbonatite dyke showing apophyses in longitudinal shear zones. S. bank of the river at Narssarssuaq.

alogically related to the third phase microdiorites and quite different from those intruded later during the Gardar period.

Dark greenish-grey carbonatitic sills and dykes occurring on the south bank of the Narssarssuaq river also show syntectonic intrusion features (fig. 24). These "carbonatites" are unlike the Gardar carbonatites and could represent a late phase in the development of the pre-Gardar lamprophyric-microdiorite suite. It is suggested on p. 60 that the Narssarssuaq Sanerutian intrusive complexes are appinitic in character and the microdiorites are an essential part of this suite. The occurrence of gas emplaced breccias associated with appinitic rocks in other regions e.g. Co. Donegal (Pitcher and Read, 1952, French and Pitcher, 1959) and West Cork (Coe, 1959) could be interpreted as being due to carbonatitic activity. Bondesen (1964) has described a gas emplaced breccia from Sermersût, S.W. Greenland, and has shown that it is related to ultrabasic igneous activity. The breccia is younger than the main phase of granitization and was emplaced between the second and third phases of folding in the area. It is cut by Kuanitic dykes so it is probably somewhat older than the Narssarssuaq appinitic rocks. However in a general way all these bodies show similar late-orogenic settings and may be due to carbonatitic gas activity associated with basic or appinitic igneous intrusions.

GARDAR ROCKS

Igaliko sandstone

This rock does not outcrop in the Narssarssuaq area but xenoliths of quartzite occur in a carbonatite plug intruded into the southern margin of the diorite pluton in Johan Dahl Land. The nearest outcrops are about 13 km away just south of Narssarssuaq and at Qagssiarssuk. The xenoliths are up to a few cm in diameter and are of medium- to fine-grained, yellowish-grey quartzite. In thin-section it is seen to consist of closely packed subrounded quartz grains, often with outgrowths. The cement is mainly microcrystalline quartz and feldspar with some calcite. It is extremely similar to USSING's slide no. 399 – Kvartsitsandsten from "Ataneritsok" Igaliko (USSING's Sydgrønland 1900 slide collection box IV). These xenoliths must have fallen down into the carbonatite magma from an originally overlying deposit of Igaliko sandstone. They indicate that the sandstone was also deposited a considerable distance outside the graben in which it is now preserved.

Carbonatites

Rocks broadly classed as carbonatites occur as sills (fig. 25), dykes and plugs in the Narssarssuaq area. Their position in the Gardar chronology is shown in fig. 1. Most of them probably belong to the earlier period of activity. Several examples have been seen of carbonatite dykes cut by early S.E. trachyte dykes. Also carbonatite plugs are cut by N.E. dolerites and trachytes. On the other hand they are younger than the Igaliko sandstone. Their relationship to early S.E. dolerites is uncertain – carbonatites have been seen cutting these dykes but they could belong to the younger period. Only one certain example of the younger period of activity was found – a carbonatite which cuts a N.E. microsyenite. Therefore most of the carbonatites were intruded early in the sequence and presumably belong to the early-Gardar igneous activity as does the large carbonatite mass at Grønnedal-Íka (EMELEUS, 1964).

Carbonatites are most abundant in a zone about 6 km wide trending E.N.E. immediately north of Narssarssuaq, and plugs (diatremes) are mainly restricted to this zone. The zone coincides with the main con-

Fig. 25. Carbonatite sill cutting foliated granite. Kiagtût.

centration of the mid-Gardar dyke swarms. A few plugs are found north of this zone, the most northerly being in southern Johan Dahl Land, and sills and dykes though not abundant are found throughout the area. Stewart (1962) has made a special study of these rocks at Qagssiarssuk and has also looked at some of the occurrences north of Narssarssuaq. He has recognised that there are often two phases of intrusion represented – a younger, pale weathering, flow-banded type which cuts or includes older, darker intrusives. The younger phase consists of true carbonatites but the older intrusives were probably alkaline, ultrabasic types which have been secondarily carbonatized to a greater or lesser extent. The younger phase has tended to preferentially intrude sites of intrusion of the earlier phase, but separate sheets also occur. The older period of carbonatite activity in the Narssarssuaq area includes both phases, but only true carbonatite has been recognised in the activity which post-dates the N.E. microsyenite dykes. The sills and dykes do

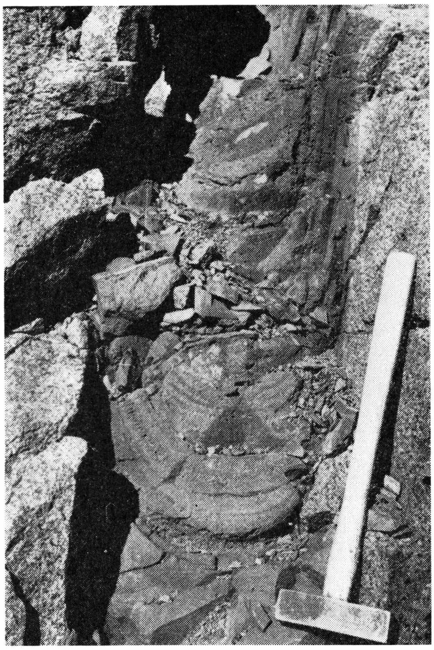

Fig. 26. Carbonatite dyke with flow banding cutting diorite. Johan Dahl Land W.

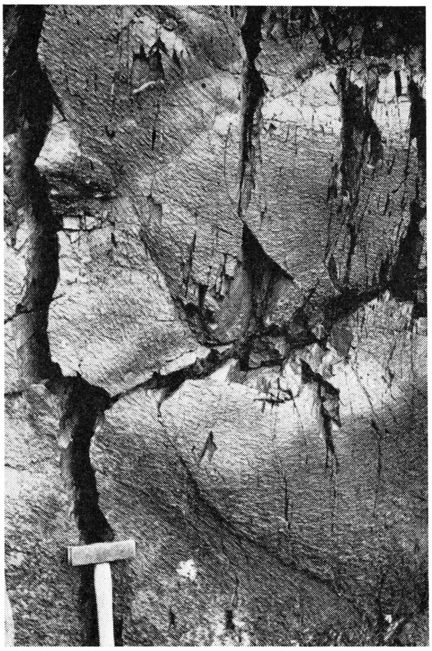

Fig. 27. Granite surface of contact with carbonatite dyke showing flow lines of "blisters". S. of Qôrnup kûa.

not generally exceed 1 m in thickness and change direction very rapidly, apparently following joints in the country rock. One dyke intruded into diorite shows flow-banding which resembles an isoclinal fold, closing downwards with a horizontal axis (fig. 26). The surface of the granite in contact with another dyke shows flow-lines of "blisters" presumably due to heat from the carbonatite magma (fig. 27).

The diatremes vary from roughly circular to lenticular in outcrop and show some tendency to be elongated in the direction of the zone of their main concentration i.e. E.N.E. – N.E. This is approximately the direction both of the granite foliation and the Gardar dyke swarm. The largest are about 300 m long by 100 m wide. Their contacts are approximately vertical. Outcrops are characteristically yellow in colour with rather cavernous rock and abundant scree. According to STEWART (1962) the matrix is highly carbonated, magnetite-bearing tuffisite formed of attrited country rock (granite), with a variable admixture of alnöitic material, partly in the form of lapilli. Angular to subrounded blocks of granite are abundant (fig. 28) and show various degrees of alteration. Well-rounded blocks of ultrabasic material are also present. The granite fragments have been subjected to carbonatization which has involved the replacement of the original minerals by fine-grained

Fig. 28. Blocks of granite (light) and ultrabasic rock (dark) within a carbonatite diatreme. N.E. of Kiagtût.

Fig. 29. Granite spheroidally brecciated by carbonatite intrusion N. of Kiagtût.

calcite, iron ore, sericite and chlorite. At times the amount of carbonatite is extremely small but the granite is brecciated partially into spheres (fig. 29). Also the variable attitude of the foliation in the granite blocks shows that they have been moved by the carbonatite intrusion.

The carbonatites have not yet been studied to any detail in thin-section but they seem to consist dominantly of fine-grained carbonate. Sometimes amygdales are present and these generally show marginal fillings of chlorite with calcite in the core, or these two minerals may show a graphic intergrowth. Patches of spherulitic zeolites (?) also occur. Magnetite and pyrite are frequently abundant and biotite also occurs. Relicts of feldspar, olivine and possibly nepheline may be present.

Dolerite and basalt dykes

Three sets of doleritic dykes may be distinguished in this area.

1) E.S.E. trending. These early dykes are cut by N.E. dolerites and may be approximately contemporaneous with S.E. trachytes though that is not known for certain. They are not common.

2) S.S.E. trending. A few dykes with this trend have been found but their relative age is uncertain.

3) N.E. trending. These dykes are abundant in the south of the area where they are associated with microsyenite, and in the north of the area (plate 2). Some are older than N.E. potassic microsyenites and some younger, but it is uncertain whether these should be regarded as separate generations.

The dolerites consist generally of plagioclase, titanaugite, olivine and iron ore, and show good ophitic texture. Olivine is nearly always altered to serpentine and chlorite and these minerals also occur interstitially. N.E. dolerites have more strongly marked alkaline affinities than the earlier S.E. dykes, and are generally true trachydolerites. In these trachydolerites plagioclase shows poorly-defined multiple twinning with narrow lamellae, and untwinned areas. These feldspars have low R.I. and some take a slight cobaltinitrite stain, so they must be sodic and possibly partly potassic. They are very similar to the feldspars in the sodic microsyenites. The N.E. trachydolerites show a small development of biotite and rarely some amphibole. Pyroxenes are always titanaugite, including in the S.E. dykes, and are frequently zoned with narrow aegirine-augite rims. Apatite is abundant in the alkali-rich dykes. N.E. dolerites show more extensive hydrous alteration than do S.E. dykes in spite of being younger. It appears that the earlier S.E. dolerite dykes of this area had suffered less differentiation than the N.E. dykes. The magma which formed the younger dykes must have been a little more hydrous as well as richer in alkalis.

Just south of Nordbosø an unusual kind of E.N.E. trachydolerite occurs. This dyke is about 30 m thick south of Nordbosø and can be traced for at least 14 km to the west where it is about 100 m thick. It is a coarse-grained, leucocratic rock with black pyroxenes up to 5 mm long. In thin-section it shows a remarkable graphic intergrowth of alkali feldspar, quartz and iron ore. Titanaugite forms large euhedral crystals sometimes with hornblendic margins. Large partially altered plagioclase crystals are also present. Chlorite and calcite occur interstitially. Because of the absence of biotite and discrete hornblende it is considered unlikely that this rock results from the mixing of basaltic and syenitic magmas. It seems more likely that it is due to abnormal enrichment of basaltic magma in alkalis, silica and water by diffusion. This would help to explain its peculiar pegmatitic texture.

Fig. 30. Rhythmic banding in gabbro. Mellemlandet.

Gabbro

Two gabbro giant-dykes occur in N.E. Mellemlandet. Both trend about 60° E. of N. The more northerly one is 200 m thick and its outcrop crosses the land between the glaciers though it was not recognised west of Kiagtût sermiat. The more southerly dyke is 700 m thick and at least 4 km long but must either thin out, or be cut off by a fault beneath Kiagtût sermiat. To the east it thins rapidly to a dolerite dyke. The gabbro has a relatively fine grained chilled margin of homogeneous dolerite and close to this igneous foliation is developed due to parallel orientation of tabular plagioclase. At the southern margin this foliation strikes 50° E. of N. and dips about 25° N.N.W. Rhythmic banding is sometimes developed parallel to the igneous foliation (fig. 30). Towards the centre of the dyke the gabbro is coarser-grained and the foliation is more irregular, though rhythmic layering is well developed and clearly

Fig. 31. Anorthosite lens cutting banding in gabbro. Mellemlandet.

indicates that the dyke has an internal synclinal structure, the axis of which plunges gently to the W.S.W. There are anorthositic patches of uncertain form up to about 50 m^2 in area, and smaller anorthosite lenses which cut across the rhythmic banding (fig. 31). These are probably best interpreted as injected differentiates of the gabbro.

Judging from the form of its outcrop in relation to topography the Mellemland gabbro giant-dyke must have steep contacts in contrast to the gentle dips of the internal banding. It may have the form of a greatly elongated funnel shaped lopolith tilted gently downwards in a westerly direction. Wilson (1956) has suggested that the Great Dyke of Rhodesia has a funnel shaped structure in cross-section, and that this may apply to other layered basic intrusions. The dolerite dyke continuation to the east could represent the feeder to the lopolith, and if so this is a comparable case to the much larger Muskox gabbro intrusion in N.W. Canada described recently by Smith and Kapp (1963). Subsurface graben-like faulting with block sinking as in cauldron subsidence could have allowed largely passive introduction of the basic magma.

The gabbro consists of plagioclase, titanaugite, olivine and ore together with a little biotite and interstitial, microperthitic potassium feldspar. Thus it has alkaline affinities which relates it to the N.E. dolerites in general. Upton (1962) has described similar parallel gabbro giant-dykes from Tugtutôq which is some cases have syenite cores, considered by Upton to be due to intrusion of syenite magma along the centre of the gabbroic dyke before this was completely solidified. A 10 m wide porphyritic potassium microsyenite cuts the Mellemlandet gabbro close to its axial line and trends parallel to the main dyke.

Microsyenite and trachyte dykes

Alkaline dykes in the Narssarssuaq region may be divided into trachytes (groundmass grain-size < 0,3 mm) and microsyenites (grainsize > 0,3 mm). The microsyenites always have chilled trachyte margins, but smaller dykes are entirely trachyte except for those immediately associated with the Igaliko batholith where even the smallest veins are still microsyenites. They may be divided into an older S.E. set which are rare in this area, and a younger N.E. set which are extremely abundant in the south of the area. Very few alkaline dykes are found north of a line trending E.N.E. through the end of Tunugdliarfik. The S.E. dykes are thin and always trachytes whereas the N.E. dykes may be of all thicknesses up to 40 m, with the majority between 10–30 m thick.

Further distinctions may be made between those which consist dominantly of sodic feldspars and those with predominant potassic feldspars, also between porphyritic and nonporphyritic varieties. The distinction between sodic and potassic dykes is readily made for the coarser-grained varieties in thin-sections, but is more difficult in the field. S.E. trachytes generally contain relatively few phenocrysts some of which are clearly albitic and others potassic. The groundmass is always dominantly albitic. In the N.E. dykes potassic types are more abundant and include porphyritic and nonporphyritic microsyenites and trachytes. However nonporphyritic sodic microsyenites are also common and a few trachyte equivalents have been collected.

S.E. trachytes are younger than early carbonatites but older than N.E. dolerites (fig. 1). N.E. potassic dykes are younger than some N.E. dolerites but older than others. N.E. sodic dykes have been found to cut N.E. potassic dykes but the reverse has not been seen. However there is a later generation of N.E. potassic dykes i.e. some which cut N.E. big feldspar dykes. Therefore N.E. sodic dykes are younger than most N.E.

potassic dykes, though possibly the same age or slightly older than others. Also phenocrysts in the dykes are nearly always potassic feldspar. These facts might suggest that potassic feldspars and the corresponding magma fraction formed slightly earlier than the albitic fraction. The possible petrogenesis is discussed in the final section of this paper.

The potassic dykes are reddish-brown when coarser-grained but finer-grained portions are dark grey or reddish if sheared. Sodic dykes vary in colour from light grey for the coarse microsyenites which typically have a flow oriented or sometimes sub-radiating feldspar texture, to dark grey for trachytes which are again reddish if sheared. Examination of thin-sections shows that there are all transitions between dominantly potassic and dominantly sodic dykes, according to the relative proportions of the two kinds of feldspar in the groundmass. All varieties may contain potassic feldspar phenocrysts but they are more common in the potassic dykes. Only the more extreme varieties can be distinguished in the field.

Potassic feldspars form relatively short and broad crystals showing a simple Carlsbad twin, whilst sodic feldspars are more elongated and show albitic twinning. Potassic feldspar phenocrysts occur as aggregates of three or four poorly-shaped crystals. Subhedral crystals of augite, sometimes with sodic rims, presumably crystallized before the groundmass feldspars. On the other hand green-brown hornblende and biotite crystallized mainly after the feldspars and occur interstitially giving a pseudo-ophitic texture. Sometimes hornblende is moulded onto augite cores. Quartz is commonly present in the potassic and sodi-potassic dykes, and accessories include allanite, serpentine and chlorite. In the more sodic dykes augite has aegirine margins, hornblende has blue rims and interstitial altered nepheline and fresh analcite (or sodalite?) occur when quartz is not present. One unusual variety of a sodic trachyte was found in N.W. Johan Dahl Land. This is a thin dyke with euhedral enstatite crystals set in a groundmass of albitic feldspars with some glassy material and ore. It is the only recorded occurrence of orthopyroxene in a Gardar rock.

Big feldspar dykes

Many of the thickest dykes in the main N.E. swarm immediately north of Narssarssuaq are of a distinctive type extremely rich in large plagioclase crystals or cleavage fragments especially near the centres of dykes (fig. 32 & 33). Margins of the dykes are often free from megacrysts and there is sometimes an intermediate zone with relatively few megacrysts. The feldspars show a planar orientation parallel to the sides of the dykes. These dykes have been described from neighbouring

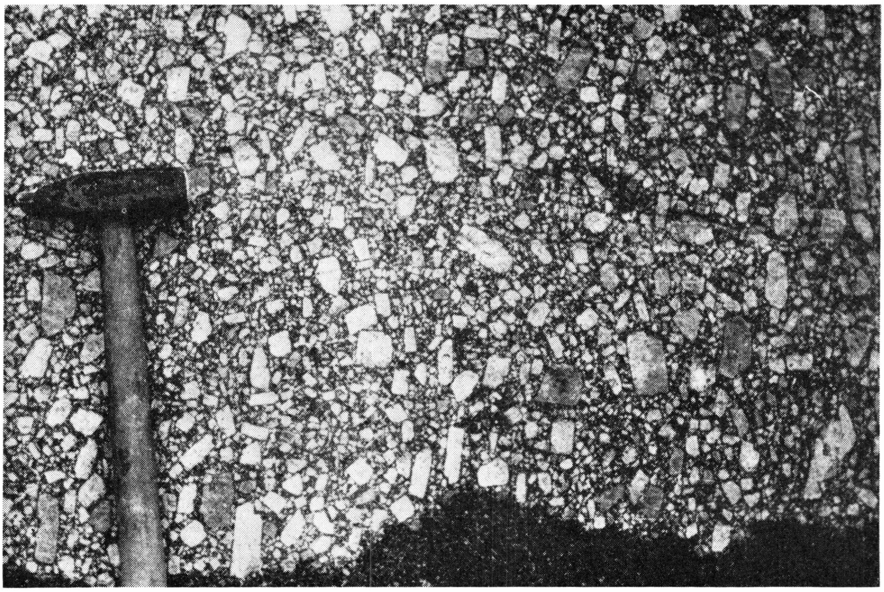

Fig. 32. Big feldspar dyke. S. bank of the river at Narssarssuaq.

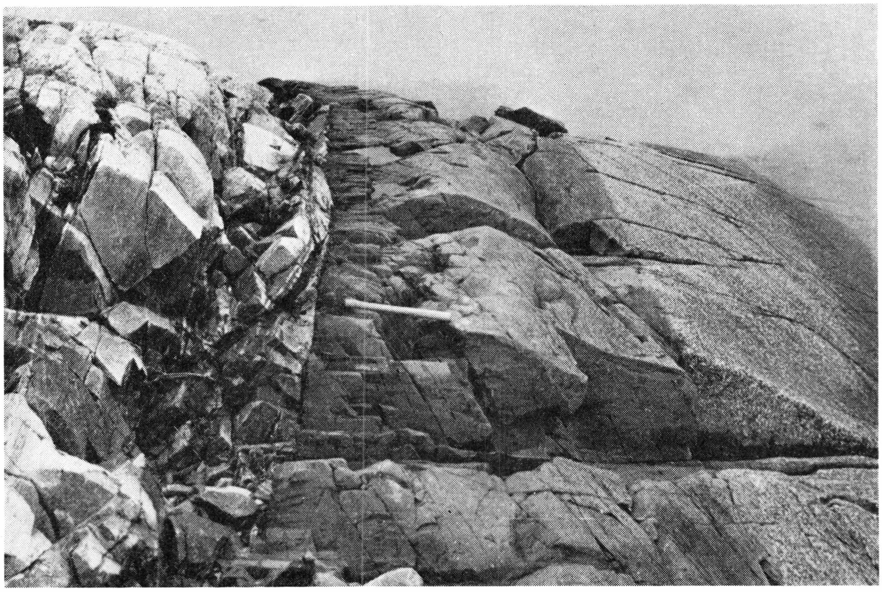

Fig. 33. Big feldspar dyke cutting foliated granite. Notice that the dyke margin is almost free from feldspar xenocrysts. Kiagtût.

areas in South Greenland e.g. UPTON (1962) and it has been generally recognised that the plagioclase crystals are xenocrysts from anorthosite. The most characteristic big feldspar dykes in the Narssarssuaq area all have a sodic trachyte ground-mass, but lesser amounts of anorthositic feldspar xenocrysts or xenoliths of aggregated feldspars (figs. 34 & 35) have been found in practically all generations of Gardar dolerites and microsyenites. North of Qínguata kûa E.N.E. trending trachydolerites containing fewer xenocrysts than typical big feldspar dykes, are quite common.

A minor generation of big feldspar dykes trends S.E. and may be approximately the same age as early S.E. trachytes but no intersections have been seen. The vast majority of big feldspar dykes trend N.E. They have been seen cutting some N.E. potassic trachytes and are cut by N.E. sodic trachytes. In thin-sections the plagioclase xenocrysts are seen to be generally more altered (sericitized) than the groundmass feldspars. A characteristic of these rocks is that they tend to be fine-grained, even near the centres of thick dykes, and this could be due to chilling against plagioclase xenocrysts throughout the dyke. Also mafics are usually completely altered to chlorite and epidote which suggests a fairly high water content of this magma fraction.

Lamprophyre

Only one example of a presumably Gardar lamprophyre has been found. This occurs as a 5 cm thick gently inclined sill cutting monzonite in central Johan Dahl Land. It is a dark-green rock weathering to light-green, and contains black needle-like crystals of hornblende up to 5 mm long. The hornblende is euhedral and flow-oriented. It has $2V = 82°$, $\gamma \wedge C = 19°$, Z (dark-green) > Y (olive-green) > X (light-yellow). The groundmass consists of fine-grained oriented feldspar. There are rectangular and six-sided phenocrysts of a colourless mineral with very low relief, and wavy low birefringence—possibly nepheline or a zeolitic alteration of it.

Igaliko syenite

The Igaliko syenite complex has been mapped by W. T. HARRY and C. H. EMELEUS, but the writer has discovered two areas of syenite which must be related to the main batholith. The smaller of these forms the hill Qáqatsiaq, immediately north of the Narssarssuaq estuary. In places the contact of the syenite with foliated porphyroblastic granite can be seen to be knife-sharp and irregular in detailed trend. A fine-grained margin, 1–2 cm thick is sometimes present in the syenite.

Fig. 34. Anorthosite xenolith in dolerite. N. bank of the river at Narssarssuaq.

Fig. 35. Xenoliths of darker microsyenite within a lighter rock of the same general type. Both rocks contain plagioclase xenocrysts. N. of Kiagtût.

The syenite is pink coloured when fresh, consisting mainly of subhedral perthitic potassium feldspar up to 7 mm in length. Smaller feldspars show indefinite multiple twinning and are presumably albite. Dark-green hornblende with colourless augite cores is quite abundant and there is also some aegirine. Completely sericitized and epidotized areas may have been plagioclase or nepheline. There is no quartz. Hydrothermal alteration veins occur. These are white in colour and show extensive sericitization and chloritization of the coloured minerals.

Mapping by Emeleus and Harry (1962) indicates that there is a small syenite outcrop immediately south of the Narssarssuaq river with which that at Qáqatsiaq is probably continuous. The whole forms a small cupola separated at the surface from the main Igaliko complex.

A larger area of syenite is present on Mellemlandet immediately north-west of Qôrqup sermia. Here the syenite is coarse-grained and in hand-specimen apparently consists only of pink feldspar and black pyroxene or amphibole. Mafic pegmatitic bands are present near the contact which strike 30° E. of N. and dip at 60° N.W.—possibly subparallel to the contact. Mafic minerals have grown perpendicular to the margins of these layers. The contact with the Sanerutian diorite is irregular in detail and syenite veins penetrate the diorite. A 50 m thick dolerite trending 100° enters the syenite on the north-east side of the largest lake near the contact. Numerous small syenite dykes cut the dolerite which continues for about 50 m into the syenite before it is cut off. N.E. trending big feldspar dykes cut the syenite. From the descriptions given by Emeleus and Harry in their unpublished report for 1962, this syenite seems to be closest in characteristics to type S^a associated with the Motzfeldt-iptasia intrusive centre.

Faulting

Faulting has not been studied in detail in this area but major shear-zones with mylonite formation have been developed in various directions and at various times before and during the Gardar period, as can be seen from their relation to the dykes. Immediately south of Johan Dahl Land, close to Kiagtût sermiat a 20 m thick massive quartz dyke is associated with an E–W mylonite. It can be traced for about 1 km. This quartz dyke is younger than a N.E. big feldspar dyke. Veins containing euhedral crystals of quartz and calcite sometimes with hematite and pyrite are occasionally associated with the faults.

PETROGENESIS IN RELATION TO THE DEVELOPMENT OF THE KETILIDIAN-SANERUTIAN OROGENY

The geological chronology of the Narssarssuaq region is shown in fig. 1. The oldest rocks are banded gneisses present as a relict band within foliated porphyroblastic granite ("Julianehåb granite"). These gneisses are presumably derived from Ketilidian sediments. The N.E. trending structures of the gneiss and granite correspond to the dominant trend of Ketilidian folding recognised elsewhere in South Greenland (Allaart, 1964). Relics of foliated, granitized amphibolite dykes are found which might represent an early period of basaltic activity (DA1s) i.e. intruded during the geosynclinal phase or between periods of Ketilidian folding. The foliation in the porphyroblastic granite developed before the second period of intrusion of basic dykes (DA2s) since these dykes are discordant to the foliation and are not themselves foliated. The granite represents an end-stage in the granitization processes operating during the main folding and regional metamorphism phase of the orogeny. It is developed in a broad belt trending N.E. through Julianehåb, and Ketilidian supracrustal rocks are well preserved to the north-west and south-east. The Julianehåb region possibly represents a root zone in the orogenic belt and it is here that the syntectonic granitization-homogenization processes have been most effective.

The foliated granite shows abundant evidence of renewed movement along the earlier foliation planes which is essentially post-crystallization in development. This shearing affected cold rocks and although penetrative, was probably localized to certain broad belts. The foliated aplitic granite was developed at this stage by granulation of coarser, more or less homogeneous granite. This penetrative cold shearing probably continued after the intrusion of the DA2s since these dykes are somewhat disrupted. However younger rocks such as the diorites and younger granites are only affected by much more localized shear zones.

The second phase of basic dyke intrusions (DA2s) were subsequently metamorphosed and partially granitized by renewed plutonic conditions the nature of which will be discussed immediately. In the Ivigtut region Kuanitic dykes can be traced from unmetamorphosed dolerite dykes into amphibolites (Bondesen and Henriksen, in press). No certain correlation is yet possible between any of the Kuanitic dykes and DA2s though some of them may be equivalent. At Narssarssuaq the dykes are much thinner than those at Ivigtut and are less typically "cratogenic", but were nevertheless probably emplaced during a tempory cratogenic phase in the development of the orogeny.

The DA2s show more thorough metamorphism than the somewhat younger microdiorites which were also emplaced before the main granite reactivation. Possibly this is because the DA2s originally had a more unstable, higher temperature mineral assemblage, i.e. doleritic, as compared with the microdiorites. Also the DA2s probably cooled completely prior to metamorphism whereas the microdiorites may have remained at a fairly high temperature while the granite was being reactivated. The second period basic dykes are always metamorphosed in the Narssarssuaq region even when they are emplaced in largely unreactivated granite. In this case it seems likely that metamorphism, due to a general rise in temperature, is more apparent in the DA2s than the enclosing granite because of the relative instability of the doleritic mineral assemblage compared with that of the granite.

A suite of rocks varying from alkali noritic gabbros to hornblende diorites and hypersthene monzonite were intruded subsequent to the DA2 intrusions. The two main plutons on Valhaltinde and Johan Dahl Land are stock-like with steeply dipping sides, but the diorite south of Nordbosø, and the gabbro in N.W. Johan Dahl Land resemble giant-dykes trending E.N.E. and N.N.W. respectively. Layering is extremely rare in these bodies but gently inclined anorthositic lenses occur in the gabbro near Nordgletscher, their lenticular form probably being due to the effect of intrusion movements on largely crystallized and differentiated magma.

The Johan Dahl Land pluton shows a gradation from hypersthene diorite near the core to hornblende diorite near the margin. In complexes elsewhere e.g. Deer (1935) a similar variation has been produced by successive intrusions of distinct diorite varieties but no evidence has been found for that here. The variation here might be due to either metamorphism or granitization of a hypersthene diorite or gabbroic mass, or to differentiation in the magmatic body. Metamorphism or granitization might be thought to be responsible because the Johan Dahl Land pluton is almost completely surrounded by reactivated granite. However chemical analyses of these rocks (Table 1) show that isochemical metamorphism is not the correct explanation. Also granitization is considered to have played only a relatively minor role in the development of these rocks for various reasons. Firstly on Mellemlandet (fig. 36) and also in N.W. Johan Dahl Land (figs. 37 & 38), original chilled margins are preserved in the diorites where they are in contact with the older mainly unreactivated granitic rocks. These margins are about 10 cm thick and distinctly fine-grained with small hornblendes showing a flow alignment. Their features show that they are original chilled contacts, not fine-grained recrystallization margins (cf. Wells and Wooldridge, 1931). They have only been observed where the diorites are in contact with older unreactivated granitic rocks. The diorites for a thickness of 0.5–1 km in contact with these chilled margins are hornblende rich with

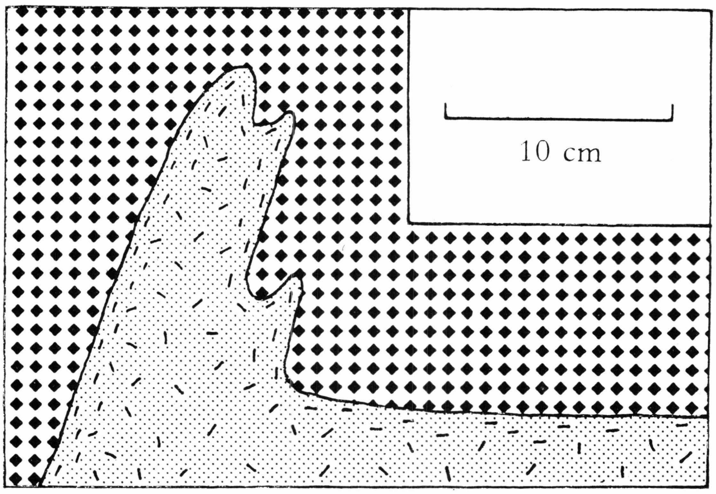

Fig. 36. Chilled contact of hornblende diorite against Ketilidian granite. Flow alignment of small hornblendes is indicated within the diorite margin. Mellemlandet.

relict augites, but without relict hypersthene or olivine, and this is also generally the case where they are in contact with younger reactivated granite. Biotite and microcline are no more abundant in the outer zones of the plutons than in the centres which suggests that not much grantization has occurred. Relationships between hornblende diorites and younger granites are essentially those of equilibrium possibly because the diorites had crystallized but were still hot i.e. at about the same temperature as the granite while the latter was active. This idea is taken from Windley (in press) who has interpreted the net-veined microdiorites in this way. The textures in the hornblende diorites are characteristically igneous or autometamorphic. Most of them should not be called amphibolites. Therefore it is concluded that metamorphism and granitization have had relatively little effect on the diorites of this area and the variation within the plutons must be dominantly a magmatic feature.

Original magmatic zoning of the type present here might be due to cooling of the magma giving crystallization at progressively lower tem-

Fig. 37. Chilled contact of hornblende diorite against Ketilidian aplite. Notice the flow alignment of small hornblendes. N.W. Johan Dahl Land.

Fig. 38. Detail from fig. 37.

peratures towards the margins of the pluton. The magma, although originally basic, had become contaminated by sialic material, including water, as a result of emplacement in the orogenic environment. It is noteworthy that the chilled contact consists of hornblende diorite i.e. not the original composition of the magma, and it would appear that crystallization was both fast enough to give a chilled contact, and slow enough to allow mineralogical adjustments to the falling temperature. An alternative explanation could be similar to that given by Smith and Kapp (1963) for the Muskox Intrusion where the chill facies contains less olivine than the main part of the body. They have suggested that the chill phase represents the fluid portion of the solid (olivine)-fluid magma. Gunn (1963) has recorded that marginal phases of otherwise hypersthene bearing dolerites in Antarctica do not have hypersthene. It seems difficult to decide which of these two processes operated for the Narssarssuaq rocks and it is quite possible that there was a combination of the two effects.

Other cases directly comparable with the Johan Dahl Land pluton are described by Anderson (1935b) for the Arrochar intrusive complex of Scotland. Appinite margins are present to several of the kentallenite bearing intrusions near Loch Lomond. In none of these cases can direct evidence of age relationship be adduced, but Anderson notes that marginal facies are usually of earlier consolidation than inner portions of intrusions, and suggests that this is possibly an example of a reversal in the normal sequence of intrusion from basic to acid in that region. Alternative explanations as outlined above might apply to these bodies also.

Textures in the basic rocks have a typical igneous character. In the hypersthene diorites and monzonites as many as seven essential minerals may be present, their textures indicating crystallization according to Bowen's reaction series. Bowen (1928, pps. 56–59) suggested that corona type textures may be well preserved when there is rapid cooling. More recently Joplin (1959) has suggested that these textures in diorites and monzonites are due to hybridization. For the Narssarssuaq rocks the writer considers the main cause of the large mineral assemblage to be the enrichment of basic magma in alkalis and water by assimilation in the orogenic environment—a contrast with intrusions such as Skærgaard.

The first phase microdiorites show the same mineralogy and textural features as the hornblende diorites and have the same position in the chronology, so they are considered to represent the more liquid portions of the dioritic magma.

Hypersthene monzonite was intruded immediately after the diorites but before the main granite reactivation. Reasons are given on p. 26

for considering that the monzonite, and locally syenite, was produced by the enrichment of the central portions of the hypersthene diorite magma chamber in potassium by diffusion consequent on the crystallization of magma at the margins and roof of the chamber.

Following the hypersthene monzonite intrusion there was a period of granitic activity. It has been shown that the adamellites developed partly by recrystallization although locally they were chemically and mechanically mobile. As a result older rocks such as the diorites, monzonites and DA2s were invaded by granitic material. It is thought that recrystallization of the granites was rather thorough at this time as there are practically no relicts of earlier foliation preserved in them. On the other hand there is little evidence of extensive introduction of granitic material either metasomatically or magmatically. The foliated Ketilidian granites are largely of adamellite composition and would require only simple recrystallization to produce the Sanerutian adamellites. In the Narssarssuaq region these younger granites closely surround the basic bodies and it seems necessary to conclude that here they are partly due to contact metamorphism and local melting. Palingenetic magma rising from greater depths probably also contributed to their development. The granite remained active after the crystallization of the basic bodies because of its lower temperature of crystallization. In the rest of South Greenland there is a less close relationship between the intrusion of basic bodies and granite reactivation. Most often these bodies are smaller than at Narssarssuaq and may be surrounded by largely unreactivated granite. In this case the basic body probably had insufficient energy to produce wholesale recrystallization of the granite. This is probably true for the south-eastern extremity of the diorite intrusion on Mellemlandet. Alternatively small basic plugs may be surrounded by very thoroughly reconstituted granite which then is more likely to be due to other processes. Furthermore basic bodies are sometimes surrounded by intrusive younger granites e.g. at Sydprøven (Bridgwater, 1963). Considering the region as a whole, basic to intermediate bodies of this age are largely restricted to the area showing reactivation. The relationship may be as follows:—During the epeirogenic uplift phase of this root zone of the orogenic belt introduction of palingenetic acid magmas, and basic magmas contaminated by sialic material, caused a general rise in geoisotherms. The palingenetic acid magmas were possibly formed mainly at greater depths during the preceding main folding and metamorphism periods but now rose to higher levels in the orogenic pile. Metamorphism and granitic reactivation during the epeirogenic phase is most noticeable in proximity to the magmatic bodies or where localized intense deformation has occurred.

After the granitic activity including most of its final pegmatitic and aplitic phase had ceased, further microdiorite dykes and sills were intruded (DA3s). Two episodes can be generally recognized for South Greenland. The earlier hypabyssals, which are poorly represented in the Narssarssuaq area, show abundant signs of mechanical mobility in the country rocks during their intrusion. The later episode most commonly shows granitic net-veining, though not in this area. Some of these rocks are lamprophyric and carbonatitic. These would seem to be the final expressions of the appinitic suite. The Gardar alkali-rich igneous activity followed.

The writer is of the opinion that the rocks of the Narssarssuaq region and of South Greenland generally can be regarded as forming a major unified cycle of development. This cycle is essentially that of the development of the Ketilidian-Sanerutian orogeny together with a prolonged post-orogenic phase. The term orogeny is here used to cover the complete sequence of events from the deposition of the geosynclinal sediments to the uplift of the mountain chain with its erosion and associated igneous activity. The unity of this sequence of events has been indicated by various writers including Tyrrell (1955) and Harpum (1960). Harpum emphasizes the importance of this concept in particular for the understanding of Precambrian geology. Sutton (1963, b) has introduced the useful term chelogenic cycle to describe a long-term cycle of crustal activity. One of these he calls the Svecofennid cycle which started between 1,900–1,700 m.yr. ago and ended between 1,200–1,000 m.yr. ago. Isotopic age dates of about 1,800 m.yr. from southern Greenland (Bridgwater, in press, Dibner *et al.* 1963, Treves, 1964) could be interpreted as indicating the main Ketilidian metamorphism. Age dates of about 2,700 m.yr. could then be taken to indicate pre-Ketilidian activity. Fairly abundant age dates cover the period from 1,800 m.yr. down to 1,020 m.yr. which represents the date of the youngest Gardar rocks. If 1,800 m.yr. is correct for the age of the main Ketilidian metamorphism then the Ketilidian, Sanerutian and Gardar together correspond closely to the complete Svecofennid chelogenic cycle. The Ketilidian-Sanerutian events represent an early orogenic belt of this cycle with the Gardar representing the igneous activity associated with the continental disruption during the later phases of the cycle. A summary and interpretation of the major geological events of South Greenland is shown in Table 2.

The term "Sanerutian" was given by Berthelsen (1961) to the plutonic reactivation which followed the intrusion of the Kuanitic dykes in South Greenland. The term was redefined by Watterson (1965) as the plutonic episode which affected the post-Ketilidian dolerite dykes (DA2s). Berthelsen thought that the reactivation was possibly related to the development of the younger Nagssuqtoqidian orogeny. However

Table 2. *Summary and interpretation of the major geological events of South Greenland.*

Chelogenic cycle		PERIODS	APPROX-IMATE DATES	CONDITIONS	GEOLOGICAL ACTIVITY
GRENVILLE CHELOGENIC CYCLE		? TERTIARY	? 50 m.y.	Cratogenic Tension	Basic dykes
GRENVILLE CHELOGENIC CYCLE		MAJOR HIATUS			
SVECOFENNID CHELOGENIC CYCLE	TECTONO-MAGMATIC CYCLE	GARDAR	1000 m.y. – ? 1400 m.y.	Post-orogenic Cratogenic Tension	Basic & alkali igneous rocks Molasse (?) sedimentation Faulting
SVECOFENNID CHELOGENIC CYCLE	TECTONO-MAGMATIC CYCLE	SANERUTIAN	1650 m.y.	Late-orogenic Epeirogenic uplift Alternating compression & tension	Formation of younger granites, intrusion of basic to intermediate magmas (appinitic suite). Sub-regional metamorphism. Localized folding. Shear faulting.
SVECOFENNID CHELOGENIC CYCLE	TECTONO-MAGMATIC CYCLE	KUANITIC		Minor cratogenic	Basic dykes
SVECOFENNID CHELOGENIC CYCLE	TECTONO-MAGMATIC CYCLE	KETILIDIAN	? 1800 m.y. – ? 2000 m.y.	Main-orogenic Compression Geosynclinal Tension	Regional metamorphism, granitization and folding. Sedimentation with basic volcanic activity.
SHAMVAIAN CHELOGENIC CYCLE		? MAJOR HIATUS			
SHAMVAIAN CHELOGENIC CYCLE		PRE-KETILIDIAN	? 2700 m.y.	Orogenic etc.	Gneisses etc. in places "Ketilidized".

the writer considers that the reactivation in South Greenland is more likely to be a late-stage in the development of the orogeny which started in Ketilidian times i.e. the earlier part of the epeirogenic uplift phase.

The writer has arrived at these conclusions mainly by a consideration of the petrogenesis and tectonic setting of the gabbro-diorite-monzonite suite of plutons in the Narssarssuaq area. This is an appinitic suite with many similarities to the type occurrences in the Scottish Caledonides. In Scotland the appinitic rocks were intruded after the main periods of folding, metamorphism and granitization but just before the formation of the Newer Granites (Tyrrell, 1955, Read, 1961). This is also true for the Narssarssuaq area in particular and for South Greenland in general. In this connection the writer regards the reactivation and the formation of the younger granites as one interconnected broad process, though varying considerably in style and exact time of development from one place to another. In Scotland, Sutton (1963, a) has suggested that there is only one Caledonian orogenic cycle i.e. the "Early Caledonides" and "Late Caledonides" of Read (1961) cannot really be separated there. Nevertheless the time of intrusion of the Newer Granites in Scotland i.e. approximately Upper Silurian to Lower Devonian, was a time of folding elsewhere in the Caledonides e.g. in Wales, and it seems likely that similar relationships might exist in Greenland.

The later stages of development of a root zone of an orogeny might be as follows: At the end of the main compressive phase of folding, metamorphism and granitization, the down-dragging convection currents beneath the orogenic belt decreased in intensity and finally stopped. The orogenic pile cooled and then, due to isostasy, started to rise up. This movement implies partial tensional conditions in the crust which would allow the intrusion of simatic basic magma. Generally the first expression of this in South Greenland was the intrusion of the second period basic dykes, closely followed by basic and intermediate plutons. Microdiorite sills and dykes could have been feeders to andesitic lavas which are characteristic of this stage of orogenic development (Tyrrell 1955). In South Greenland these lavas were subsequently removed by erosion. Abundant wrench-faulting might accompany this phase with local folding and development of foliation. Younger granites are very characteristic of this late stage in the development of orogenies. They are probably produced mainly by the intrusion of palingenetic magmas which may have formed at greater depth during the earlier main metamorphism and granitization phase. Their rise to higher levels could then be related to the general epeirogenic uplift of the orogenic pile. A certain amount of granitic material could be produced by differentiation from the basic to intermediate magmas and other granites could be formed by recrystallization of earlier granitic rocks as a consequence of the rise of geoisotherms. A large body such as the Johan Dahl Land granite may owe its origin to a combination of these processes.

Magmatic differentiation seems to be the main cause of the variations within the appinitic suite of the Narssarssuaq area and this is in agreement with workers in Scotland e.g. ANDERSON (1935a and b), BAILEY and MAUFE (1916), DEER (1935, 1950), NICHOLLS (1950) and NOCKOLDS (1941, 1946). Some authors have suggested that hybridization by the Newer Granite magmas was an important process e.g. HOLGATE (1943, 1950). REYNOLDS (1934, 1936) has suggested a metasomatic origin for similar rocks in the Newry igneous complex. READ (1961) believes that appinitic rocks are due to mixing of acid and ultrabasic magmas. JOPLIN (1959, 1960) suggests that the appinitic suite is formed from geosynclinal basic rocks by hybridization and remobilization during the subsequent folding phase, but that no further basic magma is introduced during this phase. However the writer thinks that appinitic rocks probably form a normal member of the orogenic calc-alkaline suite derived from mainly post-tectonic basaltic (presumably tholeiitic) magma represented in South Greenland by the DA2s. The Basic Interlude of N.E. Scotland (READ, 1961) seems to have a similar position in the orogenic chronology.

Regarding the postulated origin of the hypersthene monzonite by diffusive alkali enrichment in magma, the process has been considered to be responsible for related rocks in other regions, e.g. of syenite in Northern Maine by BOONE (1962) who gives a useful discussion of the process (pps. 1470–1472). Also VANCE (1961) has suggested it is the cause of potassium-rich cores to zoned granitic intrusions. ANDERSON (1949) describes the conversion of diorite to monzonite and syenite, together with the development of sericitized zones and related metallization, to potassium-rich solutions emitted from a deep magmatic source. The rocks ANDERSON describes are very similar to those at Narssarssuaq. Further examples of a similar nature are given by CHAPMAN (1939), KERR (1932), and KENNEDY (1953).

The development of hydrous alkali-rich fractions from basic magma seems to be characteristic of orogenic environments. OSBORN (1959 and 1962) has recognised two types of crystallization paths in the system FeO-Fe_2O_3-SiO_2. The first type is where the composition of the mixture remains constant and fractional crystallization leads to iron enrichment. This is typical of non-orogenic areas e.g. Skaergaard. The second type is where oxygen partial pressure remains constant and fractional crystallization leads to silica and alkali enrichment. This may be due to a higher water content of orogenic magmas consequent upon extensive contamination by sialic material, though a similar condition can be produced locally in non-orogenic magmas e.g. in Hawaii (MACDONALD and KATSURA, 1964). KENNEDY (1955) noted that alkaline rocks develop characteristically late in an igneous cycle and are either post-tectonic or in tectonically undisturbed terrain. He suggests this is precisely the position where they might be found if long periods for diffusion were required to produce high-alkaline concentrations in the cupolas of bodies of batholithic proportions. The development of potassium-rich rocks e.g. hypersthene monzonite, is in contrast to some regions e.g. the Gibson Peak Intrusion, North California (Lipman, 1963). There a suite of late-orogenic rocks ranging from trondhjemitic tonalite to hypersthene gabbro is developed, but the content of potassium feldspar is extremely small. Moore (1962) has demonstrated that K/Na ratios increase with thickness of the continental crust in the western United States. He considers that magma has been generated or contaminated in crustal material of varying composition. Such an explanation fits the potassium-rich nature of the Narssarssuaq rocks bearing in mind the presumably great thickness of Ketilidian and earlier sialic rocks in the region.

In non-orogenic regions two principal lines of descent from basaltic magma are generally recognized i.e. 1) alkali-basalt → trachyte and 2) tholeiite → rhyolite. Yoder and Tilley (1962) have shown that these two major series are established in the region of generation i.e. below 60 km within a garnet-peridotite parent, and that equilibrium thermal divides separate the two series. However these authors recognize also the calc-alkaline series, characteristic of orogenic belts, stemming from tholeiite and including particularly abundant andesites. They note, together with Tilley (1950) that assimilation may play a significant role in the genesis of this orogenic series. The appinitic suite belongs to the calc-alkaline orogenic series and locally e.g. north of Narssarssuaq, considerably alkaline rocks are developed. The final expression of the appinitic suite are lamprophyric rocks with a minor carbonatitic phase.

The relationship of the Gardar alkali igneous province to the preceding Ketilidian-Sanerutian orogeny is interesting. Tyrrell (1955) points out the connection of the Midland Valley of Scotland graben and Oslo graben alkali-rocks with the Caledonian orogeny, and of the White Mountain Magma Series of New England with the Acadian orogeny. Vorobieva (1960) ascribes the appearance of alkali magmatism to the late and last period of development of one or another tectono-magmatic cycle. She recognizes that alkali petrogenesis is developed along two lines: 1) An abysmal differentiation of ultrabasic (and basic) magmas with a diffusive alkali accumulation in a relatively quiescent stage and a long period of balanced physico-chemical condition of systems (platform regimen) i.e. the Gardar province. 2) A progressive increase of alkalinity with the evolution of granitic magmatic chambers (folded structure association) i.e. the Narssarssuaq appinitic-alkali rocks. She further notes that platform associations vary from alkali to ultra-alkali, whereas folded structure associations vary from subalkali to alkali. From Tyrrell's (1955) demonstration of the tectono-igneous cycle it seems that alkali rocks of the platform regimen normally develop in the post-orogenic environment. YODER and TILLEY (1962) suggest that alkali-basalt magmas are to be expected to be generated at greater depths than tholeiite-type magmas from the same primary source rock. SUTTON (1963, b) has suggested that with the development of a chelogenic cycle, orogenies are progressively restricted to the margins of the continental masses probably consequent on the fusion of subcontinental convection cells. The same process results in disruption of the continental masses. This disruption might be expected to be the cause of exceptionally deeply penetrating tensional zones which in turn may result in alkali magmatism.

The Gardar intrusions in the Narssarssuaq region belong to two main phases of igneous activity corresponding to the early- and mid-Gardar respectively. The early-Gardar seems to be represented by carbonatite intrusions. In the mid-Gardar dolerites were followed by trachydolerites, potassic microsyenites and eventually sodic microsyenites. Microscopic evidence agrees with field relationships in pointing to the development of potassic trachyte magma largely before more sodic magma. Although exact feldspar determinations have not yet been made, it appears that as the magma crystallized and differentiated, the plagioclase feldspars being precipitated became more sodic. Calcic plagioclase formed in the early dolerites, more sodic plagioclase in the trachydolerites and eventually albite in the microsyenites. Potassic feldspar started to crystallize at the same time as the trachydolerites were formed. The potassic feldspar phenocrysts have a peculiar irregular aggregate form and could be interpreted as xenocrysts of local derivation i.e. perhaps these crystals tended to float and accumulate in the syenitic magma chamber and were pene-contemporaneously included in the dyke intrusions.

The sodic-trachyte magma presumably accumulated in the upper parts of chambers, and it is interesting that it is the earlier part of the main sodic-trachyte phase which contains the most abundant anorthositic inclusions. It may be that when conditions made its intrusion possible it took with it parts of an earlier formed anorthositic capping to the chamber. Late-Gardar activity, which characteristically led to the formation of alkaline intrusive complexes such as Nunarssuit (HARRY and PULVERTAFT, 1963), Kûngnât (UPTON, 1960) and Ilímaussaq (FERGUSON, 1964), does not seem to be represented in this area.

In conclusion it may be said that it seems possible to interpret the rocks of this region in terms of a single tectono-magmatic cycle which in this case corresponds to the Svecofennid chelogenic cycle. Confirmation of this depends largely on a date of approximately 1800 m.yr. being firmly established for the main Ketilidian metamorphism.

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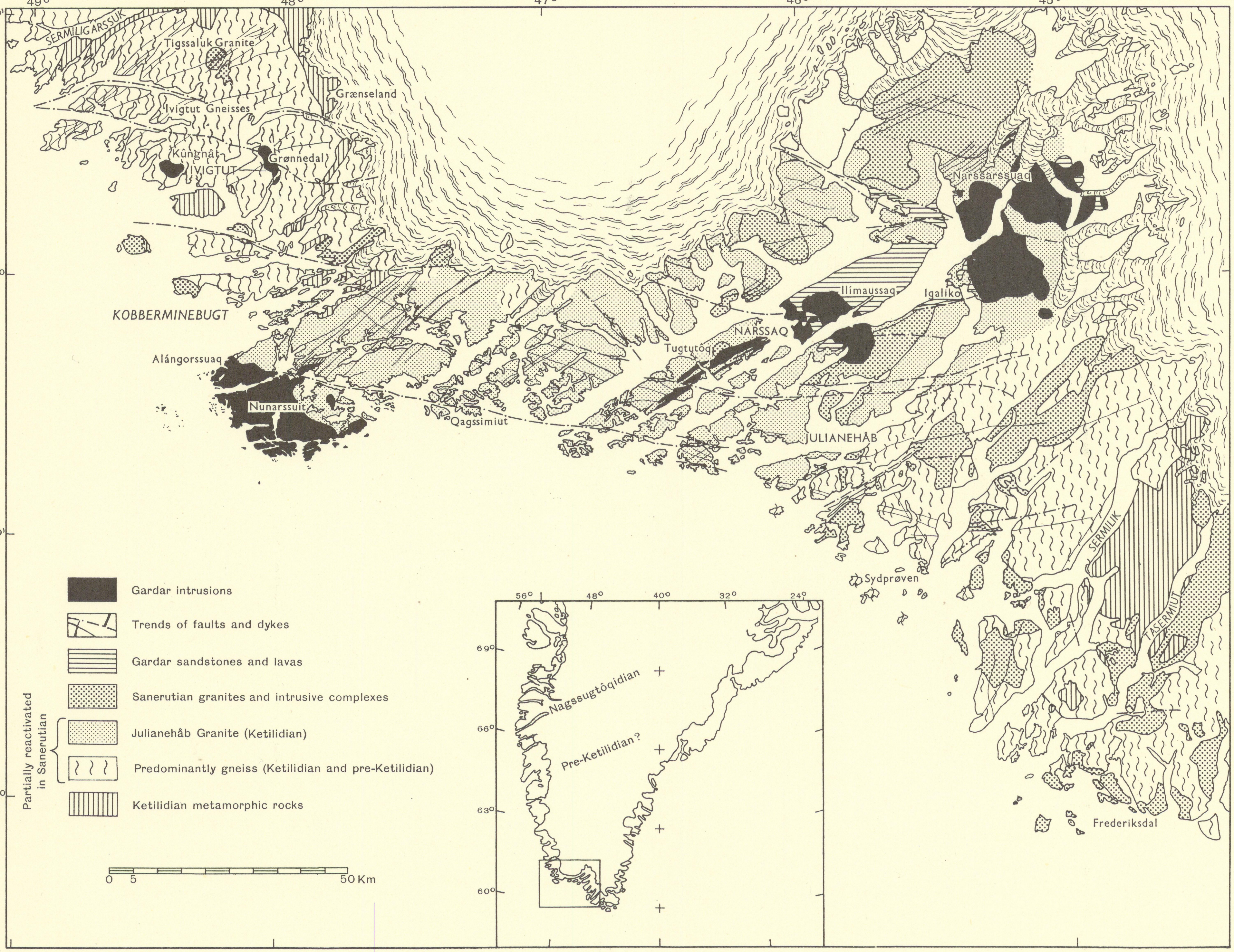
Færdig fra trykkeriet den 15. juli 1965.

PLATES

GRØNLANDS GEOLOGISKE UNDERSØGELSE
THE GEOLOGICAL SURVEY OF GREENLAND

MEDD. OM GRØNL. BD. 179 NR. 9 (B. J. WALTON)



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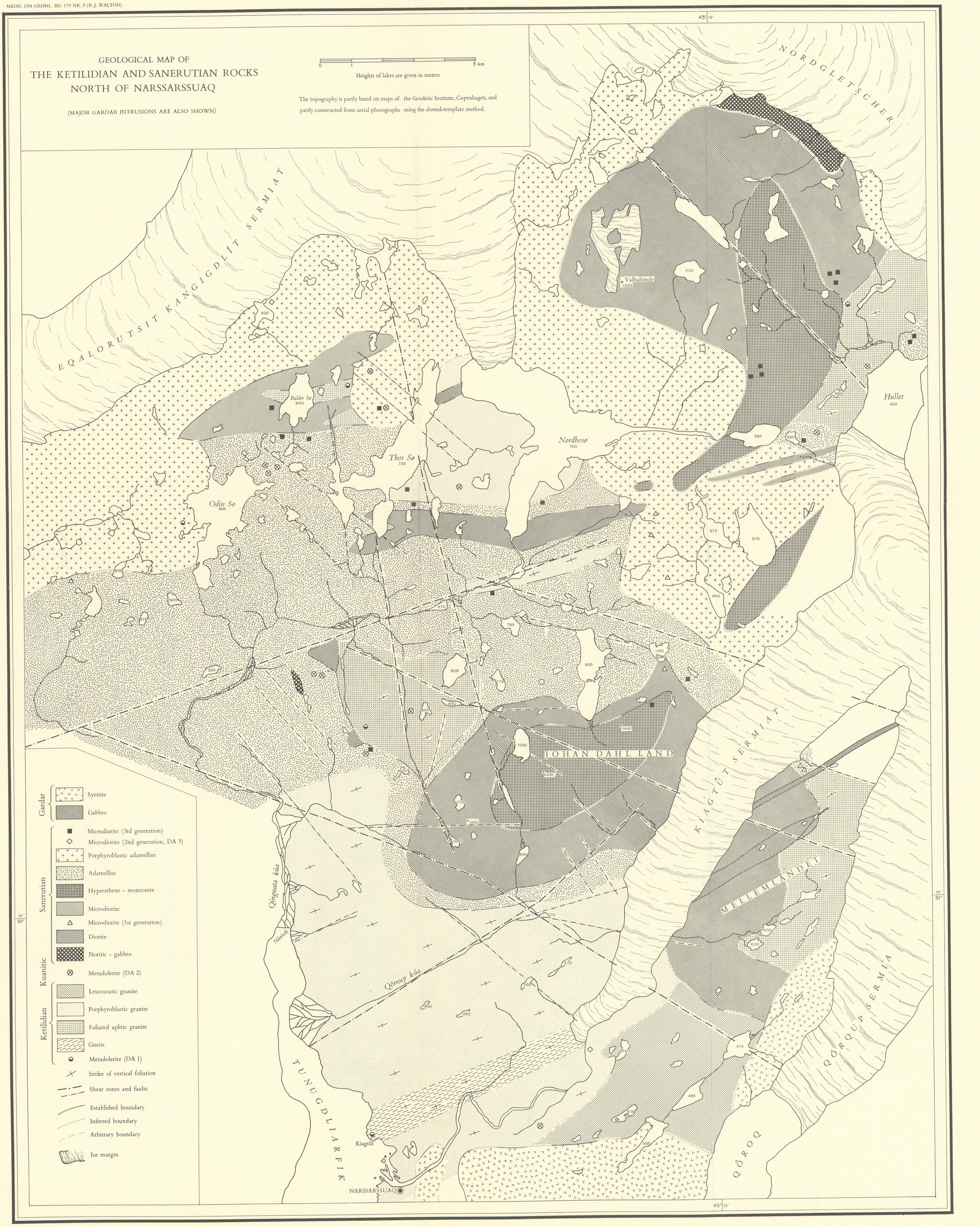

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