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Petrology and Geology of the Precambrian Gardar Dykes on Qaersuarssuk, South Greenland

by

W. Stuart Watt

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PETROLOGY AND GEOLOGY OF THE PRECAMBRIAN GARDAR DYKES ON QAERSUARSSUK, SOUTH GREENLAND

by

W. Stuart Watt

With 7 figures and 1 map

1968

Abstract

The Precambrian Gardar dykes on Qaersuarssuk consist of olivine dolerites, a group of undersaturated to saturated microsyenites including one nepheline-bearing dyke, trachydolerites and lamprophyres. The dykes are the fringe to the dense swarm of alkaline dykes on Tugtutôq to the east. As most of the dykes are sub-parallel, division is made based on their relations to movements along wrench faults. Composite dykes, with microsyenitic marginal components, and trachydoleritic centres often containing large aggregates of feldspar crystals and giant single crystals of feldspar, are comparatively common.

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INTRODUCTION

The Julianehåb region of South Greenland has long been known for its alkaline rocks with their unusual mineralogy. Besides the main intrusions there is a suite of minor intrusions and dyke rocks (fig. 1). The whole of this alkaline suite belongs to the Gardar period of the Precambrian.

Upton, in a series of papers (1962, 1964 a and b), has dealt with the geology of Tugtutôq with its giant syenite and olivine gabbro dykes and late central complex. The dyke types of Qaersuarssuk described here are all represented on Tugtutôq so that this study is complementary to that of Tugtutôq.

Upton (1962) and Bridgwater (1965) have given brief synopses of the Gardar geology of the area. They divide the period into three - early, mid- and late Gardar. The Grønnedal-Íka alkaline complex was emplaced in the early Gardar together with the lamprophyric dykes in the Ivigtut area and NW-trending trachytic dykes both in the Ivigtut area and to the east of Narssarssuaq. The basalts of Narssaq peninsula, the ESE olivine dolerite dykes and the Hviddal syenite also belong here. The mid-Gardar is marked by the NE dyke complex. This complex is particularly developed on Tugtutôq and NE of Nunarssuit. The large alkaline intrusions, with the exception of parts of the Igaliko complex, belong to the late Gardar.

The Gardar period is represented on Qaersuarssuk by the intrusion of dykes, mostly mid-Gardar, with intermittent faulting.

A post-Gardar generation of olivine dolerite dykes crosses Qaersuarssuk; these are distinguished by being later than all faulting in the area.

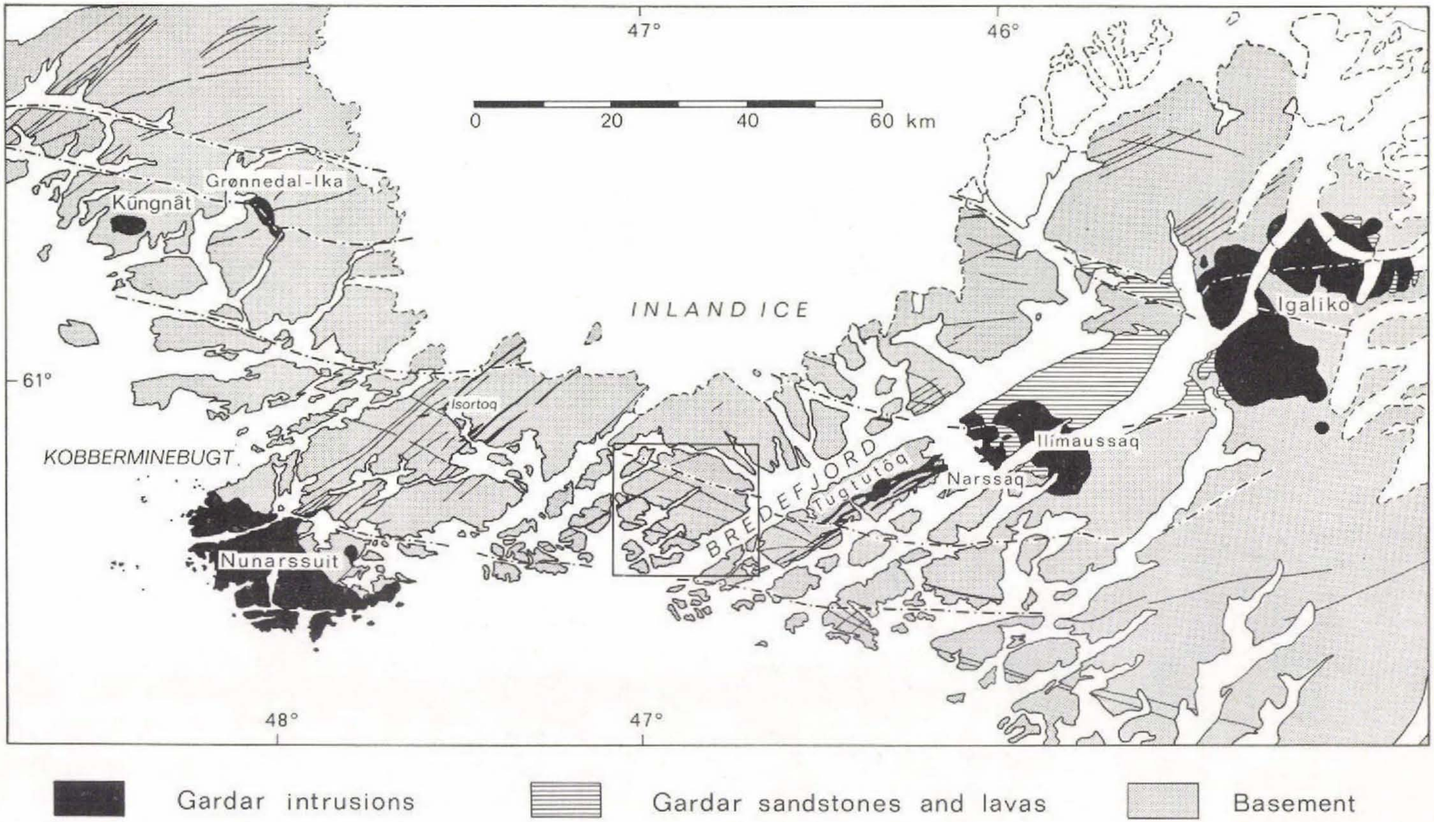

Fig. 1. Sketch map of the Gardar igneous province showing the position of Qaersuarssuk within the province.

CHRONOLOGY OF THE GARDAR DYKES

Dyke intersections in the area are rather scarce but with the aid of movements at different times on the two major directions of faulting it is possible to build up a dyke chronology. This is in general agreement with the Gardar dyke chronology obtained in the Qagssimiut area to the west (Ayrton and Burri, 1967) and in broad outline to that obtained in the Ivigtut area to the north-west (Berthelsen, 1962).

Table 1

Dyke - Fault Chronology on Qaersuarssuk

Dykes	Faults
	NNW sinistral wrench faults (possibly only local) - rejuvenated and WNW sinistral wrench faults - rejuvenated
northern composite big feldspar dyke	
	WNW sinistral wrench faults
olivine dolerite dyke (NE)	
	NNW sinistral wrench faults - rejuvenated
big feldspar dykes (some of the southern dykes) plus some NE dolerite dykes	
	(NNW sinistral wrench faults - possibly only local)
big feldspar dykes (some of the southern dykes) plus some NE dolerite dykes	
microsyenitic dykes (probably more than one generation)	
nepheline microsyenite dyke	
	NNW dextral wrench faults
olivine dolerite dykes (ESE)	

The two main fault directions in the area, NNW and WNW, show movements at different times and separate different dyke generations (map 1).

The ESE olivine dolerite dykes are the earliest Gardar dykes on Qaersuarssuk and belong to the generation termed BD_0 in the Ivigtut area (Berthelsen, 1962). The dykes are displaced dextrally by amounts up to 450 m by NNW faults.

Age relationships between the NE-trending dykes are difficult to determine as interpretable intersections are rare. The nepheline microsyenite is the earliest of the dykes in this direction. By allowing for displacement on NNW faults it can be shown that the apparently isolated lengths of nepheline microsyenite dyke on the northern side of inner Kangerdluarssuk avangnardleq are part of the same single dyke. There are so many short lengths of microsyenitic, big feldspar and doleritic dykes without known age relations that the possibility of each dyke type belonging to more than one generation must be considered. In two places big feldspar dykes cross one another, but in only one place is it possible to determine the relative ages. There is a suggestion of two generations when comparing the displacements of two big feldspar dykes by the NNW fault through Torssukátâ where one dyke appears to be affected by a sinistral displacement of 50 m and another sinistrally displaced by 200 m. Thus it appears that these dykes are not all contemporaneous. The NE olivine dolerite dyke is cut by the northern composite big feldspar dyke and is displaced sinistrally by 2600 m on the WNW fault which also, incidentally, confirms its pre-northern composite big feldspar dyke age as the latter is only displaced 1500 m on the same fault. The northern composite big feldspar dyke is the latest of the Gardar dykes on Qaersuarssuk while the other big feldspar dykes belong to two earlier generations each with both composite and non-composite members.

The NE olivine dolerite dyke is only known to be faulted once, 300 m dextrally at the lake 30. NNW faults are traceable as far as the dyke but have not been detected beyond it. Nowhere can displacement of the dyke be demonstrated but the slightly irregular course of the dyke suggests that it may be slightly affected. The dyke has the same direction, and is therefore believed to belong to the same generation, as the dyke complex north-east of Nunarssuit and the olivine gabbro giant dykes of Tugtutôq.

The chronological position of the spherulitic and lamprophyric dykes is uncertain. The spherulitic dyke cuts a microsyenitic dyke in the southern part of the area. The age of the lamprophyric dykes is uncertain, there being two possibilities by comparison with other areas. In the Ivigtut area to the north-west, the lamprophyres are the earliest of all the Gardar intrusions (Weidmann, 1964; Berthelsen, 1962). On the Julianehåb peninsula a camptonitic sill "was intruded soon after or late in the alkali dyke sequence and presumably related to a similar source." (Nesbitt, 1961, p. 215), while on Tugtutôq a camptonitic sill transects the quartz syenites of the late ring-complex as well as numerous trachytic and doleritic dykes (Upton, 1965). Thus lamprophyric dykes occur in the Gardar at two distinct times.

EARLIEST GENERATION (ESE) OF DOLERITE DYKES

The earliest generation of dolerite dykes is represented on Qaersuarssuk by a group of dykes running in a direction approximately WNW - ESE and lying to the south of the WNW fault (map 1). There are three large dykes over 60 m in width and numerous smaller ones. The smaller dykes are grouped with this generation, but in most cases their chronological position cannot be proved. In the south of the area there are two small dykes having the same direction as the three larger but which can be shown to be later than them. Therefore not all the smaller dykes belong to this generation. It is possible that on Tugtutôq and the Julianehåb peninsula this generation is also divisible into two.

The dykes of this generation are cut and displaced dextrally by amounts up to 450 m by NNW faults. By a comparison of the displacement of these dykes by the NNW faults to that of other dykes and by the very few dyke intersections the three large dykes of this generation can be shown to be the earliest dykes on Qaersuarssuk and belong to the generation termed BD_0 in the Ivigtut area (Berthelsen, 1962).

A characteristic feature of this generation of dykes is the production of large dyke offshoots which may extend up to a kilometre before terminating or rejoining the main dyke. Most of the dykes form pronounced erosion hollows. Where the dolerite is exposed spheroidal weathering is common, while certain of the smaller dykes show prominent jointing and occasionally form distinct step features.

Almost all the dykes, and certainly the three larger dykes, are characteristically flanked by reddened granite which may extend up to 20 m away from the dyke. Similar reddening of the granite occurs along faults and lines of shearing and is presumed in most cases to have been caused by shearing. The dykes themselves, and in particular their margins, are sheared. Where the shearing has been intense there are surfaces with slickensiding and veins of quartz in the dyke. A dextral displacement of 4 m is seen on a small dyke where it crosses the southern margin of the large dyke near Atertûp ilua. Since this direction of movement along the dyke margins is in the same sense as that on the WNW fault it is suggested that it is contemporaneous with one of the periods of movement along that fault.

The majority of the dykes are believed to be vertical. Two exceptions are known: one is the sector of the large dolerite dyke between Kangerdluarssuk avangnardleq and Torssukâtâ, which dips about 70^{o} to the north; the other is one of the smaller dykes which has a number of characteristics which are not entirely in keeping with the dykes of this generation, and has a steep dip to the south-west.

Coarse pegmatitic areas are only rarely seen in the dykes. Normally they appear to be richer in pyroxene than the normal dolerite but a pegmatite pipe 12 cm in diameter rich in feldspar is also known.

A sample from the southernmost of the three dykes (GGU 45297) was used to date the early Gardar. A K/Ar date of 1435 ($\pm$ 80) x 10^6 years was obtained on the clinopyroxene. The reader is referred to Bridgwater (1965) for a discussion on the reliability of the date and its implications.

Petrography

Petrographically there is no difference between the three large dykes. The texture throughout is intergranular though the larger augite crystals are poikilitic. There is a certain amount of difference from dyke to dyke in grain size with plagioclase crystals commonly 1 to 2 mm in length and poikilitic augite crystals up to 7 mm across.

Plagioclase occurs as laths twinned on the carlsbad-albite and albite twin laws. Where it fills large interstitial areas, which it does occasionally, there are also pericline twins. Compositional zoning is seen in many crystals but is particularly evident in the large interstitial plagioclase crystals. The composition range is between An_{14} and An_{64}. A bulk composition determined on plagioclase glass (see appendix for description of the method) gave $An_{54\pm2}$ wt % as the average for four samples from this generation. This figure is higher than that calculated from the chemical determination of Na_2O, K_2O and CaO on feldspar extracted from samples from the three large dykes.

The pyroxene occurs both as large poikilitic crystals and as smaller subhedral grains between the plagioclase laths. Most of it is neutral in colour though some of it has a trace of pink. Much of it is of uniform composition, to judge by its extinction, but occasional crystals show distinct compositional zoning.

The compositions of the main constituent minerals of the three dykes are given below. Within the dykes themselves there is little variation. Even within the southern of the three dykes, which includes samples of dolerite-pegmatite and a coarse grained facies as well as the normal dyke rock, there is no significant difference in the composition of the main minerals although olivine is absent in the coarsest part of the dolerite-pegmatite.

	Olivine* (mol. %)	Clinopyroxene* (average - atomic %)	Plagioclase* R.I. mol. %	Plagioclase* bulk chemical mol. %	Plagioclase* bulk glass wt %
Northern dyke	Fa_{52-66}	$Ca_{40.5}Mg_{31}Fe_{28.5}$	An_{14-48}	$Or_8Ab_{50}An_{42}$	-
Middle dyke	Fa_{44-49}	$Ca_{36}Mg_{32.5}Fe_{31.5}$	An_{34-64}	$Or_5Ab_{45}An_{50}$	-
Southern dyke	Fa_{54-64}	$Ca_{38}Mg_{34}Fe_{28}$	An_{23-49}	$Or_8Ab_{50}An_{42}$	An_{53}

* See appendix for methods of determination.

Normative minerals are given in table 4 calculated from an analysis of a sample (GGU 45501) from the southern dyke.

The middle dyke has the lowest iron content in the olivine but the highest iron content in the pyroxene. It also has a higher anorthite content than the other two dykes and the lowest calcium content in its pyroxene. The high iron content of clinopyroxene and its relation to the olivine composition has been discussed by O'Hara (1963) along with the effect of change of temperature and pressure on the ratio $\frac{Fe/Mg \text{ olivine}}{Fe/Mg \text{ pyroxene}}$; lower temperature favours iron concentration in the pyroxene.

Olivine is normally abundant as small (0.2 mm) anhedral grains which are commonly clustered together in loose groups.

Opaque material is abundant in comparatively large grains (0.5 mm), the largest of which are slightly poikilitic to plagioclase and olivine. They are practically always thinly rimmed by biotite that is pleochroic in red and pale brown, the intensity of the colour varying, sometimes within the same crystal. There are rare large biotite flakes which, though they appear to be independent of opaque grains, are associated with a green chlorite. These green chloritic patches are sometimes associated with serpentinization of olivine but appear also to occupy interstitial areas independent of olivine. On the whole there is little late stage deuteric alteration of the minerals.

Apatite occurs in the normal dolerite and is particularly evident in the pyroxene crystals. One sample from the northern of the three dykes contains a little interstitial quartz.

Pegmatitic facies occur within the southernmost of the three dykes as pods and veins of coarser grain dominated either by plagioclase or by pyroxene. Some of these areas lack olivine, others have olivine in approximately the same quantity as the normal dolerite except that around the margins of the pegmatitic areas it is intersertal and co-dominant with plagioclase. Where there is olivine it occurs in the same size of grain as in the rest of the dolerite even though the other associated constituents are of larger grain size. Apatite crystals occur in the pyroxene of these pegmatitic facies and the opaque mineral occurs as large, intricate skeletal crystals. The feldspar in these patches shows much more alteration than elsewhere; it is probably a late stage alteration that has affected the feldspar but not the mafic minerals. No quartz or zeolites have been seen in the dolerite-pegmatite.

A sample (GGU 45501) from the southern of the three large dykes has been analysed and the results presented in table 4, p. 36. A discussion of the results and comparison with other dolerite dykes is given in the section on the NE olivine dolerite dyke (p. 35).

NE-TRENDING DYKES

General remarks

A large number of dykes trending approximately NE are found between Kangerdluarssuk avangnardleq and Bredefjord. Very few dykes of this trend are found outside this area on Qaersuarssuk. On the northern side of the WNW fault a few are found more to the north-west, but they are a continuation of the main belt which has been displaced by the fault.

Out of this large number of dykes there are a few that are characteristic and have been more systematically mapped. These are the nepheline microsyenite dyke, some of the other microsyenitic dykes, the big feldspar dykes and the NE olivine dolerite dyke. These are described separately. The remaining dykes are a group of doleritic to trachydoleritic dykes with or without cognate plagioclase xenocrysts. The distinction of the big feldspar dykes at times becomes rather arbitrary so that dykes having similar composition, whether or not they have large feldspar xenocrysts, have been described together.

The dykes are treated, as far as is possible, in chronological order.

NEPHELINE MICROSYENITE

Field setting

A single nepheline microsyenite dyke is traceable discontinuously across Qaersuarssuk in an ENE direction (map 1). To the north-east J. H. Allaart (manuscript map) has mapped it across to Kangerdluatsiaq, while to the south-west Ayrton and Burri (1967) have mapped it on Qagssimiut and adjoining islands. It is thus known for 30 km in a direction 060°.

In the south-west part of Qaersuarssuk it is 5.5 to 7.0 m wide while in the northern part of the island it is up to 17 m in width. The course of its outcrop indicates that it has a steep dip to the SE. At the coast of Torssukátak and across to Kangerdluatsiaq the dyke is composite with outer margins of microsyenite without nepheline.

The dyke is light grey in colour and markedly crowded with tabular feldspars up to 2.5 cm in length and 4.0 mm long phenocrysts of nepheline. The tabular feldspars are commonly aligned with their b axes horizontal and perpendicular to the length of the dyke. In addition to the phenocrysts there are occasional rounded cognate inclusions of finer grain and of both darker and lighter grey than the dyke. Many of these inclusions are marked by their scarcity of phenocrysts and by the tangential arrangement of tabular feldspar phenocrysts in the host around their margin. The inclusions of light grey colour may contain within them other inclusions both darker and lighter grey in colour. These inner inclusions only very occasionally contain phenocrysts of nepheline. They probably represent pieces of chilled margin re-incorporated into the rock at various stages. On Qagssimiut tabular feldspar crystals have been seen in a whorl suggesting eddy currents within the magma.

The margins of the dyke are chilled against the country rock and are without phenocrysts. Radiating crystals of prehnite occur on a joint surface at Torssukátak.

The southernmost length of the dyke on Qaersuarssuk is red in colour due to the proximity of later dolerite dykes and some shearing. While the feldspar and groundmass are red the nepheline is green due to chlorite and an unknown secondary mineral pseudomorphing it and frequently accentuating its zonal texture.

Petrography

The dyke rock is fine grained with numerous large tabular alkali feldspars and euhedral phenocrysts of nepheline together with phenocrysts of ægirine-augite rimmed by ægirine. There are occasional fayalitic olivine grains. The phenocrysts are set in a finer grained trachytic groundmass containing, inter alia, alkali feldspar, ægirine-augite and a soda amphibole.

Alkali feldspar occurs as phenocrysts and also forms a large part of the matrix to the rock. As phenocrysts it constitutes about 25% of the rock. The phenocrysts are tabular with carlsbad twins and a $2V_{\alpha}$ ca. 53^{o}, hence they are probably orthoclase. They may be homogeneous or perthitic, and wholly or partly altered. The perthitic phenocrysts show approximately equal amounts of plagioclase and potash feldspar (X-ray determination). The soda feldspar of the perthite is in strips. The secondary mineral pseudomorphing the tabular feldspar characteristically consists of fibrous sheaves set parallel to the b axis of the feldspar. This secondary mineral is colourless with low relief (R.I. $<$ balsam), birefringence ca. 0.005, and length fast with parallel extinction and may be a zeolite. The presence of fresh nepheline with altered alkali feldspar suggests that this alteration is deuteromorphic. The alteration seems to have started along the margins of the crystals and forms embayments into it. More rarely it seems to have preferentially followed a cleavage plane across the crystal. It affects equally the homogeneous and perthitic feldspars. Much of the matrix feldspar seems to have been altered in the same way. Both euhedral nepheline and anhedral pyroxene may be included in the tabular feldspar. The ratio of potash feldspar to albite in the matrix feldspar is about three to one (X-ray determination).

The nepheline occurs as euhedral to subhedral crystals up to 4 mm across and constitutes about 13 % of the total rock. Regular concentric zoning may be seen in many of the grains, though frequently it is very hard to discern. The zones show as slight differences in the birefringence.

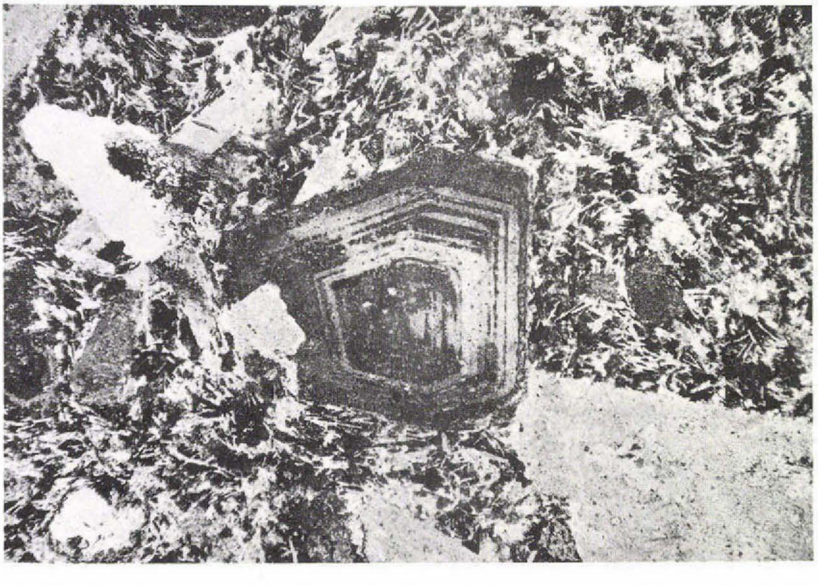

Fig. 2. An altered, zoned nepheline in the nepheline microsyenite dyke in which the zones are picked out by different alteration products. X-nicols. Sample GGU 45295. x 30.

Where the nepheline has been altered the zoning frequently becomes accentuated as there tends to be preferential alteration. Alternate zones may be replaced by a cream coloured fibrous mineral (length slow, low relief and approximately parallel extinction), or, where alteration is more complete (e.g. fig. 2), the zones are picked out by a bright green chlorite, with a little epidote, and a colourless to pale reddish-brown aggregate of minerals which may be fibrous. Parts of the nepheline may be replaced by a mosaic of colourless grains. Occasional nepheline crystals contain small rounded inclusions with the appearance of devitrified glass.

Zoning in the nepheline appears to be more prominent or only developed in the smaller crystals; the larger show no signs of zoning. X-ray determination of the bulk K/(K + Na) ratio for two nepheline crystals gave identical results of 15.3 atomic percent: this corresponds to a composition $Na_{76}Ks_{19}Qz_{5}$ (Smith and Sahama, 1954).

Ægirine-augite rimmed by ægirine occurs both as phenocrysts and in the groundmass. The subhedral to anhedral phenocrysts may have inclusions of olivine and primary opaque minerals. In the groundmass there are a few grains of ægirine in addition to the ægirine rims on the ægirine-augite. Acmite occurs in the norm. The ægirine-augite is pleochroic with α deep green, β green and γ yellow-green.

Olivine occurs in the grundmass of most of the material, and a few slices show olivine phenocrysts rimmed by opaque material. A single phenocryst removed from a slice had a composition of Fa_{75} but olivine from the groundmass is practically pure fayalite with traces of Mn.

An important interstitial mineral is soda amphibole occurring as wedges between the feldspar laths. It is probably arfvedsonitic from its pleochroic colours (α deep greenish-blue, γ cream-yellowish). Ænigmatite (pleochroic deep brownish-red to practically opaque), apatite and opaque minerals are minor accessory constituents. The proportion of opaque material is normally fairly low, but where the dyke has been affected by the proximity of later dykes and shearing there is a considerable amount of interstitial opaque material.

The dark grey inclusions found in the dyke are of alkali trachyte without nepheline in the groundmass. They are fine grained with abundant rods of opaque material. The light grey inclusions have a marked texture of radiating feldspars. Biotite is present in inclusions of both colours and is associated mainly with the opaque material. The biotite is strongly pleochroic: α light brown with touches of red-brown, β and γ very dark

Table 2

	45457	30681	30676
SiO_2	54.85	54.17	56.48
TiO_2	0.44	0.37	0.09
Al_2O_3	17.04	19.34	20.05
Fe_2O_3	4.66	6.00	3.86
FeO	4.36	1.86	0.77
MnO	0.20	0.17	0.10
MgO	0.25	0.24	0.05
CaO	2.42	1.74	1.16
Na_2O	7.93	7.71	10.37
K_2O	5.20	5.32	5.42
P_2O_5	0.12	0.10	0.02
CO_2	nil	n.d.	n.d.
H_2O^+	2.40	2.70	1.65
H_2O^-	*	0.12	*
S	-	0.02	0.02
Cl	-	0.02	0.14
	99.87	99.88	100.18
C.I.P.W. norm			
or	30.8	31.5	32.1
ab	26.7	35.2	24.5
an	-	2.4	-
ne	17.3	16.2	26.2
hl	-	-	0.2
ac	7.4	-	11.1
ns	-	-	0.3
di	10.5	1.3	2.7
wo	-	1.9	1.2
ol	0.8	-	-
mt	3.0	5.5	-
il	0.8	0.7	-
hm	-	2.2	-
Feldspar	$Or_{53.5}Ab_{46.5}An_0$	$Or_{45.5}Ab_{51}An_{3.5}$	$Or_{57}Ab_{43}An_0$
Clino-pyrox.	$Wo_{28}En_3Fs_{28}Ac_{41}$	$Wo_{54}En_{46}Fs_0$	$Wo_9En_0Fs_{10}Ac_{81}$
	$Wo_{47.5}En_5Fs_{47.5}$	-	$Wo_{47}En_0Fs_{53}$
Olivine	Fo_9Fa_{91}	-	-

45457 Nepheline microsyenite. South from Torssukátak, Qaersuarssuk. Analyst B. I. Borgen.

30681 Nepheline syenite, Hviddal composite dyke. Tugtutôq. Analyst R. Solli (Upton, 1964b, table 1, p. 59).

30676 Foyaitic syenite. Eastern end of Hviddal composite dyke, Tugtotôq. Analyst: Geochemical Laboratory, Grant Institute of Geology, Edinburgh. (Upton, 1964b, table 1, p. 59).

* Analysis on sample dried at 110°C for 2 hours.

brown in the light grey inclusions, and α yellow, β and γ brown in the dark grey inclusions. Both are iron-titanium biotite (Hall, 1941). There does not appear to be any ægirine in these inclusions and the pyroxene in the darker inclusions appears to be ferro-augite rather than ægirine-augite. These inclusions may represent an early crystallizing fraction of the magma.

MICROSYENITIC DYKES

In addition to the single nepheline-bearing dyke on Qaersuarssuk there are a number of undersaturated to saturated microsyenitic dykes all trending NE to ENE and varying in width from 25 cm to 15 m. The margins of the composite dykes are microsyenitic but are described as part of the composite unit (p. 24). The small spherulitic dyke is a saturated microsyenite but is described separately (p. 37). Only short lengths of other microsyenitic dykes are known on Qaersuarssuk. These include both undersaturated and saturated members but none have feldspathoids. These short lengths have been grouped together here as it has not been feasible to divide and describe them separately.

Many of these short lengths of microsyenitic dykes form erosion hollows and some are characterized by close jointing giving large flat slabs of rock. These slabs are excellent for building and on the coasts old Esquimo graves are frequently found on these dykes. This slab formation appears to characterize a particular type of alkaline microsyenite which has a characteristic shean on a freshly broken surface.

One of the dykes belonging to this group contains numerous spherical to elongated nodules of finer grain than the main rock of the dyke. These nodules are fairly evenly distributed throughout the dyke except along the margins where they are comparatively scarce.

Petrography

The alkali microsyenitic dykes are composed predominantly of sodic minerals. The main constituent is an antiperthitic feldspar as tabular crystals averaging 0. 3 mm long generally with a trachytic to radiating arrangement which gives the characteristic texture to the dyke. Soda amphibole, alkali pyroxene and titan-biotite together form about 20 % of the rock. No feldspathoids have been distinguished. In general most of the dykes appear to be similar to Brögger's sölvsbergite (Brögger, 1894; Johannsen, 1937) though a few are quartz microsyenites.

Many of the dykes have small, 1 mm, phenocrysts of alkali feldspar; rarely they may be as large as 2 cm long. The phenocrysts are cryptoperthitic. In one sample phenocrysts and matrix feldspar were determined independently while in another fine-grained sample only the phenocrysts were determined.

	Phenocrysts	Matrix
45228	$Or_{33.5}Ab_{43}(An_{23.5})$	$Or_{29}Ab_{69}(An_2)$
45270	$Or_{34}Ab_{60}(An_6)$	-
average bulk feldspar	-	$Or_{32}Ab_{67}(An_1)$

The matrix feldspar has an average bulk composition of $Or_{32}Ab_{67}(An_1)$ mol. %; this excludes a single example of a quartz microsyenite (GGU 45371) with a bulk feldspar composition of $Or_{30}Ab_{57.5}An_{12.5}$.

Brown amphibole (barkevikitic affinities) is the most common mafic mineral. It frequently has greener margins as it grades into a more sodic riebeckitic-arfvedsonitic type. It is commonly associated with an alkali pyroxene and occasionally also with a titan-biotite; in a few examples it is absent. Characteristically the amphibole occurs in the wedge-shaped interstitial areas between the feldspar laths. The grains are strongly pleochroic with the following pleochroic schemes from core to margin.

	α	β	γ
Core	olive green brownish green	brown	pale brown
	blue-green		colourless
	pale green		colourless
Margin	blue		pale blue

Most, though not all, of the dykes also contain an alkali pyroxene. It varies from ægiring-augite to ægirine; crystals of ægirine and ægirine rims to ægirine-augite are the most common. Ægirine occurs as stubby, prismatic crystals and also forms rims to the soda amphibole.

Titan-biotite, when present, is pleochroic from α bright red-brown to β and γ dark brown or opaque. It occupies the same interstitial position as the soda amphibole and appears to have formed contemporaneously with it; both minerals are later than the alkali pyroxene.

Interstitial quartz occurs in two dykes where it amounts to 2 to 5 % of the total rock. Opaque crystals, where they occur, are subhedral crystals of pyrite which are identifiable on a fractured surface. Where pyrite crystals are present crystallization has been under strong reducing conditions.

Accessory minerals in the dykes include apatite as tiny rods in the feldspar and as little euhedral grains. Sphene is prominent where there is no biotite. Both olivine and ænigmatite have been found and limonite occurs in some of the dykes.

One dyke has a variety of phenocrysts consisting of separate crystals of plagioclase and potash feldspar, ægirine-augite and ægirine, though the ægirine is mostly altered to a chlorite. Another dyke has a circular vug filled with a carbonate mineral and a green, fibrous amphibole.

Upton (1964a) presents continuous and discontinuous reaction series in similar microsyenitic dykes from Tugtutôq to the south-east. This work has been continued by Macdonald (1966) from dykes in the same area. Parts of this series can be recognized among the Qaersuarssuk dykes, particularly the change from a brown amphibole through a green amphibole with a sharp change to riebeckite-arfvedsonite and then to ægirine. Ægirine-augite occurs earlier in this series contemporaneous with the green amphibole. In the more differentiated dykes red-brown biotite and ægirine are abundant and there is an absence of amphibole.

TRACHYDOLERITIC DYKES WITH COGNATE PLAGIOCLASE XENOCRYSTS

The big feldspar dykes are a group of dykes about 10 to 17 m wide with a general north-easterly trend. They occur mainly in the area between Kangerdluarssuk avangnardleq and Kangerdluarssuk kujatdleq and its continuation to the south-west and north-east. There is an apparent decrease in the number of dykes to the south-west, where there are four, compared to six along the south coast of Torsukåtak (fig. 3).

A number of the dykes are composite with microsyenite forming substantial marginal components. Although the margins are quite different to the big feldspar-carrying centres they are intimately connected with the central component of these dykes and so are described along with it where appropriate.

The big feldspar dykes are characterized by the presence of large aggregates of feldspar crystals and giant single crystals of feldspar. Giant, single feldspar crystals are known up to 49 cm in length and aggregates composed of smaller crystals reach 190 cm in diameter. Besides these giant crystals and aggregates of crystals there are numerous smaller crystals of 10 to 15 cm in length which are probably derived from the break up of the larger aggregates. Crystals of 1 to 2 cm are also abundant. The smaller feldspar crystals occur along with the giant crystals and also occur in those parts of the big feldspar dykes where the giant feldspars are lacking. In addition there are dykes which appear to lack entirely the big feldspar crystals but have abundant feldspars of the smaller size ranges. In this description of the big feldspar dykes all those dykes having the same type of matrix and numerous feldspar crystals of larger size than those in the matrix have been grouped and described together.

Bridgwater (in Bridgwater and Harry, in press), in the compilation of feldspathic dykes throughout the Gardar province, recognizes a change in the soda - potash ratio of these dykes with age and with geographical position. This is most apparent in the microsyenitic margins to the composite members of the swarm. In general the microsyenitic margins of the younger dykes tend to have a higher Na/K ratio, and those dykes with a higher Na/K ratio are more frequent to the east of Tugtutôq while those in the Kobberminebugt area are more potassic. The Qaersuarssuk dykes appear to be mid-way in this scheme.

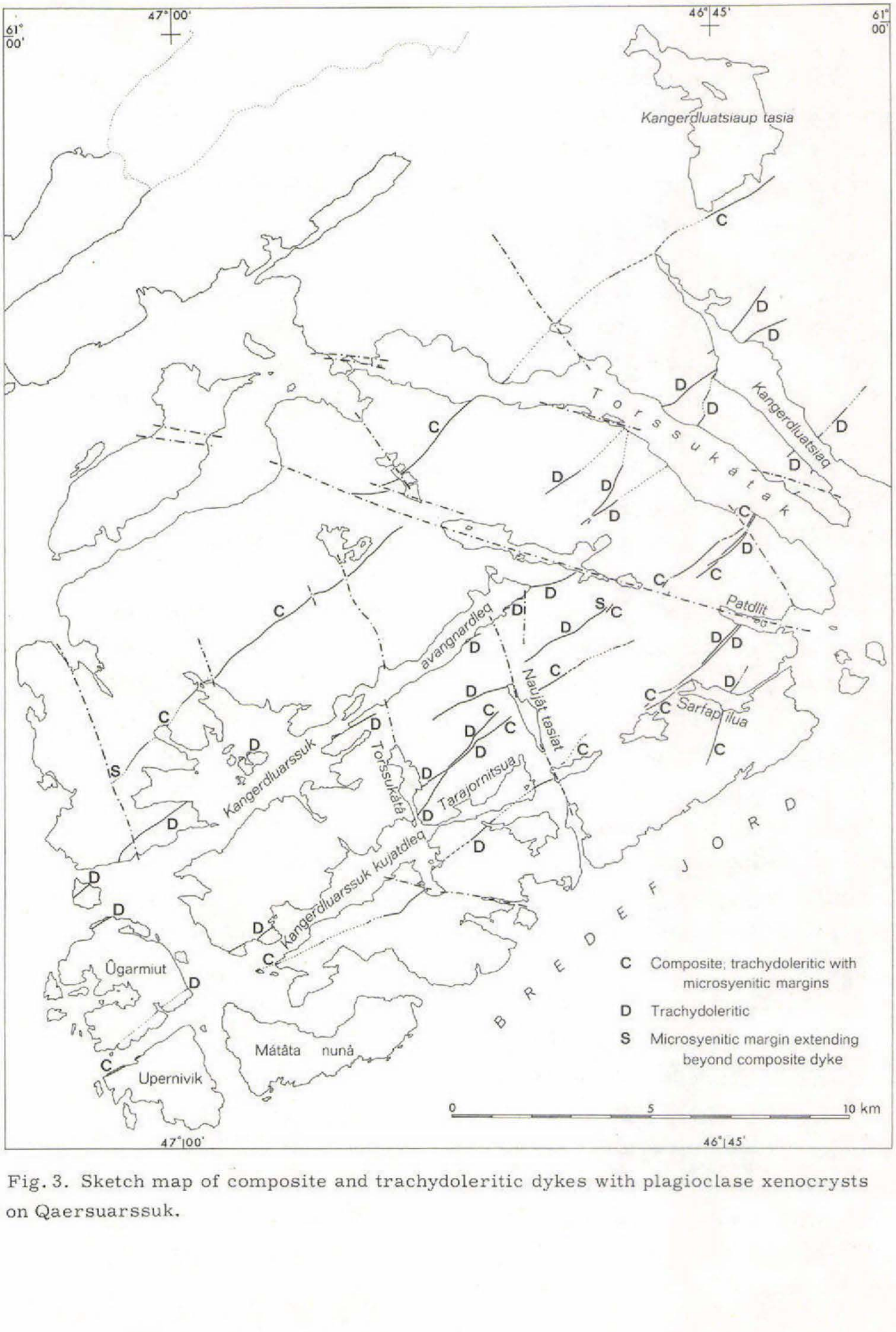

Fig. 3. Sketch map of composite and trachydoleritic dykes with plagioclase xenocrysts on Qaersuarssuk.

The best studied of the big feldspar dykes is the northern big feldspar dyke, a composite dyke with a microsyenitic marginal component. The field relations of this dyke will be described separately. Other big feldspar dykes, belonging to two earlier generations, will be described together.

The northern composite big feldspar dyke

A vertical, composite big feldspar dyke, of average width 16 m, occurs for 11.6 km across the north-west of Qaersuarssuk. It is known at least a further 7.7 km to the north-east of Qaersuarssuk where J.H. Allaart has mapped it.

The dyke, at its maximum known width of 33 m in the north-east, is made up of a porphyritic central part 27 m wide with non-porphyritic microsyenitic margins each 3 m wide. At its south-western end the dyke is extremely badly exposed but the microsyenitic margins appear to continue about 300 m beyond the porphyritic centre.

For the greater part of its length the margins are not seen at all and the centre alone is identifiable as coarse black and white gravel, which is formed on weathering, or may stand out as tors which frequently exhibit onion weathering. The margins are normally only seen on the coasts.

Central component

The central component is characterized by the cognate xenocrysts of plagioclase in a medium grained groundmass. The plagioclase xenocrysts are broken and have corroded and rounded corners, varying in size from that of the groundmass (4 mm) up to 33 cm in length with crystals commonly about 1 to 2 cm and 10 to 15 cm. There are a few aggregates of plagioclase crystals; one aggregate 30 cm long occurs on Qaersuarssuk and another of 35 cm was measured south of Kangerdluatsiaup tasia. Towards the north there is a greater tendency for the development of aggregates of plagioclase crystals, particularly in the centre of the dyke, instead of isolated crystals. Typically the large cognate xenocrysts are tabular and have a rudimentary vertical alignment.

The larger cognate xenocrysts commonly have rows of dark inclusions parallel to their length which, in some crystals, appear to be of the matrix material. Most of the cognate xenocrysts are altered but the centres of some of the larger crystals are fresh and clear. Carlsbad and polysynthetic twinning is often clearly seen in hand samples.

Marginal component

The marginal component of this dyke is microsyenitic, about 3 to 4 m wide on each flank of the trachydoleritic centre, light grey in colour and fine grained with a chilled border against the country rock. This marginal component is fairly persistent though it does appear to be lacking in a few places. The outermost metre is normally entirely free of phenocrysts and inclusions; the inner part has 1 cm euhedral to subhedral orthoclase phenocrysts scattered through it and dark fine grained inclusions in which there may also be orthoclase phenocrysts. These inclusions carrying phenocrysts appear to be darker than those that are barren. The inclusions are elongated vertically, commonly about 7 cm long but are known to reach 23 cm in length.

Contact relations between the two components

There is a marked junction between the two components of the composite dyke. Towards the central component the marginal microsyenite increases in grain size and in abundance of the fine-grained dark inclusions and there is the appearance of occasional areas of coarser grain size. Within the central, trachydoleritic component there is a rapid decrease towards the contact in the size and concentration of the cognate xenocrysts over about 10 cm. Along the contact there are occasionally slightly coarser areas of irregular shape which appear to belong to the central component of the dyke.

Other big feldspar dykes

Besides the northern composite big feldspar dyke there are short lengths of big feldspar dykes, some of which are composite, between Kangerdluarssuk avangnardleq and Kangerdluarssuk kujatdleq. These belong to two generations since there are two intersections known, but otherwise individual dykes cannot be allotted to a particular generation.

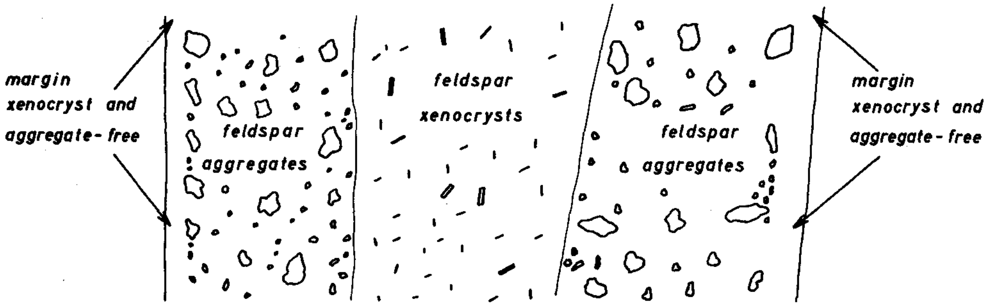

Fig. 4. A diagrammatic cross-section of the big feldspar dyke west of Naujât tasiat. See text for explanation. Width of dyke 11 m.

A length of the big feldspar dyke trending about 040^{o} on the high ground to the west of Naujât tasiat is about 11 m in width. This dyke is divisible into three parts; a central part with feldspar xenocrysts, a marginal part with feldspar aggregates and a thin border that is devoid of phenocrysts (fig. 4). There are no sharp boundaries between the parts but the feldspar aggregates of the marginal part end abruptly against an imaginary line which is taken as marking the edge of the thin border. This outer border is about 5 cm wide and is microsyenitic.

A 12 m dyke without a marginal component trending 070^{o} on the northern side of the entrance to Kangerdluarssuk kujatdleq is a possible south-westerly extension of this big feldspar dyke. The largest single plagioclase crystals and aggregates of plagioclase known on Qaersuarssuk occur in this length of dyke; aggregates of feldspar crystals are up to 190 cm across (e.g. fig. 5) and isolated single crystals are up to 49 cm in length (e.g. fig. 6). These are usually scattered along the length of the dyke; the giant crystals and aggregates are confined to the centre of the dyke but smaller crystals and aggregates are abundant right to the margin. Those near to the margin show a strong parallelism with their long axes parallel to the length of the dyke, while those in the centre only show a tendency to parallelism.

Other big feldspar dykes are in the order of 12 m wide, exceptionally reaching 19 m and, if composite, with margins of 2.5 to 3 m of alkali microsyenite. The contact between the two parts is normally gradational over about 5 cm (fig. 7) and irregular without signs of chilling.

Fig. 5. An aggregate of plagioclase crystals in a big feldspar dyke. Hammer length 30 cm. The same locality as fig. 6. W.S.W. 03.25.1959.

Fig. 6. A single plagioclase crystal 28 cm in length in a big feldspar dyke. North side of entrance to Kangerdluarssuk kujatdleq. W.S.W. 03.26.1959.

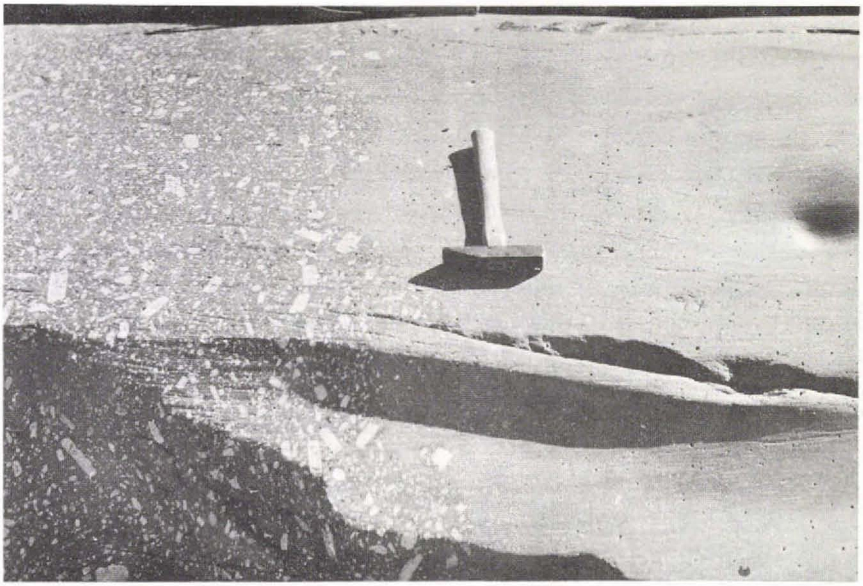

Fig. 7. The junction in a composite big feldspar dyke between the trachydolerite carrying big feldspars in the centre (left) and the microsyenite margin (right). South coast of Torssukátak. W.S.W. 04.02.1960.

In a number of places composite dykes lose one or both margins, or the centre, the dyke continuing as a thin alkali microsyenite or a big feldspar dyke. Locally a microsyenite margin may diverge from the main body of the dyke.

Petrography

Trachydolerite

These dykes are xenocrystic trachydolerites (occasionally dolerites) with an intergranular texture. Crystals of augite and biotite have an average size of 0.5 to 0.75 mm while feldspar crystals are from 4 mm upwards. Plagioclase is by far the most abundant of the mineral constituents, occurring mostly as cognate xenocrysts within a host containing plagioclase and alkali feldspar. The cognate xenocrysts commonly compose 40 to 50 % of the trachydolerite dykes. The mafic constituents are augite, biotite, and a few grains of olivine in a few of the dykes, while ilmeno-magnetite is an important accessory. Apatite is a minor constituent.

The plagioclase of the matrix is usually a sodic plagioclase occurring as short stubby laths. This is commonly the only feldspar, but in a number of dykes there are alkali feldspar rims to the matrix plagioclase and a few separate grains of alkali feldspar. In the dykes where there is a distinct alkali feldspar it may amount to an estimated 7 % of the matrix. The bulk matrix feldspar varies from $Or_{16}Ab_{49}An_{35}$ to $Or_{28.5}Ab_{53}An_{18.5}$ mol. %. Where there were xenocrysts the sample was coarsely crushed and material that appeared to be free of large crystals was hand picked before further crushing and separation. Three samples were treated in this way and gave intermediate results. The orthoclase content is possibly too low in some of the determinations as orthoclase commonly occurs as rims on the plagioclase and may be partly lost during extraction as it adheres to the adjacent mafic minerals.

The main mafic mineral is augite which occurs as subhedral, colourless to faintly pink, non-pleochroic grains constituting 10 to 15 % of the matrix. It has an average composition of $Ca_{42}Mg_{32}Fe_{26}$. Biotite is not as abundant as the augite, constituting only about 3 % of the rock. It frequently occurs associated with the large opaque grains, and is then pleochroic with α pale yellow to colourless, and β and γ deep red-brown. When not associated with the opaque grains it has the pleochroic scheme α yellow, and β and γ grey-brown. Olivine (Fa_{53}), and pseudomorphs after olivine, occur spasmodically in amounts up to 3 % of the matrix; the few, small grains are clustered together and are rimmed by opaque material. The opaque grains, both primary and secondary, may form anything up to 15 % of the total mineral content of the matrix. The large opaque grains are magnetite with exsolved ilmenite lamellae. Commonly there are also small amounts of a sulphide mineral, probably chalcopyrite. Rarely ilmenite occurs independently of the magnetite. Many of the magnetite grains show signs of alteration, biotite forming a narrow reaction rim against the plagioclase.

Apatite is a prominent accessory occurring mainly as rods in the plagioclase. Chlorite (probably penninite) is common throughout as a secondary product.

That the Qaersuarssuk big feldspar dykes are fairly alkaline is seen in the bulk matrix feldspar composition. The chemical analysis of the dyke matrix (table 3) is also fairly alkaline and rather sodic. The analysed sample (GGU 45458) was carefully picked so as not to include any large pieces of feldspar. Olivine occurs in the norm, but there is no modal olivine in the sample analysed.

Table 3

	45458	2	3
SiO_2	49.4	47.75	46.88
TiO_2	2.8	1.74	1.64
Al_2O_3	14.1	18.71	17.27
Fe_2O_3	4.3	6.08	2.47
FeO	8.5	7.11	8.84
MnO	0.3	n.d.	0.15
MgO	3.0	5.32	6.73
CaO	6.0	9.47	8.65
Na_2O	4.2	2.70	2.51
K_2O	2.9	1.20	1.25
P_2O_5	1.5	0.05	0.35
CO_2	0.0	n.d.	n.d.
H_2O^+	2.2	n.d.	3.30
H_2O^-	*	n.d.	0.28
S	n.d.	n.d.	tr
	99.2	100.13	100.32

C.I.P.W. norm of 45458

or	17.2	Feldspar	$Or_{27}Ab_{56}An_{17}$
ab	35.5	Clinopyroxene	$Wo_{50}En_{24}Fs_{26}$
an	11.0	Orthopyroxene	$En_{48.5}Fs_{51.5}$
di	7.4	Olivine	$Fo_{46}Fa_{54}$
hy	8.4		
ol	2.5		
mt	6.2		
il	5.3		
ap	3.6		

45458 Trachydolerite, big feldspar dyke (excluding xenocrysts). South side of Patdlît, NE Qaersuarssuk. Analyst B.I. Borgen.

2 Porphyritic labradorite-norite (groundmass only, 77 % of total). Napp Farm, Frakstadö, Lofoten Islands, Norway. Analysts C. Carstens and R. Marstrander. (Vogt, 1909, No. 4).

3 Dolerite-porphyrite (devonite) (groundmass only, 72 % of total). Mount Devon, Missouri. Analyst W.F. Hillebrand, record No. 2350. (Clarke, 1915, p. 57, column E).

* Analysis on sample dried at 110°C for 2 hours.

Plagioclase xenocrysts

The large plagioclase crystals in the dykes often have the appearance of being broken and their edges are corroded and corners rounded. The crystals are often intensely sericitized but in a few examples the centres are still fresh. Albite, albite-carlsbad, or occasionally pericline, twinning is common and can frequently be seen in hand samples even when sericitized. The crystals are not zoned; even the giant single crystals show no sign of compositional zoning.

Within the xenocrysts there are frequently dark inclusions parallel to the length of the crystal. These inclusions contain a variety of minerals probably derived from the dyke matrix: augite, opaque minerals, biotite and a great deal of chlorite.

Bridgwater (in Bridgwater and Harry, in press) has made a study of the plagioclase from the big feldspar dykes over a large part of the Gardar province. This has shown that plagioclase compositions based on the measurement of the twin plane to the optical indicatrix is unreliable and that the true composition can only be obtained by the measurement of the refractive indices. For a full discussion see Bridgwater and Harry. Compositions determined on the refractive indices of the xenocrysts from Qaersuarssuk average $An_{50 \pm 2}$.

The feldspar aggregates seen on Qaersuarssuk commonly have a pseudo-ophitic texture with a dark matrix that is indistinguishable from that of the host dyke. No separate measurements of the plagioclase composition are available from the aggregate matrix.

Microsyenite margins to composite dykes

The marginal component of the northern composite big feldspar dyke is an alkaline microsyenite. It is similar petrographically to the other alkaline microsyenitic dykes on the island.

In the microsyenite there are occasional euhedral phenocrysts of orthoclase about 1 cm long. The groundmass feldspar consists of laths 1 to 1.5 mm long which form a crudely radiating texture. These laths either are antiperthitic or are separate crystals of albite and orthoclase, and together they constitute about 80 % of the rock. The bulk composition of the feldspar is about $Or_{36.5}Ab_{63.5}(An_0)$ mol. %.

Biotite is the main mafic constituent, estimated at 4 to 6 % of the total. It is interstital to the feldspar and is occasionally intergrown with soda amphibole or partly surrounded by it. The biotite is pleochroic with α yellow-brown, β and γ deep red-brown but there is a good deal of colour variation with some red and some dark grey biotite, and occasionally a margin that is pleochroic from a pale yellow to green.

The soda amphibole is pleochroic in deep blue-green to a dirty green-blue or yellow-green with high dispersion and a $\alpha \wedge c$ about 24^{o} (though the extinction is not complete) suggesting that it has riebeckitic-arfvedsonitic affinities. Besides surrounding biotite grains the soda amphibole occasionally partly surrounds grains of soda pyroxene.

The soda pyroxene occurs as small grains, rarely as long as 1.5 mm. These are zoned from ægirine-augite centres out to ægirine rims with pleochroism in deep to yellow-green, though in some examples ægirine forms a complete crystal.

The accessory minerals are apatite, ? zircon and opaque material. Only a very little of the opaque material is primary.

Discussion

The feldspars

The plagioclase xenocrysts of the big feldspar dykes appear to occur in two forms: those in the large aggregates of crystals (and break down of the aggregates) and those occurring as large single crystals. Bridgwater (in Bridgwater and Harry, in press) has shown that this is only part of a complete range of aggregate types that are characterized by particular textures and the anorthite content of the plagioclase. The anorthite content of the xenocrysts is correlated with the basisity of the host dyke, the xenocrysts with the higher anorthite content occurring in dolerites, those with a lower An % in trachytes; the xenocrysts always have a higher anorthite content than the plagioclase of the host. The xenocrysts from the Qaersuarssuk dykes fit into this scheme, xenocrysts of An_{50} occurring in a trachydoleritic host with feldspar having a bulk composition below An_{35}. There is thus a considerable difference between the composition of the feldspar of the matrix and that of the xenocrysts; the xenocrysts are not in equilibrium with their surroundings. This is also seen in the form of the plagioclase xenocrysts which are commonly broken and corroded. It is thus inferred that the xenocrysts have been derived elsewhere and have been picked up and carried in the trachydoleritic magma during intrusion. Since they are foreign to the host in which they now occur but are considered to have some genetic relation to it the term cognate xenocryst is suggested (cf. cognate xenolith of Billings, 1954, p. 289 and Holmes, 1920, p. 63).

The aggregates of plagioclase crystals normally only have a little host dyke matrix and lack mafic crystals of equivalent size to the plagioclase crystals. This suggests that the plagioclase aggregates are top accumulates in a crystallizing magma chamber. This top accumulation of feldspar was broken up by a later, more alkaline, magma that carried fragments of it to a higher level.

Gorbatschev (1961) proposed a very similar explanation for dolerite-porphyrite dykes from the Eskilstuna region of eastern central Sweden which resemble the big feldspar dykes of southern Greenland. However, his explanation, like that given here, is probably an oversimplification of the problem and the reader is referred to Bridgwater and Harry for a full discussion.

Composite relationship

Some of, but by no means all, the big feldspar dykes on Qaersuarssuk, have margins of alkali microsyenite. There is a marked junction between the two rock types (fig. 7), and occasionally one of the microsyenitic margins may be lacking or only one of the rock types forms the continuation of the composite dyke. It is therefore suggested that these dykes were formed from two intrusions of magmas of different compositions. The alkali trachyte magma was intruded first and chilled against the granite; this was followed by the central trachydoleritic part of the dyke carrying the big feldspar crystals and aggregates. Since the central part is not chilled against the outer it is suggested that the second intrusion followed close after the first, but after the first intrusion had solidified sufficiently to restrict the later intrusion to the centre of the dyke with very little mechanical mixing of the two types along their contact. This order of intrusion is opposite to that commonly found in composite dykes where the alkaline magma normally follows the basic.

OLIVINE DOLERITE DYKE

A late generation of dolerite dykes is represented on Qaersuarssuk by a dyke that crosses the western side of the island trending 055°. The dyke is thin in the north-east and thickens to the south-west reaching a maximum of 200 m on Qârusuarssuk (Ayrton and Burri, 1967) before breaking up into a swarm of dykes and diminishing in total width. In the north-east it decreases to 25 m at Kangerdluatsiaq (mapped by J. H. Allaart).

For the greater part of its length the dyke forms an erosion hollow across the country with occasional tors of brown-weathering dolerite set in large areas of light brown gravel bearing no vegetation.

The dyke is medium-coarse to coarse grained with very little difference in grain size between the middle and close to the margin. Against the wall rock there is a fine-grained margin a few centimetres wide. The adjacent zone of granite 1.5 m wide is frequently green in colour and has an interstitial granophyric texture due to partial melting. Further from the dyke the granite may sometimes be red in colour due to shearing.

Vertical banding is known in two places in the dyke. The bands are seen as contrasts in colour between darker and lighter zones 2 to 4 cm across which grade from one to the other.

Pegmatite occurs rarely, usually following vertical joints but occasionally having the form of irregular "pods".

Petrography

The dyke is medium-coarse grained with a doleritic to sub-doleritic (intergranular) texture though sometimes the feldspar laths have a tendency towards a radial arrangement. The main constituents are plagioclase 74 %, olivine 9 %, augite 6 %, ilmenite 6 % and biotite 3 % by volume with apatite as an accessory mineral, and secondary minerals include serpentine, epidote and sericite.

The plagioclase has a bulk composition of $Or_{10.5}Ab_{41.5}An_{48}$; most of it is twinned on the albite and carlsbad laws. Some of the grains show distinct normal zoning. The plagioclase is all more or less altered to sericite with epidote.

The olivine is the most abundant of the mafic minerals occurring as rounded, colourless grains up to about 1 mm in diameter. They are frequently crowded together as aggregates in the mafic-filled interstices between the plagioclase laths. The olivine composition varies between Fa_{49} and Fa_{58}. On alteration crysotile (serpentine) is developed along the cracks in the grains together with a little secondary opaque material. The main alteration product is bowlingite, a brown, slightly pleochroic, fibrous mineral which is in the same optical orientation as the original olivine. In addition, in some of the more altered grains, there is antigorite, pleochroic in green to yellow-brown, and occasionally also a carbonate mineral.

Augite is interstitial to the feldspar and is sometimes moulded around grains of olivine. The grains are large, tending to be poikilitic in places with inclusions of apatite, biotite, feldspar and opaque material. It is faintly mushroom-coloured to pink and a few of the grains show faint pleochroism. The mean is about $Ca_{40}Mg_{29}Fe_{31}$.

The presence of biotite in the dyke suggests a wet magma comparatively rich in potash. It is a comparatively late formed mineral as it fills the gaps in the skeletal grains of ilmenite and rims the ilmenite against plagioclase. The biotite is markedly pleochroic with α very pale yellow (almost colourless where γ is green), β and γ deep red-brown to brown to green. Most of the biotite flakes are red-brown with a border of browner colour grading out to a thin green rim. This is indicative of a change from an early titanium-rich biotite to a later iron-rich rim.

Large skeletal grains, up to 1 mm in diameter, of ilmenite, and magnetite with very fine exsolved ilmenite lamellae, are abundant. Ilmenite is an early formed mineral in the dyke which suggests strong oxidizing conditions in the magma, and a magma comparatively rich in titanium. In addition there is fine-grained disseminated pyrite with pyrrhotite. Under high magnification the pyrrhotite is seen to have a little pentlandite and exsolved chalcopyrite. Occasionally there is sphene associated with the skeletal grains of ilmenite.

The principal accessory mineral is apatite. It occurs as little hexagonal grains or occasionally rods mainly within the augite, but also in the plagioclase. In one section examined (GGU 45305) a fibrous mineral (? pectolite) fills a few interstices. Prehnite occurs in a few of the altered biotite flakes forcing apart the cleavage flakes (cf. Struwe, 1958).

Small pegmatite pods have a concentration of large bronze-coloured biotite flakes around their rims. The pegmatite is coarse-grained with hypidiomorphic-granular texture, consisting of plagioclase with augite and ilmenite. Two samples gave different plagioclase compositions, An_7 and An_{27}, with only a trace of K_2O (chemical determination) in each. A marked feature of the plagioclase is its irregular twinning. In one large crystal the centre has regular albite twinning, but towards the margin it becomes irregular. Augite, which may be about 16 % of the pegmatite, occurs as large crystals up to 6 cm long, though the average is about 2 cm. The crystals are slightly zoned with a composition about $Ca_{44}Mg_{32}Fe_{24}$ (β 1.700 and $2V_{\gamma}55^{o}$). Ilmenite constitutes about 6 % of the pegmatite. It occurs as well-developed skeletal grains up to 2 mm across. These skeletal grains are pure ilmenite without trace of magnetite. Sphene (1.5 %) occurs associated with some of the skeletal ilmenite grains and contains needles of ilmenite. The biotite of the pegmatite is extensively altered to chloritic minerals. Apatite is an accessory mineral with hexagonal grains up to 0.5 mm across.

Chemistry of the dolerite dykes

Two analyses have been made of dolerites from Qaersuarssuk, one from each of the two dolerite dyke generations (table 4). The two analyses are similar showing that both dolerites are slightly undersaturated, the later generation (45305) more so than the earlier (45501) as the later has normative nepheline. Neither dolerite is as basic as the least differentiated dolerite from the Gardar (table 4, 20632). The dolerites from both generations show the high titania content that is characteristically found in the Gardar province and the later dyke shows a high alumina content which, as Upton has already pointed out (Upton, 1964b, p. 76), is characteristic of certain of the Gardar dolerites.

Table 4

	45501	45305	20632
SiO_2	47.15	45.45	44.60
TiO_2	3.08	2.80	1.49
Al_2O_3	14.18	17.32	16.46
Fe_2O_3	2.80	3.23	2.28
FeO	11.82	10.21	9.44
MnO	0.21	0.18	0.16
MgO	5.23	4.38	9.77
CaO	8.06	8.02	8.68
Na_2O	3.80	3.70	2.50
K_2O	1.00	1.80	0.85
P_2O_5	0.60	0.42	0.32
CO_2	0.0	0.0	-
H_2O^+	1.34	2.10	2.06
H_2O^-	*	*	*
	99.27	99.65	98.61
C.I.P.W. norm			
or	5.9	10.6	5.0
ab	32.1	23.6	20.9
an	18.7	25.3	31.2
ne	-	4.2	0.1
di	14.5	9.6	8.0
hy	1.2	-	-
ol	14.4	13.2	24.5
mt	4.1	4.7	3.3
il	5.9	5.3	2.8
ap	1.4	1.1	0.8
Feldspar	$Or_{10}Ab_{57}An_{33}$	$Or_{18}Ab_{40}An_{42}$	$Or_{9}Ab_{36.5}An_{54.5}$
Clinopyrox.	$Wo_{50}En_{23.5}Fs_{26.5}$	$Wo_{50}En_{24}Fs_{26}$	$Wo_{52}En_{31}Fs_{17}$
Orthopyrox.	$En_{43}Fs_{57}$	-	-
Olivine	$Fo_{45}Fa_{55}$	$Fo_{47}Fa_{53}$	$Fo_{62.5}Fa_{37.5}$

45501 ESE dolerite. Head of Atertûp ilua, SE Qaersuarssuk. Analyst B.I. Borgen.

45305 NE dolerite. Qaernertormiut, western Qaersuarssuk. Analyst B.I. Borgen.

20632 Dolerite. SW part of Eqaloqarfia dyke. Analyst B.I. Borgen. Assumed to represent the least differentiated Gardar magma type (Watt, 1966).

* Analysis on sample dried at 110°C for 2 hours.

SPHERULITIC DYKE

A 40 cm, blue-black dyke with a strike of 060° cuts the nodular microsyenitic dyke in the north-west tip of Mâtâta nunâ, on the island in Ikerasak, and the same dyke on Upernivik. The dyke is characterized by the well-marked spherulitic texture.

Spherulitic dykes are also known cutting the syenite at Kusanga on the Narssaq peninsula which is comparatively late in the mid-Gardar sequence of intrusions (Stewart, 1960; Ussing, 1912). On Tugtutôq Upton (1962) has described a spherulitic sodic rhyolite which he has termed comendite. If these spherulitic dykes are contemporaneous they appear to have been intruded late in the Gardar period.

Petrography

The spherulites of the dyke are up to 6 mm in diameter and are rounded, or polygonal where they interfere with one another. There is a phenocryst of alkali feldspar at the centre of each spherulite. Under crossed nicols a radiate growth of numerous crystallites is seen within each spherulite as a black extinction cross. Outside the spherulites the crystallites have a crude flow texture. Each crystallite has a vague feathery form. In the area between the spherulites there is frequently an interstitial ? carbonate mineral.

The crystallites are opaque under normal illumination but with the use of the condenser are seen to be intensely pleochroic from pale blue to yellow (riebeckite-arfvedsonite). The small colourless areas between the crystallites become pale blue with crossed nicols and illumination by the condenser.

The phenocrysts of alkali feldspar, around which the radiating feathery texture of the spherulites is developed, are in the order of 1 mm long. The bulk composition of the feldspar is albite (X-ray determination by M. Danø). These phenocrysts have rounded corners which is taken to indicate that these crystals have not been in equilibrium with the magma at the time of crystallization of the dyke.

While the dyke is similar in texture to the comendites that occur on Tugtutôq (Upton, 1964) and around Narssaq (Ussing, 1912) it lacks the quartz phenocrysts of true comendite. This is reflected in the lower silica

Table 5

	45537	2	C.I.P.W. norm for 45537	
SiO_2	61.1	64.82		
TiO_2	0.7	0.33		
Al_2O_3	13.7	14.29	Q	0.7
Fe_2O_3	4.4	2.04	or	26.0
FeO	4.8	4.27	ab	45.8
MnO	0.2	tr		
MgO	0.0	1.00	ac	12.5
CaO	2.1	1.55	di	8.2
Na_2O	7.1	5.62	hy	3.6
K_2O	4.4	5.51	mt	0.1
P_2O_5	0.0	0.13	il	1.3
CO_2	0.2	0.0		
H_2O^+	0.5	0.20		
H_2O^-	*	0.20		
	99.2	99.96		

45537 Spherulitic riebeckitic-arfvedsonitic trachyte. Mátâta nunâ by Qaersuarssuk, Julianehåb district, South Greenland. Analyst B. I. Borgen.

2 Spherulitic riebeckite trachyte. Cobble on the beach at Cape Parry, Traill Island, East Greenland. Analyst F. Herdsman. (Tyrrell, 1932, p. 522, Table 1, No. 5. S and (Ni, Co) O reported as none.)

* Analysis on sample dried at 110°C for 2 hours.

percentage (table 5). The rock is only just saturated so that it is trachytic in composition with high normative acmite and, although similar, cannot be directly correlated with the sodic rhyolites on Tugtutôq. An analysis of a spherulitic riebeckite trachyte from Traill Island, East Greenland, is given for comparison (Tyrrell, 1932).

LAMPROPHYRE DYKES

Lamprophyre dykes, 50 - 80 cm wide, occur throughout the area, commonly in swarms but single dykes are also numerous. They are normally vertical with an average strike direction of 055°, but examples occur in almost any direction. The greatest development of these dykes occurs as a NE swarm across the peninsula on the north-east side of the bay Patdlît. The swarm is parallel to the intense shearing that occurs in this part of the island sub-parallel to the Bredefjord coast. The larger lamprophyre dykes are unaffected by the shearing but parts of some of the smaller dykes are slightly affected implying later movement in the shear zone.

Many of the larger dykes display vertical layering. The layers have a sharp junction between each other and are distinguished by differences in grain size, the presence or absence of vugs filled with white or pink minerals and the degree of alteration of olivine which weathers out to leave a pitted surface.

Petrography

The dykes that have been examined petrographically are extremely altered without recognisable original minerals. They appear to have suffered late stage deuteric effects, notably the replacement of olivine by carbonate, but in the more extremely altered dykes carbonate has replaced all originally existing mafic minerals.

The dykes appear to have been fine grained with phenocrysts. Opaque material is abundant and in a few examples there are flakes of biotite. These biotite flakes may have compositional zoning shown by a difference in the pleochroism. They have α near colourless to pale brown, β and γ brown to red-brown, the stronger pleochroic colours occurring on the margins. Olivine has probably existed in some of these dykes as phenocrysts but is now pseudomorphed by green fibrous chlorite, carbonate minerals, and opaque material marking the position of original cracks in the olivine.

CHEMISTRY

Trace element analyses in the Gardar province have only been extensively carried out on the Kûngnât and Ilímaussaq igneous complexes. A few analyses and analyses of a selected element or two have been performed on other igneous bodies and minerals. Analyses of 12 elements by spectrographic methods on four dyke samples are given here in the hope that the information can be used in conjunction with analyses made in the future on other Gardar igneous rocks. Since the dykes are considered as representing various stages of a differentiating alkali olivine basalt magma the analyses in table 6 have been arranged according to their differentiation index as an approximation to the order of degree of differentiation.

The alkali elements Lithium is low (20-30 ppm) in the two dolerites, increasing slightly in the big feldspar dyke (trachydolerite) and there is a marked increase in the spherulitic dyke (trachyte). Sodium and potassium both show increases from the dolerites through the big feldspar dyke to the nepheline microsyenite, but with a slight decrease of both oxides in the spherulitic dyke. The ratio $\frac{Na_2O \cdot 100}{Na_2O + K_2O}$ drops between the two dolerites, and drops slightly further to the big feldspar dyke but then remains constant with differentiation. Cesium was below the detection level of 10 ppm in all the samples. Rubidium shows an increase in the spherulitic dyke over that in the dolerites.

Alkaline earth elements The calcium content of the samples drops with differentiation, at the same time the alk/Ca ratio consistently increases.

Rare-earth elements Yttrium occurs in amounts at, or less than, 100 ppm in all samples. Lanthanum was only detected in the spherulitic dyke where the amount is 200 ppm. Scandium was below the detection level in all the samples.

Table 6

	olivine dolerite		trachydolerite	nepheline microsyenite	trachyte
	45501	45305	45458	45457	45537
SiO_2	47.15	45.45	49.4	54.85	61.1
TiO_2	3.08	2.80	2.8	0.44	0.7
Al_2O_3	14.18	17.32	14.1	17.04	13.7
Fe_2O_3	2.80	3.23	4.3	4.66	4.4
FeO	11.82	10.21	8.5	4.36	4.8
MnO	0.21	0.18	0.3	0.20	0.2
MgO	5.23	4.38	3.0	0.25	0.0
CaO	8.06	8.02	6.0	2.42	2.1
Na_2O	3.80	3.70	4.2	7.93	7.1
K_2O	1.00	1.80	2.9	5.20	4.4
P_2O_5	0.60	0.42	1.5	0.12	0.0
CO_2	0.0	0.0	0.0	nil	0.2
H_2O^+	1.34	2.10	2.2	2.40	0.5
	99.27	99.65	99.2	99.87	99.2
Differentiation index	73.7	75.4	81.1	97.2	100.0
Alk/CaO	0.6	0.7	1.2	5.4	5.5
$\frac{Na_2O \cdot 100}{Na_2O + K_2O}$	79	67	59	60	62
Li	20 ppm	20	35		80
Rb	30	30	30		80
Cu	100	70	40		30
Sr	400	700	500		tr
Ba	450	500	1200		*
La	*	*	*		200
Y	< 100	< 100	< 100		100
Zr	350	240	400		1300
V	250	200	tr		tr
Cr	100	30	*		*
Co	60	60	40		*
Ni	70	80	*		tr

Spectrographic analyses by H. Bollingberg.

Cs, Ga and Sc not detected

* not detected.

<u>The ferrides</u> Titanium is present in amounts of 2-3 % in the dolerite dykes and drops to about 0.5 % in the syenitic dykes. Nickel and cobalt occur in small amounts in the dolerites and decrease with differentiation. Chromium and vanadium occur in the dolerites but are undetectable in the later differentiates.

Zircon increases in content in the more differentiated rocks reaching 1300 ppm in the spherulitic dyke (trachyte).

Gallium and scandium were below the detection level in all the samples.

PETROGENETIC CONSIDERATIONS

Qaersuarssuk is only a small part of the area covered by Gardar activity. The intrusive rocks on the island are only represented by dykes. These, if representing a considerable variation of rock types, are suitable for following evolutionary sequences. On Tugtutôq, on the southern side of Bredefjord, there is a Gardar intrusive centre with a suite of dykes. Only the fringe of the dyke activity about this centre is present on Qaersuarssuk.

Differentiation of alkaline olivine basalt magma normally leads to end fractions of trachytic (syenitic) and phonolitic (nepheline syenitic) composition, the undersaturated condition of the differentiate apparently being inherited from the parent magma (Yoder and Tilley, 1962). Olivine basalt lavas of Gardar age occur in abundance on the Narssaq peninsula and almost certainly covered a far larger area than their present position restricted to the "graben" would indicate.

The sequence of dyke intrusion need not necessarily be the same as the differentiation sequence. The earliest dykes on Qaersuarssuk are olivine dolerites which are not nearly as basic as the least differentiated rock type known in the Gardar, as seen from a study of all the available rock analyses on Gardar rocks (Watt, 1966).

Differentiation can be expressed in different ways. In table 6 it has been expressed as the "differentiation index" $\frac{FeO + Fe_2O_3 \cdot 100}{FeO + Fe_2O_3 + MgO}$, and the analyses arranged according to the index. When plotted on variation diagrams the few analyses available from Qaersuarssuk do not lie on a smooth curve. This would be expected since each dyke is not necessarily in direct line of differentiation from a single magma but will depart slightly from it. Only where there is a large number of analyses can a mean line representing an evolutionary sequence be drawn.

FAULTING

The topography of Qaersuarssuk is strongly influenced by the zones of dislocation; the fjords trend approximately ENE-WSW, and throughout the island there are numerous NNW lines of dislocation all forming valleys and small fjords. Although the ENE fjord direction is the most marked feature, nowhere has it been possible to see zones of crushing connecting fjords and lakes of this trend, but this may be due to lack of exposure. The long length of lake 5 and its accompanying valley also marks a large fault, trending WNW. In many examples an erosion feature is present where no actual displacement can be demonstrated.

All the faults in the area appear to be wrench faults displacing cross-cutting dykes; no vertical movement can be demonstrated on any of them due to lack of suitable markers.

NNW faults

Along these faults two directions of movement are clearly demonstrated; an earlier dextral and a later sinistral movement separated by the emplacement of a number of generations of NE dykes. From what is known of the Gardar faulting elsewhere it appears that this sinistral movement is most clearly seen on Qaersuarssuk.

Three of the early ESE olivine dolerite dykes, each over 60 m wide, are cut in a number of places by NNW faults. These dykes now show dextral displacements on these faults by the amounts given below, but since sinistral movement followed the dextral the original dextral movement after the emplacement of the ESE olivine dolerite dykes was greater.

Naujât tasiat fault	450 m
Torssukátâ fault	600 m (but the course of the dyke here may give a deceptively large figure).
Kigssaviat fault	450 m
northern extension of the Tunua fault	450 m

After the dextral movement on these faults there followed the emplacement of a number of generations of different rock types (see chronological scheme p. 7) in a NE-SW direction. The dykes were followed by sinistral movement along the same fault lines. The sinistral movement on the faults, with the exception of the Torssukátâ fault, is about 150 m. On the Torssukátâ fault it is possible that there has been two periods of movement, of 150 and 50 m, separated by dyke emplacement.

The majority of the NNW faults die out to the north. The northern composite big feldspar dyke is only locally affected by small amounts while to the north of it the NE olivine dolerite dyke, which is earlier than the northern composite big feldspar dyke, shows no displacement. But the course of the dyke is not entirely regular and the valleys following the faults continue across the dyke suggesting that there may have been shattering of the dyke without a displacement of any magnitude.

The initiation of this direction of faulting can only be shown as post-ESE olivine dolerite dyke emplacement.

The WNW fault

A great WNW fault along the lake 5 shows at least two stages of movement, both in a sinistral sense. It is part of an important line of dislocation which can be traced over a length of at least 70 km in a WNW-ESE direction across the Julianehåb district. It is parallel to a number of other faults showing a similar magnitude of sinistral displacement so that they form an important set of faults throughout the whole region. The initiation of movement is unknown. The Laksenæs fault (Henriksen, 1960) in the Ivigtut region shows sinistral movement before the Ketilidian period so that it is quite possible that the fault across Qaersuarssuk was initiated before the Gardar period. However, no movement can be demonstrated until after the emplacement of the NE olivine dolerite dyke which is relatively late in the dyke chronology (p. 7). No vertical movement can be demonstrated on the fault but, in common with the Laksenæs fault, there may have been considerable vertical as well as horizontal movement.

After the emplacement of the NE olivine dolerite dyke there was sinistral movement of 1100 m along the fault (based on the assumption that the dyke cut straight across the fault line). This was followed by the emplacement of the northern composite big feldspar dyke which was subsequently displaced 1500 m sinistrally. Thus the fault shows a total sinistral displacement of 2.6 km.

The fault itself appears to be displaced 2 km to the south-west along Bredefjord between Qaersuarssuk and Tugtutôq. The ESE olivine dolerite dykes, though, do not show any displacement across the fjord, and certainly not of that magnitude. Thus it appears as if the fault is here en échelon.

The mechanics of the Gardar fault system

This section is highly speculative as must be any theoretical approach to the fault system. While it is suggested that the WNW fault may be old, since a fault in the same direction in the Ivigtut area is old, the faults that can be shown to be oldest on Qaersuarssuk are the NNW faults. The salient point is that the NNW faults show transcurrent movement in two directions; an earlier dextral and a later sinistral. It therefore appears that there has been a radical change with time in the forces producing these faults.

With the exception of the early ESE olivine dolerite dykes the dominant dyke direction is north-east and the majority of these north-east dykes occur between Kangerdluarssuk avangnardleq and Bredefjord. Any discussion of the stress system resulting in faulting must take into account the dykes.

The earliest manifestation of a differential stress system operating in the area is the tensional fracturing in a ESE direction into which olivine dolerite dykes have been emplaced. This was followed by dextral movement on NNW faults to displace these dykes by a minimum amount of 450 m. These ESE dykes are developed on a regional scale. But ESE tensional openings on a regional scale and dextral faulting on NNW lines appear to be incompatible on the same stress system.

Small amounts of dextral movement on the NNW faults could be explained by scissor faulting or by large amounts of vertical movement when the dykes that are used as markers are not vertical. The fact that these faults die out to the north may suggest considerable scissor faulting. One of the dykes is known locally to dip 70^{o} northwards which means that a downthrow on the north-east side of the fault will show as a dextral displacement on the fault.

The prominent feature of the NE dykes on Qaersuarssuk is their abundance in only part of the island. The individual dykes are traceable over considerable distances and their emplacement appears to be quite unrelated to the fault systems. Their regional distribution is also interesting. There is a concentration of dykes on Tugtutôq that extends onto SE Qaersuarssuk where it thins out. Further to the west there are only a few dykes until the Isortoq area, to the north-east of Nunarssuit, where there is a great dyke concentration. The two areas of dyke concentration, Tugtutôq and Nunarssuit-Isortoq, are also the positions of later intrusive centres.

Appendix

Optical determinations

The composition of the zoned plagioclase was obtained from maximum γ and minimum α refractive index determinations on mounted grains in random orientation. The anorthite percentage was obtained from Hess's curves (1960).

Some plagioclase determinations were made by the measurement of the refractive index of plagioclase glass. Plagioclase extracted by crushing the rock and separating it with a magnetic separator was fused in a blow-lamp and quenched to give a glass. The refractive index of the glass was measured using a variable wave-length method at constant temperature and a standard glass (Micheelsen, 1957). The plagioclase composition, in weight percent, was obtained from the curves of Schairer et alia (1956).

Optic axial angles were determined by direct measurement about the acute bisetrix on a 5-axis U-stage and were corrected for tilt using Kleeman's nomogram (1952).

The β refractive indices of the pyroxenes were determined using a variable wave-length method at constant temperature and a standard glass (Micheelsen, 1957). It was determined on either (100) or (001) parting planes when the isogyre of the interference figure is E-W, as described by Hess (1960, p. 11), so that β is N-S. The pyroxene composition, in atomic percent, was obtained from $2V_{\gamma}$ and β R.I. on Hess's curves (1949).

X-ray determinations

The nepheline composition was determined by X-ray diffraction after the method described by Smith and Sahama (1954). The composition is quoted as the ratio 100K/K + Na.

The composition of olivine was determined by X-ray diffraction after the method described by Yoder and Sahama (1957). These authors give an accuracy of 4 mol. percent.

All X-ray determinations were carried out in the X-ray laboratory of the Mineralogical Museum, Copenhagen.

Chemical determinations

The chemical analyses were made by B.I. Borgen and I. Sørensen in the Geochemical Laboratory of the Geological Survey of Greenland. In the feldspar determinations the Na_2O and K_2O were determined flame photometrically and the CaO titrametrically. Borgen has given a description of the methods used in a separate publication (Borgen, 1967). When the CaO was not measured it has been calculated from the ideal formula by difference and quoted within brackets.

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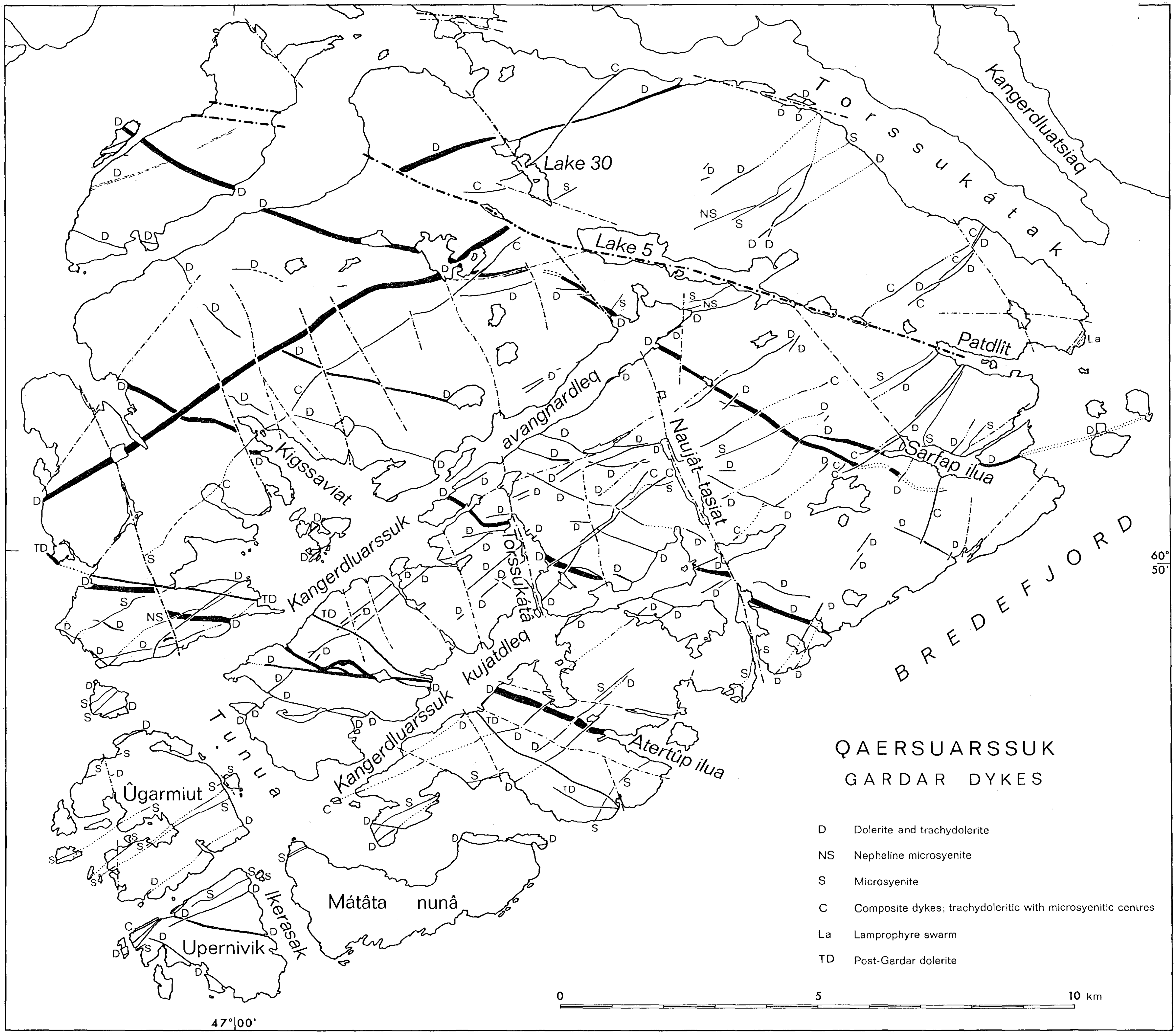

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