GRØNLANDS GEOLOGISKE UNDERSØGELSE
BULLETIN No. 44

THE GEOLOGY OF TUGTUTÔQ AND NEIGHBOURING ISLANDS SOUTH GREENLAND

PART II

NORDMARKITIC SYENITES AND RELATED ALKALINE ROCKS

BY

B. G. J. UPTON

WITH 11 FIGURES IN THE TEXT
AND 8 PLATES

Reprinted from
Meddelelser om Grønland, Bd. 169, Nr. 2

KØBENHAVN
BIANCO LUNOS BOGTRYKKERI A/S
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Abstract.

Among the Precambrian (Gardar) intrusions in the Tugtutôq area, syenitic rocks are abundantly represented. Quartz-bearing alkalic rocks were first intruded after the emplacement of a number of large gabbro dykes. Although early Gardar nepheline syenites occur on Tugtutôq, no post-gabbro undersaturated syenites occur within the area under discussion. Quartz syenites and their faster cooled equivalents occur either as ENE directed dykes or as ring-dykes and stocks within a late Gardar central complex. The earliest quartz syenite occurs as the central component in a composite sector of one of the large gabbro dykes. This was succeeded by multiple swarms of dykes with alkalic types ranging from 'rhomb porphyry' microsyenite to comendite. Dyke intrusion was virtually at an end by the time of formation of the central ring-complex. The total petrographic range of the oversaturated alkalic rocks extends from ferroaugite-fayalite syenites with relatively calcic feldspar (ca. $Or_{25}Ab_{66}An_{9}$) to highly acid riebeckite-bearing rock types. The various intrusions are considered to represent magma batches supplied, at irregular intervals, from a deep-seated syenite complex which was crystallising throughout the latter part of the Gardar period. The inferred sub-surface complex is taken to be closely comparable to the Gardar complexes exposed at Nunarssuit and Kûngnât, and to have differentiated by process of crystal fractionation. By analogy with the Kûngnât complex the parental magma of the underlying magma chamber(s) is believed to have passed through a larvikitic stage. The perthosite stock which forms the latest major intrusion on Tugtutôq is thought to indicate a slight divergence from the general larvikite-nordmarkite-alkali granite differentiation sequence. The magmas of this main differentiation sequence changed in composition along a "thermal valley" close to that of the synthetic system Or-Ab-SiO_2-H_2O.

I. INTRODUCTION

In a previous publication (Upton, 1962), a review was presented of the general geology of the Tugtutôq-Skovfjord district, laying particular emphasis on the Precambrian intrusives of the Gardar volcanic cycle which give rise to the more striking geological features of the area. The sequence of events was outlined and a brief petrographic description was given for the principal rock-types.

The earliest group of intrusions in the area generally acknowledged to be of Gardar age are the NW trending dykes of olivine dolerite which traverse the area in discordance with the regional NE to ENE strike of the older granitic terrain. These dykes were followed by a prolonged episode in which a multitude of co-genetic basic and alkaline dykes were emplaced parallel to the old-established ENE structural trends of the granodioritic and migmatitic country rocks. Igneous activity in the neighbourhood culminated in the formation of a small ring-complex. The present paper sets out in more detail the petrological and petrochemical features of the saturated and over-saturated felsic intrusions. These may be conveniently dealt with under three headings; (a) the Assorutit syenite; a quartz syenite mass occuring within an unusually large dyke of olivine gabbro, (b) narrow dykes comprising the larger part of the mid-Gardar dyke-swarms and (c) the syenite rocks composing the central ring-complex. A related nepheline syenite forming the central part of the Hviddal giant dyke preceded the more silicic rocks described in this publication and is discussed separately in part IV of this series of papers, (Upton, 1964).

The cost of much of the analytical work was defrayed by a 'Penrose Bequest Grant' from the Geological Society of America which is most gratefully acknowledged.

November 1962. B. G. J. Upton.

II. THE ASSORUTIT SYENITE

After the intrusion and crystallisation of the Hviddal composite dyke, which consists of a differentiated nepheline syenite body (UPTON, 1964) enclosed by syeno-gabbro, some large gabbro dykes were injected through the area. A composite character developed in the most northerly gabbro dyke at the eastern end of Tugtutôq island where syenite magma was intruded along the centre of the dyke. The syenite core to the dyke has been revealed by erosion over a small coastal area between the headlands of Assorutit and Nasaussardle (fig. 1). The syenite itself has much in common with the western facies of the earlier Hviddal nepheline syenite but differs in being oversaturated, containing small quantities of interstitial quartz and giving rise to small quartz-rich dykes and veins. The average rock is hypidiomorphic granular with feldspar crystals up to 7–8 mm. The subordinate ferromagnesian minerals resemble those of the western facies of the nepheline syenite intrusion and include clinopyroxene, olivine, amphibole, mica and ore. In both intrusions, feldspar, pyroxene, olivine, ore and apatite were the earliest phases to crystallise. The significant differences between the two rock types in fact lie almost entirely in their late-crystallising minerals, the Assorutit rock containing late-stage quartz, calcite and mica in place of the nepheline and analcite present in the earlier rock. Lack of chemical equilibrium in the Assorutit syenite is evinced by the strong zonation in many of the minerals and the unusually complex reaction sequences. Although no preferred orientation of the minerals has been recorded there are, in the central part of the intrusion, a few thin melanocratic layers rich in pyroxene and olivine. The sub-horizontal layers do not show gravity stratification but nevertheless are thought to be concentrations of heavy minerals sorted by action of magmatic currents.

Feldspar, predominantly antiperthitic in texture, accounts for some 80% of the syenite. The crystals are commonly Carlsbad twinned and generally show albite-twinned plagioclase with cloudy patches of potassic feldspar. Pericline twinning is more rarely observed. The polysynthetic twinning is mostly on a very fine scale, with the individual twin lamellae short and discontinuous. Commonly there is a gradation outwards from a clear quasi-homogeneous central area of cryptoper-

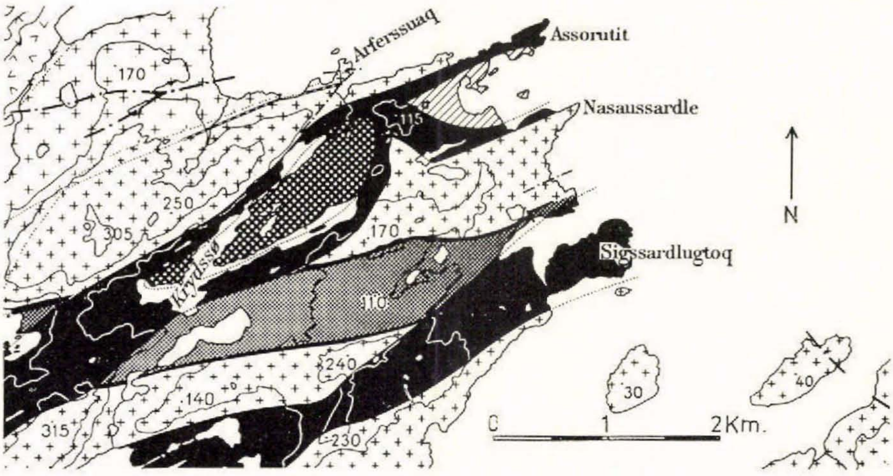


Fig. 1. Map showing relationship of Assorutit syenite to other Gardar intrusives. (Crosses; Pre-Gardar granodiorites: dotted; nepheline syenites of Hviddal composite dyke: solid; gabbros and the syeno-gabbro marginal to the Hviddal syenites: cross-hatched; Kryds Sø syeno-gabbro: lined; Assorutit syenite).

thite, occasionally showing zonal structure, to a more distinctly antiperthitic outer region. In the feldspars from the melanocratic syenite layers the normal antiperthitic textures are largely suppressed and there is a marked tendency for the feldspars to be wholly cryptoperthitic, with only very small patches showing any indication of plagioclase twinning. In the average syenite however the antiperthitic feldspars are themselves frequently mantled by an outer zone of albite in optical continuity with the plagioclase of the inner parts. Moreover this albite shows broader twin lamellae than the plagioclase of the antiperthite, is quite free from potash feldspar patches and tends to act as an interstitial cementing material between the idiomorphic Na-K feldspar crystals. Extinction angles show the plagioclase in the antiperthitic areas to be ca. An_5 in contrast to the almost pure albite, ca. An_2 forming the outermost zones. The potassic feldspar patches have a 2V α of ca. 65° whereas the cryptoperthitic areas have considerably higher optic axial angles. The somewhat more homogeneous feldspars from specimen 40521[1]), taken from one of the thin mafic bands, were investigated in some detail. Na, K and Ca determinations showed these to have a bulk composition of ca. $Or_{42.5}Ab_{55.5}An_2$ (wt. $^0/_0$). The optic plane of these largely cryptoperthitic crystals is perpendicular to (010) and the crystal form is tabular parallel (010). Extinction angle $\alpha \wedge$ a for the cryptoperthite is ca. 12° and the range in 2V α is from 69.5–80°. The variation in

[1]) The specimen numbers quoted in this paper refer to samples belonging to the Geological Survey of Greenland.

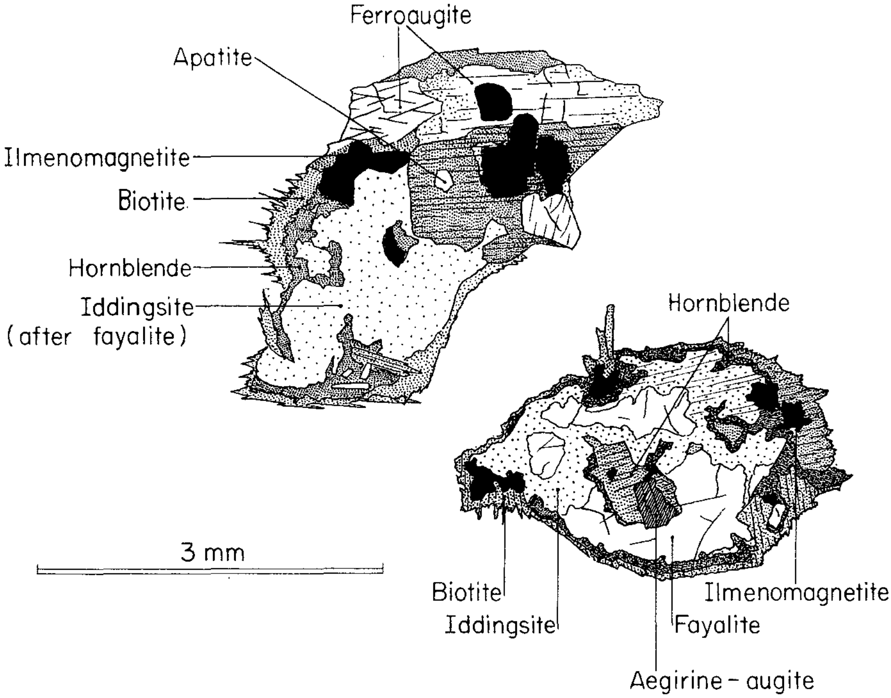


Fig. 2. Relationships within ferromagnesian aggregates in the Assorutit syenite.

2V however is considerable within the cryptoperthite of a single crystal often extending over a range of 5° or more. Small scarce patches of turbid potash feldspar give lower angles of ca. 64°. Occasional plagioclase patches with a 2V γ of ca. 83° correspond to a composition of ca. An_8 (assuming the variation curves for low temperature albite to be applicable (J. R. SMITH, 1960)). Refractive indices obtained on the cryptoperthite by immersion methods gave α 1.526, β 1.529 and γ 1.534.

Olivines occur as idiomorphic crystals, mostly in the size range .5–1 mm, and are often enclosed within the feldspars. Alteration to magnetite is apparent along cracks and around crystal margins, and there is considerable replacement by yellow-brown 'iddingsite'. Frequently the olivines contain exsolved plates of iron-ore parallel to the (001) plane. 2V measurements indicate a composition around $Fa_{96\text{-}97.5}$ in fair agreement with a result of Fa_{95} from X-ray diffraction traces.

The pyroxenes usually show colour zonation from light grey or almost colourless centres to pale green margins. The extinction angle $\gamma \wedge c$ increases outwards from 51–57° and the optic axial angle from 52–68°.

A rather extensive continuous and discontinuous reaction series occurs within the amphiboles of the Assorutit syenite. The amphiboles crystallised subsequent to the olivines and pyroxenes and show a succession from brown hornblendes to increasingly blue-green variants, these latter becoming abruptly replaced at a still later stage by members of the riebeckite-arfvedsonite series. In general, a hornblende with a $\gamma \wedge c$ of ca. 28° and pleochroic formula α light cinammon brown β brown γ deep brown (or alternatively α light brown, β brownish green and γ olive-green), growing later than the greenish pyroxenes zones outwards fairly sharply into more bluish-green but less pleochroic hornblendes with extinction angles of up to 36° (again $\gamma > \beta > \alpha$, with α olive green and γ deep blue-green). The blue-green varieties are also found as reaction rims around the olivines. Transition from the hornblendes to the riebeckites is sharp, the latter having almost complete absorption parallel α and with γ dull bluish-green. Extinction angles of up to 15° have been noted. The riebeckite may occur interstitially, intergrown with earlier amphiboles or as a mantling around the olivines. A colourless amphibole, length slow and with oblique extinction, intergrown with serpentinous material at the expense of the blue-green hornblendes, is probably a variety of grunerite.

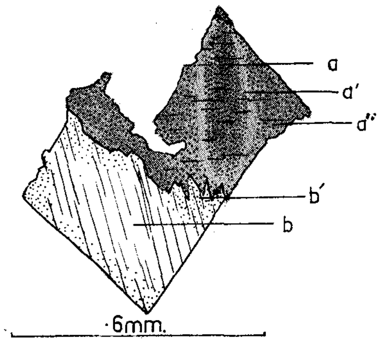


Fig. 3. Prismatic section through a zoned mica crystal adjacent to a grunerite crystal. a; core zone with pleochroism α red-brown, γ-dull green. a'; intermediate zone with α very light brown, γcolourless. a''; outer zone α greenish brown, γ dull olive green. b; core zone of grunerite, α colourless, γ very pale blue-green, b'; outer zones with α colourless, γ blue-green.

The micas in the Assorutit syenite are distinctive and, like the pyroxenes and amphiboles, show a strong zonation. Around the ore grains there are commonly small reaction coronae of lepidomelane (α pale straw, β & γ very deep sepia or almost black) similar to those of the other ferroaugite syenites in the province. From this relatively early biotite there is found to be a continuous series ranging through types with orange-brown absorption colours parallel to α and pleochroing brown or greenish brown parallel to the cleavage into micas having a pleochroism from red-brown to green. Whereas the intensely pleochroic lepidomelane is associated with the ilmenomagnetite, the later varieties are mostly found as thin reaction borders around the blue-green hornblendes and riebeckite-arfvedsonites. Considerable colour zoning is not uncommon across a single crystal and the variation is

Analysis of quartz syenite from the Assorutit intrusion, with comparisons.

	50216	1	2
SiO_2	60.64	61.33	56.53
Al_2O_3	15.37	15.87	16.61
Fe_2O_3	1.36	1.09	1.66
FeO	5.49	5.56	7.10
MgO	.42	.28	.83
CaO	3.05	2.98	3.41
Na_2O	5.15	5.66	5.98
K_2O	5.35	5.86	5.22
H_2O^+	.71	.58 (for H_2O^+ and H_2O^-)	.94
H_2O^-	.12		.08
TiO_2	.99	.57	1.29
P_2O_5	.20	.09	.36
MnO	.15	.13	.19
S	nd	nd	.08
Cl	nd	nd	.02
CO_2	.36	nd	nd
	99.36	100.00	100.30

C. I. P. W. Norm	
Qtz.	2.4 %
Or	32.4
Ab	44.5
An	3.1
Di	9.9
Hy	3.7
Mt	1.9
Il	1.8
Ap	.3

Feldspar $Or_{40.5}Ab_{55.5}An_4$
Cl. pyrox. $Wo_{47.5}En_6Fs_{46.5}$
O. pyrox. $En_{11}Fs_{89}$

Mode	
Quartz	.6 %
Feldspar	83.0
Pyroxene	5.2
Olivine	3.9
Amphibole	4.6
Mica	1.1
Ore	1.0
Apatite	.3
Limonite etc.	.3
Calcite	tr

50216, Syenite from the north side of the intrusion close to the coast. Analyst E. Godijn.

1, Mean of analyses of two quartz syenites (27647 & 26255) from the western layered series, Kûngnât. (Recalculated to 100 %). Upton (1960).

2, Syenite from western sector of the Hviddal nepheline syenite dyke (30714).

such that the absorption parallel to α increases while that parallel β and γ decreases until it is sometimes less than that parallel α ($\alpha > \beta \approx \gamma$). The more extreme varieties with α red-brown, β greenish brown and γ olive green are indistinguishable from those described from the western layered intrusion at Kûngnât (Upton, 1960, p. 72). In contrast to the usual biotites in the syenites, the late-stage mica is elongate parallel to the c axis, forming prismatic crystals two or three times as long as they are broad. Crystal form is occasionally well-displayed and hexagonal cross-sections seen, sometimes with twinning on (110). The strongly coloured mica (opt. -ve, 2V $< 10°$) does not represent the final phase in this reaction series but is itself often surrounded by a more nearly colourless version pleochroing from very pale red-brown to light bluish-green. This latest micaceous material frequently occupies small interstitial areas growing in almost fibrous, radiating bunches, showing straight extinction and up to second order interference colours.

Prominent among the interstitial minerals, and always later than the peripheral albite zones of the feldspars, are quartz and carbonate. The quartz is clear and unstrained. The presence of calcite and the unusual mica among the latest crystallising phases distinguishes the Assorutit syenite from others in the Tugtutôq area but implies a close relationship to some of the syenites of the Kûngnât complex away to the WNW of Tugtutôq, in particular to the quartz syenites of the upper part of the western lower layered series. Rather surprisingly no traces of fluorite have been noted in any of the sections of the Assorutit syenite and zircon is present only as a scarce accessory. Apatite occurs throughout in small acicular rods and, from its inclusion in the idiomorphic feldspars it is considered to have been one of the earliest minerals to crystallise. Ranking with the quartz, calcite and low temperature mica as one of the ultimate materials to crystallise are small interstitial wedges of almost wholly opaque brown ferruginous matter.

III. THE MID-GARDAR MICROSYENITIC AND QUARTZ PORPHYRY DYKES

Between the major intrusive events giving rise to the large olivine gabbro dykes and the transgressive central syenite ring-complex, large numbers of relatively small sub-acidic, acid, and basic dykes were intruded along the regional WSW trend. Detailed mapping has revealed that these were injected as a series of swarms over a considerable length of time during which the syenites and granites were emplaced in the Narssaq-Dyrnæs area, adjacent to Tugtutôq. The earliest of these dyke swarms may have been contemporaneous with the Assorutit syenite although this is not demonstrable on field evidence. The dyke swarms have provisionally been subdivided into four groups. First, a set of microsyenitic dykes, characteristically feldsparphyric, was immediately followed by a swarm of hybridic dolerite dykes rich in anorthosite inclusions. These were succeeded by a number of highly acidic dykes carrying phenocrysts of both quartz and feldspar, which in turn were followed by very numerous microsyenitic to trachytic dykes. These latter almost certainly arrived as a number of swarms, but further study would be required before these could be satisfactorily subdivided. The majority of these later microsyenites carry feldspar phenocrysts and are petrographically inseparable from the members of the earliest swarm. All of the microsyenitic dykes are oversaturated, the majority containing quartz within the groundmass. Although the names trachyte, quartz trachyte and alkali rhyolite may be preferred for those dyke rocks where the groundmass crystals are indistinguishable to the unaided eye, the majority have groundmass feldspars approaching 1 mm in length. Specific names such as quartz bostonite, lestiwarite, rhomben porphyry, etc., have been avoided in favour of a more generalised classification whereby the rock-types are described as microsyenite grading to micro-granite. With the exception of the quartz feldspar porphyries, which are given more individual and detailed treatment below, the petrography of the acid to sub-acid dykes will be described collectively.

There is a general petrographic similarity between the microsyenitic dykes and the Assorutit syenite, notwithstanding the fact that olivines and pyroxenes are scarcer and hydrous ferromagnesian minerals quantitatively more important. This, in conjunction with the relatively high Fe‴/Fe″ ratios in the two analysed microsyenites, suggests that some secondary oxidation of the magma occurred during intrusion of these comparatively small dykes.

Phenocrysts of alkali feldspar commonly constitute 20–30 % of the dyke rocks and, even in some cases where the body of the dyke is aphyric, the chilled border zone is found to be porphyritic. Smaller and scarcer micro-insets of augitic pyroxene and ilmenomagnetite occur in many of the dykes, especially in those in which quartz is scarce or absent. Still more rarely are microphenocrysts of apatite and pseudomorphed iron-olivine encountered. Almost invariably the groundmass is orthophyric, consisting of subhedral tablets of antiperthitic feldspar, often albite rimmed, with alkali amphiboles, biotite, limonite and quartz occurring within the interstices. In the more basic types idiomorphic pyroxene and ore are often present in the groundmass.

In many of the porphyritic dykes the early feldspars are found as poly-crystalline aggregates in which the individuals do not exceed 9 mm across and though often anhedral as a result of magmatic resorption, they generally retain some tabularity parallel to (010). More rarely the phenocrysts show an approach to the rhomboidal habit and the rock grades towards a 'rhomb porphyry'. In section the phenocrysts are seen to be generally clear in their central parts and turbid in the marginal zones. The cores approach optical homogeneity and normally lack any sign of polysynthetic twinning or clearly defined exsolution textures. Zonal structure, however, is not infrequently encountered and there are faint indications of oscillatory zonation in some. Very rarely in the more basic microsyenites an extremely fine-scale polysynthetic twinning grid, strongly suggestive of anorthoclase, is detectable in the phenocrysts. Phenocrysts were separated for analysis from four dykes, and for three of these it was also possible to separate the associated groundmass feldspar. These feldspars are described in some detail below:

1) Feldspar from No. 50226 (taken from the central part of a 10 m broad 'rhomb porphyry' dyke on the eastern coast of Tugtutôq). The rock contains feldspar, pyroxene, pseudomorphed fayalite, and ilmenomagnetite within a matrix of feldspar, hornblende, ilmenomagnetite, and limonite. The rock was coarsely crushed and the feldspar separated by flotation in tetrabromoethane. The larger feldspar fragments derived from breakdown of the phenocrysts were separated from the finer material and then crushed for analysis. The composite grains of groundmass material, which had sunk in the heavy liquid separation and which

appeared to be free of fragments of phenocryst feldspar, were crushed further and the groundmass feldspar extracted by means of an electromagnetic separator and heavy liquids. The average compositions of the feldspars were determined as: a) phenocryst $Or_{39.5}Ab_{53.5}An_{7}$, b) groundmass $Or_{38.5}Ab_{58}An_{3.5}$ (wt. $^{0}/_{0}$).

The phenocrysts show all variations from cryptoperthite to anorthoclase. The extinction angle $\alpha \wedge a$ was generally 7–8° although in some crystals as low as 3–5°. The groundmass crystals are idiomorphic tabular, with Carlsbad twinning and little sign of unmixing. (Plate I, fig. 1).

2) Feldspar from No. 30713 (taken from a porphyritic microsyenite dyke cutting the Hviddal syenite). Aggregates of anhedral cryptoperthite are contained in a matrix of feldspar, alkali hornblende, riebeckite, limonite, and quartz. The cryptoperthite phenocrysts occasionally show Carlsbad twinning and have a shadowy, patchy extinction. Small areas within them show excessively fine twin striae. The $2V\alpha$ ranges from 74–87°, and the extinction $\alpha \wedge a$ varies from 8–12° although most commonly it approximates to 8°. Some exsolved potassic areas have a 2V of ca. 53°. The crystals are slightly tabular parallel (010), and the the optic axial plane lies perpendicular to (010). The groundmass feldspar occurs as laths showing a fine-scale antiperthitic texture and having Carlsbad twinning. The two generations were separated using a procedure similar to that for 50226 and the compositions determined as: a) phenocryst $Or_{41}Ab_{54}An_{5}$, and b) groundmass $Or_{40.5}Ab_{55.5}An_{4}$ (wt. $^{0}/_{0}$).

3) Feldspar from No. 40498 (from a porphyritic dyke cutting the Hviddal syenite). Apart from phenocrysts of feldspar there are microinsets of ilmenomagnetite, apatite, and pseudomorphed fayalite ('iddingsite'). The groundmass consists of feldspar, soda-hornblende and associated yellow ferruginous material, biotite, and quartz. The feldspar phenocrysts are Carlsbad twinned, show a slight zonation and show fairly well defined exsolution textures in parts. Strips of unmixed plagioclase lying parallel (010) show fine scale polysynthetic twinning, with $\alpha \wedge a$ 10–14°. Refractive indices of the clear material were α 1.529, β 1.532 and γ 1.534. Groundmass feldspars closely resemble those of 30713. The feldspars were separated as decribed above and compositions determined as: a) phenocryst $Or_{42}Ab_{52}An_{6}$, b) groundmass $Or_{38.5}Ab_{57.5}An_{4}$ (wt. $^{0}/_{0}$).

These three specimens are representatives of the more basic microsyenites intruded in the main (post quartz-porphyry) phase of dyke emplacement and closely resemble a dyke rock described by Bondam (1955) from the Nassarssuaq area some 80 km further along the ENE swarm belt, containing phenocrysts of composition $Or_{37}Ab_{54}An_{9}$.

4) Feldspar from No. 30645 (collected from a considerably more acidic microsyenite (or microgranite?) dyke cutting one of the olivine gabbro dykes). Small white phenocrysts of alkali feldspar lie within a very fine grained matrix apparently composed of feldspar, quartz, and riebeckite. The phenocrysts, which are only slightly tabular parallel (010) and nearly square in (100) sections, show both Carlsbad and Manebach twinning and show some exsolution of plagioclase in strips parallel (010). Solution cavities containing needles of riebeckite are common within the early feldspars. (Plate II, fig. 1).

The slender crystals exhibit the forms (010), (001), (100) and (110), have the optic axial plane perpendicular (010), and have an extinction angle $\alpha \wedge a$ of 14°. The cryptoperthitic areas have a $2V_\alpha$ of ca. 74°. The crystals show some differentiation into a marginal cryptoperthitic zone and a core region that possesses a fine grid-like intergrowth of the marginal-type feldspar with a constituent having a much lower 2V. The core, in fact, consists of two components, the 2V of the one being 74° and of the other 53.5°. Refractive indices of the clear cryptoperthitic feldspar are α 1.524, β 1.529, and γ 1.531. The average composition of the phenocrysts is approximately $Or_{35.5}Ab_{62}An_{2.5}$, the An content being derived by difference assuming ideal formula and not from a calcium determination.

In some of the porphyritic dykes only the core regions of the phenocrysts are cryptoperthitic, the marginal areas showing pronounced antiperthitic textures in which the plagioclase displays albitic and pericline twinning. The groundmass feldspars are almost invariably antiperthitic, and in many instances these have outer zones of almost pure albite. In these cases particularly, the groundmass textures closely resemble those seen on a much coarser scale in the Assorutit syenite.

The phenocrysts extracted from these four dykes show a compositional range through from $Or_{39.5}Ab_{53.5}An_7 \longrightarrow Or_{41.5}Ab_{53}An_{5.5} \longrightarrow Or_{35.5}Ab_{62}An_{2.5}$, although it is very probable that the innermost zones of the 50226 phenocrysts are considerably more calcic than the average value of An_7.

Although olivines are never preserved fresh in the mid-Gardar dyke swarms, pseudomorphs after fayalite are sufficiently common to indicate that this mineral was one of the normal high temperature phases. Pyroxenes are moderately common, varying from greyish augite types to aegirine-augite. Only the augitic pyroxenes are ever seen as phenocrysts. The amphiboles, whenever present, grew subsequent to the feldspars and pyroxenes and are usually interstitial. Like those of the Assorutit syenite, earlier brownish or olive-green hornblendes zone more or less sharply to bluer-green species which in turn give place to length-fast members of the arfvedsonite-riebeckite series.

Normally only a part of this sequence is ever seen in any one dyke specimen, and the amphiboles themselves are frequently partially replaced by a brown ferruginous material. Whilst the amphiboles generally constitute the bulk of the ferromagnesian content of the rock, their place may be taken by biotite, haematite, or by hydrated iron oxides. Other common constituents are quartz and calcite, with fluorite, apatite, and zircon as rarer accessories.

Interspersed with the abundant microsyenite and basic dykes seen on Tugtutôq and the adjacent Skovfjord islands to the south are a number of more highly acidic dykes which can be distinguished from the closely allied micro-quartz syenites by their possession of quartz phenocrysts. Almost all of these quartz porphyry dykes are spherulitic, at least marginally, and commonly display a vitreous flow-banding. Similar features are to be found in the rapidly chilled microsyenite dykes, but they are developed to a more pronounced degree with the quartz phorphyries. Texturally these rocks range from partially devitrified alkali rhyolites to holocrystalline microgranites. Pink or white feldspar phenocrysts are invariably present in greater quantity than the quartz phenocrysts and closely resemble in form (and composition) the phenocrysts from the more acid varieties of microsyenite, being elongate parallel to the a axis and almost square in (100) section. Other early crystallising minerals present to a very limited extent in some of the dykes include hedenbergite and magnetite. Aegirine, riebeckite, and, more rarely, haematite and astrophyllite replace the hornblendes and biotites of the more basic microsyenites as the principal coloured minerals of the groundmass.

In view of the considerable diversity found within these quartz porphyries three contrasted dykes, encompassing virtually the whole range of variation, will be described in detail.

1) Composite quartz porphyry dyke extending through central Tugtutôq.

A large dyke ranging from 10–30 m. in width, running more or less parallel to and just north of the giant dykes of gabbro and nepheline syenite, is traceable for some 40 km. The principal rock type is a fast weathering reddish microgranite although the dyke has, for the greater part of its length, narrow marginal zones of fine grained dolerite. The microgranite has evidently been intruded later than the dolerite and in certain sectors it includes fragments of the dolerite precursor. Phenocrysts of antiperthitic feldspar and partially resorbed bipyramidal quartz comprise some 5–10 % of the rock. The early feldspars show Carlsbad and occasionally Baveno twinning. The albitic plagioclase shows a fine-scale polysynthetic twinning with short and discontinous twin lamellae and contains patches of exsolved K-feldspar. The groundmass is composed of small laths of similar antiperthite (up to .25 mm long in the coarser grained rocks), together with sub-equant quartzes. However, these two minerals also occur together in micrographic association, the micrographic texture being patchily distributed throughout the groundmass. In the marginal facies the quartz and feldspar are radially intergrown in spherules, presumably developed by devitrification after super-cooling. In specimens collected some 3 km to the WSW of the central ring-complex haematite is the sole dark mineral in the dyke, occurring as anhedral grains dispersed throughout the groundmass. Though slightly translucent in the central parts, these crystals are wholly opaque marginally. By contrast, specimens collected 5 km further to the WSW contain very little haematite but have considerable amounts of alkali amphibole. Small euhedral prisms of riebeckite are abundant in the groundmass, these being usually under .5 mm long and about half as broad (α deep blue-black, β dull greenish-grey, and γ pale yellowish-green with $\alpha \wedge c$ 9–10°). The riebeckite is commonly found in parallel intergrowth with a brownish mineral pleochroing from almost black parallel the cleavage direction of the riebeckite to a golden brown perpendicular to its length. This mineral is apparently an alteration product of the riebeckite and may be related to the astrophyllite which can be discerned under high magnification and which grows in small independent rosettes as well as at the expense of the riebeckite. Also intergrown with the riebeckite is an almost colourless, length slow amphibole with an extinction angle of ca. 31°, probably a variety of grunerite. Zircon, fluorite, and very small quantities of apatite are present as accessory minerals, the fluorite being mostly colourless but sometimes containing a deep violet colouration.

2) Skovfjord quartz porphyries.

A few distinctive acid dykes comprise a minor swarm in the Skovfjord region along the southern side of Tugtutôq Island. One of these, traceable for several kilometres along the Tugtutôq coast is, like the dyke described above, a composite with dolerite margins up to 1 m broad and a central component of quartz porphyry some 6 m wide. The latter is chilled against the dolerite and has doleritic inclusions probably derived from the wall rock. Similar quartz porphyry dykes outcrop on Igdlutalik Island and on the small islands between Tugtutôq and Igdlutalik. Coloration is distinctive, with dark blue-black chill-zones grading into the reddish-brown dyke centres. Crystals of pyrites up to 2 mm across are fairly common in these dykes. The phenocrysts of quartz and feldspar account for ca. 25 % of the rocks. The early feldspars, usually reddish in colour and up to 3 mm long, are often irregular in outline as a result of magmatic corrosion but display the forms (001), (010), and (011) and are only very slightly tabular parallel (010). Carlsbad twinning is common, although Manebach and Baveno twins are also found. The early feldspars in fact very closely resemble those already described from the acid microsyenite dyke (specimen 30645). The crystals are dominantly antiperthitic, possessing very fine-scale discontinuous albite and pericline twin lamellae, although with cryptoperthitic cores sometimes preserved. Rarely, the early feldspars have been partially recrystallised with the internal development of small feldspar crystallites. The extinction angle $\alpha \wedge a$ measured on cleavage fragments of the more homogeneous material was between 5–10°. Mean composition of the phenocrysts (deduced from Na and K determinations alone on crystals separated from specimen 50187) was $Or_{35}Ab_{62}An_3$, i.e., with no significant difference from the value obtained from the phenocrysts of the 30645 microsyenite. Small clusters of magnetite and 'iddingsite' probably denote the former presence of fayalite, and there are scattered octahedral micro-insets of magnetite which was evidently another early crystallising mineral. To some extent the crystallisation of amphibole also commenced prior to intrusion, and there are occasional microphenocrysts of a brown hornblende ($\gamma \wedge c \sim 26°$, α deep brown, β brown, γ light yellowish-brown) which have been partly made over around the margins to riebeckite. Normally riebeckite is the only amphibole present, and in specimen 50187 it would appear that the riebeckite itself occurs in two generations, although the great bulk of it occurs as needle-like crystals in the groundmass, either aligned in flow-patterns or showing a radial growth structure. The mineral has $\alpha \wedge c \sim 10°$, α deep blue-black, β blue-grey, and γ yellowish-green. Feldspar and quartz accompanying the riebeckite in the groundmass often show a pronounced tendency to granophyric intergrowth. Fluorite, colourless or very locally violet, is a constant accessory, often associated with the magnetite, and some zircon is generally present.

One small acid dyke, apparently related to the Skovfjord dykes, is found cutting the olivine gabbros on the mainland to the east of Tugtutôq, close to Narssaq settlement. This dyke is remarkable for its unusual devitrification textures, being composed of small 'spherules' formed from crystallising riebeckite, which have acquired a polygonal form as a result of mutual interference in the later growth stages (Plate III fig. 1). The 'spherules' are up to 1 cm across and consist of delicate sprays of curved acicular riebeckite crystals, intergrown with radiating crystals of quartz and alkali feldspar (Plate III, fig. 2). Intervening zones between the 'spherules' contain quartz, feldspar, aegirine, skeletal zircon, magnetite, and fluorite. A number of quartz porphyry dykes of

Analyses of two porphyritic microsyenite dykes from the Tugtutôq area with comparisons from other areas.

	50226	1	2	50136	3	4
SiO_2	60.42	58.98	58.77	64.22	64.31	63.12
Al_2O_3	16.55	16.33	15.78	12.87	15.05	15.44
Fe_2O_3	2.66	2.48	2.33	3.57	3.39	1.73
FeO	3.91	5.54	6.03	4.18	2.33	3.53
MgO	.63	1.03	.24	.00	.14	.62
CaO	1.87	2.10	3.55	1.21	1.54	1.31
Na_2O	5.36	5.54	4.47	4.93	4.77	5.81
K_2O	5.84	5.25	5.29	6.03	6.59	5.36
H_2O^+	.78	.42	1.22	.59	.39	.44
H_2O^-	.19	.44	.29	.13	.79	.14
TiO_2	.98	1.40	.94	.73	1.25	.51
P_2O_5	.29	.57	1.45	.06	–	.25
MnO	.17	.21	.10	.19	.09	.27
S	.04	nd	nd	nd	nd	nd
CO_2	.44	.05	nd	1.14	nd	1.89
BaO	.12	nd	nd	nd	nd	nd
	100.25	100.34	100.46	99.85	100.64	100.42

C.I.P.W. Norms

	50226	50136
Qtz	3.0 %	10.7 %
Or	35.6	36.4
Ab	46.4	33.2
An	4.0	– –
Ac	– –	8.0
Di	4.4	5.7
Hy	.3	3.4
Mt	3.8	1.2
Il	1.8	1.4
Ap	.7	– –

Modes

Phenocrysts	50226	50136
Feldspar	24.6 %	10.5 %
Pyroxene	.6	–
Olivine (pseudomorphed)	.6	–
Ore	.2	–
Groundmass		
Feldspar	52.1	40.3
Amphibole	8.9	42.1
Limonite etc.	13.0	7.1

	50226	50136
Feldspar	$Or_{41}Ab_{54}An_5$	$Or_{52}Ab_{48}An_0$
Cl. pyrox.	$Wo_{52}En_{32}Fs_{16}$	$Wo_{47}En_0Fs_{53}$
O. pyrox.	$En_{67}Fs_{33}$	En_0Fs_{100}

50226, Porphyritic microsyenite from central part of a 10 m 'rhomb porphyry' dyke.
1, Phonolitic trachyte, Mt. Cis, Ross Island. Jensen (1916).
2, Rhomben porphyry, Quincy, Massachusetts. Warren (1913).
50136, Chilled facies of 5 m porphyritic dyke on the south coast of Qángue Island, Tugtutôq.
3, Trachyte, Nandewar Mts., N.S.W., Jensen (1907).
4, Trachyte, Braigh a'Choire Mhoir, Mull. Bailey, Clough, Wright et al. (1924).

comendite type are described by Ussing (1912) as occurring around the Ilímaussaq and in general these appear to correspond to the dykes described above from the Skovfjord region. Indeed there is some probability that some of the dykes described here are merely west south–

westerly continuations of those discussed by USSING. The analysis of the chilled zone from 50187 is given below, and the analysis quoted by USSING for a comendite dyke specimen collected east of the Ilímaussaq summit is given for comparison.

3) Quartz porphyry dyke running within the Hviddal composite dyke.

A five metre dyke of quartz porphyry lies approximately along the centre of the large nepheline syenite dyke to the east of the central complex. The dyke is exposed on some small islands within the Store Pilesø and also at the eastern end of the lake, where it is blue-black in colour and marginally spherulitic. At the eastern end of Tugtutôq the dyke is conspicuous within the foyaitic syenites. The dyke is also traceable westwards from the central complex, although outcrops are few. The feldspar phenocrysts are in form identical to those already described from the Skovfjord quartz porphyries. Almost invariably there is some zonal structure within the crystals closely comparable to that described above from the 30645 microsyenite dyke. Within the slightly turbid outer fringe of homogeneous untwinned material is a central area of clear feldspar consisting of two components intergrown in a fine-scale, irregular grid-pattern when viewed in (100) section. One of these components is identical to that of the outer rim, while the other, which is confined to the core, has a distinctly lower 2V. The range in 2V for the 'higher' (rim) material noted over a number of phenocrysts in several specimens was 71–88.5°, whereas that for the component seen in the cores was 56.5–73°, although the range in any one specimen is very much less. Thus for specimens 40600a and 30691 (both spherulitic, partly glassy and evidently products of very rapid chilling) the values were as follows:

	'outer'	'inner'	
40600 a	71–80°	56.5–65.5°	(six crystals)
	(mean 74°)	(mean 60°)	
30691	85–88.5°	70–73°	(two crystals)
	(mean 87°)	(mean 71.5°)	

It is not certain whether or not this fine-scale grid pattern observed in the crystal cores is due to exsolution, but almost certainly the zonal arrangement reflects an original compositional zonation. Frequently there has been a certain amount of selective recrystallisation of the early feldspar, with growth of small, disoriented, singly twinned feldspar crystals. Usually these are restricted to the cores of the phenocrysts, although in some specimens the recrystallisation has proceeded nearly to completion. In extreme instances, although the phenocryst outlines are retained, there has been total recrystallisation to a multitude of small feldspars. In addition to the complex textures brought about by recrystallisation and unmixing there is commonly a very fine-scale lamellar twinning with short discontinuous albite twin lamellae and some pericline twinning. In the phenocrysts from 30685 the multiple twinning is seen only in the outer zones, which are apparently antiperthitic, the cores being clearly cryptoperthitic. The phenocrysts were separated and analysed for Na and K, indicating a mean compositional value of $Or_{59}Ab_{39}An_2$, significantly different from the more sodic phenocrysts from the Skovfjord dyke. In every case checked it was found that the optic axial plane lies perpendicular to (010), and in view of the relatively high 2Vs observed it is unlikely that any sanidine is preserved, although it is very probable that it was as sodic sanidine that the mineral originally crystallised. Rounded resorption cavities, common within both the feldspar and quartz phenocrysts, often contain secondary growths of aegirine, quartz, or feldspar.

Fayalite and hedenbergite were among the earliest minerals to crystallise but, whereas the hedenbergite has survived as unaltered euhedral crystals, the olivine has been entirely replaced by a mineral related to iddingsite. The pyroxene occurs as bottle-green, non-pleochroic and unzoned crystals with an extinction of $\gamma \wedge c$ of $\sim 58°$.

Just as in all the other dykes discussed the bulk of the ferromagnesian minerals is confined to the groundmass, consisting in this instance of a blue amphibole of the riebeckite-arfvedsonite series, together with its opaque breakdown products (magnetite?), and a pale green, scarcely pleochroic acmitic aegirine. The light green selvedges commonly developed along the borders of the dyke owe their colour to the abundance of aegirine, the dark bluish-black central parts being correspondingly richer in the amphibole. This mineralogical variation across the dyke probably reflects differences in the water vapour content during the crystallisation history. In certain sectors of the dyke astrophyllite makes its appearance within the groundmass, on occasion becoming an important constituent and forming small radiating growths independent of the aegirine and riebeckite. Apatite, zircon, and fluorite were not recorded in any specimens from this dyke. The greater part of the groundmass consists of complex intergrowths of alkali feldspar and various forms of silica. The degree of complexity may be exemplified by a description of specimen 30685, taken from a marginal zone in the dyke. The rock here shows a repetitive fine-scale colour banding parallel to the contacts. The bands, which do not exceed 2 mm in width, are alternately blue-black and whitish-grey. The dark layers consist of small spherules of opaque material composed of riebeckite and secondary iron oxides,

Analysis of a quartz porphyry (comendite type) dyke with comparisons.

	50187	1	2	3	4	5	6
SiO_2	75.85	73.68	76.33	74.04	74.78	73.30	72.21
Al_2O_3	10.47	11.05	12.54	10.95	11.94	11.56	9.72
Fe_2O_3	2.27	3.93	.73	2.08	2.46	1.68	3.26
FeO	2.44	1.45	.89	1.72	.88	2.41	1.07
MgO	.00	.00	.00	.02	.16	.24	.29
CaO	.29	.48	.00	.35	.07	.78	.82
Na_2O	5.04	5.20	4.92	4.46	4.77	4.84	4.42
K_2O	2.71	4.05	4.06	4.76	3.99	3.96	4.98
H_2O^+	.26	.08	.11	.65	.28*	.40	1.96
H_2O^-	.09	.17	.05	.20	.19	.30	.24
TiO_2	.32	.57	.14	.17	.17	.33	.62
P_2O_5	.02	.00	.00	.05	tr	.03	.10
MnO	.07	tr	.02	.02	.08	tr	.05
CO_2	nd	none	nd	tr	nd	nd	nd
ZrO_2	nd	.24	nd	.27	nd	nd	nd
	99.83	100.90	99.79	99.74	99.77	99.83	99.74

* loss on ignition.

C. I. P. W. Norm

Qtz	35.5 %
Or	16.2
Ab	39.1
An	– –
Ac	3.2
Di	1.3
Hy	2.5
Mt	1.6
Il	.6

Feldspar $Or_{29}Ab_{71}An_0$
Cl. pyrox. $Wo_{46}En_0Fs_{54}$
O. pyrox En_0Fs_{100}

Modes

Phenocrysts

Feldspar	20 %
Quartz	14

Groundmass

Quartz, Feldspar, Riebeckite	66

50187, Chilled facies of comendite dyke outcropping on small island between Igdlutalik and Tugtutôq. Analyst D. MAYNES.
1, Quartz porphyry (comendite) dyke, Ilímaussaq. USSING (1912).
2, Riebeckite astrophyllite granite (26272), Kûngnât, S. Greenland. New analysis. Analyst B. I. BORGEN.
3, Comendite, Liruei, Nigeria. JACOBSON, MACLEOD and BLACK (1958).
4, Comendite, Mt. Coolum, E. Moreton, Queensland. JENSEN (1906).
5, Comendite, 'El Barta', Njorowa Gorge, Lake Naivasha, Kenya. SMITH (1931).
6, Comendite, Pantelleria. WASHINGTON (1914).

set in a grey-green feldspathic matrix. The light coloured layers also consist of small spherules, ca. .25 mm in diameter, many of which have a faint concentric zonal structure. These spherules, though normally colourless, sometimes possess pale brown cores, and are found to be largely isotropic. They appear to be composed of minute granular crystals forming an ultra-fine mosaic, the crystals probably being cristobalite and feldspar. However, some of the spherules have cores composed of radiating crystals of length-fast chalcedony, these grading out into the mainly isotropic micro-granular material. Sometimes these light coloured spherules have an outer shell of green material, probably an extremely fine aggregate of aegirine crystals, driven out as a 'front' ahead of the developing spherulite. The pale greyish-green matrix of the light layers is composed of randomly oriented bunches of length-slow chalcedony (quartzine). (In a recent paper (1960) dealing with the Rockall alkali granites, SABINE describes the presence of pale-brown isotropic spherules of α cristobalite. SABINE remarks on the low temperature formation of α cristobalite from silica hydrosols and considers the possibility that the content of rare-earths enhanced the stability of the Rockall cristobalite). The cooling history of the dyke at this locality is interpreted as follows: The magma was intruded with a small content of sanidine and β quartz and was quenched rapidly to a glass. Devitrification taking place within the dyke since its intrusion in the Precambrian allowed some ordering to take place within the glass so that, with diffusion of ions taking place over distances of up to 1 mm, alternating bands of mafic and leucocratic material developed. Cristobalite was the first mineral to start crystallising from nuclei in the leucocratic layers, growing outwards in concentric shells and expelling acmitic material in the process. Subsequently, and from the same nuclei, radiating crystals of chalcedony with negative elongation started to grow outwards by inversion of the cristobalite, thereby producing spherulites within spherulites. Possibly at this time the material present in the interstices between the growing silica and riebeckite spherules remained vitreous but later crystallised to give mainly quartzine and feldspar.

In some strongly spherulitic facies of this dyke individual spherules achieve a diameter of 2 cm or more, these containing radiating chalcedony crystals (positive elongation), surrounded by deep green mantles of microcrystalline aegirine up to 3 mm thick.

WHITE and CORWIN (1961) presented an interesting account of the crystallisation of silica glass in the presence of hydrothermal solutions at moderate temperatures and pressures. At 400°C and 340 atm. devitrification of the glass by alkaline solutions was rapid. In this experimental work the glass crystallised to cristobalite and thence, via keatite and chalcedony, to fibrous quartz. Under the experimental conditions employed the chalcedony converted rapidly to quartz, but the authors suggest that the temperature range for formation and persistence for chalcedony is very approximately 100–300°C, bearing in mind, however, that pressure and pH of aqueous solutions are also important parameters controlling the formation of this mineral.

Comparisons of the mineralogy of the three contrasted quartz porphyry dykes.

	Dyke 1	Dyke 2	Dyke 3
Alkali feldpsar	+	+	+
Quartz	+	+	+
Chalcedony	—	—	+
Christobalite	—	—	+
Fayalite (pseudomorphs)	—	+	+
Hedenbergite	—	—	+
Aegirine	—	—	+
Katophorite	—	+	—
Riebeckite	+	+	+
Astrophyllite	+	—	+
(Primary) magnetite	—	+	—
(Primary) haematite	+	—	—
Zircon	+	+	—
Fluorite	+	+	—

IV. THE CENTRAL RING-COMPLEX

a) Early syenites and microsyenites of the central complex.

In the general account of the Tugtutôq geology (UPTON, 1962) it was suggested that the central complex was inaugurated by the intrusion of porphyritic microsyenite at two localities, one situated across an abrupt flexure in the Hviddal composite dyke and the other a little to the east, stradling the Hviddal dyke and the large gabbro dyke immediately south of it. Both intrusions may possibly have been ring-dykes and the more easterly marked the location of the succeeding intrusions of the eastern centre. Both were brecciated by intrusive veinlets of the later syenites and alkali granites and are accordingly designated as the western and eastern microsyenite breccia zones. Since they are considered to be the earliest components of the ring-complex this microsyenite type is referred to as composing Unit 1 of the complex. The extent of these early microsyenites seems to be rather greater than previously supposed. A mass of this material occurs within the southern part of the Blå Månesø syenite (the latest intrusion of the complex), presumably as a xenolithic body. Furthermore dykes of the same microsyenite following the regional trend have been found cutting the gabbros and older granites close to the southern contacts of the Blå Månesø stock. Also, in the small triangular area of nepheline syenite caught between the alkali granites of the eastern centre and the Blå Månesø perthosite, masses of the microsyenite occur (presumably intrusive into the nepheline syenite although no contacts were seen), dissected by pegmatite veins from the Blå Månesø intrusion.

The microsyenite is composed essentially of alkali feldspar, hedenbergite (grading to aegirine-augite), hornblende and ore. Fayalite is commonly present and biotite and apatite occur in small quantities. A little interstitial quartz occurs in some of the microsyenite from the 'breccia zones' in the eastern centre. Such minerals as riebeckite, aenigmatite, astrophyllite, zircon and fluorite frequently encountered in the later units of the central complex are absent. The feldspar phenocrysts, which are almost always present in the microsyenite, are generally similar in appearance to those described from the microsyenite dyke swarms.

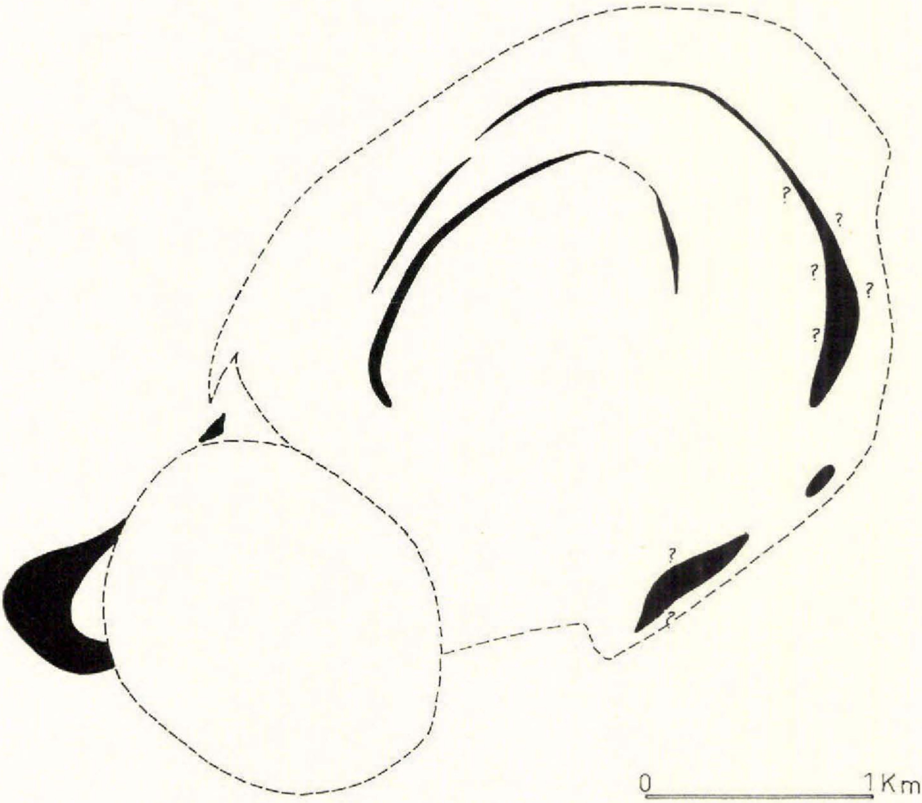


Fig. 4. Sketch map of central complex indicating known and probable areas of outcrop for the Unit 1 microsyenite (breccia).

The crystals are up to 6 mm. long, show tabular habit and are often Carlsbad twinned. Strong zoning is common and not infrequently the outer parts are microperthitic whilst the centres are homogenous, occasionally displaying a barely detectable excessively fine-scale twinning, parallel (010) and (001). However, in some cases the phenocrysts tend to be antiperthitic and, as in 30720, exsolution may be greater centrally than marginally.

The groundmass feldspar is present as approximately lath-shaped crystals though characteristically never showing the high degree of idiomorphism exhibited by the groundmass feldspars in the typically orthophyric microsyenite dykes. The majority of the 2nd generation feldspars show a coarse perthitic texture, with the exsolution lamellae lying more or less perpendicular to the length of the crystals. Carlsbad twins are common and again it is not unusual for the centres to be poorly exsolved in comparison to the outer parts of the crystals (plate IV fig. 2). In 30720 the cryptoperthitic parts of the feldspars were observed to have a 2V range of from 86°–90.5°. However, along with the perthiticcryptopertithic feldspars there are generally some with more plagioclase than potash feldspar and with the plagioclase displaying fine lamellar twinning parallel (010). The phenocryst feldspars were separated from no. 50345 and the composition $Or_{34.5}Ab_{63.5}An_2$ (wt. $^0/_0$) obtained from partial analysis. The groundmass feldspar in this specimen was all of the microperthitic variety without any of the antiperthite. This feldspar, perhaps slightly contaminated by phenocryst material, gave a composition of $Or_{43}Ab_{56 \cdot 5}An_{.5}$. Fayalite is commonly present as small anhedral crystals in the groundmass, often pseudomorphed by 'iddingsite'. Clinopyroxene may in some specimens, as in 50345, have occurred as scarce phenocrysts although generally it is confined to the groundmass as idiomorphic crystals surrounded by the second generation feldspar. Usually the pyroxene is pale green although it varies from nearly colourless to a slightly pleochroic green. Normal zoning is frequently observed with the intensity of the green colouration increasing outwards and the extinction angle $\gamma \wedge c$ increasing from $\sim 54°$ to 60°. Brown or brownish-green hornblende showing a very strong pleochroism is an important constituent of the unit 1 rocks, (α light brown, β brown and γ deep brown, $\gamma \wedge c$ 22°). The hornblende grows around much of the pyroxene and forms symplectic intergrowths with the feldspars. Although the brown or greenish-brown hornblendes are typical they occasionally grade to a blue-green variety and, wherever the fayalites are surrounded by amphibole rims, it is this blue-green type that occurs, a relationship analogous to that in the Assorutit syenites and in the more basic nepheline syenites from the Hviddal giant dyke. Biotite is present in variable amounts and generally surrounds the ilmenomagnetite crystals.

The microsyenite of the western breccia zone forms an arcuate outcrop whose shape suggests that it was intruded as a small ring-complex and later intersected by the intrusion of the Blå Månesø syenite. Partially enclosed by this arcuate zone is a coarser-grained fast-weathering syenite which is older than the perthositic syenite of the Blå Månesø and which, from its general appearance and location was formerly considered to be a remnant mass of the Hviddal nepheline syenite. However, search has failed to reveal any trace of nepheline in this rock and the petrography suggests greater affinity with the porphyritic Unit 1 microsyenite than with the latter. Its age, relative to the surrounding microsyenite is not known but it seems likely that it is a slightly later intrusion very similar in composition to its microsyenite precursor. It is accordingly designated as Unit 1 a. The feldspars tend to be strongly zoned, some even retaining cores of oligoclase with very fine-scale albitic and pericline twinning, free of exsolved potassic phases. Many of the crystals are cryptoperthitic grading to antiperthitic. Occasionally fine-scale exsolution textures within the crystals define a faint oscillatory

Analysis of Unit 1 microsyenite.

	50345	1
SiO_2	60.75	60.64
Al_2O_3	15.28	15.37
Fe_2O_3	1.63	1.36
FeO	6.17	5.49
MgO	.63	.42
CaO	2.19	3.05
Na_2O	5.18	5.15
K_2O	5.54	5.35
H_2O^+	.82	.71
H_2O^-	.21	.12
TiO_2	1.05	.99
P_2O_5	.25	.20
MnO	.20	.15
CO_2	nd	.36
	99.90	99.36

C. I. P. W. Norm		Mode	
Qtz	2.3 %	Quartz	tr
Or	33.2	Feldspar phenocrysts	64.4 %
Ab	44.1	Feldspar groundmass	17.3
An	2.2	Pyroxene	5.8
Di	5.8	Olivine	--
Hy	7.4	Hornblende	8.8
Mt	2.3	Biotite	1.8
Il	2.0	Ore	1.9
Ap	.7	Apatite	tr

Feldspar $Or_{42}Ab_{55}An_3$
Cl. pyrox. $Wo_{48}En_9Fs_{43}$
O. pyrox. $En_{15}Fs_{85}$

50345, Porphyritic microsyenite from inner breccia zone, eastern centre (anal. D. MAYNES).
1, Assorutit syenite, no. 50216 (see p. 10).

zonation (fig. 5) and it is evident that the earlier parts of these crystals possessed the rhomboidal form similar to that of the well-known Oslo lardalites and to the rhomboidal cores of the zoned cryptoperthitic feldspars in the chilled augite syenite of the nearby Ilímaussaq complex. The ferromagnesian minerals are precisely similar to those of the microsyenite. Quartz is entirely absent, apatite is present as an accessory and, in contrast to the microsyenites, a little zoned zircon also occurs.

b) Syenites[1] comprising units 2, 3, 4 and 5 of the central complex.

Following the Unit 1 intrusions, a suite of closely related syenites and quartz syenites were emplaced. These occur in the form of a central plug (Unit 2) containing a wide variety of the older rocks as inclusions, followed by two broad ring-dykes and one very narrow ring-dyke (Unit 5). With the exception of the last, each intrusion occurs peripherally to its predecessor. The discontinuous strips of porphyritic microsyenite within the ring-dyke assemblage are interpreted as relict screens of an earlier (Unit 1) intrusion. Again excepting the Unit 5 quartz syenite which has distinctive textural features, the rocks of the various intrusions are not too readily distinguishable. Each is not homogeneous in itself and there is petrographic overlap between the three recognised phases. Furthermore the three intrusions are considered to have been separated by only short time intervals so that, except for some minor apophyses from the Unit 4 ring-dyke, chilled internal contacts are missing. Petrographically the rocks have many features in common with the foregoing Assorutit syenite and the mid-Gardar alkaline dykes, being composed of alkali feldspar with subordinate quartz, amphibole, pyroxene, olivine and ore. There is a tendency for successive intrusions to contain increasingly low-temperature mineral assemblages. Thus whereas the Units 2 and 3 syenites contain much cryptoperthite, hedenbergite and comparatively fresh fayalite, the Unit 4 ring-dyke has mainly coarsely exsolved feldspar, wholly pseudomorphed fayalite and relatively scarce pyroxene. Unit 5, with fully exsolved feldspars and abundant hornblende, has only relicts of pyroxene and olivine.

Within the Unit 2 area there is every variation from quartz syenite (or even alkali granite) into comparatively mafic quartz-free rocks rich in hedenbergite and fayalite. These melanocratic and leucocratic facies are not related in any form of layered association but nevertheless recall the contrasting light and dark facies described from the layered complex at Kûngnât (UPTON, 1960). The rusty-brown mafic rock type is found predominantly in association with the inclusions of older granites but, even here, there is abrupt and irregular passage into the more quartzo-feldspathic variants. Similar melanocratic syenites are found in a narrow belt alongside the marginal Unit 3 syenites, on the southern side of the complex, between these and the country-rock granodiorite, and also as an inclusion within the perthositic syenite around the Blå Månesø. In these mafic rocks the feldspars are generally anhedral, occasionally poikilitic and distinctly later than the bulk of the pyroxenes and olivines

[1] N. B. Unit 3 quartz syenite referred to in part I as 'nordmarkitic granite'. Unit 4 quartz syenite formerly described as 'hornblende granite' (UPTON, 1962).

(Plate V, Fig. 1). Exsolution patterns are hazy and indistinct, the majority of crystals being of cryptoperthite. Feldspar of this type, taken from a mafic syenite (Specimen 50280) in the central part of the Unit 2 area, was extracted and partially analysed, giving a composition of $Or_{33}Ab_{66}$ An_1 ($\alpha \wedge a$ 14–15°).

The more feldspathic rocks typical of Units 2 and 3 consist of sub-idiomorphic feldspars, aggregates of ferromagnesian minerals, mainly hornblende, and quartz occurring interstitially or in sub-equant crystals. The Unit 3 "nordmarkitic granites" contain a scattering of larger than average feldspars, up to 1 cm across, and having a marked zonation apparent in hand-specimens. This tendency towards porphyritic texture is considerably more pronounced in Unit 3 than in Units 2 or 4 and suggests that, at this stage, an already crystallising magma underwent relatively rapid crystallisation on emplacement. The inner and outer parts of two such large crystals were carefully chipped from a thin slice of the rock (Specimen 50263). The two portions of outer and inner material respectively were combined and analysed for Na, K and Ca and the mean compositions thereby obtained were; core, $Or_{25}Ab_{66}An_9$ – and outer zone, $Or_{40}Ab_{54.5}An_{5.5}$. In section the core regions of these bigger feldspars are found to be generally crypto- to microperthitic, the cores passing more or less sharply out into material showing a much more clearly defined perthitic texture. Small variations in the degree of exsolution in the core areas frequently delineate a faint multiple zonation suggesting an oscillatory compositional zoning (Fig. 5). These inner growth zones show the feldspars to have had a euhedral form throughout much of their growth, with a tendency to the rhomboid form. Very occasionally the central areas are found to be of oligoclase alone, showing very narrow albite-twin lamellae discernible only in sections normal or almost normal to (010), the plagioclase being surrounded by, and largely made over to, cryptoperthitic alkali feldspars. The early growth stages of these feldspars have thus evidently been very similar to those of the Unit 1a feldspars. The cryptoperthitic areas have a 2V α ranging from 75–88°. Smaller optic axial angles down to 55° are recorded for the more turbid exsolved potassic feldspar. The latter have extinction angles $\alpha \wedge a$ of ~ 7°, several degrees less than for the cryptoperthites. The unmixed plagioclase in the later zones is not more calcic than An_8. The smaller feldspars which constitute the bulk of the rocks appear to be entirely identical to the outer zones of the larger feldspars. However there is little doubt that the An content of these "second generation" feldspars is less than the $An_{5.5}$ obtained as a mean value from the imperfectly separated outer zones of the "phenocrysts". In the Unit 4 quartz syenite the sub-porphyritic texture of the Unit 3 rocks is generally suppressed and the amphiboles have a greater tendency

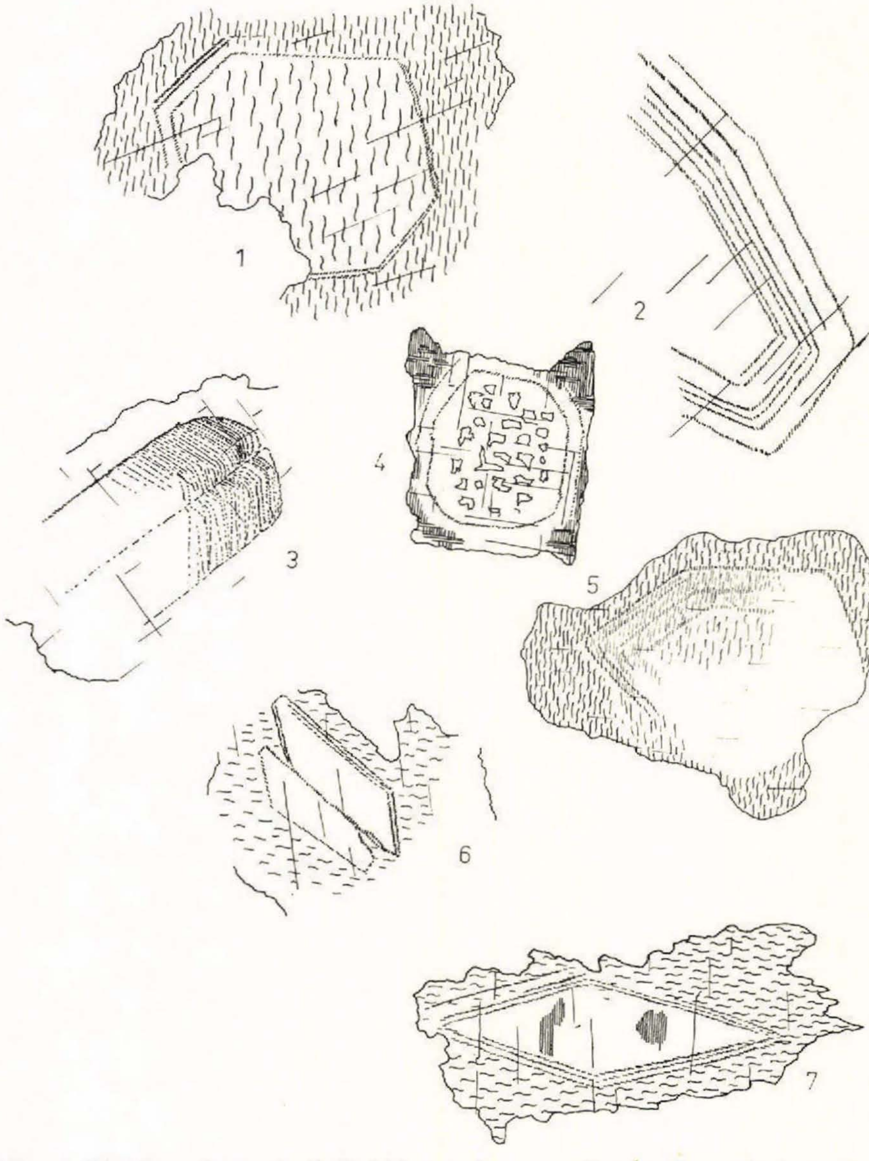


Fig. 5. Sketches of zoned alkali feldspars from syenites in the central complex. (No.s 1–5 are feldspars from Unit 3 syenites, 6 and 7 from Unit 1a syenites).

to form interstitially between the sub-idiomorphic feldspars. The latter tend to be more nearly square in (100) section than the feldspars of the earlier rocks but still retain a slight tabularity parallel (010). Cryptoperthitic areas are generally scarce and have optical properties identical to those of the earlier rocks. Manebach and Carlsbad twinning is common and the coarsely unmixed feldspars frequently display a herring-bone pattern when viewed on (010), with the plagioclase and K-feldspar constituents arranged at an angle of $\sim 70°$ to (001). In the marginal facies adjacent to the country rock granodiorites the Unit 4 syenites undergo considerable modification. In addition to relict crystals of (anti-)perthitic feldspar similar to those of the typical quartz syenite, are microcline microperthites showing the typical cross-hatched twinning in the microcline, with the relatively early feldspars largely replaced by small late-stage albite crystals. In some apophyses from Unit 4, the bulk of the rocks consists of a mosaic of microcline and nearly pure albite with some quartz and ferromagnesian minerals.

In the micro-quartz syenite of the Unit 5 ring-dyke the feldspars are subhedral, exhibiting the forms (010) and (001). The crystals are rectangular, 2–4 mm long parallel the crystallographic *a* direction and 0.5–1 mm across. In sections perpendicular to *a*, the crystals are square and the characteristic tabularity of the feldspars in the earlier intrusions is not seen. Considerable variability in the crystal sizes is such in some cases as to suggest two generations of feldspar, i.e. it is likely that this magma also was intruded after its crystallisation had commenced. Manebach twinning and to a lesser extent, Carlsbad twinning, is widespread. As in the exsolved feldspars from the Units 2, 3 and 4 rocks, the perthitic constituents are arranged at an angle of $\sim 70°$ to (001). Finely developed polysynthetic twinning is sometimes clear in the plagioclase constituent whereas the potassic lamellae frequently show the microcline cross-hatching.

In each of the intrusions orange-yellow "iddingsite" pseudomorphs after fayalite occur within the hornblendes. Fresh olivine is apparently restricted to the rocks of Units 2 and 3 and in the melanocratic facies alteration is to magnetite rather than to iddingsite. Olivine from one of the melanocratic rocks was determined by X-ray diffraction traces as being close to Fa_{94} and it is unlikely that the olivines in any of the eastern centre intrusions are more basic than this. Exceptionally as large as 4 mm, the olivines are generally no larger than 1 mm in diameter. The two cleavages parallel to (010) and (100) are commonly developed and a faint pleochroism is often detectable (α very pale yellowish, β and γ pale grey).

The pyroxenes range from pale brownish ferroaugites as seen in some of the melanocratic rock-types to aegirine-augite. Most commonly the pyroxene is a scarcely pleochroic green species that is probably a mildly sodic hedenbergite. Colour zoning is common, accompanied by an increase of 2V from core to margin of at least 56–71° and an increase in $\gamma \wedge c$ over a minimum range of 55–63°. The subordinate aegirine-augite in the Unit 5 rocks is more strongly pleochroic, with α deep blue green, β green, γ yellow green. The pyroxenes in the more typical leucocratic rocks are almost invariably surrounded by, and partly reacted to, alkali hornblendes. Acmitic aegirine is occasionally seen in the Unit 3 ring dyke and in the marginal modifications of the Unit 4 granite, in both cases apparently developing later than the amphiboles. The pleochroism of the hornblendes is somewhat variable but is typically α light brownish-green, β olive green and γ deep blue-green, with $\gamma \wedge c$ 27–28°. However, the hornblende is very frequently patchily intergrown with riebeckite-arfvedsonite (α blue-black, β slaty blue-green and γ dull yellowish-green with $\alpha \wedge c$ 7–10°). Riebeckite is the main coloured mineral in the marginal facies of the Unit 4 granite and in associated pegmatites. In the marginal rocks the riebeckite occurs in small "mossy" micropoikilitic patches, commonly partially replaced by albite or, by contrast, in well-formed elongate prisms. In the Unit 5 rocks the amphibole, which is characteristically poikilitic towards the feldspar, is almost entirely of hornblende although, in certain sectors of the ring-dyke, this mineral is replaced by riebeckite.

Small quantities of biotite occur in the earlier intrusions, particularly in some facies of the Unit 3 rocks, (pleochroism from reddish-brown or orange-brown to brown). Crystallisation appears to have been later than the riebeckite amphibole phase. Aenigmatite, a very scarce component in some specimens of the Unit 4 syenite is more persistently present in the Unit 5 ring-dyke where, like the more abundant hornblende, it occurs poikilitically. The absorption is intense but there is some pleochroism from mahogany-red (parallel α) to black (parallel γ). The extinction, $\gamma \wedge c$ is $\sim$ 46°. The aenigmatite has grown around the alkali hornblendes and the aegirine-augite but does not show any structural continuity with these minerals. In one specimen, minute tufts of astrophyllite were observed growing around the aenigmatite. This reaction relationship between astrophyllite and aenigmatite has previously been commented upon by both Fersmann (1937), who has observed it in nepheline syenites from the Kola peninsula, and by Warren (1913) in a discussion of the Quincy granite. Astrophyllite is not uncommon in the Unit 4 syenites, particularly in the marginal aegirine and riebeckite-bearing facies and in its pegmatites. In the latter crystals of up to 1 cm have been noted.

Fluorite is surprisingly abundant in these four intrusions, usually occurring as colourless and lobate crystals up to 1 mm across, most frequently within the hornblendes. Very rarely, adjacent to zircon crystals, intense violet colouration is developed in the fluorite. Zircon is one of the commoner accessory minerals, frequently showing a complex zonation, usually euhedral but sometimes, as in the Unit 4 pegmatites, skeletal in form. Often light grey or brownish-grey, the zircons occasionally possess clear but isotropic core regions. Apart from small quantities of apatite, a number of rare minor accessories are present. Poorly-

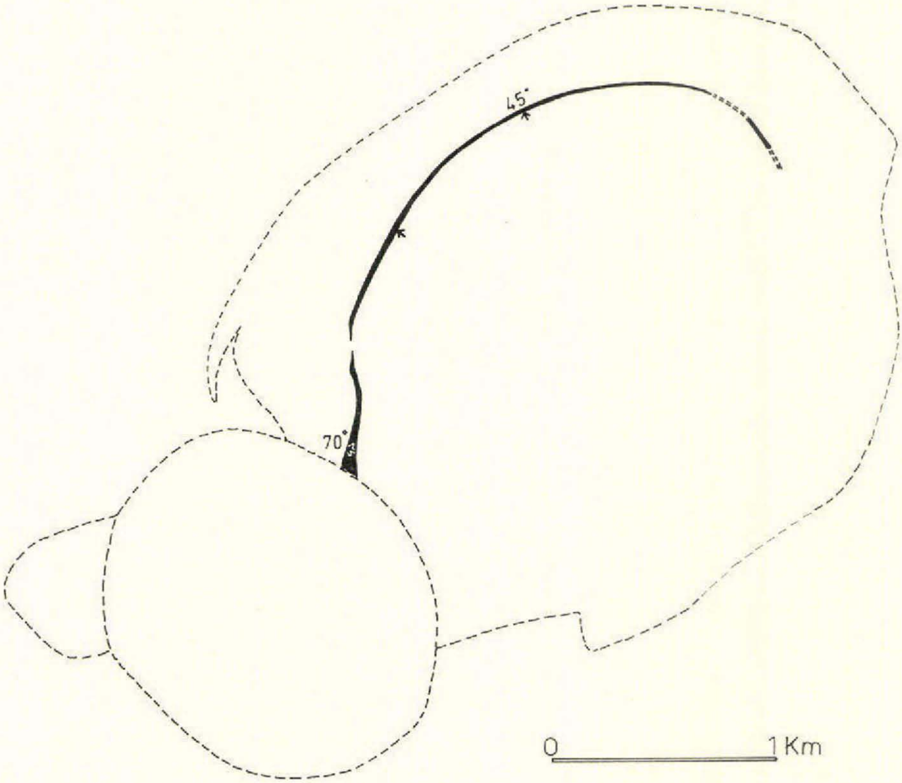


Fig. 6. Sketch map of outcrop of the Unit 5 quartz syenite ring-dyke.

formed, dark-coloured crystals pleochroic from dark chocolate-brown to black are not uncommon, and are probably a form of chevkinite. These frequently have a zonal structure and often have completely opaque cores. Whenever they are enclosed by the hornblendes, pleochroic haloes have developed around them. One crystal was found within a large fresh fayalite which had a well developed set of cracks radiating from the included mineral (fig. 7). Another scarce accessory present only as occasional small pale-yellow crystals, forms well-shaped prismatic crystals. These are non-pleochroic, have high positive relief, are length slow, show 2nd–3rd order interference colours and have a 2V of around 90°. In basal section these are seen to have a hexagonal outline and the extinction is parallel, or very nearly so, to the prism axis. The mineral possibly belongs to the hainite-guarinite group or alternatively, it may be a variety of mosandrite. In one instance the core to such a crystal was seen to be a dark brown to black pleochroic material and it is conceivable that the growth of the chevkinite preceeded that of the yellow mineral. In one of the feldspathic veinlets giving rise to the

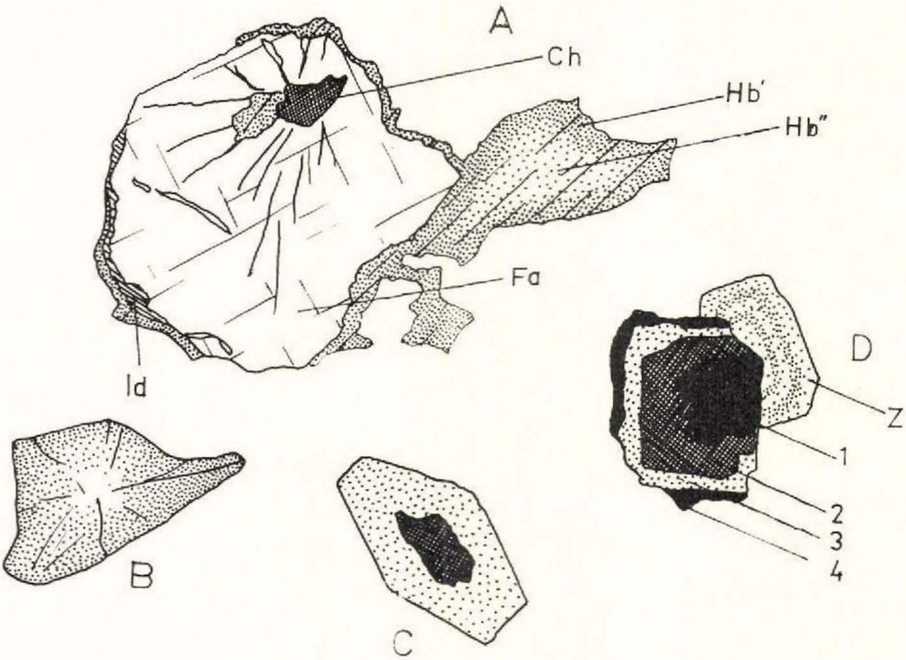


Fig. 7. Minerals from Unit 3 and 4 syenites. A; (001) section of fayalite crystal (Fa) slightly altered to iddingsite (Id), rimmed by zoned hornblende (Hb′ and Hb″), and containing a small crystal of chevkinite (?), (Ch). B; typical zoned zircon with clear centre and brownish-grey marginal areas. C; Basal section of prismatic accessory mineral, guarinite (?) containing dark pleochroic core of chevkinite (?). D; Zoned zircon crystal (Z) lying alongside (1), isotropic opaque core to pleochroic brown chevkinite (?) (2) which is surrounded by (3) guarinite (?) which is itself surrounded by a rim of opaque material (4).

intrusion-brecciation of the main western area of Unit 1 microsyenite are some pale yellowish cubes .1–.5 mm diameter. The euhedral cores of these very small crystals often show a rough zonal structure. Although usually partly or wholly isotropic, anisotropic areas give 2nd–3rd order interference colours. Surrounding the light-coloured cores in every case are orange-brown zones of less distinctly crystalline material that is entirely isotropic. The early cubic crystals are almost certainly members of the pyrochlore group. Apart from one or two minerals which may or may not be variants of species already described, small flakes of silvery white mica have been noted in some of the pegmatitic joint incrustations in the eastern centre granites. Probably these are flakes of taeniolite, a lithia-mica recorded from augite syenite pegmatites at the Igaliko and Kûngnât intrusive centres.

Analyses of quartz syenite-alkali granite from the eastern centre.

	40589	50272	1	2	3	4
SiO_2	66.45	65.62	65.63	69.42	66.60	65.43
Al_2O_3	15.89	15.72	15.33	15.15	15.05	16.11
Fe_2O_3	1.03	1.33	2.61	1.49	1.07	1.15
FeO	3.07	3.21	1.52	3.50	4.42	2.85
MgO	.00	.02	.70	.09	.36	.40
CaO	.89	.68	1.09	.96	2.21	1. 40
Na_2O	6.03	6.03	6.56	3.35	4.03	5.00
K_2O	5.49	4.93	5.09	5.12	5.42	5.97
H_2O^+	.31	.36	.22			
H_2O^-	.07	.10	.25	.47	.41	.49
TiO_2	.34	.31	.91	.20	.76	.50
P_2O_5	.02	.02	.20	tr	–	.33
MnO	.12	.13	.17	.10	tr	.23
CO_2	.00	nd	–	–	–	(misc).28
	99.71	98.46	100.28	99.85	100.33	100.14

C. I. P. W. Norms

	40589%	50272%
Qtz	7.6	5.7
Or	32.5	30.6
Ab	51.3	53.9
An	.3	1.5
Di	3.7	1.8
Hy	2.6	3.9
Mt	1.4	2.0
Il	.6	.6

	40589	50272
Feldspar	$Or_{39}Ab_{60}An_1$	$Or_{36}Ab_{62}An_2$
Cl. pyrox.	$Wo_{43.5}En_0Fs_{56.5}$	$Wo_{44}En_0Fs_{56}$
O. pyrox.	En_0Fs_{100}	En_0Fs_{100}

Modes

	(40589[1])%	50272%
Quartz	8.0	6.0
Feldspar	79.0	82.0
Pyroxene	1.1	.5
Olivine (pseudomorphs)	tr	tr
Amphibole Rie.	2.6	–
Amphibole Hbde.	9.0	9.9
Aenigmatite	tr	.9
Biotite	tr	–
Ore	.3	–
Fluorite	tr	.7
Zircon	tr	tr

[1]) Mode determined not on 40589 but on a closely similar specimen, 40506).

40589, Quartz syenite (alkali granite), north side of unit 4 ring-dyke, eastern centre Analyst B. I. Borgen.

50272, Quartz syenite, Unit 5 ring-dyke, eastern centre. Analyst D. Maynes.

1, Quartz syenite, Sande cauldron central intrusion, Oslofjord. Brögger (1933).

2, Nordmarkitic hornblende granite, Cape Ann, Massachusetts. Warren & McKinstry (1924).

3, Akerite, Gloucester, Massachusetts. Warren & McKinstry (1924).

4, Nordmarkite, Mt. Ascutney. Warren & McKinstry (1924).

c) The Blå Månesø perthosite.

The latest major intrusion in the Tugtutôq area is a highly variable syenite, nevertheless composed almost wholly of alkali feldspar. This syenitic plug intersects the earlier Gardar nepheline syenite and olivine gabbro dykes as well as the Units 1, 1a, 3, 4 (and 5?) intrusions of the central complex. The variation observed is primarily one of grain size rather than of composition. Whereas much of the intrusion is excessively coarse grained with the feldspar crystals 10 cm or more in length, other facies have an average crystal size of little over 2 mm. Between these extremes however are varieties containing idiomorphic feldspar tablets ca. 1 mm thick by 7 mm across, that is corresponding more or less in grain size to the average syenites from the western Hviddal dyke, the Assorutit intrusion, and the Units 1a, 2, 3 and 4 of the central complex, suggesting that these varieties represent an original texture and that the abnormally coarse and fine grained pegmatitic and aplitic facies have arisen through recrystallisation of the syenite at lower magmatic temperatures. In places a certain degree of parallelism in the crystals of this intermediate grain-size syenite gives a rough low-angle lamination to the rock. Although exposure is unusually poor across this intrusion, raising the possibility that the rocks outcropping are not fully representative of the intrusion as a whole, it would appear probable that some $95^0/_0$ or so of the intrusion consists of feldspar, the remainder consisting of interstitial biotite, soda amphiboles, aegirine-augite and aegirine, magnetite and quartz.

The feldspars: In size, form, microtextures and compositions the Blå Månesø feldspars closely resemble those of the earlier syenitic intrusions, perhaps most closely corresponding to those of the Assorutit syenite. The crystals which are commonly Carlsbad twinned, grade from nearly optically homogeneous to finely antiperthitic. Just as in most of the other intrusions so far described there appear at first sight to be both perthitic and antiperthitic crystals present but there is little doubt that only one feldspar phase was ever crystallising at any particular time. Fig. 8 is an attempt to illustrate the characteristic appearance of the feldspars as viewed in sections parallel to (100), (001) and (010), drawn from oriented thin sections of a single crystal. On sections cut parallel to (010) the crystals display a braided or flamboyant lamellar perthite texture making an angle of $71° \pm {}^1/_2°$ to the (001) cleavage trace, the potassic feldspar component having an extinction $\alpha \wedge a$ of 11°. This exsolution pattern is identical to that seen in, for example, the typical feldspars from the Unit 4 and 5 ring-dykes but it is on a much finer scale. This exsolution plane corresponds to the Δ plane referred to by SPENCER (1930) in his very detailed description of moonstones from Ceylon. However in these latter the angle between the microperthite lamellae and the basal cleavage was determined precisely as 73° 53′, corresponding to (13.0.$\bar{2}$). Spencer observes that other workers who have made goniometric determinations on similar feldspars obtained various angles from 72° to over 75° opening the possibility that the exsolution plane may in fact correspond to (15.0.$\bar{2}$) or (80$\bar{1}$) or even, according to Bøggild, to no fixed crystallographic plane at all. Spencer concluded that the discrepancies must either be due to inaccuracies in

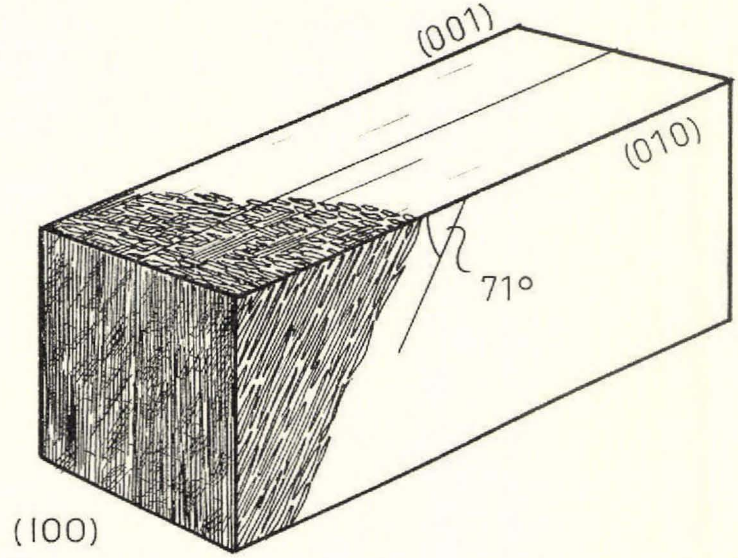


Fig. 8. Diagrammatic illustration of exsolved alkali feldspar from the Blå Måneso perthosite.

the angular measurements or to a slight variation governed by the feldspar composition. In these Tugtutôq microperthites precise angular determination was not attempted although the angle does not exceed 72°. It is possibly significant that these feldspars are some 25–30% more albitic than Spencer's moonstones. On sections parallel to (001), the polysynthetic twins of the plagioclase "host" are seen perpendicular to the direction of the K-feldspar blebs, and in the plane parallel to (100), the twinning is seen around the patchy areas of K-feldspar where the plane of the exsolution texture intersects at an oblique angle. However, in the more standard, medium grained syenites the crystal centres are largely cryptoperthitic showing neither clear exsolution textures nor any albitic twinning. Albite rims, reminiscent of those in the Assorutit syenites, are commonly present. The bulk feldspar from the standard syenite type (specimen 50242) has a composition of $Or_{35.5}Ab_{64}An_{.5}$, not differing significantly from the composition obtained from one of the large pegmatitic crystals (specimen 30709), namely $Or_{36.5}Ab_{63.5}$

An_0. The large bluish-grey pegmatite feldspars are commonly strained and show curved crystal and cleavage faces.

Other minerals: There appears to be no trace of fayalite in the Blå Månesø intrusion and the only pyroxene present, in very restricted amount, is a variety of aegirine (α deep blue-green, β green γ yellow-green $\alpha \wedge c$ 10°). Alkali hornblendes, (α light greenish brown, β olive-green, γ bluish-green) and riebeckite-arfvedsonites (α deep blue-black or opaque to γ dull greenish grey) forming later than the pyroxene, occur interstitially. Biotite is relatively important in contrast to its scarcity in the preceding alkali rocks of the eastern centre. Pleochroism is extreme with complete absorption parallel to β and γ and golden yellow-brown transmission parallel to α. Although normally seen as interstitial scraps, the biotite is sometimes seen in intergrowths with the feldspar. In some fast-weathering standard syenite from the eastern margin of the intrusion the biotite occurs as large poikilitic plates, with crystals up to 6 cm × 1 cm enclosing the euhedral feldspars. This remarkable rock-type appears to have a very limited distribution. Biotite also occurs to a considerable extent in the areas of pegmatite and particularly in the pegmatite veins extending out into the country rocks. Aenigmatite occurs to a very minor extent associated with the riebeckite, with pleochroism and extinction precisely as in aenigmatites from the Unit 5 ring-dyke. Astrophyllite has been identified in some specimens, again as a minor accessory, occurring in matted yellow-brown bunches (α lemon yellow, β yellow and γ orange yellow). In some of the finer grained facies and in the pegmatite veins magnetite takes the place of biotite as the dominant dark mineral. Zircons, generally scarce in the intrusion, are likewise of some importance in the pegmatites. Colourless fluorite, particularly associated with the aegirine and amphiboles is conspicuous in most of the thin sections examined and apatite is present as occasional minute needles within the feldspars. Quartz, in interstitial crystals, is a fairly common accessory but does not appear to be more abundant in the pegmatitic rocks.

V. NOTES ON THE FELDSPARS

In the great majority of cases where the syenitic rocks are found in a rapidly chilled condition, they are to some extent feldsparphyric, and it is probable that all the syenitic intrusions were below their liquidus temperature prior to emplacement. Most commonly the feldspar in these rocks is present as tabular crystals, low in calcium and with between 50 and 70 % albite constituent. Optics and composition place these between the low-albite-orthoclase series and the anorthoclase-low sanidine series (MacKenzie and Smith, 1955), and it is highly probable that these feldspars crystallised as soda-sanidines at temperatures in excess of 600°, their perthitic and antiperthitic textures being the result of unmixing. To a very much more restricted extent early feldspar crystals of rhomboid habit occur in some of the intrusions, these being closely similar to those in the rhomb-porphyries well-known from other alkaline volcanic fields. These crystals have higher anorthite contents, tend to be less coarsely exsolved, and very occasionally almost submicroscopic albite twinning or a cross-hatched twinning occurs strongly suggestive of anorthoclase. In composition and in their environmental association they are comparable to the anorthoclases of Mt. Kenya and Ropp, Nigeria, which MacKenzie (1952) showed to invert to the monolinic form at temperatures of 600° and 540° respectively. On the basis of this analogy it is concluded that the rhomboidal alkali-feldspars in the syenites under discussion crystallised as relatively Ca-rich soda-sanidines and that fast chilling allowed the monoclinic-triclinic inversion to occur before there was significant K-Na unmixing. The rhomboidal shape of these crystals due to the development of $(1\bar{1}0)$, (110), $(\bar{2}10)$ forms became modified in the progressively differentiating magmas with the appearance of the (010) faces. Whereas in the more alkalic and undersaturated magma series associated with the Hviddal dyke the (010) development became increasingly exaggerated to yield the very thin tabloid crystals characteristic of the foyaites, in the acid series, particularly in the more advanced fractionates, the (001) form achieves equal prominence and the crystals are not tabular but rectangular with square cross-section. The terminal faces are usually poorly developed. In the Unit 1a it appears that a primary plagioclase was precipitating at an early stage, this probably being a potash oligoclase. If this were so, then it is probable that the rhomb-shaped Ca-rich sanidines were crystallising alongside with it in a situation similar to that described from the basic "Erebus-kenyte" lavas by JENSEN (1916) and by SMITH (1954). That there are close affinities between the Oslo rhomb-porphyries, the kenyte lavas of Kilimanjaro and Mt. Kenya and the Erebus-kenytes of the Ross-archipelago has been stressed by various authors. Many of the features held in common by these lavas were also shared by the more basic syenite magma-types of south Greenland. In each case the rhomboid feldspar co-precipitated with small amounts of iron-rich olivine and clinopyroxene and ilmenomagnetite. However, the more primitive Gardar syenite magmas were distinguished by somewhat lower Na/K ratios. Analyses of the kenyte-rhomb-porphyry type lavas usually show much greater Fe‴/Fe″ ratios than those believed to have obtained in the analogous Gardar magmas, a difference probably ascribable to greater oxidation accompanying the extrusion of the lavas.

The basic intrusions of Tugtutôq, described in a separate publication, show a range of feldspar composition from $\sim An_{70}Ab_{30}$ down through K-rich oligoclase to Ca-bearing alkali feldspars. At the low temperature end of this sequence there is no indication that two feldspars, i.e. a plagioclase and a sanidine, were coprecipitating; rather there is a continuous single sequence with a switch from triclinic to monoclinic structure as the Or content approaches 20–25 %. Furthermore it would seem likely that the adoption of monoclinicity is accompanied by the abrupt change from a tabular plagioclase habit to a rhomboid habit and that there is thenceforward a gradual resumption of tabloid form. OFTEDAHL, (1952) considers that the rhomboid feldspars of the Oslo lavas crystallised as plagioclase, but at least in the Tugtutôq area of the south Greenland province it would seem that primary plagioclase invariably possessed the typical tabular or lath-shaped habit.

There is thus some slight doubt whether there was a stage, corresponding for example to the Unit 1a intrusion, when the magmas passed through a monzonitic phase with both plagioclase and alkali feldspar crystallising or whether in fact there was simply a single one-feldspar sequence as indicated by the basic rocks. However, apart from this uncertainty in connection with the Unit 1a rocks, the syenite magmas are believed to have produced one-feldspar rocks at least until the latest residual portions when co-precipitation of microcline and albite may have occurred at high H_2O vapour pressures, as for instance in the marginal modification of the Unit 4 ring-dyke.

With the exception of the rapidly chilled rocks where inversion to anorthoclase preceded Na-K-Ca unmixing, the sub-solidus history of the feldspars was probably much like that described for the larvikite

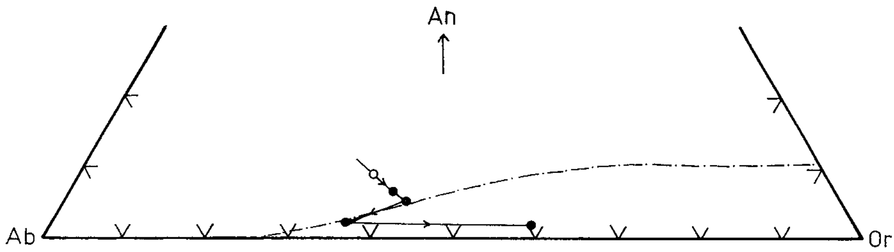


Fig. 9. Feldspar phenocrysts from mid-Gardar dykes plotted on the Or-Ab-An triangle. Open circle, feldspar of relatively undifferentiated larvikite-type syenite from Kûngnât. Dashed line, ternary cotectic at 5000 bars H_2O v. p. (Yoder, Stewart and Smith 1957).

feldspars investigated by Smith and Muir (1958), which were considered to have exsolved into Na and K rich sanidine phases which then, by Al-Si ordering, proceeded towards low-temperature oligoclase (or albite) and microcline.

The observed changes in composition of the feldspars from the acid series can be interpreted in the light of the experimental work on the ternary feldspars at 5000 bars H_2O v. p. by Yoder, Stewart, and

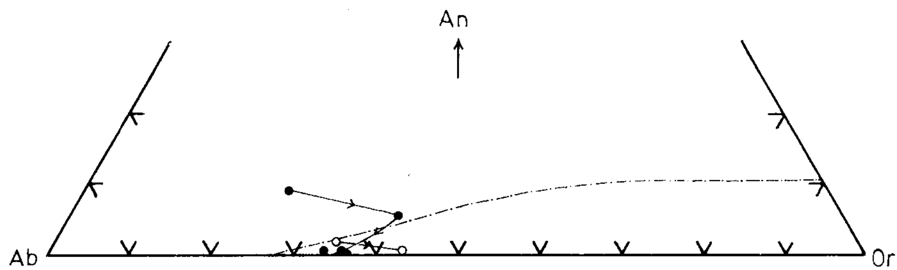


Fig. 10. Feldspars from central complex rocks plotted on Or-Ab-An triangle. Open circles, phenocryst and groundmass feldspar from Unit 1 microsyenite. Solid circles, feldspar sequence in later central complex syenites.

Smith (1957). As the liquid phase approached the feldspar cotectic the equilibrium feldspars showed increase in K/Na ratio with falling Ca content. After the cotectic curve is reached the Ca content continues to decline while the K/Na value begins to decrease. The feldspar normally approaches an end member composition of ca. Or_{35-40} and with 0–2 % An. However, strong fractionation giving end liquids of comendite or grorudite type can once again direct the feldspar towards the Or corner of the ternary diagram, with little if any further decrease in An content.

Rubidium values:

The content of Rb as well as the Rb/K ratio tends to increase with fractionation as would be expected.

(*a*) *Feldspars from porphyritic mid-Gardar dykes in order of increasing silica enrichment.*

		Phenocrysts			Groundmass Feldspars		
	Specimen	Rb ppm	K %	Rb. 10^4/K	Rb ppm	K %	Rb. 10^4/K
	50226.......	58	5.10	11	100	4.91	20
SiO_2	40498.......	84	5.55	15	85	5.03	17
	30713.......	103	5.78	18	124	5.60	22
↓	50187.......	(300)*	4.95	61	n. d.	n. d.	–

(*b*) *Successive, arbitrarily defined, zones from core to margin of phenocryst from a Unit 3 quartz syenite (50271).*

	Rb ppm	K %	Rb. 10^4/K
Core....................................	74	4.20	21
Int. zone................................	117	6.45	28
Marginal	184		

(*c*) *Feldspars from other saturated or oversaturated syenites.*

Specimen	Rb ppm	K %	Rb. 10^4/K
Assorutit syenite 40521	120	5.52	21
Unit 1 microsyenite, 50345			
a) Phenocrysts	105	4.59	23
b) Groundmass feldspars	140	5.58	25
Unit 2 mafic syenite, 50280................	135	4.30	32
Blå Månesø syenite, 30709	155	4.92	31

Strontium-barium values:

The Sr and Ba content of the alkali feldspars decreases rapidly with decline in Ca and poverty in these elements, together with richness in Rb, can be used as a criterion for extensive fractionation.

(*a*) *Feldspars from porphyritic mid-Gardar dykes, in order of increasing silica enrichment.*

		Phenocrysts			Groundmass Feldspars		
	Specimen	Sr ppm	Ba ppm	CaO %	Sr ppm	Ba ppm	CaO %
	50226...............	760	2900	1.32	145	1450	.63
SiO_2	40498...............	335	2300	1.14	185	1700	73.
	30713...............	375	2300	.96	95	1600	.81
↓	50187...............	(50)*	n. d.	n. d.	n. d.	n. d.	n. d.

* ±10 %

(*b*) *Successive, arbitrarily defined, zones from core to margin of phenocryst from a Unit 3 quartz syenite (50271).*

	Sr ppm	Ba ppm	CaO %
Core	780	4400	1.80
Int. zone	650	4200	1.41
Margin	110	1400	.72

(*c*) *Feldspars from other saturated or oversaturated syenites.*

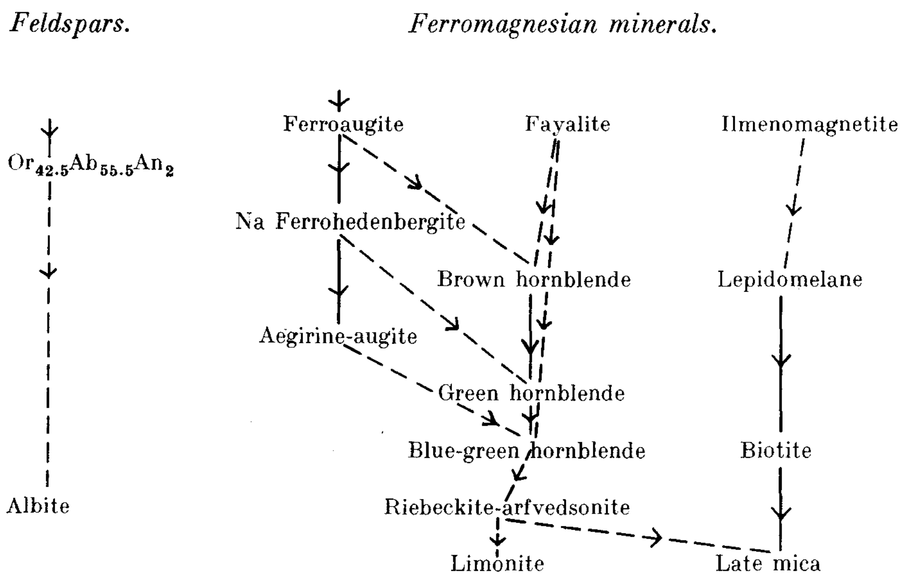
Specimen	Sr ppm	Ba ppm	CaO %
Assorutit syenite, 40521	80	1200	.37
Unit 1, microsyenite, 50345			
(a) Phenocrysts	70	450	.37
(b) Groundmass	40	400	.07
Unit 2 syenite, 50280	30	50	.14
Blå Månesø syenite, 30709	40	20	.005

(Method: Rb, Ba, Sr and determinations using a Phillip's Norelco X-ray spectrometer. W. target; 50 kV, 40 ma. LiF crystal and scintillation counter for Sr and Rb and flow-proportional counter for Ba and Ca. Samples finer than 120 mesh, diluted with 10 % corn-starch and held in Al sample holders with "mylar" film. Standards for Rb and Sr were feldspars kindly supplied by B. J. WASSERBURG on which these elements had been determined by isotope dilution procedures. Standards for Ca and Ba were feldspars for which these elements had been determined gravimetrically).

VI. DISCONTINUOUS REACTION SERIES IN THE SYENITES

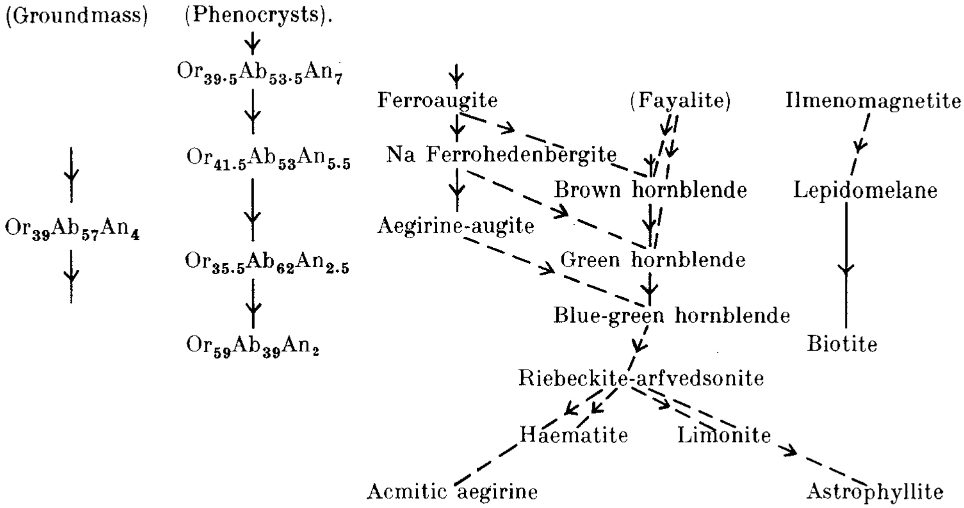
In all cases the early crystallisation course of the ferromagnesian minerals has been similar and it is only in the low temperature reactions that the rocks display significant diversity and individuality. Olivines, highly ferriferous even in the most basic of the syenites, became unstable with lowering temperature and commonly acquired a reaction corona of ferrohastingstite ("blue-green hornblende") or of riebeckite-arfvedsonite. At still lower temperatures the olivine was often replaced wholly or in part by yellow-brown iddingsite. An exception to this is found in the drier environments of the mafic facies in some of the larger syenite bodies where the amphibole rims fail to develop and magnetite takes the place of the iddingsite. Clinopyroxene accompanied the olivines in crystallisation. In contrast to the olivines, strong zoning is generally preserved. The pyroxenes have not been adequately studied, optically or chemically, but appear to range from titaniferous augites through increasingly alkalic ferroaugites and ferrohedenbergites to aegirine-augite (cf. Carmichael, 1962). As cooling proceeded pyroxene crystallisation gave way to amphibole formation, probably as a consequence of rising water concentration in the magma. The precise stage at which the pyroxene series switches to the amphibole series is subject to considerable variation and, taking the syenites as a whole, there is little doubt that there is a large overlap between the lowest temperatures of pyroxene formation and the upper limits of amphibole formation. The higher temperature amphiboles are brown (barkevikitic) hornblendes which zone continuously towards blue-green (ferrohastingsite) hornblendes. The latter give place abruptly to riebeckite-arfvedsonites in which colour zoning is very slight. It is the temperature range below the lower stability limits for riebeckite-arfvedsonite that has produced the greatest mineral complexity. Passage from amphibole to mica is witnessed only in the Blå Månesø and Assorutit syenites. In the former an intensely pleochroic biotite appears unheralded in the latest stages and is the characteristic dark mineral of the pegmatites. By contrast, in the Assorutit rocks the amphibole gives place to a mica series which itself represents the low temperature stages of a continuous reaction series from lepidomelane through biotite. Whereas it is extremely common for the early ilmeno-magnetites of the syenites to be partly replaced by lepidomelane, it is only in the Assorutit syenite that the mica series is so remarkably prolonged. Alternatively, either acmite, aenigmatite or astrophyllite can appear in place of the riebeckite-arfvedsonite. These are very rarely seen in association although both acmite and aenigmatite may give rise to reaction fringes of astrophyllite. It is thus clear that for the conditions under which the various magma intrusions cooled, the stability field for astrophyllite extended to lower temperatures than for the other two minerals. However, under certain circumstances, particularly in the narrower dykes, it is found that either limonite or haematite crystallised at low temperatures in place of the riebeckite-arfvedsonite or, occasionally, in place of the ferrohastingsite.

Continuous and discontinuous reaction series in the Assorutit syenite.



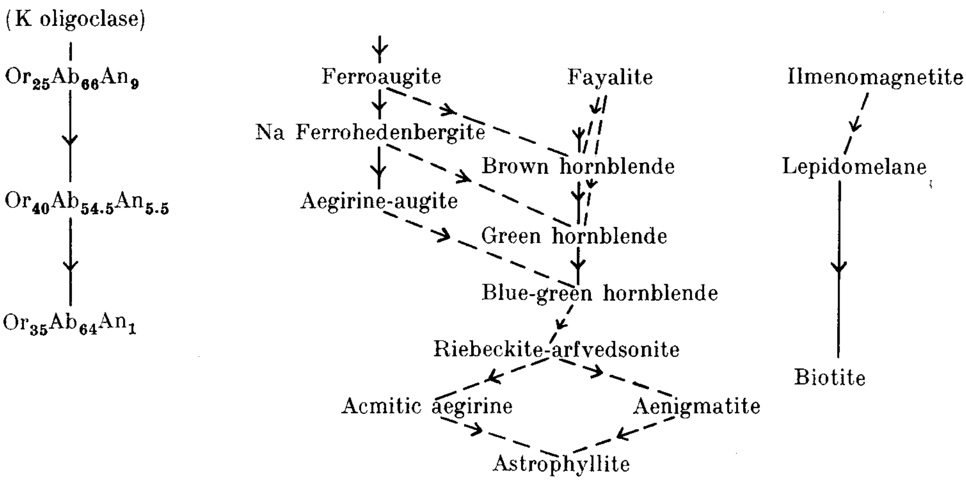
Continuous and discontinuous reaction series in the mid-Gardar microsyenite dykes.

Feldspars. *Ferromagnesian minerals.*



Continuous and discontinuous reaction series in the central complex.

Feldspars. *Ferromagnesian minerals.*



VII. PETROGENESIS OF THE INTRUSIVES

a) Petrogenesis of the Assorutit syenite.

Just as syenite magma was available in the early Gardar to take advantage of the plane of weakness offered by the Hviddal syeno-gabbro dyke, so also was it available to utilize the pathway provided by the subsequent olivine gabbro dykes thus producing a new composite dyke in the vicinity of Assorutit. The intrusion of the gabbro marked an important break in the evolutionary history of the Tugtutôq-Skovfjord area. Whereas formerly the syenites differentiated to yield feldspathoidal and zeolitic products syenite differentation now proceeded only in the direction of silica enrichment, the trends followed differing only slightly from those displayed in the late Gardar complex at Kûngnât. The most significant differences between the syenite intruded at Assorutit and the more basic facies of the earlier Hviddal syenite lie in the lower Na and higher Si contents of the younger intrusion, resulting in the formation of quartz-bearing, rather than nepheline-analcite-bearing residuals. Both normatively and modally these two rock types are otherwise much alike. The analysed sample from the Assorutit syenite has a close chemical and mineralogical similarity to the quartz syenites found within the lower layered sequence of the main western intrusion at Kûngnât and, considering the geographic separation of these two occurrences (ca. 130 km) and the probable time differences between their intrusion (mid-Gardar and late Gardar respectively), the near identity of these rocks is of particular interest. The feldspar in the Assorutit syenite is $Or_{42.5}Ab_{55.5}An_2$ whereas that in the corresponding syenites from the Kûngnât intrusion was determined as $Or_{41}Ab_{54}An_5$ (the correspondence probably being closer than indicated as the spectrographic Ca determination for the latter is almost certainly too high). Both carry zoned pyroxene (hedenbergite to aegirine-augite), zoned alkaline amphiboles, a little fayalite and magnetite and contain zircon, calcite, and the distinctive late mica phase although fluorite, present in the Kûngnât rocks, is not found at Assorutit. The chief difference appears to be in the closer approach to equilibrium conditions in the Kûngnât syenite, undoubtedly a consequence of a higher cooling rate at Assorutit. Since the analogous Kûngnât syenites occur within a fairly thick sequence of layered rocks it is hard to avoid the conclusion that the parental magmas were the same in both instances and that the Assorutit magma was derived through its fractionation. The thin mafic horizons at Assorutit suggest that this intrusion has, in a small way, some of the characteristics of a layered intrusion. It was argued for the Kûngnât rocks that whereas the lower rocks of the sequence were clearly of accumulitic origin, there was no direct evidence for this being true of the higher rocks comprising the unlaminated series. The feldspars and other early minerals probably sank to some extent during growth but did not produce a well-defined "floor", i.e. interface between predominantly solid and predominantly liquid environments; the rocks could be referred to as semi-cumulitic. The Assorutit syenites probably have a similar nature and the 50216 analysis is taken as being only slightly removed from "the line of liquid descent". (The initial composition of the syenite magmas at Kûngnât is not adequately known, there being no well-chilled uncontaminated marginal facies to give this information. The best estimate that can be made is by equating the early magma with an analysis made of a basic larvikite-type syenite from the border group of the eastern centre).

An interesting feature of the melanocratic horizons of the Assorutit syenite is the relative lack of unmixing in the feldspars. The feldspars also lack the albite rims and the rock has little or no quartz or carbonate. The olivines are less altered to iddingsite than in the standard rock. These features have previously been noted in the melanocratic syenite facies at Kûngnât where the explanation advanced was that the early minerals had a closer packing in these facies and that the greater availability of water and other volatiles in the feldspathic rocks by virtue of their greater content of volatile-enriched intercumulus material could be called upon to account for the coarser unmixing in the feldspar as well as for the more extensive alteration of the olivines.

b) Petrogenesis of the mid-Gardar microsyenite and quartz-porphyry dykes.

Although there is no simple relationship between dyke composition and order of intrusion, the entire suite of mid-Gardar alkaline dykes presents a petrologically continuous series ranging from quartz-free members through micro-nordmarkitic types into peralkaline granitic types. This suite is comparable to that of the Oslo region where there is a range from the rhomb porphyries through more acid nordmarkite porphyries with rectangular phenocrysts to highly acidic end members (Oftedahl, 1948 & 1952). There is sufficient petrographic similarity between the acid microsyenites and the Assorutit syenite for the conclusion to be drawn that all were descended from a closely similar if not identical source magma and, as has been suggested above, there is reason to consider that the parental magma for the Assorutit syenite was substantially the same as that for the late Gardar Kûngnât complex, if not for those of other mid to late Gardar quartz syenite-alkali granite complexes such as those at Nunarssuit and Narssaq-Dyrnæs. Moreover many of the features of the Gardar dyke swarms can be explained satisfactorily on the supposition that a crystallising complex of Kûngnât type underlay the area for much of the Gardar period. This being so the more important events at Kûngnât will be briefly recapitulated. At that centre, two major intrusions of syenite followed one another with such rapidity that the earlier (western) intrusion was not wholly crystalline before the second was emplaced. The earlier intrusion, consisting largely of syenite and quartz syenite is layered and was differentiated *in situ* to produce small bodies of riebeckite astrophyllite granite and still later aegirine-rich rocks of grorudite type. It is thought that during the latter part of its cooling history the western magma chamber was divided horizontally into two parts by a semi-collapsed layer of gneissose roofing rocks and that in each similar, but not identical, magma trends were followed. By the time the second intrusion occurred the first was still at a high temperature perhaps in the region of 600° C but largely crystalline and possessing considerable rigidity. If one estimates the initial amount of intercumulus magma in the western layered rocks at 40–50 %, considerable rigidity would have been achieved after only a small percentage of this had crystallised and it would probably have fractured cleanly without plastic deformation by the time say 50–60 % of the intercrystal liquid was solidified when some 16–25 % of magma would still have remained. The second intrusion at Kûngnât may have been of the same composition as the first or may have been slightly more basic, representing a somewhat less advanced composition on the same line of liquid descent. Fractionation was less pronounced in the second intrusion but proceeded in the same manner as in the first, through the sinking out of large quantities of alkali feldspar accompanied by smaller amounts of clinopyroxene, olivine and ilmenomagnetite. If, at some stage during the crystallisation of the second intrusion, increasing tension across the confining rocks had allowed magma to be drawn off from the complex as dykes, then not only would relatively large quantities of more or less undifferentiated magma have been available from the second intrusion but considerably more advanced liquids would have simultaneously been derivable although in lesser quantity from the first. As has been pointed out, the residual liquids from the upper part of the western intrusion may have differed from those of the lower part, adding to the variety of magma types simultaneously available for dyke formation. When the second intrusion was sufficiently crystalline to allow ring-faulting to occur across it, alkali basalt magma was injected to form a ring-dyke. When this latter was crystalline there still remained highly mobile granitic residuals from the earlier of the two main syenite intrusions. Hence, there must have been a stage at which fissuring of the super-incumbent gneisses could have allowed dyke intrusion of alkali basalt magma as well as of syenitic (or trachytic) magma in various stages of fractionation, perhaps giving rise to composite dykes. There is reasonable evidence that the syenite magmas at Kûngnât were, at some periods in their cooling history, undergoing a vigorous convective circulation and it is probable that the early crystallising phases precipitated in the cooler upper levels and were brought down by convection currents to accumulate as crystal mush on the intrusion floor, (cf. Skaergaard, Wager and Deer, 1939). Consequently if magma batches had been abstracted by dyke formation from time to time from the upper levels of the intrusion, these could have been either phenocryst-rich or aphyric according to the stage in the convective cycle at the time of fissuring.

If some of the metamorphosed basic masses present in the upper parts of the Kûngnât syenites actually represent inclusions of Gardar basalts then it is clear that the complex penetrated the basal Gardar unconformity. Whether or not this is so it is probable that the present exposures at Kûngnât represent a considerably deeper level section of a syenitic complex than witnessed anywhere in the Tugtutôq-Skovfjord area. Furthermore the dyke types actually present in the Tugtutôq region conform closely to the varieties which might have been produced in the roofing rocks above Kûngnât, had the stress pattern allowing ENE dyking continued unabated beyond the late Gardar ring-complex episode. On Tugtutôq there are, in relatively large numbers, microsyenite dykes both with and without phenocryst compliments. The phenocrysts are similar in size, relative abundances and compositions to the minerals distinguished as cumulus phases in the layered Kûngnât syenites. The composition range of the feldspar phenocrysts, $Or_{39.5}Ab_{53.5}An_7 \longrightarrow Or_{41.5}Ab_{53}An_{5.5} \longrightarrow Or_{35}Ab_{62}An_3 \longrightarrow Or_{59}Ab_{39}An_2$ is comparable to the range $Or_{32}Ab_{57}An_{11} \longrightarrow Or_{39.5}Ab_{56}An_{4.5} \longrightarrow Or_{59}Ab_{37}An_4$ noted in the Kûngnât rocks. (In these latter feldspar compositions the anorthite content is almost certainly too high). Several of the quartz porphyry dykes can individually be matched fairly closely among the varied sheets and dykes of peralkaline granite at Kûngnât. For example there is equivalence between the riebeckite-bearing comendites with small quantities of early magnetite (and pseudomorphed fayalite) and some of the riebeckite granites. The aegirine-riebeckite and astrophyllite-bearing comendites can be equated with the grorudite-type "grey-dykes". The presence of haematite in the largest of the quartz porphyry dykes possibly indicates that the ppO_2 was higher than in any of the Kûngnât rocks. In this connection it may be added that some oxidation may have attended the intrusion of many or all of the smaller alkaline dykes. Both the analysed microsyenites have higher Fe'''/Fe'' ratios than the comparable plutonic rocks of the region. The olivines have invariably been oxidized and hydrated whereas fresh fayalite is frequently encountered in the coarser grained rocks.

Limonite and haematite are common in the dyke rocks in contrast to their scarcity in the more slowly cooled syenites. The oxidation may have occurred through the influx of water from the intruded granites into the relatively anhydrous and reduced syenitic magmas.

With the concept of a moderately complex assemblage of syenites under the whole area from mid-Gardar onwards there is no difficulty in accounting for the irregular sequence of the mid-Gardar dyke types nor in explaining the large number of complex and multiple dykes. In most of the composite and complex dykes in the area there was evidently a considerable time-lag between the intrusion of the first and second pulses, the second often being cleanly chilled against the first. This was so for some of the composite quartz porphyry-dolerite dykes, the dolerite being the earlier. Some of the microsyenites also were intruded along the centres of chilled dolerite dykes. In contrast most of the basic dykes intruded after the olivine gabbro dykes were intruded up and along the first suite of microsyenite dykes and frequently the doleritic centres are not chilled against the microsyenite walls, but show hybridization and lateral gradation. An extreme case was noted on Niaqornaq island in the Skovfjord where a dyke consists of a basic rock intermingled with an aphyric microsyenite giving the dyke a patchy or mottled appearance. Since the basic patches tend to occur in rounded pillow-like masses it was inferred that doleritic magma was injected along a microsyenite dyke that was largely liquid and mechanically incapable of parting along its median plane as in the general case. The dolerite, having a considerably higher temperature than the syenite mush into which it was erupted, chilled to the characteristic pillow-like form (cf. Wager and Bailey 1953).

Although the analogy between the inferred underlying complex and the Kûngnât complex is a useful one there must be a very considerable disparity in size. Any underlying complex must have dimensions at least as great as those of the Nunarssuit centre and be some 30–40 km in radius.

c) Petrogenesis of the central ring-complex syenites.

The rocks comprising the eastern centre of the Tugtutôq ring-complex are not strikingly different from the foregoing acid and sub-acid dykes. In this instance however there is some suggestion that the successive intrusions represent pulses of more and more strongly fractionated magma. The first pulse, yielding the Unit 1 rocks, was of relatively primitive type and cooled to give quartz-free rocks. The magma of the Unit 1a was sufficiently basic for plagioclase to appear as one of the earliest mineral phases although, with continued cooling, the plagioclase was in most cases entirely made over to an alkali feldspar. Among the late crystallising phases of the units 2–3 magma were quartz, riebeckite and fluorite. The magma intruded in the Unit 4 and 5 events was still more silicic and still more volatile rich than the Units 2 and 3 magmas. As a result of the higher water (and HF?) content of this magma the ratio of hydrous to anhydrous ferromagnesian minerals is increased, the pyroxene being very largely replaced by alkali hornblendes or by riebeckite-arfvedsonites and fayalite only being represented by occasional iddingsitic pseudomorphs surrounded by amphibole. The strong exsolution of the feldspars in comparison to the frequent occurrences of cryptoperthitic types in the Unit 2 and 3 rocks as well as the first appearances of microcline twinning in the exsolved potash feldspar also suggests a comparative richness in volatiles acting as fluxes in promoting Na-K and Al-Si ordering. This progression towards more differentiated magmas in the ring-dykes may well be indicative that a further pulse of the undifferentiated (larvikitic) magma which previously had given rise to the mid-Gardar syenite dykes moved up into higher crustal levels at the beginning of the upper Gardar central complex stage and was differentiating by crystal fractionation beneath the Tugtutôq central complex. Ring-fracturing and cauldron subsidence permitted portions of the differentiating underlying magma to ascend in contrast to the previous circumstances where only by crustal fissuring were the high level syenites emplaced. In several respects the Unit 1 syenite differs from all others in the Tugtutôq neighbourhood. The perthitic textures of the feldspars are themselves unusual, contrasting with the strongly antiperthitic textures in the groundmass feldspars of the earlier dykes. The idiomorphic groundmass feldspars of the mid-Gardar microsyenites responsible for the characteristic orthophyric textures of these rocks are not seen in the Unit 1 microsyenites where the feldspars tend to possess curvilinear boundaries with the crystallographic faces very largely suppressed. Whereas the phenocryst-groundmass feldspar pairs from the porphyritic microsyenite dykes had shown, in each case investigated, a simple trend towards the ternary feldspar cotectic line and thence towards the minimum melting composition the relationship of the phenocryst to groundmass feldspar in the Unit 1 rock is different. The bulk composition of the phenocrysts lies practically on the experimentally determined ternary cotectic line and it would be expected that the groundmass feldspar bulk composition also lay on the same line but with a less calcic and more soda-rich composition. In actuality the groundmass feldspar is more potassic and not more sodic than the phenocrysts, the composition plotting well inside the K-rich field of the YODER, STEWART and SMITH ternary diagram for the 5000 bars H_2O isobar (fig. 10). This suggests that some factor other than mere increase of cooling rate accompanied the greatly increased nucleation when the porphyritic magma was intruded and it is likely that the intrusion was accompanied by a large decrease in water vapour pressure and that it was loss of volatiles as much as the chilling against wall rocks that produced the rapid groundmass crystallisation. Possibly the cotectic curve for the ternary feldspars moves closer to the K-feldspar corner of the diagram, reducing the size of the K-rich feldspar field. If this is the case then the relatively K-rich groundmass feldspars of the Unit 1 rock may themselves lie on or close to the cotectic curve appropriate to the lower H_2O pressure conditions obtaining after de-gassing. A further indication that the intrusion of these rocks was accompanied by loss of water is the unusually high proportion of clinopyroxene retained within the groundmass of these rocks. In the preceding swarms of microsyenite dykes, groundmass clinopyroxene is scarce in comparison to the amounts of hydrous ferromagnesian material. In these, intrusion is not thought to have involved any loss of volatiles and, as mentioned above in the discussion of the anomalously high Fe'''/Fe'' ratios of these dyke rocks in comparison to the analogous plutonics, the reverse may in fact have occurred. Certainly the investigation of the feldspars in these dykes has given no grounds for supposing there to have been significant de-gassing. On the basis of the present evidence it is therefore suggested that the Unit 1 intrusions reached the earth's surface and that the central ring-complex may have commenced with some surficial extrusion. Although the subsequent intrusions clearly penetrated the Gardar basalts and sandstones there is no reason to suppose that these too were responsible for any volcanicity. It would appear more likely that they cooled as essentially closed systems. The only contemporary sign of the developing ring-complex may then have been the growth of one of two small trachyte cones in an area of basalt flows and agglomerates.

Differentiation of the various eastern centre intrusions in place was comparatively slight. Some gravity segregation of early olivines and pyroxenes into thin discontinuous layers occurred to a very minor extent in the Unit 3 magma. The larger concentrations of olivine and pyroxene associated with predominantly cryptoperthitic feldspar found within the Unit 2 and 3 syenites in some localities are not seen in any layered association with the more leucocratic varieties and are scarcely explicable in terms of crystal settling and magmatic winnowing. There seem to be three main occurrences of these unusually mafic rocks. In the first place there is a zone several metres wide of the melanocratic syenite separating feldspathic Unit 3 rocks from the country rock granites on the south side of the complex. Well within the Unit 3 rocks is a steeply dipping layer or reef of the fayalite-hedenbergite rock dipping toward the intrusion centre confocally at 60–80°. This "reef" is certainly not a later intrusion of cone sheet type but an integral part of the Unit 3 intrusion. These two instances may be explicable in terms of temporary cessation of feldspar precipitation at times during the steady inward solidification of the Unit 3 syenite so that only pyroxene and fayalite precipitated upon the contemporary cooling wall. The feldspar in these rocks is interstitial, often poikilitic and near the minimum melting point composition. The cessation of crystallisation of the more calcic feldspar which was, in the average rocks, in equilibrium with the early olivine and pyroxene may possibly be connected with a sudden change in vapour pressure. The third main outcrop of the mafic type is in the area distinguished as Unit 2 where it forms much of the matrix around the abundant inclusions of country rocks.

The Unit 4 ring-dyke may also have been slightly porphyritic on intrusion though less markedly so than the Unit 3 magma. Analysis of the rock shows it to be similar to the quartz syenites occurring high in the western lower layered series at Kûngnât, although having a distinctly lower K/Na ratio. However, the correspondence is not as close as that of the Assorutit syenite to a rather lower level in the Kûngnât sequence. The analogy with the Kûngnât sequence is furthered by the occurrence of facies containing riebeckite rather than alkali hornblende, with the presence of astrophyllite and occasionally calcite, as accessory minerals. These rocks show an approach to the riebeckite-astrophyllite residual granites at Kûngnât. Fairly consistently developed around the periphery of the Unit 4 quartz syenite alongside the country rock granites is a zone containing riebeckite, aegirine and sometimes astrophyllite. Microcline cross-hatching is prominently developed in the potash feldspar and late-stage albite in a replacive rôle is widely developed. Although finer grained than the typical Unit 4 rock it is clear that this typically low temperature assemblage does not represent an early chilled selvedge but may have formed from volatile-rich magma that was the latest part of the intrusion to crystallise. Enrichment in volatiles may have come about through diffusion of water and other materials towards the cooler contact zones as the intrusion cooled. However if this had occurred a significant zone of metasomatised country rock would have been expected to occur as an aureole around the intrusion. No such zone has been detected; the metamorphic effects on the country rock granodiorite are slight and restricted to within one metre of the sharp contact with the ring-dyke. The alternative possibility that water diffused inwards from the relatively hydrous country rocks into the cooling syenite may be the correct interpretation.

Analysis of the Unit 5 ring-dyke syenite shows it to have a composition virtually identical to the preceding Unit 4 intrusion. The presence of small amounts of aenigmatite in this rock may be of some significance. ERNST (1962), on the basis of synthetic studies considers that the presence of aenigmatite and sodic pyroxene in a nordmarkite probably indicates a H_2O p. p. of less than 1000 bars.

Just as the main mineralogical differences between the western facies Hviddal syenite and the Assorutit syenite are confined to the late crystallising phases, so also are the distinctions between the quartz syenites of the eastern centre and those at Assorutit. In the eastern centre intrusions the following minerals occur which have not been recorded at Assorutit: a) fluorite, b) aenigmatite, c) astrophyllite, d) aegirine, e) taeniolite (?), f) chevkinite (?) and g) guarinite (?). Conversely the following minerals from Assorutit are rare or absent in the eastern centre ring-dykes: a) calcite b) goethite (?) and limonite.

The perthosite stock, which was emplaced after the crystallisation of the eastern centre ring-dykes, was evidently the product of a residual magma. Since the intrusion consists very largely of feldspar whose composition lies at or close to the ternary feldspar minimum melting composition the question of whether the perthosite represents a crystal cumulate or not is of little importance. In either case, the magma must have had a composition approximating to $Or_{36}Ab_{64}$. Magmas whose composition approximates to impure alkali feldspar are not too uncommon in alkaline provinces. The trachyte flows at Otago N. Z., described by MARSHALL (1906), consist almost wholly of rectangular sanidines with scarce magnetite and aegirine-augite; the quartz-bostonite sill described by JENSEN from the Nandewar Mts., N.S.W. (1907), contains some 99 $^0/_0$ alkali feldspar with minute amounts of aegirine-augite, haematite, riebeckite and quartz. Plutonic analogues, directly comparable to the Blå Månesø stock, have recently been described from the Nyasaland Chilwa series. These include the Chikala Hill perthosite (STILLMAN and COX, 1960), composed of tabular crystals of cryptoperthite (grading to subordinate antiperthite) and small amounts of aegirine-augite, biotite, hornblende and ore, and the Chaone Hill perthosite consisting mostly of antiperthite (VAIL and MONKMAN, 1960). As with some of the other rock types the Blå Månesø perthosite finds close analogy with one of the facies of the Kûngnât syenites. The upper layered series of the Kûngnât western intrusion grades upwards into variably textured leucocratic syenites consisting predominantly of alkali feldspar. The lamination of the feldspar tablets is lost sight of in the highest preserved rocks where coarser and pegmatitic facies become increasingly important. From the textural variability of these rocks it was tentatively concluded that they crystallised close to the roof of the intrusion. Similarly the Blå Månesø perthosite may represent the uppermost levels of a differentiated syenite body although it is more likely that the feldspathic magma was generated at depth by strong crystal fractionation and then intruded to its present level where it crystallised with very little further differentiation.

VIII. ACID FRACTIONATION TRENDS IN TUGTUTÔQ AND KÛNGNÂT INTRUSIVES

The seven analyses of Tugtutôq quartz syenites, microsyenites and quartz porphyry can be approximately expressed in terms of the system Or-Ab-SiO_2 and have been plotted on the Or-Ab-SiO_2 triangle (fig. 11). These analyses may be utilised as approximations to magmatic compositions, bearing in mind that for those rocks, such as the Assorutit syenite, where some degree of feldspar accumulation is suspected the points will fall too close to the Or-Ab side-line and in other cases, such as the porphyritic dyke rocks, some degree of feldspar depletion through crystal settling may give a bulk composition plotting too far from the feldspar sideline. It would appear that fractionation of the Tugtutôq acid magmas (as opposed to the undersaturated Hviddal suite leading to foyaite) took place primarily through the agency of gravitational removal of feldspar, the residuals becoming increasingly silicic until the two phase boundary was reached when quartz precipitated alongside feldspar. Similar fractionation has been described in some detail for the Beverly and Cape Ann granites and syenites by Toulmin (1960). The disposition of the analyses in the triangle suggests that strong fractionation caused the residual liquids to change composition along a "thermal valley" close to that determined by Tuttle and Bowen (1954) for the synthetic system Or-Ab-SiO_2-H_2O at 1000 kg/cm^2. These authors consider there is little change in the position of the "thermal valley" between water-vapour pressures of 1000 and 3500 kg/cm^2. It is unlikely that crystallisation of the magmas in either the high level intrusions, such as at Assorutit or the central complex, or in the larger underlying magma chamber(s) proceeded under isobaric conditions. With the possible exception of the Unit 1 intrusions crystallisation probably occurred in virtually closed systems, largely within basement granites and beneath a thick cover of plateau basalts, with water vapour pressure increasing with advancing fractionation. (Although equilibrium conditions certainly did not hold, there can only have been an approach to ideal fractionation conditions).

For comparison, four analyses of rocks from Kûngnât believed to lie close to the line of liquid descent have also been plotted. Strong fractionation in this instance directed the liquid compositions from a larvikitic stage (corresponding to point 4, an analysis of a basic syenite from the eastern Kûngnât border group), through a quartz syenite stage (3, an analysis of unlaminated nordmarkite from the western lower layered series), to a granitic magma (2, analysis of late-stage riebeckite

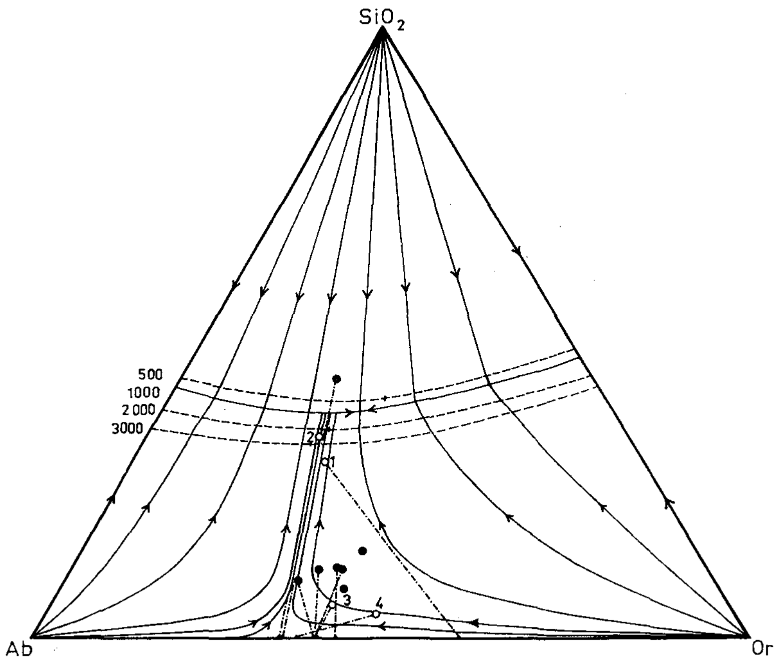


Fig. 11. Isobaric fractionation curves for system Or-Ab-SiO_2-H_2O at 1000 kg/cm² H_2O v. p. and also two-phase boundaries and ternary minimum points in the system, at pressures of 500, 1000, 2000 and 3000 kg/cm² (from TUTTLE and BOWEN, 1954). Open circles, analyses of Kûngnât rocks. Solid circles, analyses of rocks from Tugtutôq. Tie lines indicate compositions of average feldspar for the coarse grained rocks and feldspar phenocrysts from the porphyritic dyke rocks.

astrophyllite granite). The riebeckite granite lies close to the ternary minimum corresponding to a vapour pressure of ca. 2500 kg/cm². Still later (grorudite) residues (1, analysis of a grorudite, "grey-dyke", western Kûngnât) plot closer to the Or-Ab side-line, probably also approximating to a ternary minimum but for a water-vapour pressure well in excess of 3500 kg/cm². The Tugtutôq comendite, 50187, plots in line with the "thermal trough" and the Kûngnât riebeckite granite but at a considerably more silicic composition. It may be reasonably suspected that this porphyritic rock has either been relatively depleted in feldspar phenocrysts through settling or else enriched in quartz phenocrysts.

The liquid composition was probably extremely similar to that of the Kûngnât riebeckite granite magma, falling like the latter at the ternary minimum point corresponding to a vapour pressure of around 3500 kg/cm^2. In spite of the difficulties in correlating data from the natural rocks with those of synthetic systems it appears clear that in the generation of the late comendite and grorudite residuals in these south Greenland occurrences there is no substantial departure from the experimentally determined "thermal valley" and ternary minimum compositions in the striking manner shown by the pantelleritic residuals as demonstrated by CARMICHAEL (1962).

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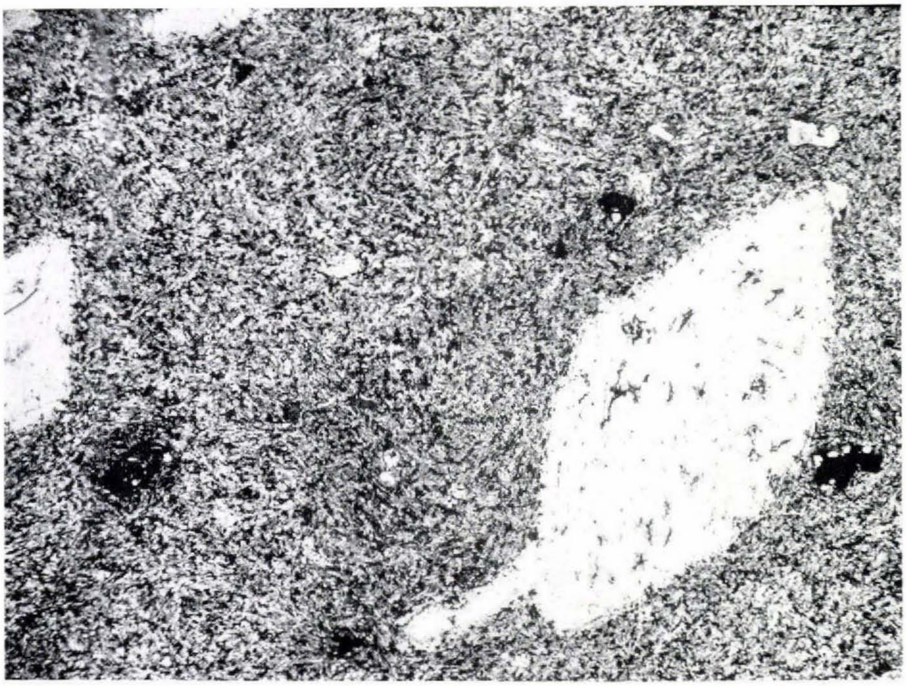
Færdig fra trykkeriet den 18. juni 1964.

PLATES

Plate I.

Fig. 1. Photomicrograph of a 'rhomb-porphyry' microsyenite dyke rock. Specimen 50226. Plane polarised light. x 10.

Fig. 2. Photomicrograph of a porphyritic microsyenite dyke rock. Specimen 40570. Plane polarised light. x 10.



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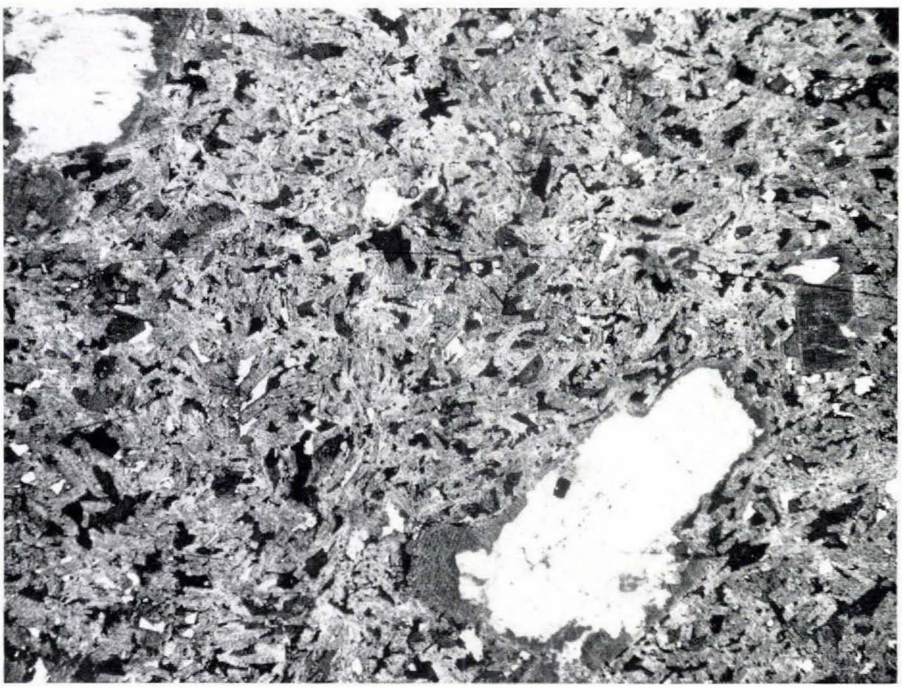
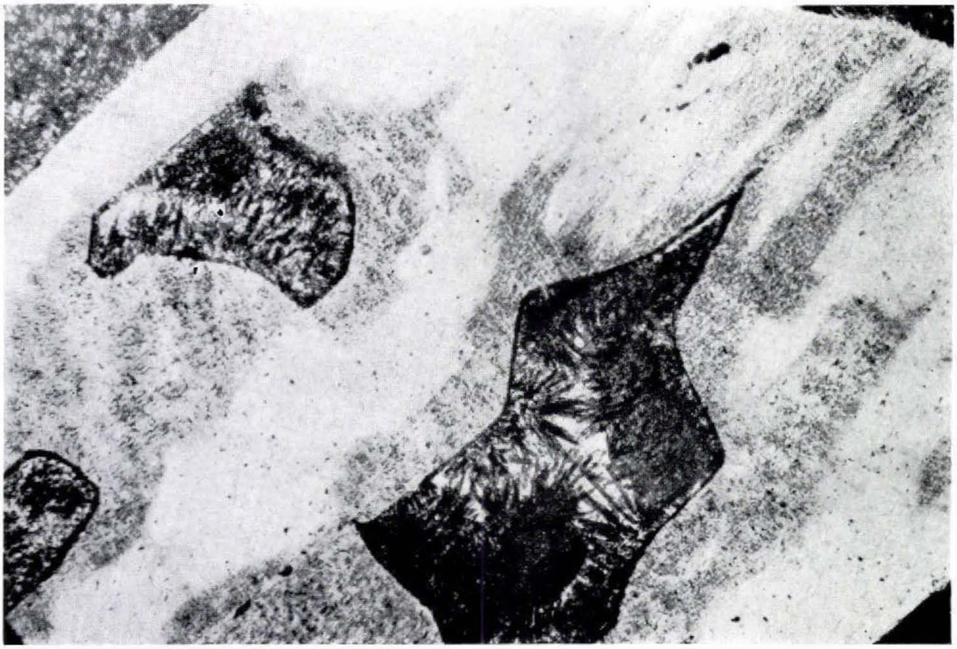


Fig. 2.

Plate II.

Fig. 1. Photomicrograph of cavities within a feldspar phenocryst from a fine grained acid dyke rock. Cavities contain needles of riebeckite. Specimen 30645. Plane polarised light. x 150.

Fig. 2. Photomicrograph of banded texture in a spherulitic comendite dyke rock. Partially resorbed quartz and feldspar phenocrysts are seen. Specimen 30685. Plane polarised light. x 10.



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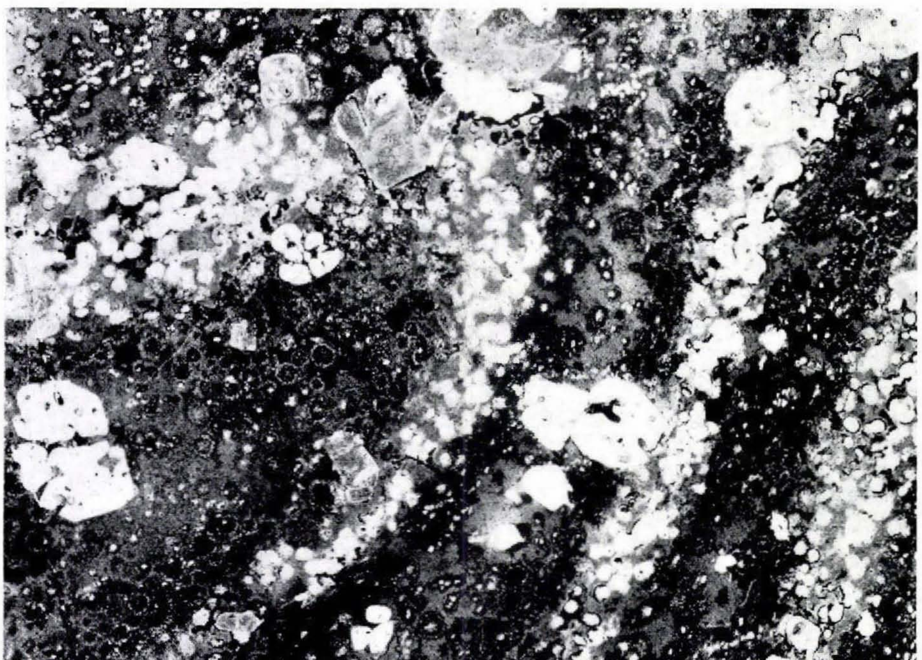
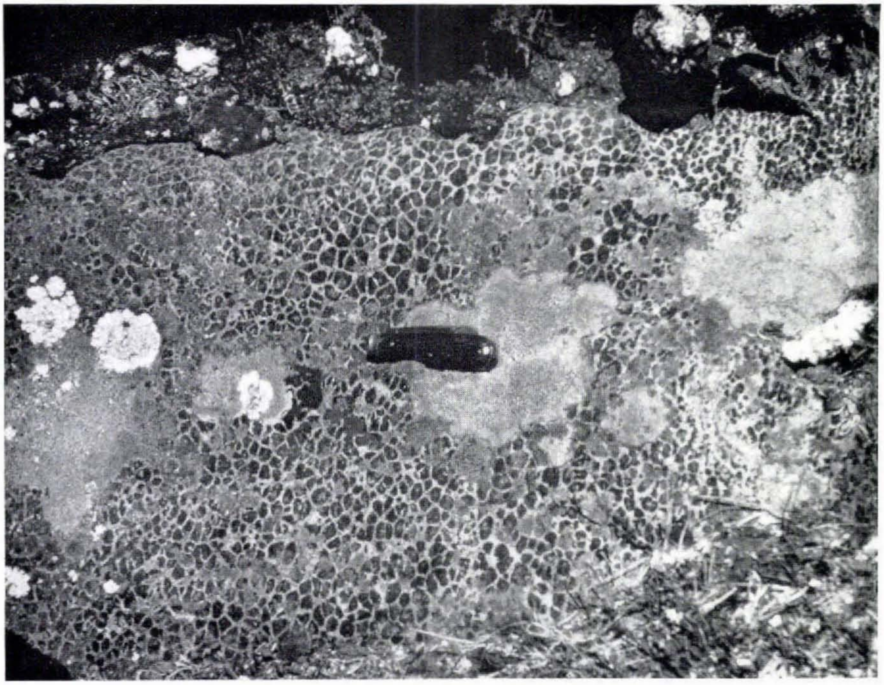


Fig. 2.

Plate III.

Fig. 1. Photograph of a devitrified comendite dyke cutting gabbros near Narssaq, showing polygonal 'spherules' composed largely of riebeckite. Exposure partially obscured by lichens.

Fig. 2. Photomicrograph of the rock type illustrated in fig. 1 above, showing 'fronds' of riebeckite and a partly resorbed quartz phenocryst. Specimen 30758. Plane polarised light. x 10.



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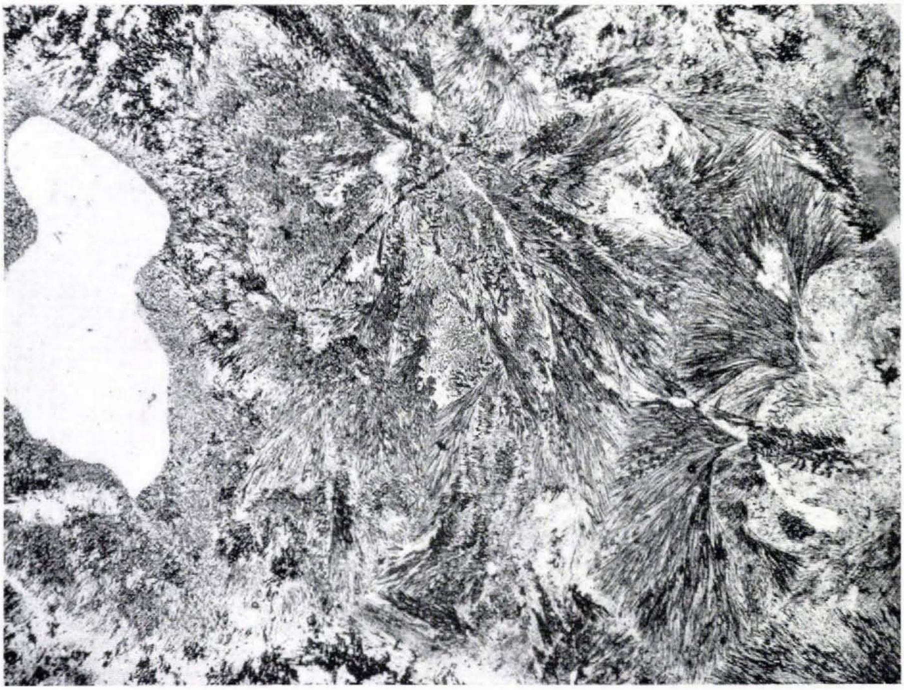
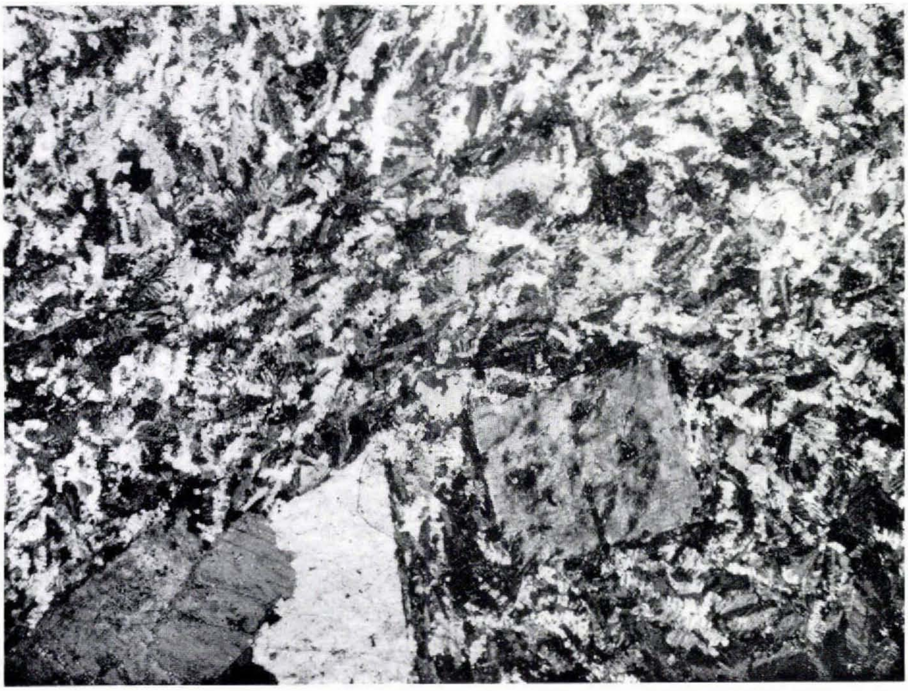


Fig. 2.

Plate IV.

Fig. 1. Photomicrograph of porphyritic microsyenite of the Unit 1 intrusion in the central complex. Specimen 50345. Plane polarised light. x 10.

Fig. 2. Photomicrograph of typical Unit la syenite from the central complex. The irregular form of the feldspars is characteristic. Note perthite texture is often better developed close to crystal margins. Specimen 30720. Plane polarised light. x 20.



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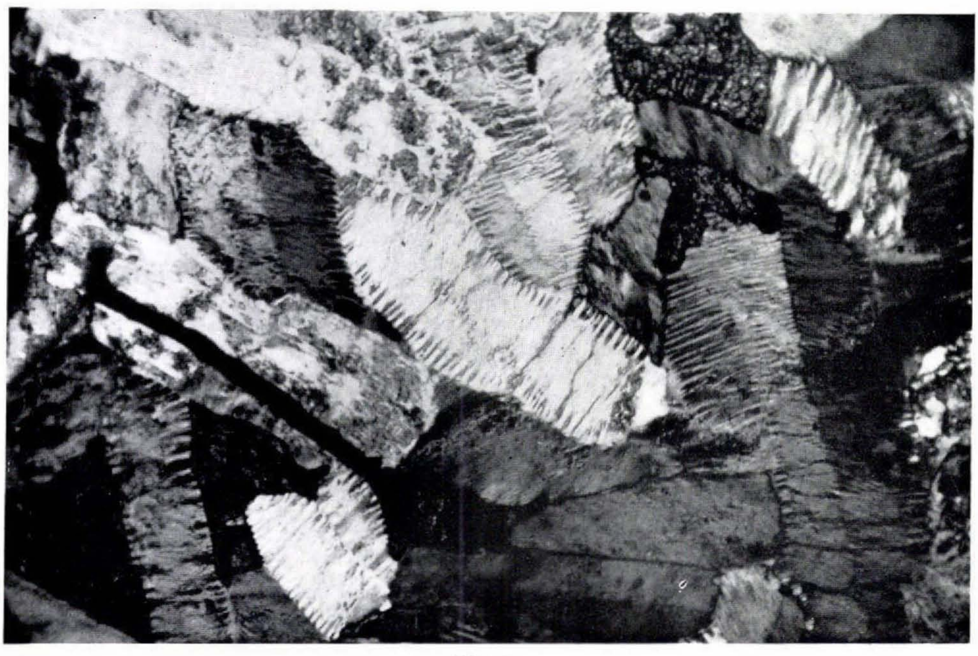

Fig. 2.

Plate V.

Fig. 1. Photomicrograph of mafic syenite from the Unit 2 intrusion of the central complex. The rock consists essentially of ferrohedenbergite (zoned), fayalite, (much altered to magnetite) and alkali feldspar. Specimen 50282. Plane polarised light. x 15.

Fig. 2. Photomicrograph of quartz syenite from the Unit 5 ring dyke. Specimen 40591. Polarised light, crossed nicols. x 15.

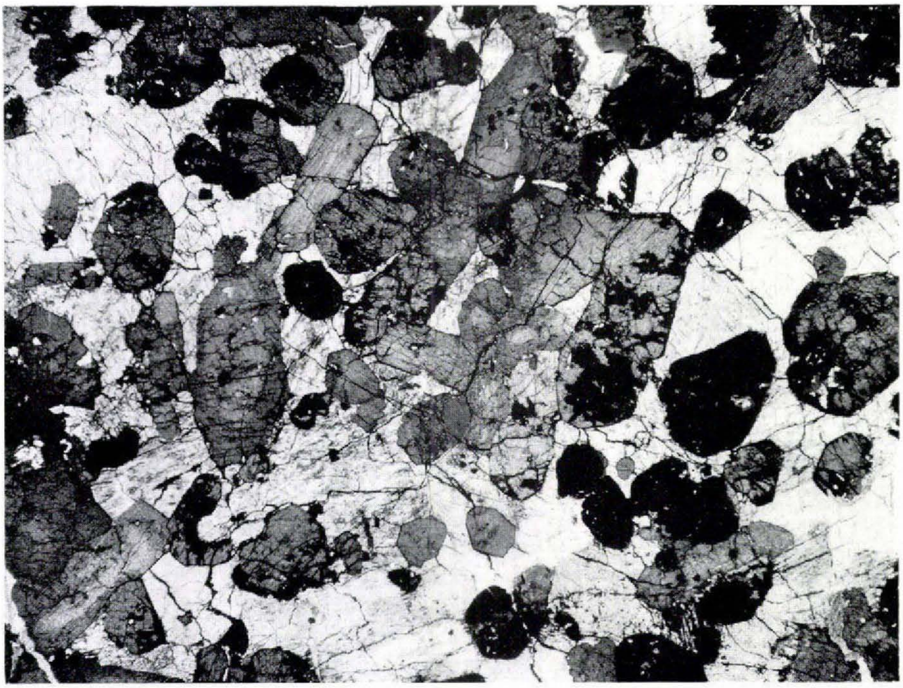

Fig. 1.

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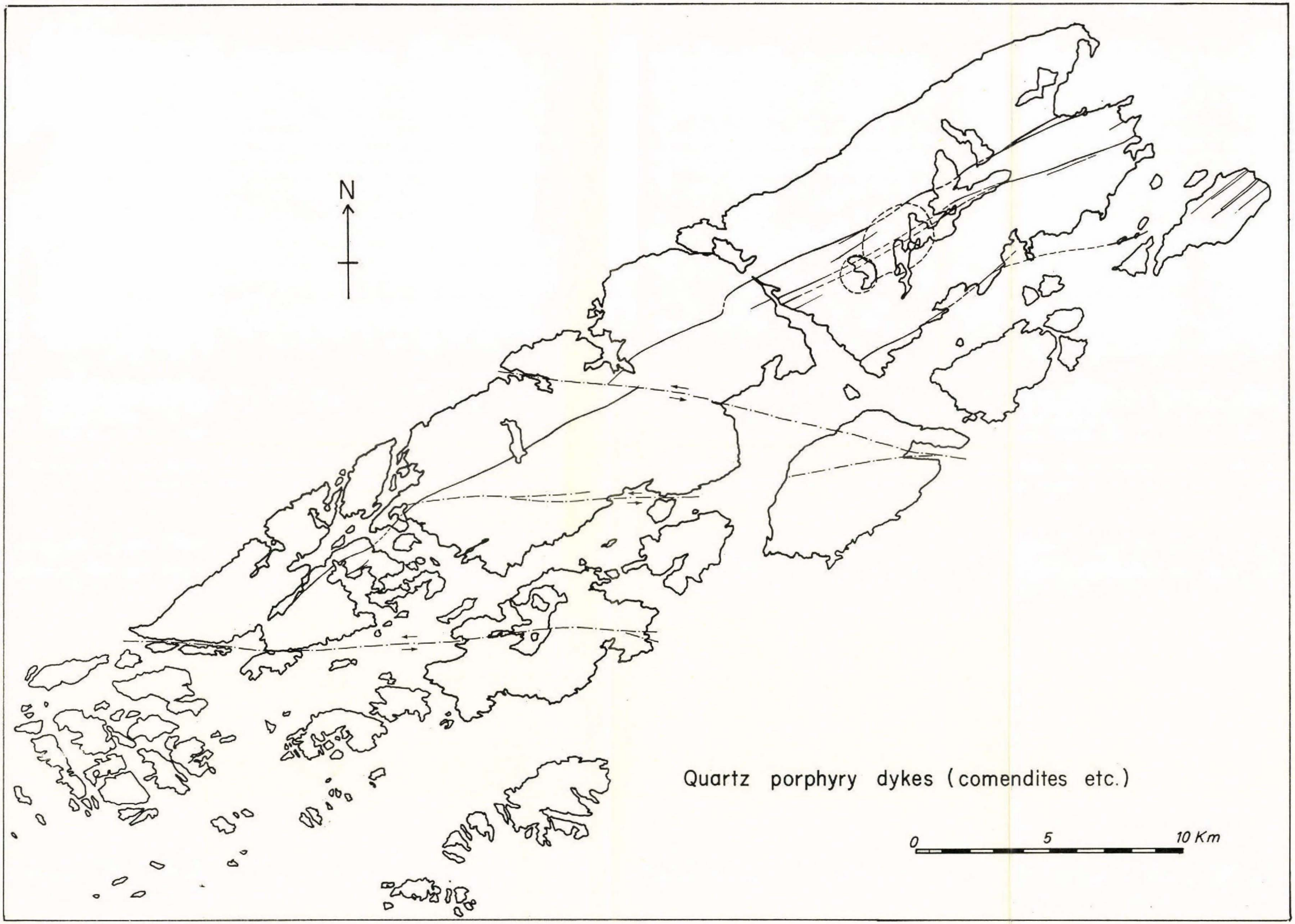
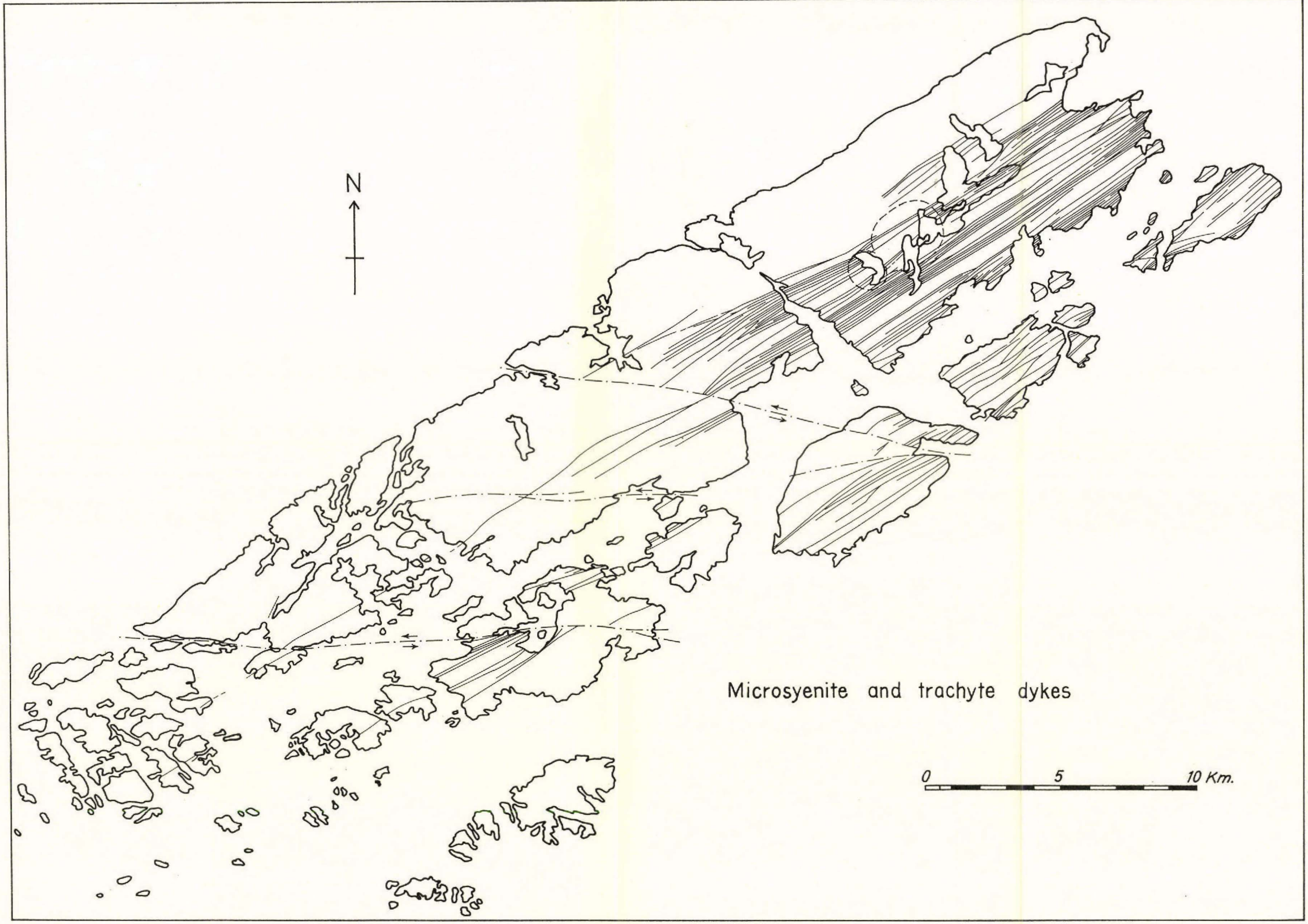


Quartz porphyry dykes (comendites etc.)


N
Microsyenite and trachyte dykes
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GEOLOGICAL MAP OF THE
CENTRAL TUGTUTÔQ RING-COMPLEX

(Blå Månesø) perthosite	Unit 6	Central Complex	Gardar
Quartz microsyenite	Unit 5	Central Complex	Gardar
Quartz syenite	Unit 4	Central Complex	Gardar
Porphyritic quartz syenite	Unit 3	Central Complex	Gardar
Quartz syenite	Unit 2	Central Complex	Gardar
Syenite	Unit 1 a	Central Complex	Gardar
Microsyenite (breccia)	Unit 1	Central Complex	Gardar
Olivine gabbro			Gardar
Nepheline syenite			Gardar
Syeno - gabbro			Gardar
Basalt inclusions			Gardar
Quartzite inclusions			Gardar
Leucocratic granodiorite			Pre - Gardar
Older granodiorite complex			Pre - Gardar
Dykes and sills			Mostly mid - Gardar

—— Established contacts

- - - - Inferred ”

········ Extrapolated ”

—·— Crush - lines

Contours at 50 m. intervals