GRØNLANDS GEOLOGISKE UNDERSØGELSE
BULLETIN No. 48

THE GEOLOGY OF TUGTUTÔQ AND NEIGHBOURING ISLANDS, SOUTH GREENLAND

PART III

OLIVINE GABBROS, SYENO-GABBROS AND ANORTHOSITES

AND

PART IV

THE NEPHELINE SYENITES OF THE HVIDDAL COMPOSITE DYKE

BY

B. G. J. UPTON

WITH 22 FIGURES IN THE TEXT
AND 8 PLATES

Reprinted from
Meddelelser om Grønland, Bd. 169, Nr. 3

KØBENHAVN
BIANCO LUNOS BOGTRYKKERI A/S
1964

ERRATA

MEDDELELSER OM GRØNLAND BD. 169, NR. 3. B. G. J. UPTON.

Correction to page 60:

Table 2. C. I. P. W. Norms.

	30743	30714	50241	30640	30681	30676
Or	29.9	30.9	34.4	35.8	32.7	32.6
Ab	43.2	38.7	43.8	42.1	36.2	25.2
An	2.6	3.3	4.4	—	2.6	—
Ne	3.8	6.6	3.3	5.9	16.7	26.3
Ac	—	—	—	—	—	11.2
Ns	—	—	—	—	—	.5
Wo........	—	—	—	4.3	1.6	.7
Di	7.4	9.4	5.8	.8	1.3	3.0
Ol.........	7.7	5.4	2.2	5.0	—	—
Mt	2.6	2.3	4.4	4.7	5.5	—
Il	2.1	2.4	1.4	1.1	.8	.2
Hm	—	—	—	—	2.3	—
Ap	.7	1.0	.3	.3	.3	.3
Feldspar	$Or_{39\cdot5}Ab_{57}An_{3\cdot5}$	$Or_{42\cdot5}Ab_{53}An_{4\cdot5}$	$Or_{41\cdot5}Ab_{53}An_{5\cdot5}$	$Or_{46}Ab_{54}An_{0}$	$Or_{46}Ab_{50\cdot5}An_{3\cdot5}$	$Or_{56\cdot5}Ab_{43\cdot5}An_{0}$
Cpx	$Wo_{50}En_{9\cdot5}Fs_{40\cdot5}$	$Wo_{48}En_{8}Fs_{44}$	$Wo_{48}En_{10}Fs_{42}$	$Wo_{44}En_{5}Fs_{51}$	$Wo_{54}En_{46}Fs_{0}$	$Wo_{47}En_{3\cdot5}Fs_{49\cdot5}$
Olivine	$Fo_{18\cdot5}Fa_{81\cdot5}$	$Fo_{15}Fa_{85}$	$Fo_{18}Fa_{82}$	$Fo_{8\cdot5}Fa_{91\cdot5}$	—	—

These changes involve a correction to page 77, where '$Or_{54\cdot5}Ab_{45\cdot5}An_0$' should become '$Or_{56\cdot5}Ab_{43\cdot5}An_0$'.

Furthermore on page 57, line 3, (table 6) should read (table 5).

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Abstract.

Large Precambrian (Gardar) ENE-WSW dykes traverse the Tugtutôq region and can be traced for some 50 km. Thicknesses of up to 800 m in the ENE diminish rapidly towards the WSW. The earliest of the large dykes is composite with intrusion of syeno-gabbro followed by median intrusion of nepheline syenite. The syeno-gabbro has feldspar zoned from ca. An_{57} to $Or_{21\cdot5}Ab_{65}An_{13\cdot5}$, with olivines ranging from Fa_{54-64}, augitic pyroxene, biotite, ore and apatite. Subsequent intrusion of high aluminous alkali basalt magma produced massive dykes of troctolitic gabbro in the granitic basement complex, a large sill-like body along the unconformity separating the granitic rocks from the Gardar series of sediments and volcanics, and smaller sills within the Gardar series. The gabbro dykes have synformal internal structures defined by mineral banding and feldspar lamination developed at irregular intervals along their length as does also the large overlying sill. The gabbro intrusion as a whole is regarded as a layered body displaying limited cryptic and phase layering. The gabbroic rocks are orthocumulate sequences formed by bottom accumulation of crystals in a period of tectonic instability. As a result of tilting towards the ENE, lower level rocks are exposed towards the WSW of the intrusion where the cumulus phases were feldspar ca. An_{72} and olivine Fa_{35-40}. Interstitial pyroxene is a titanaugite, $Ca_{45\cdot5}Mg_{37\cdot5}Fe_{17}$. In the higher rocks towards the ENE the cumulus feldspar (An_{65}) and olivine are joined by cumulus ilmenomagnetite and fluorapatite. In one sector a gabbro dyke is composite with median intrusion of syeno-gabbro followed by quartz syenite. This syeno-gabbro has feldspar zoned from $Or_4Ab_{62}An_{34}$ to $Or_8Ab_{73}An_{19}$, with early clinopyroxene ($Ca_{44\cdot5}Mg_{36}Fe_{19\cdot5} \rightarrow Ca_{44\cdot5}Mg_{32\cdot5}Fe_{23}$), olivine, ($Fa_{72}$), biotite, ore and fluorapatite. Four rock analyses and three pyroxene analyses are presented for the gabbros and syeno-gabbros. Inclusions of labradoritite and gabbroic anorthosite, considered to be samples from a large anorthositic body at depth, are brought up by the large dykes and also by a later swarm of hybridised dolerite dykes. The inclusions range from layered labradorite-orthocumulates ((with An_{67}) and interstitial olivine (Fa_{33}) and augite) to cataclastic varieties with no fresh ferromagnesian minerals. A late Gardar swarm of ENE dykes and associated sills of camptonitic dolerite is believed to be genetically related to the earlier syeno-gabbros and gabbros.

PREFACE

The field work on the Tugtutôq area was conducted in the summer field seasons of 1957, 1958 and 1960 as part of the mapping of the Julianehåb area undertaken by the Geological Survey of Greenland. Most of the laboratory studies were carried out at the Mineralogical Museum in Copenhagen and, subsequently, at the Division of Geological Sciences of the California Institute of Technology.

The author wishes to express his thanks to Mr. R. Solli (Oslo), Miss E. Godijn (Caltech.) and Dr. E. L. P. Mercy (Edinburgh) for the chemical analyses. A Penrose Bequest Grant from the Geological Society of America, from which the cost of one of the analyses was defrayed, is gratefully acknowledged. The author is grateful to Dr. W. J. Wadsworth for his critical reading of the manuscript.

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February, 1963.

INTRODUCTION

This paper deals with the petrology of the various basic rock-types, varying from olivine dolerite and gabbro to anorthosite and syeno-gabbro, which occur within the ENE dyke swarms of the Tugtutôq-Skovfjord area in South Greenland. These dykes are among the numerous intrusions of Precambrian age erupted during the Gardar igneous cycle in this relatively small part of the South Greenland igneous province. An outline of the field relationships and chronologic sequence of these has already been presented (UPTON, 1962). Of the original thick sequence of early Gardar basalts that overlay the migmatitic and granitic basement in this area (*vide* USSING, 1912) only fragments remain in some of the mid-Gardar vents and late ring-dykes of syenite, and no further account of these will be given in this publication. Several unusually large dykes constitute early members of the ENE Gardar swarms and, of these, the earliest is a composite dyke several hundred metres broad consisting of a wide central zone of nepheline syenite contained within relatively narrow marginal strips of syeno-gabbro (previously simply referred to as gabbro). The dyke was intruded in two stages with the highly alkaline magma injected along the uncongealed centre of the cooling syeno-gabbro dyke. Following the crystallisation of this composite dyke a suite of olivine dolerite and olivine gabbro dykes, closely related to the earlier syeno-gabbro but distinctly more basic, were intruded. Traced towards the ENE these dykes broaden and coalesce as they approach the later Narssaq and Ilímaussaq alkaline intrusive complexes and, at the eastern end of Tugtutôq island, one of the gabbro dykes is found to be composite over a short distance. Along one sector the centre is occupied by syeno-gabbro and in another by quartz syenite. A swarm of smaller basic dykes associated with syenitic dykes and largely contaminated by alkaline material succeeded this major intrusive episode. All of these early basic intrusions, especially those of the last mentioned swarm, contain inclusions of a coarse grained labradorite anorthosite. For most of the remainder of the Gardar period the intrusions in the Tugtutôq-Skovfjord and Narssaq areas were predominantly of quartz syenites and alkaline granites although, in the closing stages of activity, a minor swarm of andesine- and oligoclase-dolerite dykes grading to camptonite were intruded along the regional trend.

A fairly detailed account is presented of the earlier olivine gabbro and syeno-gabbros and of the anorthosite inclusions together with briefer descriptions of the smaller mid-Gardar basic dykes and the culminating "lamprophyric" intrusions.

Syeno-gabbroic rocks of the Hviddal composite dyke.

A large dyke, some 500–600 m across, traverses the granodioritic rocks of Tugtutôq, extending in an east-north-easterly direction for approximately 25 km. The dyke is composite consisting mainly of nepheline syenites (UPTON, 1964) but having margins of syeno-gabbroic material. The syeno-gabbro appears to be present in symmetrical marginal strips 50–100 m wide along most of the dyke although it is apparently absent over a short stretch to the east of the later cross-cutting syenite ring-complex.

The Hviddal syeno-gabbro is an even-grained, hypidiomorphic-granular, sometimes sub-ophitic, rock composed of plagioclase and alkali feldspar, olivine, ore, clinopyroxene, biotite and apatite, the grain size not exceeding 4 mm. The rock is generally massive although occasional weakly developed melanocratic banding is present dipping inwards from the dyke walls towards the nepheline syenites, suggesting that very locally the original dyke possessed a slight synformally layered structure analogous to those much better developed in the succeeding olivine gabbros.

Feldspar is the principal component, invariably showing vigorous zoning. The crystal cores are slender laths of normal zoned plagioclase and in these, the most calcic centres recorded are of An_{57} although in several specimens An_{46} represented the most extreme composition. The outermost plagioclase zones are ca. An_{32}. Carlsbad twinning is common, pericline twins being more unusual. In the albite twinning one set of the twin lamellae are normally less than one quarter the width of those of the other set. Around these polysynthetically twinned cores are broad zones of clear untwinned feldspar. In these a fine-scale perthitic texture oriented perpendicular to (010) is often discernible. In one instance this microperthitic zone showing the forms (010) and (110) was itself surrounded by a further zone of clear untwinned feldspar in which no exsolution textures were detectable under the microscope (Fig. 1). The earliest feldspar to crystallise within the dyke was a sodic labradorite although it is possible that along much of the dyke the earliest phase was not more calcic than An_{50}. The zonal arrangement reflects a regular compositional change outwards with increase of sodium and in the outer zones, of potassium content. Microscopically visible twin-lamellae failed to develop beyond a composition of ca. An_{32} and it is likely that the outermost zones crystallised as monoclinic feldspar. Exsolution phenomena are confined to the more calcic zones of the alkali feldspar with the outermost zones of fairly pure K-Na cryptoperthite lacking ostensible unmixing. IWAO (1939) described similarly zoned feldspar from trachydolerites on Sakhalin where the lamellar twinning is confined to the zoned plagioclase laths which are surrounded by anorthoclase in optical continuity with the core and also, from monzonitic rocks where andesine grades out through oligoclase into a mantle of anorthoclase and microperthite. The bulk feldspar was separated from specimen 30684 and was arbitrarily divided into four

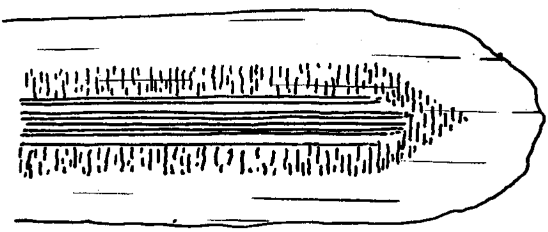

Fig. 1. Sketch of a zoned feldspar in Hviddal syeno-gabbro displaying core of lamellar twinned plagioclase, intermediate zone of microperthitic feldspar and outer zone of optically homogeneous, untwinned material.

portions of differing density by means of tetrabromoethane. The lightest of these (very approximately 5–6 % of the total) had a composition of ca. $Or_{21 \cdot 5}Ab_{65}An_{13 \cdot 5}$ the second portion $Or_{17}Ab_{68}An_{15}$, the third $Or_{14 \cdot 5}Ab_{68}An_{17 \cdot 5}$ and the densest portion, some 30 % of the total, was $Or_{8 \cdot 5}Ab_{64}An_{27 \cdot 5}$.* Probably the outermost two thirds of the crystals precipitated as lime-rich anorthoclase, the centre being zoned from labradorite or andesine through potassic oligoclase. Very occasionally small interstitial areas of turbid 'gieseckite'-like material appear between the feldspar grains which may have been formed at the expense of nepheline. Nepheline, however, does not appear in the norm of the one analysed sample.

2V and X-ray diffraction measurements on olivines from these rocks indicate compositions within the range Fa_{54}-Fa_{64} although zoning was not noticed in individual crystals. The olivines are sub-idiomorphic to anhedral. Alteration to magnetite, especially along grain boundaries and cracks is common and frequently coronae of serpentinous material surround the crystals. The coronae often consist of a pale-green microcrystalline mineral surrounded by a narrow outer zone composed of radiating crystals of antigorite. The pyroxene is pale pinkish brown in

* Na, K determinations by flame-photometer; Ca by X-ray fluorescence.

Table 1. Analysis of specimen 30684 from the northern side of the Hviddal composite dyke towards its eastern extremity, together with some comparisons.

	30684	1	2	3	4	5	6
SiO_2	41.15	45.78	47.30	44.41	44.81	45.81	45.76
Al_2O_3	13.52	14.29	9.49	10.77	13.96	12.90	15.23
Fe_2O_3	5.03	2.74	5.54	5.51	3.75	4.36	3.72
FeO	13.13	13.35	14.96	13.14	16.66	10.31	10.00
MgO	4.12	4.41	3.28	5.37	5.44	5.75	5.07
CaO	7.34	8.74	7.60	9.98	8.53	7.52	7.47
Na_2O	3.53	3.08	3.28	2.60	3.35	3.36	3.13
K_2O	1.68	1.66	2.69	1.08	0.33	1.70	1.87
H_2O^+	1.03	0.37	1.50	0.75	0.34	1.91	3.07
H_2O^-	0.23	0.08	—	—	0.19	0.88	0.02
TiO_2	4.71	3.24	3.20	5.30	2.55	4.03	4.14
MnO	0.25	0.27	0.29	0.25	0.17	0.20	0.24
P_2O_5	3.13	2.22	1.44	0.76	0.08	1.11	0.42
	98.85*	100.23	100.57	99.92	100.16	99.84	100.14

30684 Specimen from northern side of the Hviddal composite dyke towards its eastern extremity. Analyst, E. GODIJN.
1 Ferrogabbro, Okonjeje (specimen 106), SIMPSON, 1954.
2 Halleförs dolerite, KROKSTRÖM, 1936.
3 Halleförs dolerite, KROKSTRÖM, 1936.
4 Hortonolite ferrogabbro, Skaergaard (Specimen 1907), E. Greenland. WAGER & DEER, 1939.
5 Andesine-phyric andesine basalt (Specimen 2225), E. Greenland. ANWAR, 1955.
6 Oligoclase dolerite, from dyke nr. Skaergaard (Specimen 2567), E. Greenland. VINCENT 1952.
* the low summation probably due to F, not determined, and possible loss of silica as fluoride.

Mode of 30684

Feldspar	56.6 %
Olivine	13.4
Pyroxene	6.2
Biotite	7.7
Ore	9.4
Apatite	6.7

C. I. P. W. Norm of 30684

Or	10.3
Ab	30.5
An	16.3
Di	1.6
Hy	2.3
Ol	15.0
Mt	7.3
Il	9.2
Ap	7.5

Feldspar	$Or_{18}Ab_{53}An_{29}$
Cpx	$Wo_{50}En_{25}Fs_{25}$
Opx	$En_{43\cdot5}Fs_{56\cdot5}$
Olivine	$Fo_{43}Fa_{57}$

colour, non-pleochroic and possessing a faint patchy zonation with a 2V range varying from 49.5–53°. The crystals are sub-ophitic and anhedral. Ilmenomagnetite is an important constituent, commonly occurring in elongate crystals 1–2 mm long. These usually possess reaction rims of strongly pleochroic lepidomelane (light straw yellow to deep mahogany red). However the biotite often grades out into a light greenish chlorite. Apatite occurs up to several percent of the rock as euhedral, slightly barrel-shaped crystals up to 2 mm long by 1 mm broad. Analysis by emmission spectroscopy shows these to be fluorapatites.

Olivine gabbro and olivine dolerite dykes.

Broad gabbroic dykes, often several hundred metres wide, intruded along the ENE direction succeeded the early composite dyke of nepheline syenite and syeno-gabbro. The dyke-like form characterised the intrusions within the granitic basement but probably a sill-like form was more typical for the gabbro at higher levels, especially above the basal Gardar unconformity. The gabbros are composed very largely of plagioclase and olivine. The plagioclase alone commonly accounts for 50–70 % of the rocks. The bulk of the plagioclase falls within the labradorite range, the accompanying olivines being hyalosiderites. Towards Narssaq ilmenomagnetite becomes an essential component of some of the gabbro bodies. Other, more subordinate phases, are titanaugite and biotite together with smaller quantities of apatite, alkali feldspar and sulphides. In those facies particularly deficient in pyroxene the rocks grade towards troctolite. By analogy with the gabbroic rocks of the Oslo region, Ussing (1912) described the Narssaq occurrences as essexite whereas Wegmann (1938) preferred the term essexite-gabbro for these same rocks.

In some of the banded localities encountered along the dykes the melanocratic facies could be adequately described by the terms picrite and cumberlandite. For the most olivine-rich rocks containing up to 70 % of this mineral the term picrite would be preferable to peridotite, this being in accordance with the general usage of the name picrite to cover olivine-rich rocks related to alkalic gabbros and dolerites. The name cumberlandite, which was proposed for the rocks at Iron-Mine Hill, Rhode Island containing nearly 50 % olivine (Fa_{36}), 31 % ore minerals and 14 % labradorite (Johnson and Warren, 1908), would embrace some of the melanocratic facies but must exclude those with low ore content. Nevertheless since the rocks in this intrusion are, in large part, accumulitic with their modal content dictated by various fortuitous factors, there is little advantage in employing specific names to describe the entirely gradational rock types and it is more convenient to follow the nomen-

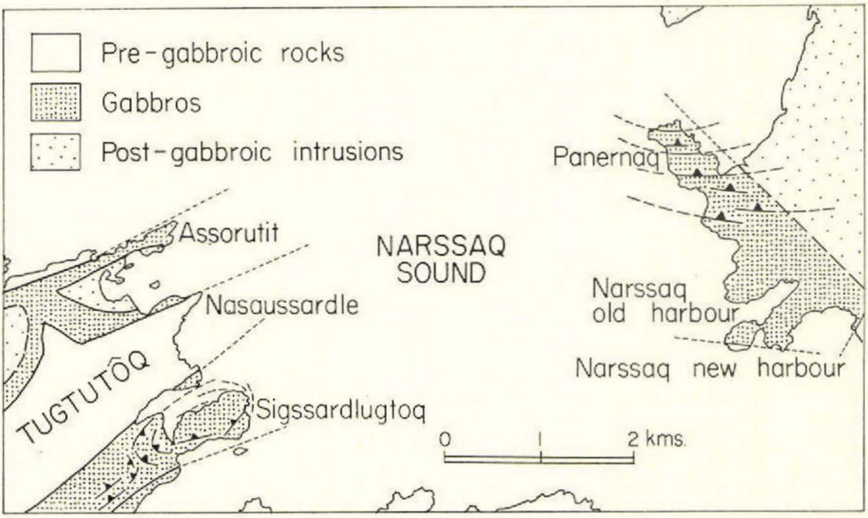

Fig. 2. Sketch map showing the distribution of olivine gabbros in the vicinity of Narssaq and eastern Tugtutôq.

clatural system for accumulitic rocks advocated by Wager, Brown and Wadsworth (1960), i.e. using the term cumulate preceded by a list of the main cumulus minerals in order of their abundance. Accordingly much of the gabbro can be described as plagioclase-olivine-ore-cumulate, the picritic facies as olivine cumulate, the cumberlandite as olivine-ore-plagioclase cumulate and the anorthosites which are found as inclusions in the gabbro, as plagioclase cumulates.

The gabbro dykes normally display chilled margins against the older granitic rocks. Although the grain size of much of the rock diminishes rapidly towards the contacts, the marginal facies are normally characterised by the irregular development of veins and patches of gabbro pegmatite. Uncontaminated, homogeneous chilled specimens are not easily obtainable and it is general to find that the basic rock has been metasomatised in the vicinity of the older granites with widespread development of biotite and alkali feldspar. Metamorphism of the country rocks has been extremely slight, confined to within one metre or so from the intrusion. Granophyric development in the granodiorites close to the contacts suggests some degree of remelting and it is probable that the contamination of the marginal gabbros has occurred through the agency of alkaline solutions liberated from the heated granitic rocks, passing into the relatively anhydrous basic dykes. Even in the smaller gabbroic and doleritic dykes marginal contamination seems to have been the rule rather than the exception. Chilled margins are sometimes seen to be virtually aphyric. In other places (cf. fig. 3), glomerophenocrysts of plagioclase are scattered through the rock. The analysed gabbro, 40452, is judged to be uncontaminated but its picritic nature makes it unlikely that the analysis is close to the composition of the intruded magma.

Primary structures within the gabbro dyke system.

In the mainland outcrop of the gabbros on the coastal region around Narssaq and Panernaq a sharp and approximately vertical contact is seen against the pre-Gardar granodiorites on the island guarding the entrance to the old harbour. The gabbros close to the contact are chilled and fine grained but possess pegmatitic segregations. An intrusive contact of very different character is seen about one kilometre to the east where the gabbro is overlain at a low angle by basal Gardar quartzites and chilling is not at all so evident. To the east the gabbros are interrupted by younger Gardar syenites (Ussing, 1912, p. 99). Small intrusions of biotite-pyroxenite, dolerite, quartz microsyenite, comendite and microgranite, are seen within the gabbro area. Both Ussing and Wegmann have commented on the well-developed flow pattern present over much of the outcrop. This flow pattern, defined by parallelism of the early plagioclase is, over much of the area, highly irregular and chaotic but in the northern part of the outcrop a consistent strike and dip is measurable. The dip of the lamination is mostly between 10–40° to the north. Although lamination is not well defined in the southern half of the outcrop there is a tendency, as noted by Wegmann (*op. cit.* p. 72) for the internal structure to be approximately horizontal. On the eastern coast of the Panernaq peninsula discontinuous melanocratic bands appear conformably within the sequence, the feldspars of which tend to display a more perfect parallelism than those in the average feldspathic gabbro. This was taken as an indication (Upton, 1961) that these dark horizons, rich in olivine, apatite and ore, originated through crystal sorting by relatively fast moving magmatic currents and that these latter were responsible for the preferred orientation of the fairly small percentage of feldspar crystals that accumulated along with the more dense early crystals. On occasion these heavy segregates contain up to 50 % olivine, 30 % ilmenomagnetite and 7.5 % apatite. Abundant sharp changes in dip and strike of the lamination and the truncation of the mafic horizons by apparently pre-consolidational faulting reflect tectonic instability during the development of a crystal mush which interfered with the formation of a regular and evenly layered gabbroic intrusion (Plate 1, fig. 1). As discussed by Wegmann, it is reasonable to conclude that on reaching the stratified Gardar rocks above the basalt unconformity, the intrusion expanded to form a thick laccolith or sill-like body in this region, the vertical contact at the end of the island between the old and new

Fig. 3. Stellate clusters of plagioclase and associated ferromagnesian minerals in the terminal chilled facies of a gabbro dyke in central Tugtutôq.

harbours reflecting the dyke form in the basement granite and the shallow contact with quartzite being evidence of the lateral spreading at higher levels.

On Tugtutôq island, immediately opposite to the Narssaq coast in the vicinity of Sigssardlugtoq, the gabbros are seen in a somewhat finer grained form, as a large steep sided dyke some 800 m broad. This is chilled marginally against the older granites and, in its inner part (up to 50–100 m from the contacts), well laminated. The feldspars show an inward dip at angles of up to 40° towards the dyke centre. However the structure is not a simple basin form but contains several minor depressions at the centres of which the lamination is horizontal. No obvious mineral banding occurs within this area although the variation in the content of ferromagnesian minerals is such as to suggest that there may have been some crystal sorting by current action. Followed WSW from Sigssardlugtoq the dyke shows but slight indications of internal layering and remains largely massive for some 4 km up to the point where the dyke divides into two branches. Close to the junction the more northerly of the two branches exhibits a simple internal layered structure. As shown diagrammatically in Fig. 4 (section 1) there is, inside narrow border zones a few metres wide, feldspar lamination dipping towards the dyke centre at ca. 30° becoming horizontal in the axial region. This layering persists for about one kilometre further to the WSW before the dyke reverts to an apparently structureless state. Two kilometres further along the dyke however

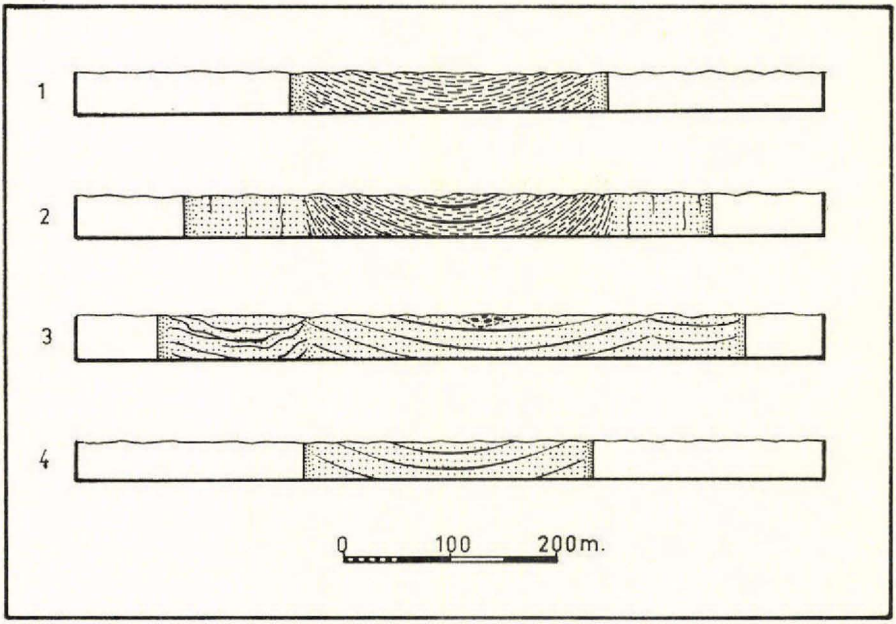

Fig. 4. Diagrammatic sections through the gabbro dykes. 1; the northern branch of the southern dyke system in eastern Tugtutôq. 2; the southern branch of the southern dyke system at Marrait, Tugtutôq. 3; dyke at Itivdlip Sarqâ, western Tugtutôq. 4; layered dyke ca. 4 km west of Itivdlip Sarqâ.

layering reappears in the central part of the dyke, this time without obvious feldspar lamination but with the presence of rhythmically alternating olivine-rich and feldspathic layers. The melanocratic horizons here are gravity stratified with sharp lower and gradational upper limits. Still further towards the distal end of this dyke branch and close to its blunt termination against an older crush zone in the country rock granites, an olivine-rich rock outcrops along the dyke centre. The synformal structure is still evident from the orientation of the occasional feldspar tablets distributed through the rock. This rock differs from melanocratic facies of the gabbros seen further to the ENE in that apatite is almost absent and the ilmenomagnetite is only seen interstitially and in small amount. These highly picritic rocks may be occurring as thick and resistant layers, perhaps as much as 10 m thick, within a more normal feldspathic gabbro. Internal synformal layering is also seen sporadically developed along the more extended southern branch and at Marrait, where the dyke is intersected by a small inlet from the Skovfjord, coastal exposures provide a useful cross-section through the dyke. The dyke width here is ca. 500 m of which the border zones, each ca. 150 m wide, consist of coarse gabbro with a "stellate" texture due to the plagioclase growth in radiating clusters. A few thin melanocratic layers parallel

Fig. 5. Angular unconformity in banded gabbro from the disturbed trough on the southern side of the gabbro dyke at Itivdlip Sarqâ.

to the dyke contacts contain vertically orientated plagioclase laths. The central 200 m of the dyke is occupied by layered rocks possessing both laminated feldspars and contrasted mineral banding. There appears to be no sharp break between the border zones and the inner layered rocks. The layering first seen on approaching the dyke centre is weak and steeply dipping (ca. 50°), but becomes more clearly pronounced as the dip decreases towards the axial region. The mafic layers in the horizontal axial zone are up to 10 cm thick and are rich in olivine, ore and apatite. Mineralogically these heavy segregations resemble those described above from the mainland outcrops but differ in their high content of early ore and apatite from the thick picritic horizons of the northern dyke branch.

The generally broader and considerably longer gabbro dyke which can be traced from the Tugtutôq east coast at Assorutit and Nasaussardle through the length of Tugtutôq shows far less tendency to develop any internal structures, and apart from a few relatively short sectors where layering is strongly developed the gabbro is massive and uniform. Along the northern margin of the dyke about one kilometre east of the central ring-complex inward-dipping 'inch-scale' layering occurs where there are thin and highly repetitive layers of alternating feldspathic and melanocratic material. The light layers average some 2–3 cm thick, the dark horizons being about one quarter to one third of this thickness. Neither feldspar lamination nor gravity stratification is found. Several kilometres

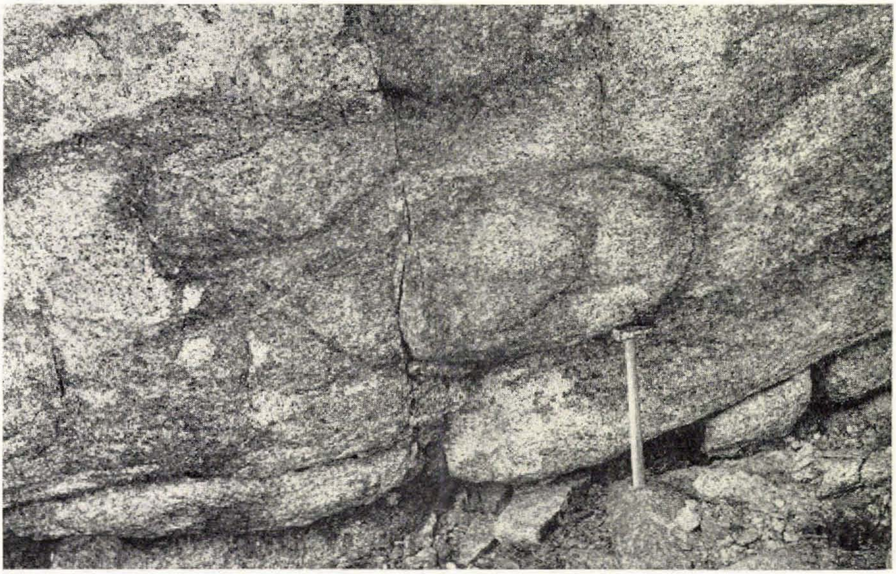

Fig. 6. 'Roll-structures' defined by olivine-rich layers in gabbro near Marrait. Possibly the result of slumping in steeply dipping gabbro cumulates.

further to the WSW the dyke is displaced by an ESE trending sinistral tear-fault and on the southern side of this, exposed along the coast at Itivdlip Sarqâ, is a more complexly layered situation than is seen anywhere else along the dykes. The dyke at this locality is 550 m wide and is found to comprise three synformal structures lying side by side. The precise nature of the contacts between these is not known. That alongside the dyke's southern wall is a relatively steep-sided trough some 150 m wide containing thick, sharply defined layers of gabbro picrite up to 1 m thick as well as subordinate melanocratic layers showing gravity stratification. The layering is traceable to within a metre or two of the chilled contact with the older granites.

Unconformities in the layering abound and the rocks appear to be current-bedded. Layers are commonly bent or fractured although there is no sign of mylonitisation along the fracture planes, indicating that the deformation of these rocks occurred when they were still in a fairly plastic condition prior to complete solidification (Plate 1, fig. 2). A shallower and more regular trough less than 100 m across lies along the northern side of the dyke containing conformable layers of gabbro-picrite with neither gravity stratification, current-bedding nor late-stage deformation. Between these two marginal troughs is a broad central one, closely similar to that on the northern flank but differing in that it contains along its median zone a 'breccia' facies where rounded to sub-angular blocks of gabbro-picrite are held in a matrix of the average feldspathic gabbro. The dark blocks in this central area are seen up to 1 m across (Plate 2, fig. 1) and are of precisely the same material as the gabbro-picrite seen in the layered sequences.

Within a distance of half-a-kilometre inland from this locality all trace of layering has gone from the dyke and, except at one locality, the dyke remains internally structureless over the remainder of its outcrop. The exception is seen immediately to the west of an older NW-SE trending dolerite dyke which is cut by the gabbro dyke about 4 km inland of Itivdlip Sarqâ. Against the eastern side of the older dyke the gabbro dyke is expanded but it is much attenuated on the western side. It is in the much narrowed gabbro dyke just beyond the intersection that strong layering reappears for a distance of less than 500 m (Plate 2, fig. 2). The actual contact zones of the dyke are well-chilled against the older granites. Immediately inside the chilled marginal zones on the northern side of the dyke, still within a few metres of the contact, are vertical layers containing feldspar laths lying perpendicular to the dyke walls. These plagioclase crystals are slightly curved with convex side uppermost and the rock-type is identical to the perpendicular feldspar gabbro described previously from the Kûngnât ring-dyke (Upton, 1960) which itself is closely similar to the perpendicular feldspar rocks of the marginal border group of the Skaergaard gabbros in east Greenland (Wager and Deer, 1939). On the inside of the narrow marginal zones the gabbros are layered with picritic horizons ranging from a few centimetres to over one metre thick dipping inwards towards the median line of the dyke, commencing with dips of ca 40° which shallow rapidly as the centre is approached. Simultaneously the width of the individual mafic bands increases, just as in the example at Marrait. Along the axial region, which coincides with the floor of a steep sided valley excavated within the dyke, cognate inclusions of gabbro-picrite are found like those of the central layered structure at Itivdlip Sarqâ.

Petrography of the olivine gabbros.

The feldspars: In the broad dykes on Tugtutôq the plagioclase tablets are generally ca. 10 mm across and 1 mm thick whereas in the (presumably) more slowly cooled mainland gabbros these dimensions are approximately doubled. Albite, pericline and Carlsbad twins are ubiquitous with Baveno twins occasionally present. Generally the earliest plagioclase to precipitate was calcic labradorite ca. An_{61-65} although more calcic cores of sodic bytownite An_{71-72} are found in some specimens from the more westerly parts of the dyke system. Normal zoning is invariably present although its extent varies widely from one facies to the next. The feldspars zone out through calcic oligoclase and may pass more or less sharply into untwinned alkalic feldspar which is usually cloudy and sericitised. The alkali feldspar contributes only a very small percentage to the total rock. Occasionally an even later phase can be distinguished in interstitial areas, sharply demarkated from the surrounding alkali feldspar. These areas consists of a micaceous material probably secondary after nepheline. Small amounts of nepheline appear in the norms of the two analysed gabbro specimens. In addition to the normal zoning a small-amplitude oscillatory zonation is frequently present, the difference between

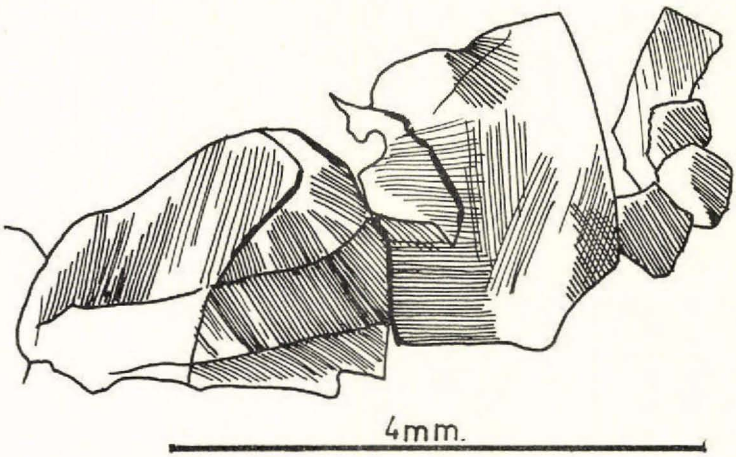

Fig. 7. Cluster of typical olivine crystals with hair-like pleochroic inclusions. Itivdlip Sarqâ.

adjacent zones not exceeding 4 °/₀ An. Up to 15 clear repetitions may occur in a single crystal together with fainter and less readily descernible minor zones.

Olivine is quantitatively the second most important mineral in the gabbro suite, usually comprising 15–30 °/₀ of the rocks and, in the picritic facies of the layered rocks, up to 70 °/₀. Typically the olivines occur as fresh idiomorphic crystals up to 2 mm diameter, the composition in the average gabbros being from Fa_{36-43} (determined from 2V measurements). However the full range recorded from the intrusions is from Fa_{32-55}. Zoning has not been detected. Like the plagioclase, the olivines had commenced crystallisation at the time of intrusion and some of the chilled facies contain two generations (Plate 5, fig. 1). The inclusions of anorthosite present in some parts of the intrusion are commonly mantled by olivine-rich rims in which the crystals attain sizes of up to 20 mm or over. Although normally free from inclusions, olivines from the gabbros immediately south-west of the central ring-complex are rendered semi-opaque by the presence of abundant minute inclusions. In a more striking instance, the olivines from rocks in the deformed synformal structure at

Itivdlip Sarqâ contain fine hair-like inclusions, pleochroic from dark-grey to brown. The inclusions may be orientated along several directions within a single crystal (Fig. 7). A similar instance is recorded from the olivinites of Taberg, Sweden, where the olivines (Fa_{35}) have a pleochroism α greyish-brown to γ reddish-brown, attributed by Hjelmqvist (1950) to the presence of a very fine grained brownish-black dust. Possibly the inclusions in these instances represent exsolved rutile. Narrow coronae of magnetite, amphibole and antigorite are occasionally developed around the olivines in the same manner as described for the Hviddal syeno-gabbro.

Relatively small quantities of interstitial titanaugite occur within the gabbros. As discussed in an earlier publication (Upton, 1961) the content of clinopyroxene in these rocks depends upon the degree of packing of the early mineral phases, principally plagioclase and olivine. In some of the laminated gabbros believed to be relatively 'close-packed', partly as a result of load-compression and partly because of the laminated texture imparted by deposition during gentle magmatic flow conditions, the titanaugite content is as low as 0.2 % whereas in loosely packed rocks where the early minerals trapped a high proportion of interstitial magma the pyroxene content may be as high as 12 %. A partial analysis of the titanaugite from specimen 40452 (table 4) indicates a composition $Ca_{45.5}Mg_{37.5}Fe_{17}$. The pleochroism that is sometimes weakly developed in the titanaugite is α pale pinkish, β very pale yellow-grey and γ very pale pink. The patchy zoning seen in the crystals involves a 2V range from 44–54°, although typically the 2V is 48–49°. Sagenitic inclusions are not seen and the crystals are untwinned.

The biotite which makes up 2–5 % of the rocks is, like that of the syeno-gabbro, a strongly pleochroic lepidomelane, frequently found as reaction fringes around the ilmenomagnetite crystals. Ilmenomagnetite is present to the extent of 3–5 % in the average gabbros although rising to as high as 28 % in some of the melanocratic ore-rich layers. In some of the gabbros on the mainland which have been hydrothermally altered the lamellae of ilmenite have been replaced by leucoxene.

The opaque minerals of the gabbros were investigated in four polished specimens. The specimen from the most westerly locality was an olivine cumulate containing small quantities of interstitial and homogeneous magnetite. In the other three specimens, each containing fairly abundant cumulus oxide crystals, the individual grains were composite ilmenomagnetites. The ilmenite occurs typically in both broad and very narrow lamellae forming an (equilateral) triangular grid pattern within the host magnetite. However discrete grains of ilmenite may also be present and in one specimen non-lamellar but generally parallel-sided patches of ilmenite were dispersed throughout the magnetite together with the more regular lamellae. The sulphides display marked variation in total content and in their relative proportions in the four specimens. In the olivine cumulate relatively abundant irregular grains of sulphide occur between the olivines. These are very largely of pyrrhotite with fine lamellae, probably of pentlandite, in association with small patches of chalcopyrites. Sulphides were similarly abundant in a specimen of olivine-oxide-apatite cumulate from Marrait but in this rock the chalcopyrites was predominant over the associated pyrrhotite (and pentlandite?). In a plagioclase-olivine-oxide cumulate from Sigssardlugtoq sulphides were notably scarcer but the association and relative proportions were the same as for the Marrait rock. In the fourth specimen, an olivine-oxide-apatite cumulate from the mainland north of Narssaq, sulphides were again very scarce. The occasional small grains appeared to be of homogeneous chalcopyrite without associated pyrrhotite.

Differentiation within the main gabbro intrusions.

Besides small-scale differentiation into melanocratic and mesocratic rocks in the layered localities there is some suggestion of differentiation over the intrusion as a whole. It seems probable that the gabbros of the ENE extension of the dyke system were crystallised from a slightly more highly fractionated magma than those of the WSW end. Various lines of evidence suggest this to be so, each in itself inconclusive, but, taken in conjunction strongly suggesting that there is a small compositional gradient along the dyke. Whereas plagioclase cores in the range An_{60-65} are common to all the intrusion cores as basic as An_{68-72} appear to be confined to specimens from the more westerly parts of Tugtutôq. Ilmenomagnetite occurs as idiomorphic to sub-idiomorphic crystals in the neighbourhood of Narssaq, Sigssardlugtoq and other localities towards the ENE end of the outcrops. In the layered rocks from this part of the intrusion ilmenomagnetite is found to be concentrated alongside olivine in the melanocratic layers and lenses and evidently behaved as a cumulus mineral whose crystallisation range largely overlapped that of the plagioclase and olivine. In layered rocks from the more westerly localities in Tugtutôq this is not found to be so. Melanocratic layers from this region consist of olivine with interstitial plagioclase, ilmenomagnetite etc. (plate 4 fig. 2) and the Fe-Ti oxide did not occur as cumulus phase. Furthermore, in the average gabbro from these parts of the intrusion the ore does not occur in the same well-formed crystals as seen in the gabbros nearer to Narssaq. Hence it would appear that ilmenomagnetite precipitated with plagioclase and olivine in the ENE but in the WSW the crystallisation relative to these two minerals was somewhat delayed. Apatite behaves in a similar fashion, occurring in relatively large, well-

Table 2. Analyses of the olivine gabbros from Tugtutôq and Narssaq with comparisons.

	40452	30765	mean	1	2	3	4
SiO_2	44.41	45.65	45.03	45.38	45.70	45.3	44.95
Al_2O_3	16.80	21.24	19.02	17.99	18.85	17.9	19.35
Fe_2O_3	1.97	3.05	2.51	3.09	1.47	2.9	2.30
FeO	12.95	8.52	10.74	11.92	11.44	11.7	10.47
MgO	8.26	4.67	6.46	5.10	6.15	5.1	7.52
CaO	7.42	8.79	8.10	7.65	7.73	8.5	7.82
Na_2O	3.10	3.63	3.36	3.70	3.74	3.2	2.80
K_2O	.92	.75	.83	.91	.99	.50	.81
H_2O^+	.79	.59	.69	.35	.48	.62	1.18
H_2O^-	.07	.05	.06	.05	.01		
TiO_2	2.44	2.52	2.48	3.19	3.02	3.4	1.73
P_2O_5	.65	.47	.56	.25	.40	.29	.31
MnO	.22	.10	.16	.18	.17	.19	.16
S	.05	.02	.03	Ba0.10	n.d.	n.d.	.20
CO_2	n.d.	n.d.	—	F .03	.06	n.d.	rest
Cl	.02	.02	.02	n.d.	n.d.	n.d.	.27
	100.07	100.07	100.05	99.89	100.21	99.60	99.87
O for S & Cl	.02	.01					
	100.05	100.06					

40452 Fine-grained marginal gabbro facies, giant-dyke, western Tugtutôq. Anal. R. Solli.
30765 Medium grained fresh olivine gabbro, Narssaq new harbour. Anal. R. Solli.
Mean of the two above analyses.
1 Olivine-gabbro from ring-dyke, Kûngnât, S. Greenland. (Upton, 1960).*
2 Olivine-gabbro from Alangorssuaq, S. Greenland (Harry and Pulvertaft, 1963).
3 Olivine-gabbro, Insch differentiated suite, Aberdeenshire, Scotland (Read, Sadashivaiah & Haq, 1961).
4 Typical 'hyperite', Taberg, Sweden (Hjelmqvist, 1950).

40452				30765			
Mode		C. I. P. W. Norm		Mode		C. I. P. W. Norm	
Feldspar	60.3 %	Or	5.6	Feldspar	75.2 %	Or	4.4
Olivine	28.8	Ab	23.9	Olivine	13.9	Ab	28.1
Pyroxene	4.4	An	29.5	Pyroxene	1.0	An	40.0
Biotite	1.4	Ne	1.4	Biotite	.9	Ne	1.4
Ore	4.0	Di	2.8	Ore	8.7	Di	1.2
Apatite	1.1	Ol	27.7	Apatite	.3	Ol	14.8
		Mt	2.8			Mt	4.4
		Il	4.6			Il	4.7
		Ap	1.7			Ap	1.0
Feldspar	$Or_9Ab_{41}An_{50}$			Feldspar	$Or_6Ab_{39}An_{55}$		
Cpx	$Wo_{50}EN_{25}Fs_{25}$			Cpx	$Wo_{50}En_{25}Fs_{25}$		
Olivine	$Fo_{50}Fa_{50}$			Olivine	$Fo_{54}Fa_{46}$		

* Figures for Mn and Ti redetermined since 1960.

formed crystals, concentrated in mafic segregates in the Narssaq region and occurring to a lesser extent in the more westerly rocks in which it is not found as a cumulus mineral.

In the sub-parallel Hviddal composite dyke the syenite central zone displays a remarkable variation from augite syenite in the WSW to a highly sodic foyaite in the ENE (Upton, 1964). The explanation advanced for this lengthwise variation is that the syenite is itself a layered intrusive and that the dyke has been tilted along its own axis some 5° to the ENE with erosion now revealing successively lower level rocks towards the WSW. The syenite exhibits phase and cryptic layering but apparently neither rhythmic layering nor regular feldspar lamination. The slight variations along the gabbro dykes can be explained on the same basis; namely that the slightly more basic troctolitic rocks of the WSW are probably the lower zones in a cryptically layered dyke. In the upper rocks phase layering is displayed by the appearance of cumulus ilmenomagnetite and apatite. It is reasonable to surmise that cumulus pyroxene appeared in the uppermost levels in the intrusion although any such rocks as may formerly have existed are lost to study as a consequence of later intrusions and deep erosion. The small amount of information available from polished specimens suggests that the lower gabbros are more sulphide rich than the more fractionated rocks of the ENE.

In the gabbro dyke close to the coast at Marrait, a number of thin irregular sheets, 10–20 cm thick, were observed within the olivine gabbros. These are of coarse grained syenite with euhedral tabular feldspar crystals over 1 cm long. The feldspar are mostly micro-antiperthites, often zoned, some with oligoclasic cores and most are margined by albite free of K feldspar. Early olivines have been oxidised and largely replaced by magnetite. Subhedral crystals of green-grey clinopyroxene, locally zoned to aegirine-augite and partially replaced by brown hornblende occur, together with large euhedral ore crystals and small apatites. Ilmenomagnetite has been replaced by leucoxene. Calcite occurs interstitially and some secondary green hornblende and brown biotite is also present. Interstitial areas of micaceous material may imply the original presence of nepheline. In spite of substantial (hydrothermal?) alteration the rock bears some resemblance to the more basic syenites associated with the Hviddal syeno-gabbro. It would seem highly probable that these alkalic segregates at Marrait are residual crystallisation products of the cooling gabbros.

The Krydssø syeno-gabbro.

A lenticular body of alkaline basic rock extending for some three kilometres occupies the central part of the more northerly olivine gabbro dyke in the vicinity of the Krydssø (lake). This is thought to be a separate intrusion post-dating the gabbro and is not regarded as an *in situ* differentiate of the main dyke. It is however earlier than the neighbouring Assorutit quartz syenite intrusion whose late stage acid veins transgress it. Although referred to as syeno-gabbro the main rock type differs from that of the Hviddal dyke in being richer in clinopyroxene, which crystal-

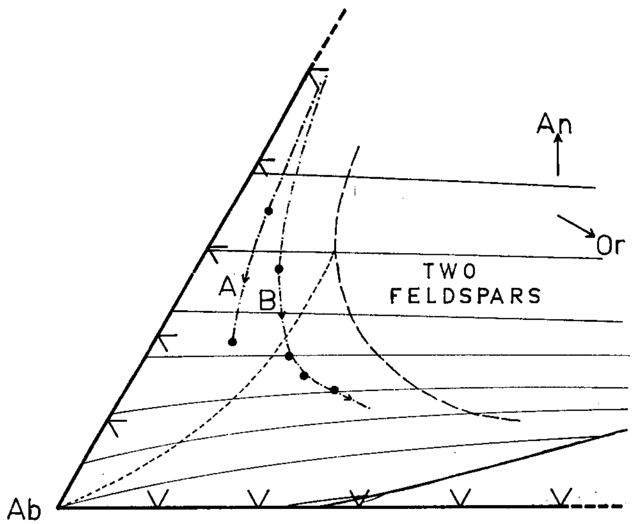

Fig. 8. Curve A; crystallisation course of feldspar from Krydssø syeno-gabbro. Curve B; crystallisation course of feldspar from the Hviddal syeno-gabbro.

lised earlier than in the Hviddal syeno-gabbro, and chemically in being more siliceous and potassic. Rather indistinct mineralogical banding within the body defines a broad synformal structure suggesting that the rocks may be an accumulitic suite. Some 60 % of the rock is composed of feldspar, zoned from twinned cores of andesine or oligoclase into broad untwinned mantles of optically clear and homogeneous material. The feldspars are anhedral with interlocking boundaries and average ca. 10 mm across. A typical zoned feldspar crystal from the analysed sample (40552) was included among a number of samples whose K and Ca contents were investigated with an "A.R.L." electron micro-probe (Scripp's Institute of Oceanography, through the courtesy of G. Arrhenius and R. Fitzgerald). The zoning was found to be abrupt, an andesine core averaging $Or_4Ab_{62}An_{34}$ being surrounded by a K-bearing oligoclase with an average value of $Or_8Ab_{73}An_{19}$. The plagioclase core and also the mantle feldspar were themselves virtually unzoned.

The remaining 40 % consists of augite, biotite, ilmenomagnetite, apatite and olivine. The pyroxenes are weakly coloured, sub-hedral to idiomorphic, with slight zoning from pinkish-grey centres to more green-

Table 3. Analysis of Krydssø syeno-gabbro, from the ENE corner of the intrusion.

	40551	1
SiO_2	48.08	48.42
Al_2O_3	13.70	13.97
Fe_2O_3	5.07	4.17
FeO	9.19	9.57
MgO	3.45	4.61
CaO	7.38	8.86
Na_2O	4.22	3.30
K_2O	2.72	1.29
H_2O+	1.15	.84
H_2O-	*	.42
TiO_2	3.76	3.25
MnO	.22	.17
P_2O_5	1.45	.91
	100.39	99.78

40551 analysed at the Geochemical Laboratory, Grant Institute of Geology, Edinburgh.
* Results on sample dried at 110°C, 2 hrs.
1 Aphyric andesine basalt, Mauna Kea, Hawaii. H. S. Washington, 1923.

Mode of 40551		C. I. P. W. Norm of 40551	
Alk. feldspar	49.2 %	Or	14.1
Plagioclase (cores)	9.9	Ab	29.6
Olivine	2.4	An	9.2
Pyroxene	19.3	Ne	8.4
Biotite	8.4	Di	12.2
Ore	7.7	Ol	9.7
Apatite	3.1	Mt	7.7
		Il	6.2
		Ap	2.9

Feldspar	$Or_{27}An_{56}An_{17}$
Cpx	$Wo_{52}En_{28 \cdot 5}Fs_{19 \cdot 5}$
Olivine	$Fo_{57}Fa_{43}$

ish-grey margins (2Vγ (core) 51° → 56° (margin)). The cores are mildly pleochroic from light yellowish-grey parallel to β and pale pink-grey parallel to α & γ. The pyroxene was separated and arbitrarily divided into more and less ferromagnetic portions with an electromagnetic separator in the very approximate ratio 2:3. The more magnetic material corresponds to the greener marginal pyroxene. Analyses of these portions gave compositions of $Ca_{44.5}Mg_{36}Fe_{19.5}$ (core) and $Ca_{44.5}$ $Mg_{32.5}$ Fe_{23} (margin). The later idiomorphic to anhedral olivines are ferrohortonolites, ca. Fa_{72}

Table 4. (Partial) analyses of clinopyroxenes from 1) olivine gabbro and 2) Krydssø syeno-gabbro.

		40452	40551(a)	40551(b)
	SiO_2	48.81	51.04	50.98
	Al_2O_3	4.06	.96	1.05
	Fe_2O_3	3.04	2.54	2.41
	FeO	6.97	9.41	11.44
	MgO	11.78	12.23	10.51
	CaO	20.28	20.73	20.69
	Na_2O	n.d.	.61	.72
	K_2O	n.d.	.08	.14
	TiO_2	2.33	1.44	1.33
	MnO	n.d.	n.d.	n.d.
		97.27	99.04	99.27
No. of atoms to 6 oxygens;				
Z	Si	1.865	1.938	1.949
Z	Al	.180	.043	.047
Z	Ti	—	.020	.014
WXY	Al	—	—	—
WXY	Fe'''	.087	.073	.070
WXY	Fe''	.223	.299	.366
WXY	Mg	.678	.698	.605
WXY	Ca	.833	.844	.849
WXY	Na	n.d.	.044	.053
WXY	K	n.d.	.004	.007
WXY	Ti	.067	.021	.024
WXY	Mn	n.d.	n.d.	n.d.
Z		2.045	2.001	2.010
WXY		1.888	1.983	1.974

40452: Ophitic pyroxene from marginal olivine gabbro facies.
40551(a): Pink-grey cores (less magnetic) of sub-hedral pyroxenes, Krydssø syeno-gabbro.
40551(b): Greenish-grey outer zones (more magnetic) from Krydssø pyroxene.

All analyses on material dried at 110° C, 2 hours. Analyses by the Geochemical Laboratory, Grant Institute of Geology, Edinburgh.

(X-ray diffraction determination). Strongly pleochroic biotite encloses much of the ilmenomagnetite. In polished section the oxide grains are seen to be mainly composite, the magnetite host containing both broad and also very narrow lamellae of ilmenite. Exsolved ulvöspinel was present in the magnetite in some crystals. No sulphides were seen in the specimen examined. Sharply defined fringes of antigorite are commonly developed around the biotite. Ore and apatite, as in the

Hviddal syeno-gabbro, crystallised early, the crystallisation of the apatite preceding that of the pyroxene.

The petrography of the Krydssø rock corresponds fairly closely with that of the Oslo kjelsåsites.

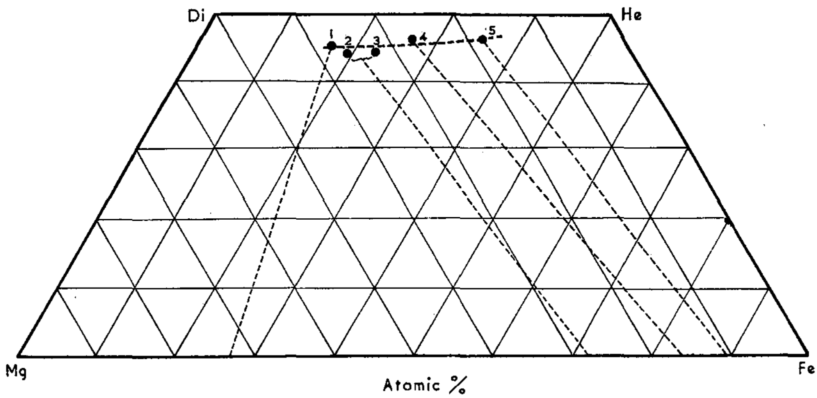

Fig. 9. Clinopyroxenes from gabbros, syeno-gabbros and syenites from the Tugtutôq-Ilímaussaq region. 1, gabbro, 40452; 2, syeno-gabbro, 40551 (a); 3, syeno-gabbro 40551 (b); 4, augite-syenite, chill, Ilímaussaq; 5, augite-syenite, 30714, Hviddal dyke. (For analyses 4 & 5, see 'The geology of Tugtutôq & neighbouring islands, pt. IV. Upton, 1964). Tie-lines indicate optically determined compositions of associated olivines.

The anorthosites.

Inclusions of labradorite anorthosite material are common in a number of the intrusions in the Tugtutôq-Narssaq area just as they are in other parts of the Gardar province. In the area under discussion the oldest intrusion in which these inclusions have been encountered is the syeno-gabbro of the Hviddal composite dyke in which, however, they are extremely scarce. In the olivine gabbros anorthositic material occurs abundantly in two restricted localities; namely the district around the Nasaussardle-Assorutit headlands on the east coast of Tugtutôq and the southern part of the mainland outcrop around Narssaq. Subsequent to the gabbro intrusions, some ENE trending dykes of porphyritic microsyenite were erupted, these being followed rapidly by intrusion of doleritic magma, in many cases with the production of composite dykes in which the centre part is basic and the margins alkalic. It is in these basic dykes particularly that fragments of anorthositic rock are present in quantity and commonly it is in the innermost parts of these dykes that one finds the greatest concentration of the inclusions. The microsyenite precursors to the dolerite dykes are normally free from the plagioclase

Fig. 10. Minor masses of laminated anorthosite detached from main block and surrounded by intrusive olivine gabbro. Assorutit.

fragments but, in a few instances they also bring up altered plagioclase xenocrysts. The later syenitic and granitic intrusions on Tugtutôq are entirely lacking in anorthositic inclusions but the later 'camptonitic' dolerite dykes sometimes contain large fragments of plagioclase which may originate from the same source as those of the earlier basic dykes. There would seem to be a considerable uniformity in composition of the anorthosite feldspar involved in these various intrusive episodes and in all cases investigated the plagioclase composition falls within the range An_{61-55}. Although most commonly the anorthosites have been completely fragmented into single crystal pieces (Fig. 11), composite blocks, in one case almost 100 m across, within the gabbros appear to represent the original rock type that has given rise to the abundant plagioclase debris (Fig. 10). The multicrystal inclusions range from virtually monomineralic labradoritites to gabbroic anorthosites containing up to 20 or even 30 $^0/_0$ of ferromagnesian minerals (plate 3, fig. 1). In the gabbros near Assorutit and, rarely in those around Narssaq the anorthosite is fresh and unaltered, whereas the most general condition is one of considerable secondary alteration. The doleritic dykes succeeding the gabbros are moderately alkalic, a state probably acquired through hybridisation with the syenite magma which immediately preceded them and the plagioclase xenocrysts are frequently so much corroded and sericitised that

Fig. 11. Aligned xenocrysts of labradorite in a post-gabbro basic dyke. South coast, Tugtutôq.

only exceptionally are unaltered cores available for examination. Around Narssaq both the host gabbros and inclusions have been subjected to an extensive and thorough hydrothermal alteration which has affected all the minerals except the magnetite and apatite. The plagioclase, olivine, augite, biotite and ilmenite initially present in the gabbros and anorthosites are converted into complex aggregates of sericite, clino-zoisite, epidote, penninite, antigorite, leucoxene and other secondary materials. This intense alteration may have been connected with the evolution of water-rich solutions from the later syenites and granites which transect the gabbro although this does not seem to have been a general phenomenon. It is of interest that a similar hydrothermal alteration has affected the gabbros around the Assorutit syenite on Tugtutôq but this has been on a relatively small scale and may be related to a joint pattern in the gabbros. Certainly

Fig. 12. Assorted xenoliths of anorthositic and troctolitic gabbro together with labradorite xenocrysts in a post-gabbro basic dyke. Small island south of Sigssardlugtoq.

there is no consistent aureole of altered gabbro around the syenite. The anorthosite masses on the Assorutit peninsula which by and large, are extremely fresh, do in fact lie adjacent to the syenite and any hydrothermal alteration resulting from its intrusion has been very limited. These Assorutit anorthosites contain, in addition to some 90 % of labradorite, olivine, augite, biotite, ore, chlorite, hornblende, sericitised alkali feldspar and apatite, these being listed very approximately in order of abundance. The composition of the olivine at this locality is approximately Fa_{30}.

Whereas there is compositional uniformity there is considerable diversity in the rock fabrics displayed by the anorthosites. At Assorutit the large masses are clearly layered. The tabular labradorites possess a strong preferred orientation giving a very distinct lamination to the rock. Parallel to this are more or less well-defined subordinate layers with a greater concentration of olivine than in the average rock (Upton, 1961). Each of the ferromagnesian minerals crystallised later than the plagioclase and is restricted to an interstitial habit. The average grain size of these anorthosites is considerably greater than that of the surrounding gabbros and still greater than that of the coarse olivine gabbros of the mainland outcrop. Feldspar sizes vary widely within a single hand-specimen from ca. 15–120 mm across to 1–8 mm thick and the interstitial olivines are frequently in excess of 30 mm. Such large thin feldspars

Fig. 13. Olivine-rich horizon in layered anorthosite, Assorutit.

often show signs of strain in thin-section but scarcely to a greater extent than that normal in the host gabbros and there is an overall lack of the cataclastic fabric commonly associated with anorthositic bodies. Apart from the Assorutit occurrences, similar masses of well-laminated to poorly-laminated coarse anorthosite have been observed in several of the inclusion-rich doleritic dykes which cross the smaller Skovfjord islands and a few inclusions of this type have also been found within the gabbros at Narssaq. One large mass of fresh and moderately laminated anorthosite north of the old harbour at Narssaq contains crystals up to 20 cm across. Within the layered Assorutit masses a few cognate inclusions of earlier anorthosite have been noted, these being somewhat coarser than the host anorthosite. In contrast to these relatively unstrained anorthosite types with their idiomorphic feldspars, the majority of the inclusions in the Narssaq region are compacted masses of broken plagioclase crystals which lack any preferred orientation, together with small amounts of ferromagnesian minerals, chiefly chlorite believed to be secondary after olivine (Plate 3, fig. 2). Individual crystal pieces are commonly found up to 10 cm across. Within the post-gabbro dolerite dykes similar cataclastic anorthosite material is common, often in association with non-clastic varieties. This shows considerable variation both in grain size and in content of dark minerals, rare inclusions being more troctolitic than anorthositic (Fig. 12). Although plagioclase crystals in excess of ca. 20 cm have not been noted in the gabbros either on Tugtutôq or on the mainland, occasional crystals measuring up to 60 × 10 cm have been recorded from the post-gabbroic dolerite swarm, presumably having originated from the disintegration of an excessively coarse anorthosite variety (Fig. 11).

From these observations one may draw the following conclusions: (a) that there exists at depth a large body of labradorite anorthosite through which the basic magmas for the ENE Gardar gabbroic and doleritic dykes were erupted; (b) that in view of the great scarcity of anorthositic inclusions in the syenitic intrusions it is probable that the bulk of the syenitic magmas were of relatively high level provenance, i. e. were generated above the domain of the anorthosites; (c) that the anorthosites varied in grain size from ~ 1 cm to a maximum in excess of 60 cm and included all gradations from finely laminated and layered unstrained varieties to strongly cataclastic types and (d) that the anorthosites were either fully crystalline or very largely so at the time of their disruption and they were sufficiently cool to cause considerable chilling of the gabbroic magma against the larger masses at Assorutit. In order to achieve the degree of coarseness exhibited by these rocks the parental magma must either have had an efficient circulatory mechanism to supply new material to the growing crystals or else must have had an exceptionally long cooling history.

Dykes and sills of camptonitic dolerite.

In the preliminary paper on the geology of Tugtutôq a brief description was given of the ENE dykes and related sills which are seen to postdate all the Gardar intrusions up to and including those of the central ring-complex. The dykes are not particularly abundant and are seldom over 4 or 5 metres thick but they are very persistent and appear to be fairly evenly spaced over a broad belt. The sills are rarely more than 3 m thick. The rocks consist of zoned soda-lime and alkali feldspar, with titanaugite, brown hornblende, ore and apatite with chloritic pseudomorphs after olivine. The dykes and sheets have a characteristic flow banding and frequently contain ocelli of calcite and epidote. Petrographically these rocks match closely the (presumed Tertiary) camptonites described by BAILEY and others in the Mull Memoir (1924) and likewise the oligoclase basalt/camptonite dykes described by VINCENT (1952) from the east Greenland Tertiary swarms. VINCENT concluded that the camptonitic suite was derived by fractional crystallisation and filter-pressing from a parental basalt type lacking orthopyroxene or pigeonite. Such an explanation can readily be adopted to account for the production of these South Greenland hypabyssals assuming the parental magma to have been the same as that for the gabbroic and syeno-gabbroic dykes, but it does not in itself account for the relative enrichment in water and carbon dioxide which must have occurred in these intrusions. The syeno-gabbroic rocks on Tugtutôq must represent a comparable state of differentiation and yet these retain fresh olivine and pyroxene, chlorite is not abundant and there is neither brown hornblende nor carbonate. However, the very frequent occurrence of calcite and hydrous minerals as the latest products of crystallisation in the Assorutit syenite and in many of the mid-Gardar microsyenite dykes suggests that residual volatile-rich fractions from the cooling syenitic magmas may have enriched a portion of moderately advanced basaltic magma to produce the late stage camptonitic dolerites.

Origin of layered structures in the giant dykes.

The laminated gabbros outcropping in the Narssaq-Panernaq area together with those occurring in two of the layered localities in the Tugtutôq dykes have been discussed in a comparative paper dealing with some of the accumulative rock types encountered in the Gardar intrusions (Upton, 1961). In this it was proposed that the very marked parallel and sub-horizontal orientation of the plagioclase originated through the precipitation and accumulation by sinking of the crystals through magma undergoing gentle flow. The tabular habit is common to the plagioclase of the whole intrusion but pronounced lamination is restricted to a few limited areas. In general the weak mafic banding found at these localities is attributed to current winnowing of an accumulate crystal mush consisting of labradorite, olivine, ore and apatite. Rhythmic layering with gravity stratification is very scarce throughout the intrusion but where it is developed it is likely that it originated through crystal sorting by magmatic currents of varying velocities, much in the manner described by Wager and Deer (1939) for the banded rocks at Skaergaard. In all probability simple convective circulations developed at irregular intervals along the intrusion and, on this interpretation, the Sigssardlugtoq area for example may be regarded as the site of one convective cell where lamination became pronounced as a result of flow-orientation, and the Marrait locality as the site of a more vigorous convective circulation where substantial crystal sorting took place with the formation of melanocratic heavy segregates consisting largely of olivine, ore and apatite. At Marrait there was evidently a considerable amount of crystallisation inwards from the dyke walls giving rise to the comparatively thick 'border-groups' at this locality. The synformal attitude of the

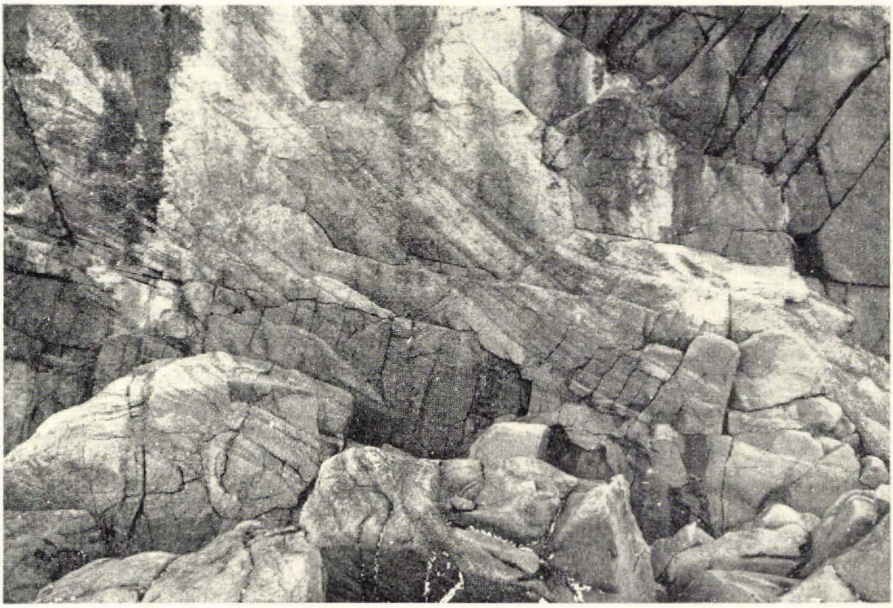

Fig. 14. Current-bedded olivine gabbro cumulates in the southern 'trough' at Itivdlip Sarqâ.

layering in the inner part of the dyke originated, as at Skaergaard, from the higher rate of crystal deposition close to the cooling walls, beneath the descending limbs of the convection cell.

Further to the west, still more vigorous convective activity may have been responsible for the current-bedding seen in the southern marginal trough at Itivdlip Sarqâ. However, at a number of localities, particularly towards the west-south-westerly part of Tugtutôq, horizons of gabbro picrite occur which are abruptly defined above and below, and which show no signs of gravity stratification within themselves. In these rocks it appears that olivine was the sole cumulus mineral, the other constituents of the rock having crystallised from the intercumulus magma (Plate 4, fig. 2). Explanation of these very clearly defined picrite layers in terms of magmatic sorting of mixed feldspar-olivine cumulus material is not acceptable and it would appear more likely that they are due either to sudden showers of olivine crystals or to cessation of plagioclase precipitation. Of these alternatives, the second is the more probable in instances such as in the more northerly troughs at Itivdlip Sarqâ where all the feldspar in the picrite appears to be of intercumulus origin. However in the northern branch of the southern giant dyke system where thick horizons of picrite occur containing sparse oriented tablets of early crystallised plagioclase it may well be that the picrite merely represents a sudden accentuation and acceleration in olivine nucleation. Of the possible factors that may inhibit or accelerate the crystallisation of either of these two principal components the most probable is fluctuation in vapour pressure. It is known that the intrusion reached well into the Gardar volcanic series, and it is not inconceivable that some surface effusion of the magma occurred along fissures or aligned vents. YODER (in ABELSON, 1954) considering experimental work of OSBORN on the Di-An-H_2O system suggested that the alternation of pyroxenite and anorthosite in some layered intrusions may be related to vapour pressure control since position of the An-Di eutectic varies with pressure. Similarly, according to YODER (*vide* BROWN, 1956, p. 47) the An-Fo eutectic varies with water vapour pressure, an increase of which will lower the eutectic and drive it toward the anorthite end of the system. Assuming that the behaviour of the labradorite-hyalosiderite-water system (approximating to the olivine gabbro magma) is similar, and that the average mesocratic gabbro with ca. 25 % olivine, 75 % feldspar represents crystallisation along the cotectic, then increases in water vapour pressure which need have been but small and temporary may from time to time have allowed only olivine to precipitate. Magma trapped by the olivine crystals would have continued to crystallise interstitially until the cotectic was regained and plagioclase precipitation recommenced. Although the water content of the magma was undoubtedly small, it was not negligible and, on fall of temperature, the already crystallised ilmeno-magnetite reacted with the hydroxyl enriched residual magma to produce biotite coronae. For the more basic, westerly parts of the intrusion the magma would have corresponded very approximately to the system An-Di-Fo investigated by OSBORN and TAIT (1952) with crystallisation following the olivine-plagioclase cotectic (apart from the minor deviations giving rise to the olivine cumulates) until the stability field for pyroxene was reached. Although no anorthosite layers occur within the gabbro dykes such as might have occurred as a result of pressure release, it has been pointed out in an earlier publication (UPTON, 1961, p. 20) that the layered anorthosite masses brought up by the gabbro may have been produced in this manner from a very similar magma.

In summary therefore it is suggested that the banding in the intrusion may have come about as a result both of current winnowing and fluctuations in the partial pressure of volatiles, in some localities both mechanisms operating concurrently. Proceeding on the assumption that the rocks in the layered sectors of the intrusion are cumulates derived through the sinking and accumulation of early mineral phases, it is logical to regard the homogeneous, unbanded and unlaminated gabbros characteristic of long stretches of the giant dykes similarly, that is as cumulates which have not been differentiated by either vapour pressure control or magmatic winnowing. It would therefore follow that analyses of representative specimens of average rock will differ to a more or less marked degree from the composition of the original magma. The mapping of the dykes revealed some tendency to 'pinch and swell' structure, in both vertical and horizontal senses. It was perhaps the localised blockage of the crystallising dykes by settling crystals that led to the formation of a 'floor' upon which sedimentary layered successions could be developed. Furthermore, it may have only been as a result of such dyke-fissure blockages that conditions necessary for the commencement of convective overturn could ensue.

On the terminology proposed by WAGER, BROWN and WADSWORTH (1960) for cumulitic rocks, the gabbroic rocks described would fall into the category of orthocumulates. That is, the trapped interstitial magma in the primary crystal mush has crystallised and fractionated *in situ*, zoning or making over the cumulus minerals and with negligible diffusion effects between the crystallising intercrystal spaces and the main magma body. In two specimens where it appeared feasible to distinguish with fair confidence between cumulus and intercumulus material, an attempt was made to determine the relative proportions. This was done in the case of a gabbro picrite (Plate 4, fig. 2) and for a mesocratic laminated gabbro (Plate 5, fig. 2) by cutting out and weighing the 'cumulus crystals' in the enlarged photomicrographs. For the picrite the values 67 % cumulus (olivine) and 33 % intercumulus were obtained, the corresponding figures for the mesocratic Sigssardlugtoq gabbro being 71 % and 29 %. In each case the maximum euhedral forms which could be cut out of each 'early crystal' were taken as cumulus, it being considered that a better estimate could be arrived at in this manner than by point-counting. In spite of the inevitable subjectivity of such a determination it would appear that 30 % is a likely figure for the original content of intercumulus liquid in these two rocks but, in the average non-laminated mesocratic gabbros, the intercumulus content may well be higher.

Interpretation of the complex structures at Itivdlip Sarqâ.

Inasmuch as the trough alongside the southern margin of the dyke at Itivdlip Sarqâ shows numerous signs of deformation preceding complete crystallisation whereas the layered rocks forming the main, northern, part of the dyke do not, it is inferred that the southern trough is the earliest of the three trough structures. If this is so then it is probable that the dyke at this locality was intruded in two or possibly more separate episodes. The first intrusion (corresponding to the southern trough) cooled with vigorous convection to give a layered sequence showing abundant small unconformities (Fig. 5). Most of the banding in this trough can be reasonably attributed to current winnowing although the occasional massive picrite layer intercalated among the minor banding may be the result of a temporary vapour pressure increase as described above. After the formation and main crystallisation of this layered gabbro dyke a further intrusion of identical magma was injected, arising along the northern contact zone between the early dyke component and the older granite. The act of intrusion compressed the layered rocks of the earlier unit which could still yield plastically to some extent by virtue of a small content of unsolidified intercrystal liquid. Possibly the unusually steep form of the southern synform is itself a result of lateral compression. Conceivably the presence of the two very shallow synformal structures in the central and northern parts of the dyke is due to two gently moving convective cells, the horizontally bedded axial regions of the two troughs underlying the two ascending currents of these cells. The absence of minor banding suggests that any convective overturn there may have been was slow and insufficient to accomplish any significant sorting of light and heavy minerals. The picritic layers which define the structures are of the type which are tentatively attributed to temporary cessation of plagioclase crystallisation. A further feature of the dyke at this locality is the presence of rounded blocks of picrite set in a matrix of the mesocratic gabbro along the axial part of the central trough, a feature which, as pointed out in an earlier section, is not unique to Itivdlip Sarqâ. It is likely that this 'conglomeratic' material may be the the result of turbulent flow along the floor of the trough or else the result of slumping of material down the sides of the trough and its accumulation in the centre. This latter is less probable since (a) the angle of dip is slight, (b) actual slump structures have not been recognised in the intrusion* and (c) the generally high degree of rounding of the masses suggests greater transport than would be involved in lateral slumping over a distance of only 50–100 m.

Discussion of the manner of intrusion.

The majority of the smaller dykes were undoubtedly emplaced in single rapid episodes but many dykes are composite, usually, though not invariably, having the more felsic magma intruded later than more basic magma. Not only are dykes such as the Hviddal dyke evidently composite but the gabbro dykes may, in their broader parts, have been emplaced by a series of magma pulses along the same channel. Clear evidence of such a mode of intrusion however is only obtained at Itivdlip Sarqâ where study of the layered structures indicates intrusion of two separate intrusions of identical basic magma. Here the second pulse was sufficiently delayed for the first to have largely completed crystallisation by the time of its arrival.

* i. e. other than such problematical 'roll-structures' as illustrated in fig. 6.

In the general case of the gabbro dykes however, where these attain widths of 200 to 900 m it is likely that intrusion was accomplished fairly slowly with successive influxes of new magma from depth as the crustal tension persisted; these following each other at time intervals insufficient to allow significant crystallisation of one pulse before the next was introduced until the process pauses for long enough for crystallisation of the whole to occur.

The closest analogues of the Tugtutôq giant dykes of which the author is aware are the large east-west dykes of central Sweden, two of which were described in detail by Krokström (1930 and 1936). These dykes are considered to be of late Precambrian age, possibly post-Jotnian, and, like the Tugtutôq dykes, are concordant to the strike of the Archaean country rocks. Of these two, the Breven dyke (30 km long and 300 to 1,200 m broad) is doleritic with, in its eastern part, a late central granophyre component producing hybrid zones in the outer dolerite lining. The other, (Halleförs) dyke is 40 km long, with an average width of 1000 m i.e. slightly wider than the Tugtutôq dykes. (The Hviddal dyke averages 500–600 m and the gabbro dykes from 1–900 m). This dyke is composed of two intrusions of closely similar olivine gabbro followed by a median intrusion of more highly differentiated basic magma. Krokström too was of the opinion that a fissure even the width of the central component could scarcely have formed suddenly but rather developed gradually in response to increasing tensional forces. No internal layering was reported from these dykes, but in a recent paper (1960), Simpson and Otto describe elongate intrusions of gabbro associated with the Kunene anorthosite in Angola which possess rhythmic banding and shallow synclinal structures transverse to the length. Structurally, these authors compare these intrusions to the Rhodesian great dyke.

The source of the anorthosite inclusions.

From the evidence afforded by the feldspathic inclusions in the gabbros and dolerites an extensive and possibly thick sequence of anorthosite and anorthositic gabbro may be assumed to underlie the area. This hypothetical anorthosite complex may have much in common with the great anorthosites of the north American Precambrian as well as possessing some distinctive peculiarities of its own.

In the Adirondacks anorthosites and anorthositic gabbros were cut by dykes and sheets of gabbro which were in turn intruded by quartz syenite and other rocks. The plagioclase rocks of the Willsboro quadrangle (Buddington and Whitcomb, 1941) have a platy structure and vary from evenly grained rocks of medium coarseness to facies consisting mostly of large plagioclases up to an inch or more long. The average feldspar is An_{48} although the total range extends from labradorites of An_{57}. The rocks are typically crushed, often granulated, and may contain up to 25 % of dark minerals. Blocks of anorthosite included within anorthosite of slightly different character are found in the border facies. In the anorthositic complex of the San Gabriel Mts., California, which OAKESHOTT (1958) believes to have formed from a high alumina anorthositic gabbro that differentiated *in situ*, irregular banding, lamination and occasional development of giant crystalline facies are found. OAKESHOTT comments on the occurrence of anorthosite inclusions within anorthositic host rocks and explains the crushing phenomena in the rocks as resulting from movements and readjustments in the mass during its cooling history. The rhythmic banding he believes can be interpreted as a product of differential settling of plagioclase and pyroxene accompanied by directional currents in the magma. HIGGS (1954), describing these same rocks, records plagioclase crystals of up to 56 × 172 cm showing uniform composition and little or no zoning. HIGGS puts the average feldspar composition as andesine, An_{43} but OAKESHOTT points out that in the more basic rocks, especially those relatively enriched in olivine, the plagioclase is labradorite. Mineralogically the main difference between the anorthosites at these localities and the Gardar inclusions is the absence of orthopyroxene in the latter and the total absence of modal quartz.

Still more instructive are the anorthosites of the Lake Superior region. TAYLOR (1958) describes the lowest and earliest unit of the Duluth complex as a coarse-grained anorthositic gabbro consisting of 75–90 % calcic labradorite. This is intruded by gabbro which forms a layered sequence some 5000 m thick overlying the anorthositic rocks, involving troctolite, olivine gabbro and syeno-gabbro. Multiple intrusions of basic magma were followed at a later date by intrusion of more leucocratic derivatives. The anorthositic gabbro, which contains abundant cognate inclusions of various gabbro types and boulder-like masses of anorthosite, was probably intruded as a crystal mush and most of the inclusions are believed to be early phases that solidified and were broken up by later pulses of magma. The anorthositic gabbro is spotted with poikilitic titanaugite and ilmenomagnetite and occasional facies are rich in olivine. True anorthosite is only found in discrete rounded inclusions which sometimes have additions of mafic minerals around them from the enclosing magma. Some of the anorthositic rocks have well-developed fluxion structures and parallel orientation of the plagioclase plates whereas others have a cataclastic texture and may be so fine grained as to resemble chert. The crystals of labradorite occasionally reach lengths of up to 36 cm. In the Keweenawan lavas above the main body of the Duluth complex are many sheets and dykes of olivine dolerite and troctolitic gabbro comprising the Beaver Bay complex (GROUT and SCHWARTZ, 1939).

These intrusions contain a myriad inclusions of anorthositic rocks ranging from xenocrystic particles to masses up to 400 m across. Some blocks show laminar texture and mineralogical banding; others are brecciated with a 'cement' of crushed and granulated feldspar. Grains are commonly around 8 cm long whereas the largest measured cleavage flake was 38 cm. Only rarely do the anorthosites contain orthopyroxene whereas augite, olivine and ore are common constituents. The feldspar average is ca. An_{65} and the full compositional range An_{57-85}. The Beaver Bay occurrences are most remarkably similar to those of Narssaq-Tugtutôq over 3000 km distant. The age of formation is probably similar in the two instances ca. 1.1 aeons (MOORBATH, SMALES & WEBSTER 1960 and GOLDICH et al. 1961). The Nain anorthosites of Labrador (WHEELER, 1960) are intruded by the layered alkalic gabbros of the Kiglapait intrusion (MORSE, 1962) and large inclusions of the anorthosite are found within the troctolitic gabbros. The anorthosite, according to MORSE is not younger than 1480 ± 50 my.

Layered sequences of coarse grained olivine-bearing anorthosites having great thickness and areal extent have been described by SIMPSON and OTTO (1960) from Angola. The anorthositic rocks outcrop for some 38,000 sq. km. In the region south of the Kunene river a sequence of massive anorthosite of extremely variable grain size and containing crystals of up to 20 cm is overlain by a thick succession of olivine anorthosite. The olivine anorthosite is coarsely banded, commonly laminate and lacks the great size range of the constituent plagioclase seen in the lower series, the crystals ranging from .5–10 cm. STONE and BROWN (1958) describing a traverse across the anorthosite body report cryptic variation from rocks with An_{76} and Fa_{16} to those with An_{55} and Fa_{35} and they note the occasional presence of feldspars up to 38 cm long.

In the Colony complex of Sierra Leone WELLS and BAKER (1956) describe a layered succession with evidence of formation through crystal accumulation including a 760 m layer of coarse grained anorthosite composed of scarcely zoned plagioclase crystals, of composition between An_{56-64} and accompanied by olivine Fa_{35}. Marked lamination is noted for some of the rocks and some protoclastic textures in the anorthosite are ascribed to filter-pressing.

In texture and composition, and with regard to such features as giant grain size and inclusions of anorthosite within anorthosite, the South Greenland anorthosites correspond closely to the examples cited above. The compositions of plagioclase and olivine also agree closely with those reported from several of the great Precambrian occurrences. However whereas many of the anorthosites described in the literature are orthopyroxene-bearing and not infrequently possessed of modal quartz, the Tugtutôq-Narssaq masses are of distinctly alkalic type. Possibly the closest analogy from the mineralogical point of view is to the Duluth-Beaver Bay anorthosites although even in these, occasional orthopyroxene has been recorded. In form the South Greenland anorthosite complex may resemble the Angolan mass with which STONE and BROWN compare the Rhodesian Great Dyke.

Inclusions of anorthosites comparable to those described in this paper are mentioned by HJELMQVIST (1950), brought up by the magnetite-olivinites of Taberg in south Sweden. These have plagioclase An_{50-62}, (average An_{55}) with some 8 % of olivine and its pseudomorphs and a further 9–10 % composed of augite, biotite, titanomagnetite and apatite. Within the Oslo alkaline province, a petrographic province very much akin to the Gardar province, OFTEDAHL (1953) describes an outcrop of anorthosite with feldspars of rather constant composition at An_{55}. The rock is ophitic and contains interstitial chlorite. OFTEDAHL finds this occurrence hard to explain but, in view of the many similarities between the Oslo and South Greenland provinces it seems possible that this anorthosite also was brought up from a more extensive body at depth by the Permian intrusives.

Inter-relationships of the gabbros, anorthosites, and syeno-gabbros.

The various basic rocks of Gardar age in the area appear to be the varied differentiation products of a common alkali basalt parent magma. There is however, no correlation between the time of intrusion and the degree of fractionation which had been achieved.

The precise composition of the initial magma of the olivine gabbro dykes is not known. However one may conclude with confidence that it was an alumina-rich alkali basalt which had already achieved moderate enrichment in iron and alkalies. In terms of the generalised basalt system, Ne-Ol-Cpx-Qz, discussed by YODER and TILLEY (1962) the composition may be assumed to have fallen close to the plagioclase position on the Ne-Qz edge and on the 'plane of critical undersaturation', i.e. the plane Ol-Plag-Cpx, within the tetrahedron. Iron enrichment is more pronounced than is usual in the alkali basalt-hawaiite-mugearite-trachyte line of liquid descent, a fact probably related to low initial oxidation state inhibiting crystallisation of magnetite until relatively late in the course of differentiation. YODER and TILLEY conducted heating experiments at 1 atmosphere on a number of basalts including a typical alkali basalt from Hualalai having 18.48 % normative olivine and 48.95 % plagioclase. From the melt olivine appeared at 1235°C, plagioclase at 1160° and clinopyroxene at 1155°. For initial intrusion of the olivine gabbro dykes the normative olivine was probably slightly over 20 % and the normative plagioclase, very approximately, 65 %. The sequence of crystallisation is deduced to be first (?) plagioclase, second (?) olivine; clinopyroxene not appearing until considerably lower temperatures were reached and after the appearance of apatite and magnetite. It should be pointed out that the Hualalai basalt is a considerably less aluminous alkali basalt

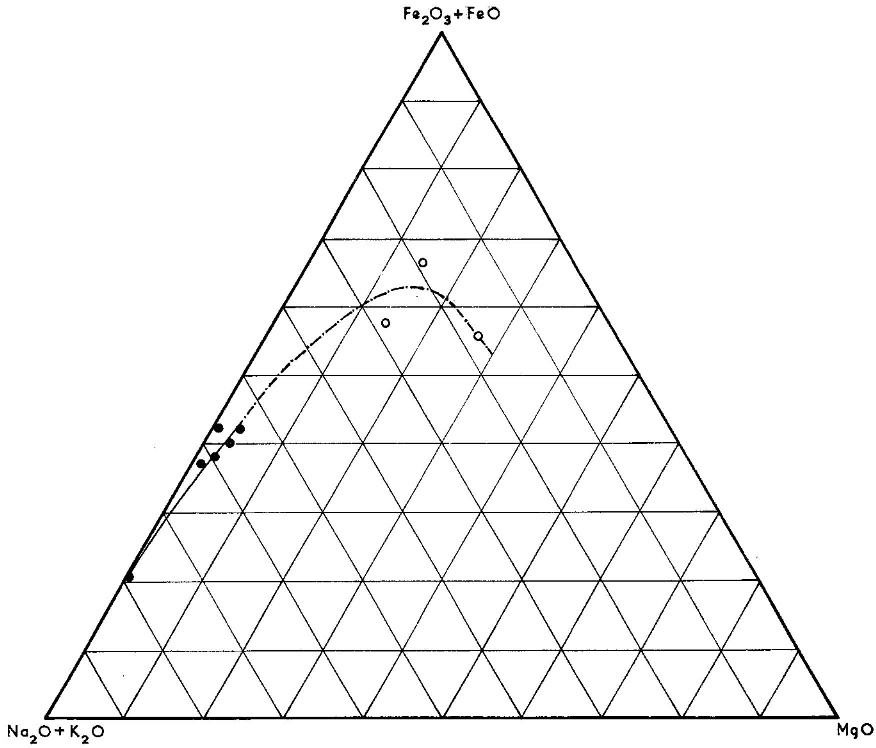

Fig. 15. Total iron – MgO – Alkali diagram for mean olivine gabbro analysis and Hviddal and Krydssø syeno-gabbro analyses. (open circles). Solid circles, differentiated nepheline syenite suite from the Hviddal dyke (Geology of Tugtutôq & neighbouring islands, Pt. IV. Upton, 1964).

type (Al_2O_3, 14.31 %) than those typical of the Gardar province (Al_2O_3, approximately 18 %). In the case of the anorthosites it is clear that the order of crystallisation was feldspar, then olivine, followed by clinopyroxene. The anorthosites appear to be orthocumulates derived from a high aluminous alkali basalt magma which had reached a state of iron and alkali enrichment appropriate to that of hawaiite.

The earliest feldspar to appear in the gabbroic rocks was ca. An_{72}. The plagioclase was accompanied by olivine, ca. Fa_{40} for much of the cooling history. The stability fields for ilmenomagnetite and apatite were reached by the cooling magma when the equilibrium feldspar was approximately An_{65}. In the main gabbros the crystallisation of feldspar and olivine was largely complete by the time the stability field for clinopyroxene was encountered but, in the Krydssø syeno-gabbro ferroaugite was precipitating abundantly alongside the (andesine-oligoclasic) plagioclase and was mostly earlier than the ferrohortonolite. It would seem reasonable to assume that the larvikites, which play a parental role in the petrogenesis of the many syenitic varieties in the province, were themselves residual fractions produced by the extensive crystal fractionation of large bodies of high alumina alkali basalt. However, rock types fully intermediate between the gabbroic→syeno-gabbroic rocks and the larvikites are very scarce and where seen, as in the basic ring-dyke at Kûngnât (UPTON, 1960) there is the strong possibility that they were produced by hybridisation. In spite of the large number of variegated intrusions on and around Tugtutôq there would appear to be a gap between rocks with silica content 40–48 % and those with silica 54–75 %. Nevertheless it is necessary to bear in mind the existence of such layered sequences as those of Kiglapait (MORSE, 1962) and Insch (READ, SADASHIVAIAH and HAQ, 1961) where continuous sequences are seen from olivine gabbros through syeno-gabbros into syenites of larvikitic type. At Kiglapait, Labrador, MORSE describes a sequence rising from troctolites with An_{62},Fa_{28} through rocks with An_{54},Fa_{36} into an upper zone characterised by cumulus augite and magnetite and continuing into a final 1 % of larvikitic syenite.

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PLATES

Plate 1.

Fig. 1. Disturbed structures in olivine gabbro cumulates from Panernaq, near Narssaq. Weakly banded orthocumulates, (right) disrupted along line of pre-consolidational normal faulting (centre and left).

Fig. 2. Small fault deforming well-banded olivine gabbro cumulate, southern 'trough', Itivdlip Sarqâ, Tugtutôq.

Fig. 1.

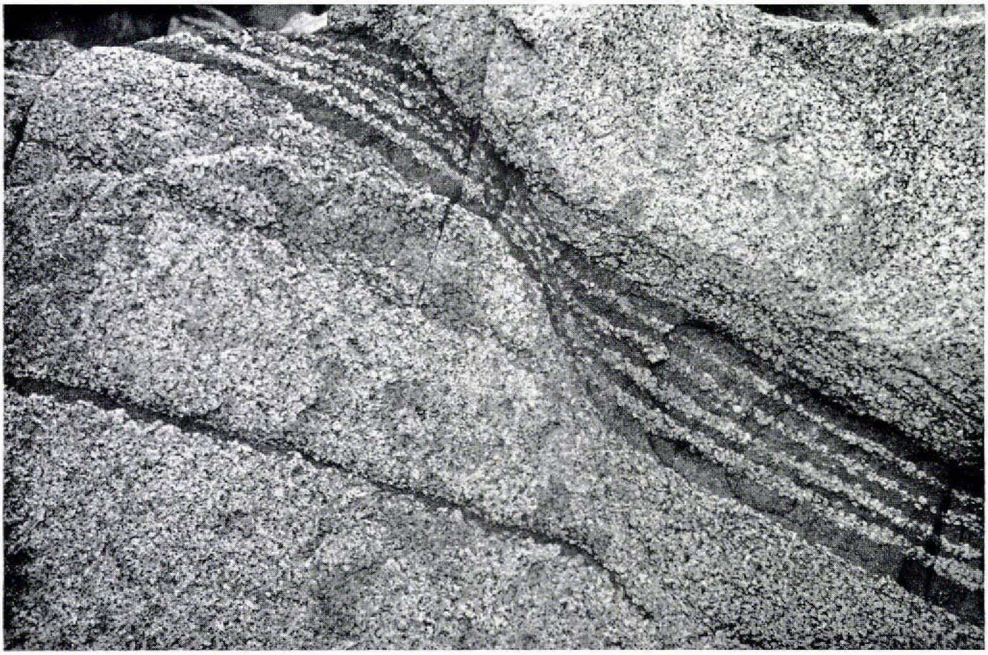

Fig. 2.

Plate 2.

Fig. 1. Moderately well-rounded blocks of early consolidated olivine cumulate within a matrix of leucocratic gabbro in axial zone of the central 'trough' feature at Itivdlip Sarqâ, Tugtutôq.

Fig. 2. Clearly defined strata of olivine cumulate thickening down-dip seen on the northern limb of a simple synformal structure in gabbro dyke ca. 4 km west of Itivdlip Sarqâ.

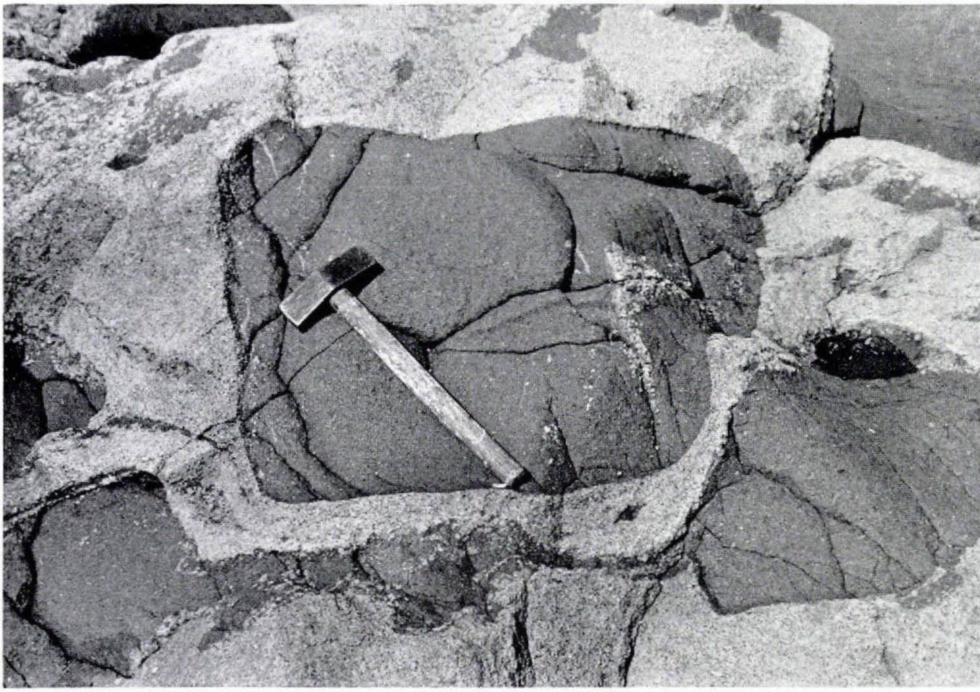

Fig. 1.

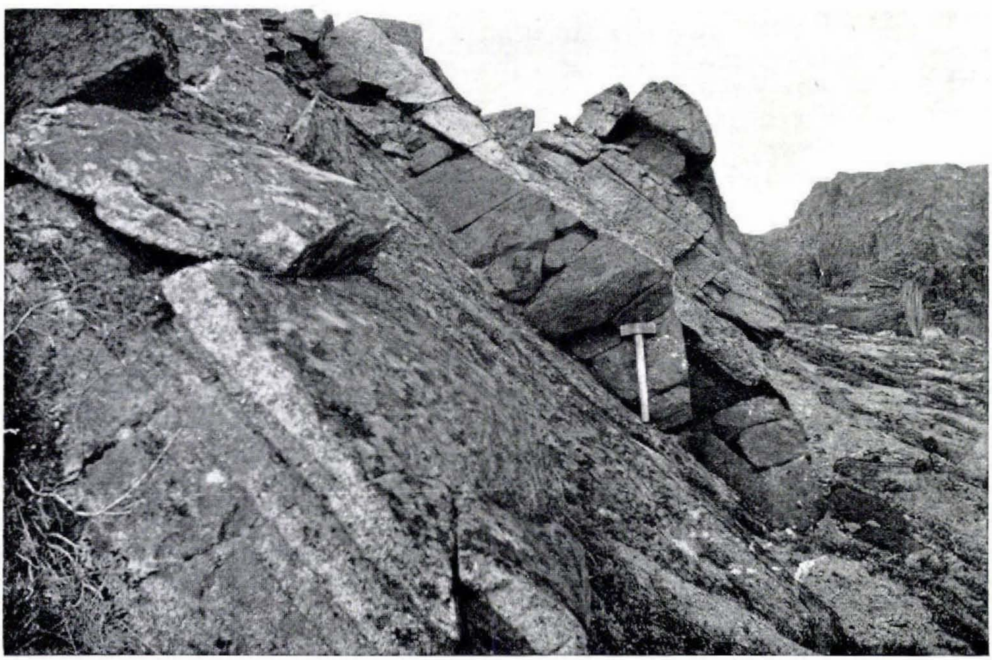

Fig. 2.

Plate 3.

Fig. 1. Mafic facies within the Assorutit anorthositic gabbros. Poorly laminated euhedral labradorite crystals with large olivine crystals in the interstitial areas.

Fig. 2. Hydrothermally altered olivine gabbro in Narssaq settlement enclosing plagioclase xenocrysts and xenoliths of cataclastic anorthosite. The dark chloritic mantles around the xenoliths are believed to be secondary after olivine.

Fig. 1.

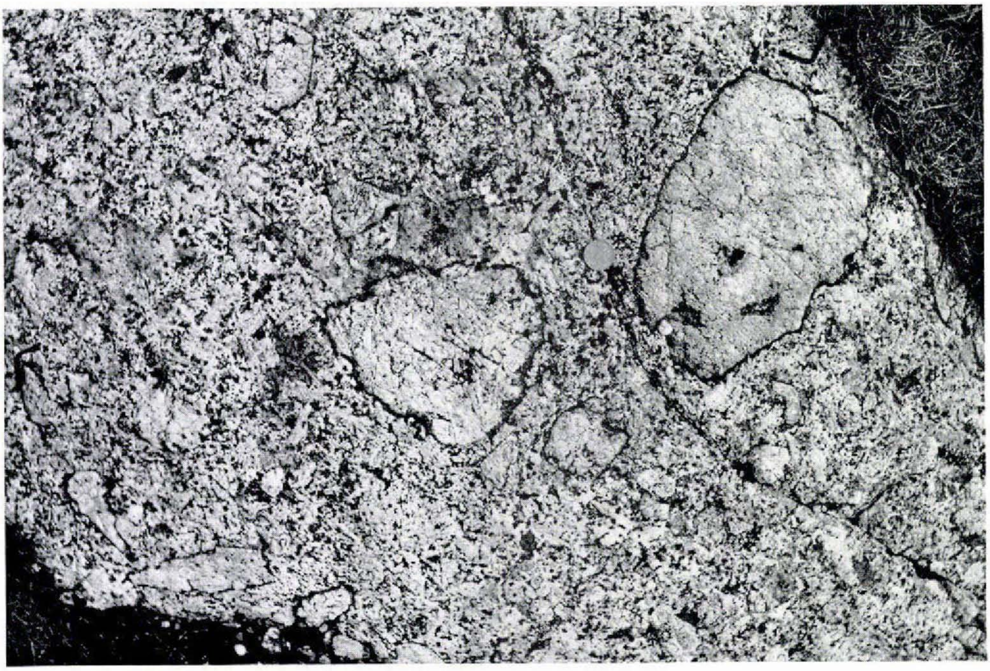

Fig. 2.

Plate 4.

Fig. 1. Plagioclase-olivine cumulate with intercumulus augite, ilmenomagnetite and biotite from leucocratic horizon in layered gabbros ca. 4 km west of Itivdlip Sarqâ. Uncrossed nicols, x 15.

Fig. 2. Olivine cumulate with intercumulus plagioclase, augite, ilmenomagnetite and biotite from melanocratic horizon adjoining the leuco-gabbro (see fig. 1 above). Uncrossed nicols, x 15.

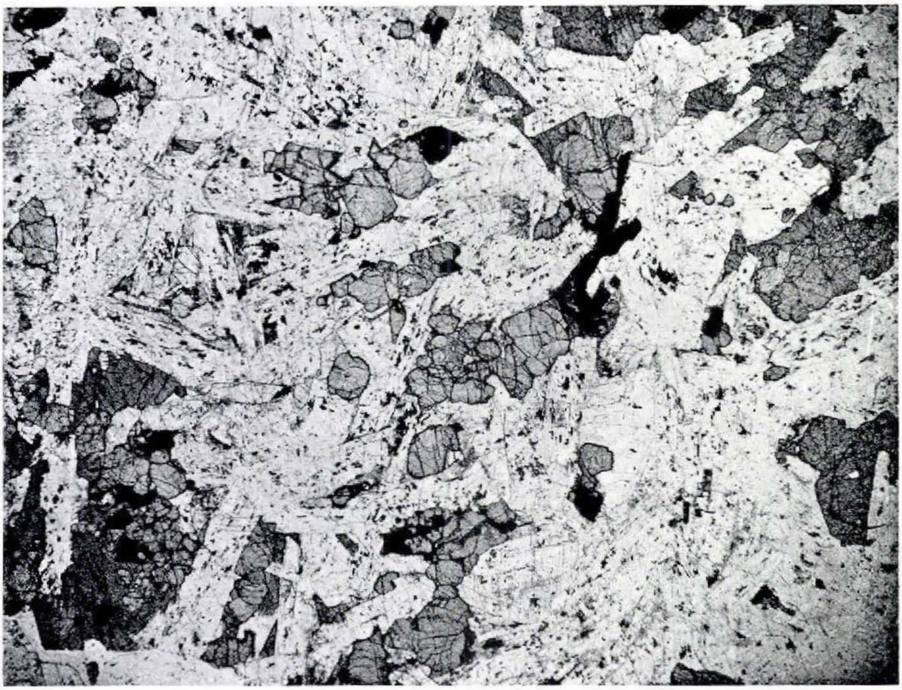

Fig. 1.

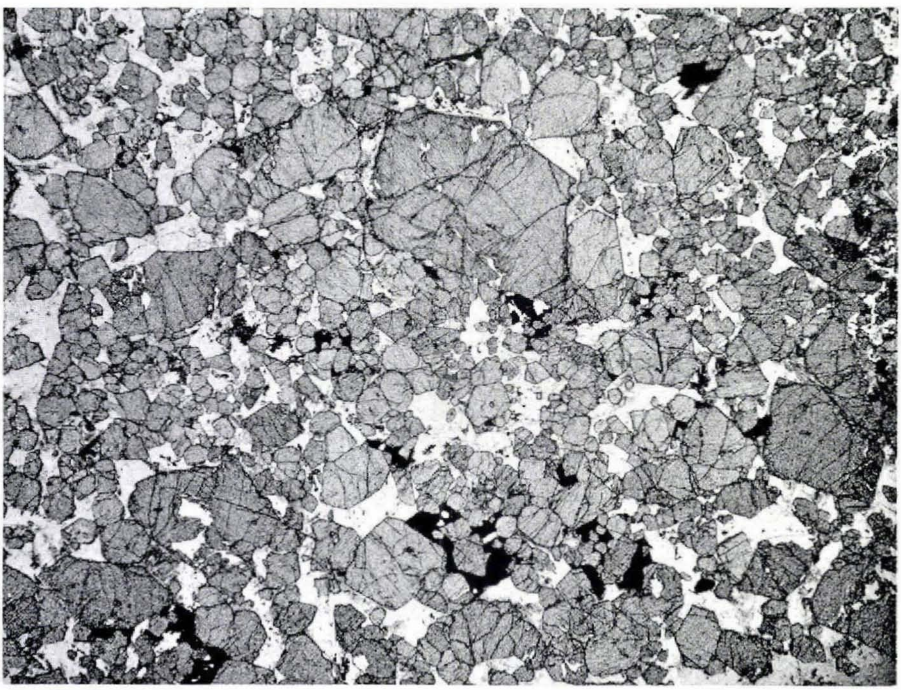

Fig. 2.

Plate 5.

Fig. 1. Photomicrograph of chilled facies gabbro 40452. Uncrossed nicols, x 15.

Fig. 2. Photomicrograph of plagioclase-olivine- ilmenomagnetite- (apatite) laminated cumulate from Sigssardlugtoq, Tugtutôq. x 10.

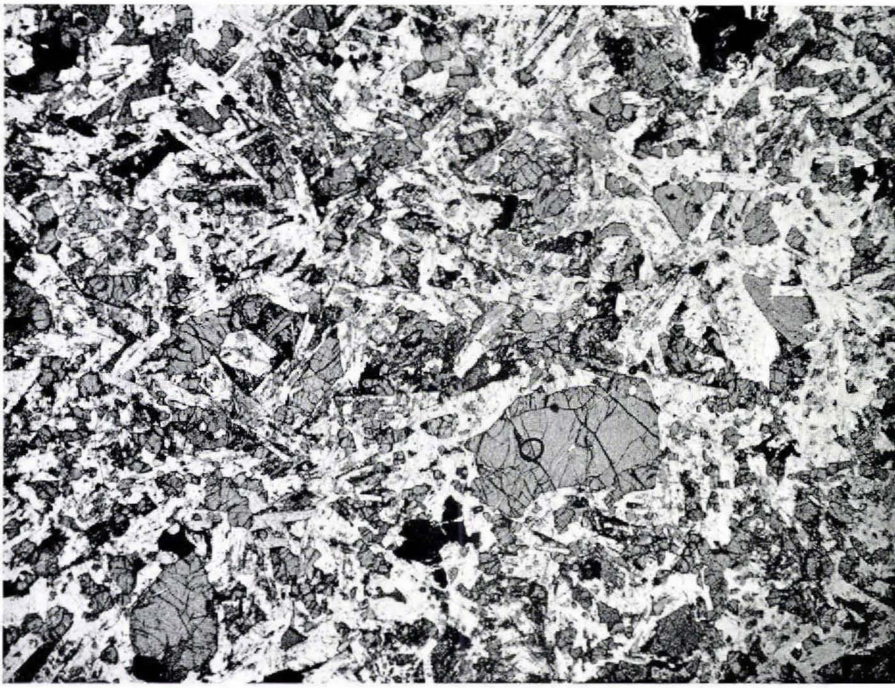

Fig. 1.

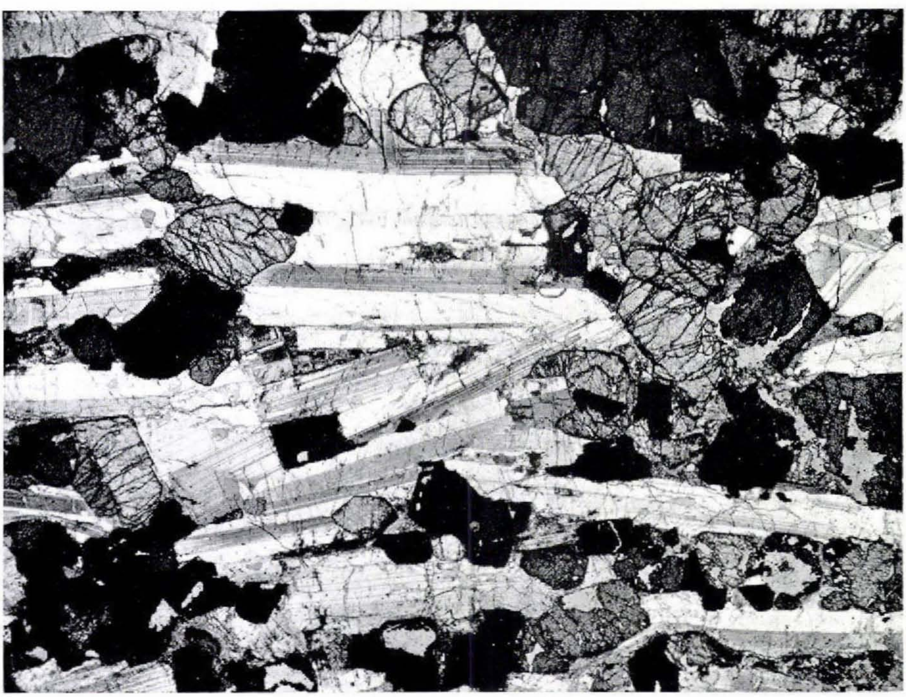

Fig. 2.

PART IV.

THE NEPHELINE SYENITES OF THE HVIDDAL COMPOSITE DYKE

Abstract.

A 20 km composite dyke ca. 550 m broad intruded early in the Precambrian Gardar igneous province of south Greenland, consists of a central intrusion of syenite and relatively narrow margins of syeno-gabbro. The syenite is later than the syeno-gabbro. The syenite varies along the dyke from a larvikite-type augite syenite at its WSW extremity to a soda-rich nepheline syenite in the ENE end. The feldspar composition range from WSW to ENE is in excess of $Or_{38.5}Ab_{61}An_{.5}$–$Or_{49}Ab_{51}An_{0}$ and the pyroxene changes from titanaugite towards nearly pure aegirine. Amphiboles vary from barkevikite-type hornblendes to ferrohastingsites and are absent in the more alkalic ENE dyke-rocks. Ferrohortonolite and lepidomelane are present in the syenites of the WSW outcrops. Sodium increases at least from Na_2O 5.84 $^0/_0$ to 10.37 $^0/_0$ and the Fe'''/Fe'' ratio rises towards the ENE. Ca, Mg, Ti and P decrease in this same direction. Six rocks from along the dyke were analysed for major and (by emission spectroscopy) for minor elements. Ba and Sr decrease rapidly in the ENE direction through ranges of at least 6000–10 ppm and 340–14 ppm respectively. In the six rocks examined the Rb/K ratio increases by a factor of over three and the Ga/Al ratio by a factor of over 2 in the ENE direction. Two pyroxene analyses are presented in addition to six partial analyses of feldspars. The observed longitudinal variation is believed to be due to cryptic and phase layering in an accumulitic suite of dyke syenites which has been tilted and eroded to reveal a sequence of perhaps 2000 m of layered rock. Neither the original base nor roof of the series is seen. The dyke is believed to have crystallised below a thick cover of volcanics under confining pressures in excess of 840 kg/cm² from a 'parental' larvikite magma. Crystallisation of this body is believed to have extended from above 750° to the region of 400° C.

PREFACE

The laboratory work on the Hviddal dyke rocks was carried out partly at the Mineralogical Museum, Copenhagen, and partly at the Division of Geological Sciences of the California Institute of Technology during the tenure of a research fellowship. The author is indebted to Mr. R. SOLLI and Mr. B. I. BORGEN for analyses carried out on behalf of the Greenland Survey, to Mr. D. MAYNES for analyses made at Caltech. and to Dr. E. L. P. MERCY for analyses performed at Edinburgh. A 'Penrose Bequest Grant' from the Geological Society of America, which was used in part to defray the costs of laboratory work at Caltech., is gratefully acknowledged. Further thanks are due to Mrs. ELIZABETH BINGHAM for carrying out the spectrographic analyses, to Mr. A. CHODOS for guidance in the X-ray fluorescence analyses, and to Dr. C. H. EMELEUS for many helpful discussions during the course of the investigation.

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University of Edinburgh.

B. G. J. UPTON.

April 1963.

INTRODUCTION

In part I of this series of publications concerning the geology of the Tugtutôq-Skovfjord region, a review was presented of the geological history, laying particular emphasis on the Precambrian intrusives of the Gardar volcanic cycle which are abundantly represented in the area. The area itself forms but a small part of the entire South Greenland province in which the Gardar igneous rocks occur. Together with the outline of the sequence of events, a brief petrographic description was given for each of 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 SW to WSW strike of the older granitic terrain. These dykes were followed after a period of unknown duration by a prolonged episode in which a multitude of co-genetic basic and alkalic dykes were emplaced parallel to the old established trends of the granodioritic and migmatitic country rocks. Igneous activity in the South Greenland province culminated in the formation of a number of central complexes, one of which is now exposed on the main island of Tugtutôq. However, it is with the nepheline syenites intruded as the central component of a large composite dyke on the island that this paper is concerned. This dyke was among the earliest of the ENE-WSW trending Gardar dykes. In all likelihood it was intruded later than and below a thick sequence of early Gardar basic volcanics and intercalated sandstones, a part of which has been preserved in the nearby Narssaq-Igaliko area. The nepheline syenite dyke is distinctly older than the intrusive rocks of the Ilímaussaq complex (Sørensen, 1958) which lie in line with the presumed and unseen east-north-easterly continuation of the dyke. The early Gardar nepheline syenites of Grønnedal-Íka (Callisen, 1943 and Emeleus, 1963) and the Igaliko area (Ussing, 1912) may possibly have been contemporaneous with the Hviddal syenite. The dyke forms a conspicuous ENE-WSW trending feature along the centre of Tugtutôq island. It can be followed for some 20 km from the coastline opposite Narssaq to a blunt termination against an older line of crushing in the pre-Gardar granodiorites. The dyke maintains a moderately constant width of 500–600 m. The composite nature of the dyke over the greater part of its outcrop is attributed to the intrusion of two separate pulses of contrasted magmas, the first admitting an iron-rich alkali gabbroic or syeno-gabbroic magma and the second admitting syenite magma. The earlier basic phase (UPTON, 1964) is now seen as relatively narrow zones up to 100 m broad on either side of the massive central unit of leucocratic syenites. The latter are not chilled against the syeno-gabbro and there is evidence that the second intrusion occurred before the crystallisation of the first was complete (see Pt. I). Whereas the syeno-gabbroic margins are moderately homogeneous along the length of the dyke the syenitic interior changes in composition and texture from a slightly undersaturated augite syenite at its west-south-westerly extension to a strongly undersaturated soda-rich rock as it approaches the Ilímaussaq intrusive area to the ENE. Whether the dyke formerly continued beyond the Tugtutôq area as far as the area now occupied by the Ilímaussaq nepheline syenites is not known. The intervening ground is now partly beneath the waters of Narssaq sound, partly occupied by later intrusions of gabbro and saturated syenites and also by the Gardar volcanics.

At one point on Tugtutôq the dyke is displaced sinistrally by later Gardar transcurrent faulting and at another it is displaced by a broad gabbroic dyke which cross-cuts it at an acute angle. In central Tugtutôq over 3 km of the dyke were removed by abyssal stoping or by ring-faulting and subsidence during the emplacement of the Tugtutôq quartz syenite ring-complex.

One of the earliest intrusions of the central complex is a quartz syenite ('Unit 2') that lies across the former course of the Hviddal dyke (UPTON, 1962, p. 45). That the quartz syenite intrusion transected the basal Gardar unconformity is clear from the fact that it contains large numbers of inclusions of pre-Gardar granites together with masses of the Gardar quartzites and basalts. Fragments of small mid-Gardar alkalic and basic dykes are also present. However, and in spite of careful search, no inclusions of Hviddal syenite or syeno-gabbro have been found although from the situation of the intrusion, such inclusions might well be expected to occur abundantly. From the behaviour of the other inclusions, the possibility of their having been totally assimilated must be discounted. The conclusion drawn was that the Hviddal dyke had its upper termination below the level of the unconformity and that all blocks of the syenite and syeno-gabbro lie below the present level of erosion in the Unit 2 intrusion. On the tentative correlation of the Hviddal syenites with the early but post-volcanic phase syenites of Igaliko (pers. comm. C. H. EMELEUS) it may be supposed that the Gardar volcanic series is older than the Hviddal intrusions and that it provided a thick cover above them at the time of their crystallisation.

The Hviddal syenites form low ground at ca. 10–12 m above sea-level for much of the outcrop, rising to a culmination at 110 m on a low ridge of foyaitic syenite towards the ENE. Compositional variation to the WSW of the central Tugtutôq fjord is indeterminate owing to the extreme scarcity and badly rotted nature of the exposures. The syenites tend to be massive, non-vesicular and uniformly textured away from the rather variable and coarse-grained marginal zones. Mineralogical banding and laminar texture are rare or absent although small vertical structures up to 2 m in diameter, defined by concentric cylindrical mafic bands, have been noted at three localities between the central Tugtutôq fjord and the central complex. One of these remarkable pipe-structures is illustrated in Part I (p. 19). Irregular development of pegmatite with radial growths of aegirine occurs in the marginal zones.

Petrography of the syenites.

The augite or ferroaugite syenites of the WSW consist largely of feldspar in thick sub-idiomorphic tablets up to 5–6 mm long, associated with clusters of black lustrous ferromagnesian minerals and enclosing small acute-angled interstitial areas of nepheline and zeolite. The interstititial areas of feldspathoid and zeolite increase in volume as the dyke is followed to the ENE. In the syenites occurring east of the cross-cutting olivine gabbro giant dyke the large interstitial areas rich in zeolite remain conspicuous but it would appear in these rocks that nepheline was crystallising in subhedral crystals at a relatively early stage in the crystallisation history. The appearance of early nepheline coincides with the increase in modal content of zeolites and feldspathoids from ca. 15 % to 35–40 %.

The ferromagnesian minerals of the syenites are clinopyroxenes, alkali hornblendes, ferriferous olivines, dark micas and iron-titanium oxides. All five phases are to be found in the westerly facies augite syenites although olivine becomes scarcer towards the ENE and is entirely lacking in the syenites ENE of the central ring-complex. Biotite too decreases in this direction and is absent from the nepheline-rich foyaites of the ENE. It is highly probable that the poor exposure of syenites in the west-south-western part of the dyke is attributable to the relatively high content of mica and olivine. Experience with such relatively mafic syenites from other South Greenland localities has shown that they are highly susceptible to weathering. Hornblende, like the biotite, becomes rarer and eventually disappears as the dyke becomes more alkalic in character towards the ENE until aegirine, with a little associated magnetite, is left as the principal ferromagnesian mineral.

The increase of zeolites and low-density feldspathoids such as sodalite is reflected in the lowering of the specific gravity of the rocks from ca. 2.75 in the region of the central fjord to ca. 2.60 in the ENE.

The dyke is almost unaffected by any metasomatism or metamorphism due to the later intrusions of gabbro and quartz syenite. In the remnant block of nepheline syenite partially enclosed between the eastern and western centres of the central ring-complex, nepheline and analcite are preserved fresh in specimens collected within two or three metres of the quartz syenite contacts.

The rock on which Williams (1890) based his name pulaskite contained cryptoperthite, arfvedsonite, 'diopside', biotite, nepheline, with sphene, apatite and rare sodalite. He emphasized that the nepheline is merely a characteristic accessory and not essential in defining the rock. With some qualification, pulaskite is a name that could be employed in describing the nepheline syenites from the middle stretches of the dyke in which the principal components are alkali feldspar, alkali hornblende, clinopyroxene and biotite together with some nepheline. However the more westerly rocks carrying crypto- and antiperthite, ferrohortonolite, ferroaugite, barkevikite, lepidomelane, ilmenomagnetite and apatite are clearly related to the type larvikites of the Oslofjord. They differ from these principally in having finer grain size, more thorough unmixing of the (less calcic) alkali feldspar, no primary oligoclase, and in being generally less aluminous than the Norwegian rocks. The sequence displayed along the dyke is more immediately related to the rock-series of the Ilímaussaq complex where Ussing employed the terms augite-syenite, pulaskite, foyaite and lujavrite (among others) in his descriptions. If specific names are to be used arbitrarily in the description of a gradational suite of rocks the dyke could be described as transitional from larvikite (or augite syenite), through pulaskite and foyaite and tending, in the most easterly varieties towards an aegirine-lujavrite.

The homogeneous syenites from the coastal exposures beside the central Tugtutôq fjord are mesocratic and moderately coarse grained. The feldspars are white, sometimes showing a silvery schiller, and are sub-idiomorphic with tabularity parallel (010). The feldspars are antiperthitic for the most part although cryptoperthitic crystal centres are common. The plagioclase component is twinned on the albite law and, to a lesser extent on the pericline law. The bulk composition (specimen 30714), determined by analyses for Na, K and Ca is $Or_{38.5}Ab_{61}An_{.5}$. The pyroxene, which like the feldspar appears to have crystallised early, occurs in smaller idiomorphic prisms displaying a distinct zoning. Those from west of the fjord are pinkish, slightly pleochroic titanaugites whereas those from the eastern side of the fjord show a colour zoning from pinkish centres to green peripheral zones of alkalic pyroxene. In specimen 30714

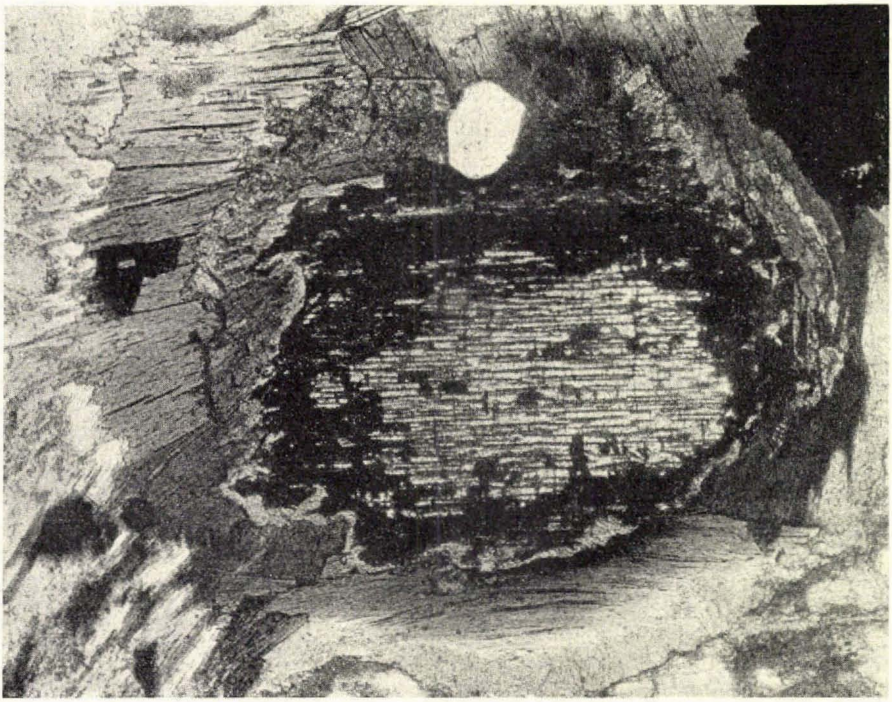

Fig. 1. Reaction zones around a fayalitic olivine in syenite (specimen 30714). The olivine (centre) contains oriented plates of magnetite and has been largely oxidised marginally to magnetite. This oxide zone is surrounded by a narrow zone of ferrohastingsite which in turn is mantled by a relatively wide zone of biotite. An Apatite crystal, upper centre, lies within the amphibole-biotite zones. Plane polarised light. × 50.

from east of the fjord the 2V range is 51–64° from core to margin, this corresponding approximately to an increase in extinction angle from 50–62°. This pyroxene was separated and analysed, (table 6), giving an average composition of $Wo_{44}En_{15}Fs_{35}Ac_{6}$. Iron-rich olivines, also of early crystallisation, are considerably less abundant than the pyroxenes and are frequently much oxidised to magnetite and, more rarely, pseudomorphed by 'iddingsite'. 2V measurements indicate a composition of ca. Fa_{89}. In some olivine crystals conspicuous plates of magnetite lie parallel to (001). (Fig. 1).

In addition to the feldspar, pyroxene, and olivine it appears that ilmenomagnetite and apatite also precipitated at relatively high temperatures. Specimens 30714 and 30743 were polished and examined in reflected light when it was seen that the ilmenomagnetite crystals, rarely exceeding 1 mm diameter, consist of coarse, moderately straight-edged ilmenite lamellae set in a magnetite host. With high power objectives and oil immersion the magnetite was also found to possess an exceedingly fine grid of ilmenite lamellae parallel to the (111) planes of the host. Ulvöspinel was sought after but not found. Commonly the composite oxide grains are grown around minute sulphide crystals ($\sim$ .01 $\rightarrow$ .05 mm). These tend to be rounded (early droplets?) and are generally of homogeneous pyrrhotite, often associated with still smaller particles of chalcopyrites. Frequently the pyrrhotite crystals are mantled and veined by magnetite, suggesting that some of the magnetite grew as reaction zones by oxidation of the sulphide.

Amphibole reaction zones are developed about the pyroxenes and olivines and lepidomelane fringes frequently envelop the ilmenomagnetite. The pyroxenes are typically surrounded by barkevikitic hornblende ($\gamma \wedge c \sim 26°$, α light brown, β brown and γ deep sepia to almost opaque) which then zones out into blue-green hornblende ($\gamma \wedge c$ up to 38°, α and β green and γ deeper blue-green). Interstitial nepheline is clear and fresh in some specimens, cloudy and altered to 'gieseckite' micaceous areas in others. Its composition (30714) estimated by means of the X-ray diffraction data published by HAMILTON and MACKENZIE (1960), is $Ne_{80}Ks_{14}Qz_{6}$. Small quantities of birefringent analcite and natrolite are also present, the latter occurring in radiating clusters associated with the nepheline and analcite.

Exposures of fresh nepheline syenites occur a few kilometres ENE of the 30714 locality on the northern side of the central complex. These syenites are free of olivine and have distinctly greener pyroxenes and amphiboles. In specimen 50241 (analysed) the feldspars are largely cryptoperthitic ($\alpha \wedge$ a 11–14°, mainly ca. 13°) and have a bulk composition $Or_{43}Ab_{57}An_{0}$. The pyroxenes grade outwards from mildly pleochroic cores of ferrohedenbergite to strongly pleochroic marginal zones of aegirine-augite (α bluish-green, β green, γ yellow-green), the extinction angle increasing outwards from 59–76°. Ilmenomagnetite is relatively abundant as small idiomorphic crystals largely enclosed within the pyroxene. The hornblende, grown mostly around the pyroxene has an extinction angle $\gamma \wedge c$ of ca. 27° with α light brown, β greenish-brown and γ deep brown. Some biotite is present and there are small crystals of apatite and sphene. Interstitial to the feldspars are clusters of fresh subhedral nephelines, $Ne_{78}Ks_{17}Qz_{5}$ (X-ray diffraction), set in a slightly turbid matrix composed of analcite and a zeolite with negative elongation and nearly straight extinction (thomsonite?) which appears secondary after the analcite.

Of the three-and-a-half kilometres of dyke between the central complex and the cross-cutting gabbro dyke relatively little is known since it lies almost wholly beneath the waters of the Store Pilesø. However there are occasional exposures on the small islands and in one or two places along the lake shores. To judge from these the syenite along

Table 1.
Analyses of nepheline syenites from the Hviddal composite dyke.

	30743†	30714	50241	30640	30681	30676†
SiO	57.03	56.53	58.53	57.51	54.17	56.48
Al_2O_3	17.48	16.61	17.42	16.54	19.34	20.05
Fe_2O_3	1.97	1.66	3.08	4.32	6.00	3.86
FeO·	5.54	7.10	4.56	4.56	1.86	.77
MgO	.68	.83	.47	.27	.24	.05
CaO	3.28	3.41	2.43	2.37	1.74	1.16
Na_2O	5.84	5.98	5.82	6.15	7.71	10.37
K_2O	5.00	5.22	5.74	5.89	5.32	5.42
H_2O^+	1.59	.94	.64	1.19	2.70	1.65
H_2O^-	—	.08	.08	.20	.12	—
TiO_2	1.14	1.29	.71	.54	.37	.09
P_2O_5	.29	.36	.16	.10	.10	.02
MnO	.16	.19	.17	.20	.17	.10
S	.06	.08	nd	nd	.02	.02
Cl	.01	.02	nd	nd	.02	.14
	100.07	100.30	99.81	99.84	99.88	100.18
–0 for	.02	.03			.01	.05
S & Cl........	100.05	100.27			99.87	100.13
$\frac{Na_2O}{Na_2O + K_2O}$	.538	.534	.504	.487	.592	.870
$\frac{FeO}{FeO + Fe_2O_3}$	.74	.81	.60	.51	.24	.17
"Solidification Index"*	3.52	3.99	2.39	1.27	1.14	.20
"Agpaitic index"**	.62	.67	.66	.73	.68	.79
Density	2.74	2.75	2.74	2.69	2.67	2.60

† analyses on samples dried at 110°C for 2 hours.

$* = \frac{MgO}{MgO + FeO + Fe_2O_3 + Na_2O + K_2O}$ (Kuno *et al.* 1957).

$** = \frac{K_2O + Na_2O}{Al_2O_3}$ (*vide* Ussing, 1912 and Sørensen, 1960).

Analyses 30743 & 30676 by The Geochemical Laboratory, Grant Institute of Geology, Edinburgh; 30714 & 30681 by R. Solli, 50241 by D. Maynes and 30640 by B. I. Borgen.

this sector is somewhat altered. The feldspars are typically pink and red haematite staining is still more strongly seen in the interstitial areas occupied by minerals secondary after nepheline. In some localities signs of crushing were noted and development of epidote becomes conspicuous. However specimen 40499, a coarse variant from a tiny island in the lake,

Table 2. C. I. P. W. Norms.

	30743	30714	50241	30640	30681	30676
Or	29.9	30.8	34.4	36.6	32.7	33.2
Ab	43.2	38.6	43.8	48.1	36.2	28.1
An	2.6	3.3	4.4	—	2.6	—
Ne	3.8	8.1	3.3	3.2	16.7	25.5
Ac	—	—	—	—	—	11.5
Ns	—	—	—	—	—	.5
Wo........	—	—	—	—	1.6	—
Di	7.4	9.6	5.8	.7	1.3	.8
Ol.........	7.7	5.4	2.2	5.2	—	—
Mt	2.6	2.3	4.4	4.8	5.5	—
Il	2.1	2.4	1.4	1.1	.8	.1
Hm	—	—	—	—	2.3	—
Ap	.7	1.0	.3	.3	.3	.3
Feldspar	$Or_{39.5}Ab_{57}An_{3.5}$	$Or_{42.5}Ab_{53}An_{4.5}$	$Or_{41.5}Ab_{53}An_{5.5}$	$Or_{43}Ab_{57}$	$Or_{49}Ab_{51}$	$Or_{54.5}Ab_{45.5}$
Cpx	$Wo_{50}En_{9.5}Fs_{40.5}$	$Wo_{48}En_{8}Fs_{44}$	$Wo_{48}En_{10}Fs_{42}$	$Wo_{44}En_{5}Fs_{51}$	$Wo_{54}En_{0}Fs_{46}$	$Wo_{3}En_{0}Fs_{3}Ac_{94}$
Olivine	$Fo_{18.5}Fa_{81.5}$	$Fo_{15}Fa_{85}$	$Fo_{18}Fa_{82}$	$Fo_{8}Fa_{92}$	—	—

Modal analyses.

	30743	30714	50241	30640	30681	30676
Feldspar	73.6	74.4	79.2	72.4	41.4	56.8
Nephelinе		4.0	7.6	5.0	2.5	24.1
Gieseckite	11.5	—	—	—	10.6	—
Analcite		1.4	.1	2.8	27.1	9.0
Zeolite*, prehn.	—	—	—	7.0		
Sodalite.......	—	—	—	—	tr	1.9
Cancrinite.....	—	—	—	—	tr	—
Olivine	.8	.6	—	—	—	—
Pyroxene	2.8	5.5	4.3	8.1	14.6	8.2
Amphibole	5.6	9.8	5.0	.5	—	—
Mica	1.5	2.1	.5	1.7	—	—
Fe.Ti Oxide ...	3.0	1.3	3.0	2.5	3.8	—
Apatite	1.2	.9	.1	tr	—	—
Sphene	—	—	.2	—	—	—

* i. e. other than distinguishable analcite.

is entirely free of alteration. Texturally the rock is atypical, lacking the strongly tabular habit in the feldspars and possessing some 40 % nepheline in contrast to the typical situation for this reach of the dyke where there are only 15–20 % of nepheline and its by-products in isolated interstitial patches. The feldspar, $Or_{41}Ab_{59}An_{0}$ occurs alongside a translucent and greenish nepheline, determined as $Ne_{73}Ks_{23}Qz_{4}$. Some of the nepheline is present as single crystals 2–3 mm across but the majority of the nepheline areas are composed of a mosaic of small subhedral crystals. Early and strongly zoned aegirine-augite, studded with small crystals of magnetite, is to a small extent replaced by hornblende, pleochroic from α light yellowish brown to γ deep green. Minute crystals of apatite and scattered anhedral grains of fluorite occur.

At the eastern end of the lake, where the syenites are pinched out against the younger giant dyke of olivine gabbro, further limited exposures of very fresh nepheline syenite appear. These too appear atypical in texture and may be described as sub-pegmatitic, the pyroxene occurring in sheave-like aggregates. Strongly pleochroic aegirine-augite occurs together with antiperthite, $Or_{46}Ab_{54}An_0$, clear nepheline, $Ne_{73}Ks_{23}Qz_4$ and large wholly isotropic grains of sodalite (specimen 40494). As accessories in this rock occur diminutive yellow cubes (isotropic), probably of a pyrochlore mineral, and small rare grains of isotropic to slightly birefringent material, probably melanite.

Table 3.

Comparisons (A)

Of the more westerly facies of the Hviddal syenite with other basic syenites from south Greenland.

	30714	1	2	3	4
SiO_2	56.53	55.79	53.3	53.71	57.24
Al_2O_3	16.61	15.76	14.8	15.37	17.14
Fe_2O_3	1.66	1.60	2.8	3.28	2.74
FeO	7.10	7.56	6.1	5.72	4.32
MgO	.83	.41	2.9	1.58	1.55
CaO	3.41	3.70	5.1	5.20	3.95
Na_2O	5.98	7.72	6.5	6.84	4.56
K_2O	5.22	4.34	4.5	4.11	6.02
H_2O^+	.94	.18	} .6	.45	.20
H_2O^-	.08	.34		.33	.21
TiO_2	1.29	1.81	2.2	3.40	1.68
P_2O_5	.36	.36	.6	.52	.30
MnO	.19	.14	.2	.14	.11
S	.08	nd	nd	nd	.09
Cl	.02	none	nd	nd	nd
CO_2	nd	none	nd	nd	.00
BaO	nd*	nd	.5	nd	.06
	100.30	99.71	100.1	100.65	100.17

* see spectrographic data, p. 66.
1. Augite syenite, Nunasarnausak, Ilímaussaq. N. V. Ussing (1912).
2. Chilled augite syenite, Ilímaussaq. Unpublished analysis: Analyst, E. Hamilton.
3. Augite syenite, Korok, Igaliko. N. V. Ussing (1912).
4. Syenite from the eastern border group, Kûngnât (no. 26135). Analys, B. I. Borgen.

Table 4.

Comparisons B
Of the eastern foyaitic syenite with other foyaite types from south Greenland.

	30676	5	6	7	8
SiO_2	56.48	55.65	56.31	53.53	52.83
Al_2O_3	20.05	19.79	20.11	19.69	16.03
Fe_2O_3	3.86	4.98	3.93	5.09	10.61
FeO	.77	3.03	1.45	2.83	1.12
MgO	.05	.52	.36	none	.04
CaO	1.16	1.40	.62	1.87	.70
Na_2O	10.37	7.60	8.76	9.61	10.65
K_2O	5.42	5.27	4.65	5.23	3.38
H_2O+	1.65	.82	1.13	.25	3.06
H_2O^-		.04		.34	
TiO_2	.09	.15	2.82*	.44	.11
P_2O_5	.02	.22	.13	.31	—
MnO	.10	.15	.60	.24	.29
S	.02	.03	nd	nd	nd
Cl	.14	nd	.15	.04	—
CO_2	nd	.28	nd	.40	—
BaO	—	.09	nd	nd	nd
ZrO_2	—	—	—	—	1.31
	100.18	100.02	101.02	99.87	100.13

5. Nepheline syenite porphyry, Ekaluit, Grønnedal. K. Callisen (1943).
6. Foyaite, Naujakasik, Ilímaussaq. N. V. Ussing (1912).
7. Foyaite, Korok type, Igaliko. N. V. Ussing (1912).
8. Aegirine-lujavrite (mean of three analyses), Ilímaussaq. N. V. Ussing (1912).

Where the dyke reappears on the east side of the olivine gabbro dyke, the very fresh, non-epidotised syenites contain idiomorphic feldspar in which the flattening parallel (010) is pronounced. The feldspars are antiperthitic with a bulk composition (specimen 30640) $Or_{43}Ab_{57}(An_0)$. The main ferromagnesian component is deep green aegirine-augite showing only slight pleochroism. Zonation is again conspicuous with $\gamma \wedge c$ increasing from centre to margin from 60–71°. Hornblende is scarce. Biotite, often fringing the hornblende, displays a colour zoning with the inner parts pleochroing red-brown parallel α in contrast to the outer zones where the colour is pale yellow. Absorption is intense parallel β and γ. Relatively large fresh nephelines occur interstitially to the feldspars marginally altering to 'gieseckite'. Interstitial analcite is also present. The analcite is of the 'eudnophitic' variety, birefringent with patchy irregular extinction and with the cubic cleavage pattern well developed.

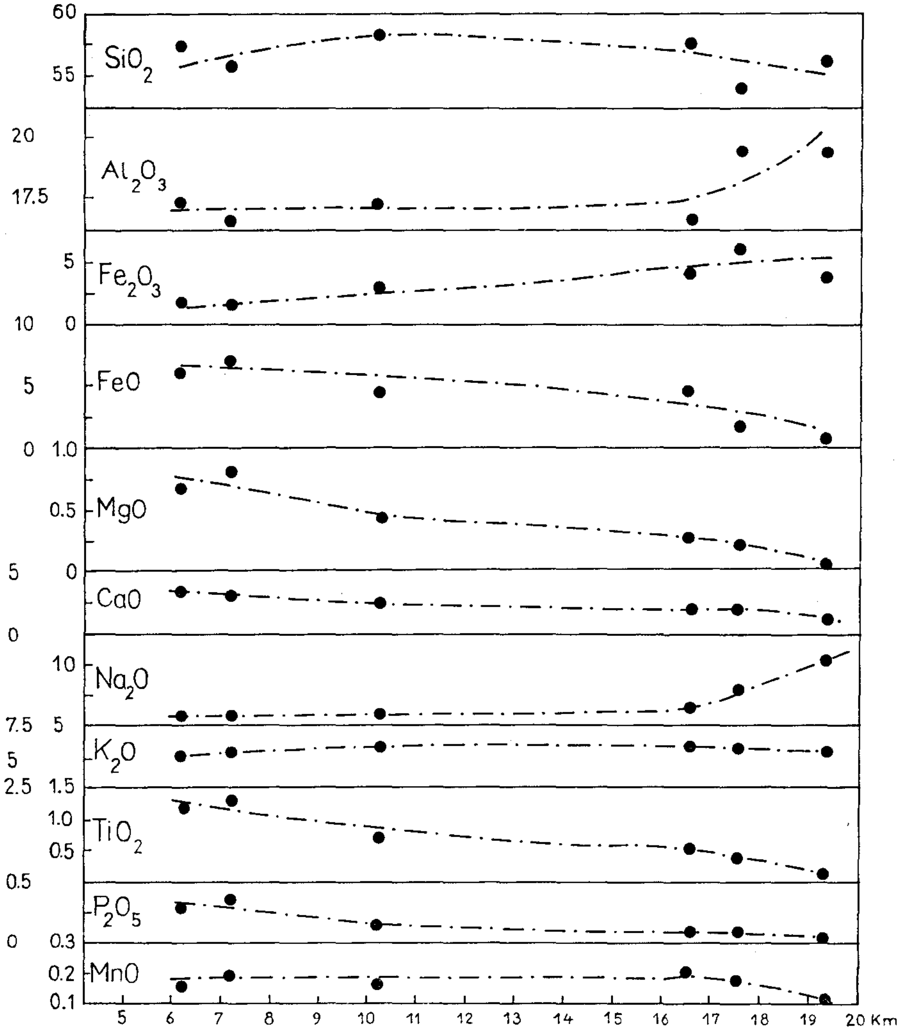

Fig. 2. Chemical variation along the dyke. The lower scale indicates distance in kilometres from the WSW termination of the dyke.

Between 500 and 600 m east of the 30640 locality the rock type undergoes a marked change with the appearance of substantial quantities of well-formed nepheline. Specimen 30648 is fairly typical of these feldspathoid-rich syenites. The thin feldspar tablets (~ 4 mm across and ~ .75 mm thick) have an overall composition of ~ $Or_{49}Ab_{51}$ An_0. Idiomorphic prisms of nepheline, up to 6 mm across are, for the most part, pseudomorphed by 'gieseckite' and by prehnite exhibiting a pleochroism (possibly due to minute inclusions) grey-brown parallel to length and light-fawn at right angles to length. The pyroxenes, containing abundant small crystals of magnetite, are distinctly interstitial to the feldspars and nephelines in contrast to their more idiomorphic form in the western facies rocks. The aegirine-augite (yellow-green parallel γ to deep green parallel α) has an extinction angle $\gamma \wedge c$ extending from ca. 89° in the cores to 77° in the outer zones, i. e. the angle now shows a decrease from centre outwards. This corresponds approximately to an observed change in $2V\alpha$ from core to margin of 68° → ~ 60°. Pyroxene separated and freed, as far as possible, of all magnetite was analysed (Table 5).

Table 5. Analyses of clinopyroxenes from nepheline syenites.

	30681	30714	1
SiO_2	48.77	48.43	50.74
Al_2O_3	2.08	2.17	1.99
Fe_2O_3	22.27	1.91	1.74
FeO	5.62	18.04	13.27
MgO	.58	5.69	8.98
CaO	7.77	20.28	21.33
Na_2O	9.88	.99	nd
K_2O	.17	.29	nd
H_2O	.00	.00	.11
TiO_2	.42	.92	.93
MnO	.50	.46	.36
	98.06	99.18	99.45

Analyst, D. Maynes.

No. of atoms to six oxygens;

		30681	30714	1
Z	Si	1.940	1.920	1.954
	Al	—	.067	.090
	Ti	.002	—	—
WXY	Al	.096	.033	—
	Fe'''	.660	.057	.051
	Fe''	.186	.601	.425
	Mn	.017	.017	.012
	Mg	.034	.340	.517
	Ca	.330	.866	.880
	Na	.761	.077	—
	K	.009	.014	—
	Ti	—	.026	.028
Z		1.942	1.987	2.044
WXY		2.093	2.031	1.913

30681: Aegirine(-augite) from eastern end of dyke. 30714: ferroaugite from western facies of dyke. 1: augite from chilled marginal syenite at Ilímaussaq.

The optics of the outermost zones, with $2V\alpha\ 60°$ and $\alpha\wedge c$ of $\sim 13°$ indicate a composition close to pure aegirine. Biotite and hornblende are scarce or absent in this and all the more easterly foyaite-type syenites. Conspicuous intergranular areas of reddish material constitute approximately one third of the rock. This material is found to be a fine grained intimate

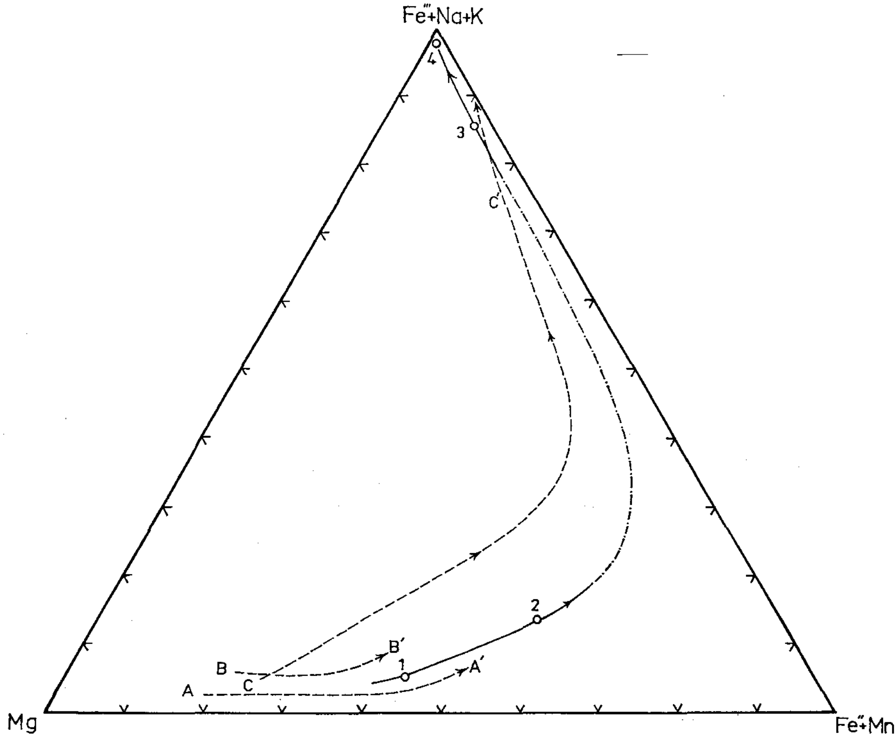

Fig. 3. Pyroxene crystallisation course. Open circles indicate compositions of analysed clinopyroxenes from Hviddal and Ilímaussaq nepheline syenites. 1, augite from chilled augite syenite, Ilímaussaq. 2, ferroaugite from Hviddal, specimen 30714. 3, aegirine from Hviddal, specimen 30681. 4, aegirine from Ilímaussaq lujavrite (Sørensen, 1962, p. 192). Curve C–C', Sakhalin trend (Yagi, 1953), B–B', Blackjack teschenite trend (Wilkinson, 1957) and A–A', Garbh Eilean teschenite trend (Murray, 1954). Diagram modified from Carmichael, (1962).

association of analcite with subordinate quantities of albite, prehnite, cancrinite, 'gieseckite' and a negative zeolite with oblique extinction up to 14°, possibly scolecite or mordenite. An acid leach from this interstitial material produced a slight precipitate when tested with $AgNO_3$ solution suggesting the presence of small quantities of sodalite.

The degree of alteration suffered by the early nephelines in these more easterly syenites is very variable. In some specimens the nephelines are largely replaced by cancrinite, growing peripherally and along cracks.

Often the original nepheline appears to have been wholly replaced by sodalite. Pseudomorphs consisting of both sodalite and cancrinite are common, the textural relationships suggesting that the sodalite is later than the cancrinite. By contrast in some specimens the nepheline remains almost wholly fresh, as in the analysed specimen 30676 from the most easterly outcrops. There is no evidence for any primary crystallisation of sodalite in these rocks and the sulphatic variety, hackmanite, so abundant in some of the Ilímaussaq syenites is not found.

Minor elements in the nepheline syenites.

The variations in minor element content along the dyke show trends similar to those described from the vertical succession in the layered quartz syenites from the western half of the Kûngnât complex (UPTON, 1960). This latter succession was interpreted as a layered series of accumulitic rocks formed at the base of a magma chamber slowly differentiating by crystal fractionation. Rubidium and the Rb/K ratio increase from WSW to ENE along the Hviddal dyke whereas barium and strontium show a striking decline in this direction. The scandium decrease in the same direction can be correlated with the decreasing Fe'' and Mg'' of the rocks, ions for which the Sc may be expected to substitute. There

Table 6. Minor elements in the nepheline syenites. Determination by emission spectroscopy. Analyst, Elizabeth Bingham.

Specim.	Li	Rb	Cu	Be	Sr	Ba	Sc	Ga	Yt	La	Yb	Zr	V	Nb	Cr	Co
30743	70	80	17	—	340	6000	17	20	57	nd	nd	360	42	54	—	6
30714	58	90	27	7	450	3600	22	23	73	—	8	520	16	55	—	—
50241	87	95	11	6	180	1400	9	33	70	—	7	630	22	75	27	27
30640	50	150	25	10	93	64	—	22	59	210	8	540	18	62	—	—
30681	480	170	25	6	40	21	—	46	105	280	9	750	18	150	—	—
30676	90	300	9	6	14	9	—	50	65	nd	nd	470	42	44	—	—

The following elements were sought but not detected: Ag, As, B, Bi, Cd, Ce, Mo, Ni, Pt, Sb, Sn, Zn.

	Ga . 10^5/Al	Rb . 10^4/K
30743	22	19
30714	26	22
50241	36	21
30640	25	33
30681	45	41
30676	47	67

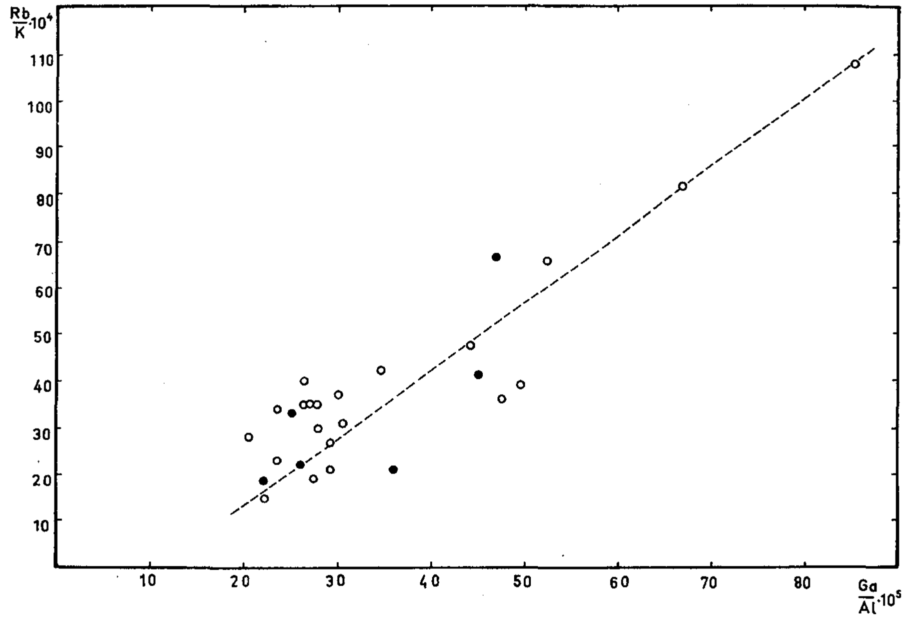

Fig. 4. Rb/K and Ga/Al ratios of Gardar alkaline rocks. Open circles, syenites and alkali granites from Kûngnât (Upton, 1960) and closed circles, nepheline syenites from the Hviddal dyke.

is enrichment of the more alkaline rocks in Ga, whereas the Zr content remains fairly constant around 500 ppm. The relative abundance of La and Yt as compared to Yb and Ce is an apparent reversal of the Odell-Harkins rule which states that elements of even atomic number should be more abundant than those of odd Z.

Ga/Al and Rb/K ratios for the differentiated suite larvikite → nordmarkite → riebeckite-granite → grorudite at Kûngnât, where fractionation was dominantly a result of feldspar removal, show a simple linear relationship. The corresponding ratios for the Hviddal rocks are plotted on Fig. 4, together with those of the Kûngnât rocks (in some cases revised from the 1960 figures), where it is seen that there is close conformity between the two sets of values.

Each of the Hviddal specimens was crushed for analysis on different occasions and using different mortars, sieves, etc. This being so there is reason for discounting the anomalously high values of 27 ppm for Cr and Co in the case of sample 50241 where contamination may reasonably be suspected.

In the fractionated nepheline syenite magma of the Rocky Boy stock, Montana (Pecora, 1942), Ba has also been shown to decrease quite markedly as the Na/K ratio of the magma increased. However, in this case Sr, Ti and Zr increased, contrasting with the situation on

Tugtutôq where Sr and Ti were progressively removed and the Zr trend is uncertain.

The feldspars themselves show a small but continuous K/Na increase from WSW to ENE despite the fact that whole rock compositions demonstrate a persistent overall K/Na decrease. The feldspars are remarkably poor in calcium compared to those from the more acidic syenite rocks of Tugtutôq. In the absence of still more basic undersaturated syenites than those of the western Hviddal facies on the island, one may turn to the Ilímaussaq augite syenite for evidence concerning the higher temperature equilibrium compositions of the feldspar series, if one assumes that the augite syenite chill lies on or close to the same line of liquid descent as the Hviddal sequence. Feldspar from the one chilled specimen investigated (40527) has a composition of $Or_{32}Ab_{58\cdot5}An_{8\cdot5}Cn_1$, notably more calcic than the most basic Hviddal feldspars ($Or_{38\cdot5}Ab_{61}$

Specimen	Rb ppm	K $^0/_0$	$Rb.10^4/K$	Sr ppm	Ba ppm	CaO $^0/_0$	Hviddal dyke
1. 30527	92	4.53	20	710	4850	1.73	W
2. 30714	82	5.37	15	280	3100	.13	↑
3. 50241	176	5.55	32	125	1500	.04	
4. 40499	240	5.59	43	40	450	.01	
5. 40494	262	6.42	41	35	780	.12	
6. 30681	272	6.76	40	60	550	.35	↓ E

$An_{\cdot5}$) and it may be that a sharp early decline in Ca content characterises the series. Barium and strontium also decrease rapidly from the feldspars of the higher temperature facies rocks to those of the lower and, as might be anticipated, there is an increase in the Rb/K ratio.

(Method: Rb, Ba, Sr and Ca determinations using a Phillip's Norelco X-ray spectrometer. W.target; 50kV,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 $^0/_0$ 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).

Mineral parageneses.

Nepheline crystallised late with respect to the relatively sodic feldspars of the augite syenites but the crystallisation ranges for nepheline and feldspar overlapped more and more widely as one passes through the pulaskitic rocks and into the foyaites. In the latter, textures indicate approximately contemporaneous growth of the two minerals. The compositions of feldspar-nepheline pairs have been obtained from four syenite specimens, the feldspars being determined by flame-photometry (for Na and K) and by X-ray fluorescence (for Ca), and the nephelines being approximately determined from the positions of their $21\bar{3}0$ and $20\bar{2}2$ X-ray reflections, using the method of SMITH and SAHAMA (1954) and the data presented by HAMILTON and MACKENZIE (1960).

Specimen	Feldspar	Nepheline
30714...........	$Or_{38\cdot5}Ab_{61}An_{\cdot5}$	$Ne_{80}Ks_{14}Qz_{6}$
50241...........	$Or_{43}Ab_{57}An_{0}$	$Ne_{78}Ks_{17}Qz_{5}$
40499...........	$Or_{41}Ab_{59}An_{0}$	$Ne_{73}Ks_{23}Qz_{4}$
40494...........	$Or_{46}Ab_{54}An_{0}$	$Ne_{73}Ks_{23}Qz_{4}$
30676...........	n. d.	$Ne_{76}Ks_{19\cdot5}Qz_{4\cdot5}$

Possibly these figures indicate a slight real decrease in the amount of SiO_2 held in solid solution by the nephelines in the more easterly rocks together with some change in the Na/K ratio towards K enrichment. HAMILTON (1961) considers that with falling temperature a nepheline changes its composition in two ways: (a) by changing its Na/K ratio by exchanges with the melt and the coexisting feldspar, and (b) by changing its Si/Al ratio by exchanges with the melt, in such a way as to approach the theoretically ideal composition of $Na_3KAl_4Si_4O_{16}$. Although the compositional differences for the Hviddal nephelines indicated by the

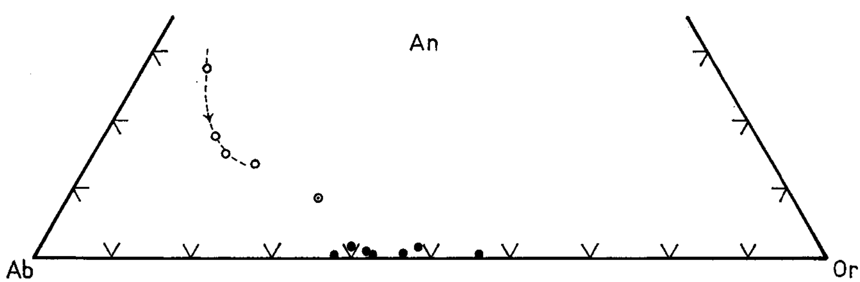

Fig. 5. Feldspar compositions, Wt. %s. Open circles indicate course of crystallisation in the Hviddal syeno-gabbro (UPTON, 1964); centred circle, cryptoperthite from chilled augite syenite, Ilímaussaq; closed circles, alkalic feldspars from Hviddal nepheline syenites.

above data are slight, one may tentatively conclude that the interstitial nephelines from the augite syenites in the vicinity of the central Tugtutôq fjord crystallised at temperatures slightly above those of the more euhedral nephelines from the foyaites.

In the same paper HAMILTON gives the experimentally determined limits for solid solution in the system $NaAlSiO_4$-$KAlSiO_4$-SiO_2-H_2O at 500°, 700° and 775° under a water vapour pressure of 15,000 psi (ca.

1050 kg/cm[2]). The Hviddal nephelines are seen to fall between the limits of silica solid solution at 700° and 750° (Fig. 6) on Hamilton's SiO_2-Ne-Ks diagram. The vapour pressures attendant on the cooling of the Hviddal intrusion were, at least in the later crystallisation stages, probably only a little less than the confining pressure. No vesicular (pegmatitic) facies have been noted, suggesting that the confining pressure was

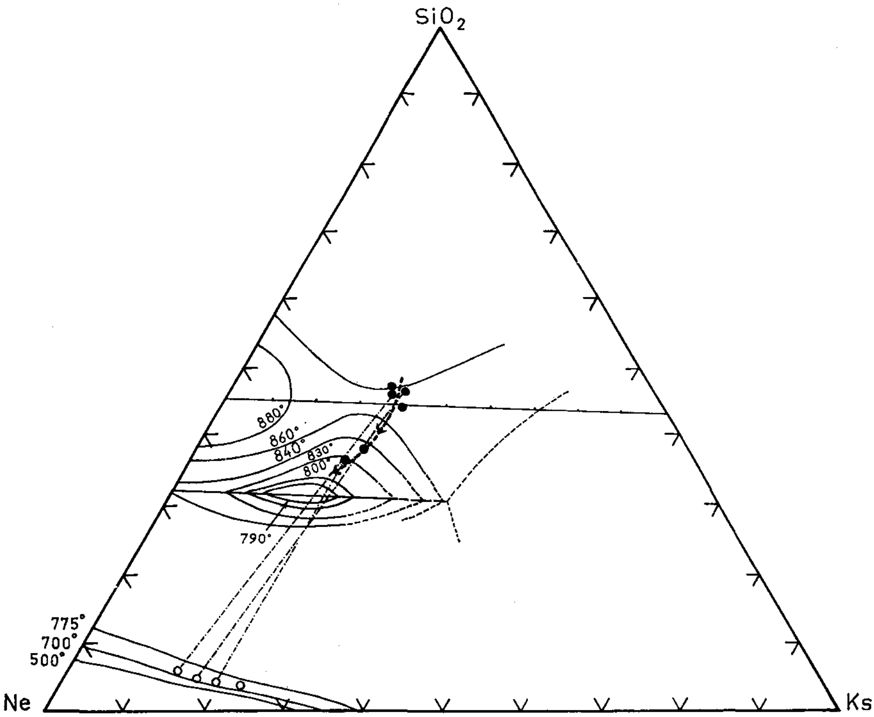

Fig. 6. Analyses of Hviddal nepheline syenites and compositions of four nephelines plotted on preliminary liquidus diagram, isobaric projection at 15,000 p.s.i. H_2O pressure of part of the liquidus surface of the system $NaAlSiO_4$-$KAlSiO_4$-SiO_2. (Hamilton, 1961). The curves in the lower part of the diagram are the experimentally determined limits of nepheline solid solution at 500,700 and 775°C.

not exceeded. There are some 2,600 m of (predominantly basaltic) volcanics with some sandstone preserved in the vicinity of Tugtutôq which undoubtedly originally overlay the whole area. Furthermore there can be little doubt that this 2,600 m of superficial rock represents but a part of the original cover and one may reasonably assume a minimum of 3,000 m of Gardar stratified rock. As explained on page 54, there is good reason to believe that the Hviddal dyke did not rise above the basal Gardar unconformity which separates the stratified series from the underlying batholithic granitic rocks. If this is accepted then the upper part of the dyke crystallised under a hydrostatic pressure of at least 840 kg/cm² (assuming a cover density of ~ 2.8 gm/c.c.). In that the nepheline syenite magma approximated to a somewhat contaminated $NaAlSiO_4$-$KAlSiO_4$-SiO_2-H_2O system which, in its upper parts, may have had a water vapour pressure not greatly different from that employed by HAMILTON, the experimental data may be provisionally used as a guide and a temperature of ca. 750°C taken as a likely figure for the crystallisation of the nephelines. (This may be compared with crystallisation temperatures of 750°C for Oslo lardalite nepheline, 500° and 600° for Dunedin and Sardinian phonolite nephelines and temperatures between 790–900° for nephelines from three Kenyan phonolites (HAMILTON), 1961). Furthermore from textural relationships the conclusion can be drawn that the feldspars, olivines, pyroxenes, ores and apatites of the more westerly dyke rocks crystallised at temperatures in excess of 750°.

MACKENZIE (1956) crystallised a synthetic glass ($Ne_{45}Ks_{20}Qz_{35}$, an "artificial nepheline syenite magma") under a lower pressure of H_2O than was used in the later experiments to determine solid solution limits, namely 8000 psi. Crystallisation between 775–625° yielded feldspar and nepheline crystals whose compositions remained more or less constant through this range at ca. $Or_{46}Ab_{54}$ and $Ne_{93}Ks_7$ (SiO_2 in the nepheline not determined). Taking specimen 30648 as more or less representative of the eastern rocks with equilibrium pairs feldspar-nepheline, the gross composition approximates to $Ne_{40}Ks_{22}Qz_{38}$, the feldspar being $Or_{49}Ab_{51}$ and the nepheline approximately $Ne_{72}Ks_{24}Qz_4$. The resemblance to MACKENZIE's system is fair considering the presence in the natural system of some 10 % (modal) aegirine, Ac_{72}. Some of the Kenyan phonolites described in detail by HYTÖNEN (1959) on cooling behaved similarly to the Hviddal magma, yielding as early phases anorthoclase cryptoperthite, fayalite, alkali pyroxene and brown hornblende, the nepheline-feldspar pair in one being $Or_{44}Ab_{56}$ — $Ne_{85}Ks_{15}$ (SiO_2 not determined).

It may be deduced, from their composition, that the feldspars of the Hviddal syenites crystallised as soda-sanidine and that with falling temperatures their compositions were modified in the direction of K enrichment. In the region of 750°C nepheline also commenced to crystallise and, one may presume, at still lower temperatures perthitic exsolution began in the feldspars although, particularly in the more basic westerly rocks, this often did not go beyond the formation of cryptoperthitic intergrowths. As temperatures declined the nepheline became marginally or wholly altered to muscovite ('gieseckite') and at still lower temperatures acquired reaction coronae of analcite or cancrinite. Analcite appears abundantly in the more easterly rocks, as a reaction product around the 'gieseckite' and nepheline, as interstitial crystals and also to a small extent replacing aegirine and feldspar. MACKENZIE's synthetic 'nepheline syenite' melt, on crystallisation below 500° C produced feldspar and analcite rather than feldspar and nepheline. However, at water vapour pressures in excess of the 8000 psi employed in this experiment, the upper stability limit of analcite would be correspondingly raised. HYTÖNEN reviewed the work done on the systems $Na_2O.Al_2O_3.SiO_2.H_2O$ and $K_2O.Al_2O_3.SiO_2.H_2O$ up until 1959, showing that, in the former system at 1000 kg/cm^2, analcite is the stable phase below 525°, being joined by natrolite at 290°; the minimum temperature for nepheline formation at this pressure is 460°. Below 460° the nepheline decomposes to a hydrated nepheline phase. By contrast, in the potassic system there is an absence of hydrated phases other than muscovite.

Whereas in the phonolites described by HYTÖNEN natrolite appears as an important low temperature species crystallising with, and later than, analcite, this mineral is insignificant in the Hviddal syenites although it has been noted, apparently as a derivative from the analcite in the western augite syenites. Analcite and cancrinite occur in association in the foyaitic rocks and it is probable that their crystallisation periods were largely coincident. As with the analcite there is often a clear reaction relationship between the nepheline ('gieseckite') aggregates and the cancrinite, the latter growing as a fringe of prismatic crystals around the former. The cancrinite also occurs interstitially and in very fine scale intergrowths with analcite. The cancrinite is optically negative with a birefringence high enough to suggest a 'normal' CO_3 rich variety. Pseudomorphs after nepheline consisting of cancrinite and sodalite are such as to suggest that the sodalite crystallised later than the cancrinite. The paragenesis of sodalite is unclear although it can be stated that this mineral is by no means uniformly developed in the eastern syenites and it appears always to be secondary after nepheline (or nepheline derivatives) and to be confined to the latest crystallisation stages. The relationship of prehnite to the other low temperature minerals is likewise uncertain. TYRRELL (1928) writes of the association of analcite, thomsonite, subordinate natrolite and brownish rosettes of prehnite in analcite syenites from the Howford Bridge sill in Scotland and similarly GILLULY (1927) noted analcite, thomsonite(?) and natrolite in the syenitic centre of a composite sill in Utah. Another comparable example is cited by YAGI (1953) who reported prehnite, thomsonite and natrolite in the analcite syenites of the Morotu area, Sakhalin and it would seem that the low temperature alumino-silicate parageneses in these instances were similar to those in the Hviddal dyke.

The complex and discontinuous reaction series shown by the aluminosilicates almost certainly reflect, not only falling temperatures, but also a steady increase in the concentration of water and other volatiles in the residual magma. This is also clearly indicated by the sequence shown by the ferromagnesian minerals. Ilmenomagnetite intergrowths reacted with the melt to yield lepidomelane biotite. The olivines acquired reaction zones of magnetite and 'iddingsite' and, although these are often surrounded by mantles of ferrohastingsite and biotite, it is likely that they originated through oxidation of the olivines after the growth of the amphibole and mica. Much of the ilmenite within the ore grains may also represent late stage oxidation products, possibly derived from an original magnetite-ulvöspinel intergrowth. The occurrence of fluorite, calcite and sodalite, in addition to the cancrinite and hydrous aluminosilicates in the foyaitic rocks is evidence of considerable concentration of water, carbon dioxide and halogens in the intercrystal magmatic residues of the most easterly syenites.

The publication, by SCHAIRER and BAILEY (1962), of the preliminary results emerging from a study of the system Na_2O-Al_2O_3-Fe_2O_3-SiO_2 has an interesting bearing on the observations on Tugtutôq. Investigating the equilibria within this quaternary system at 1 atmosphere pressure, SCHAIRER and BAILEY infer the presence of a univariant line along which nepheline, albite and acmite are in equilibrium with the melt. The line connects a quaternary reaction point (Haem. Ne. Ab. Ac.) at ca. 915°C with a eutectic point (Ne. Ac. Ab. Ns) at less than 727°C. This finds some correspondence in the eastern syenites where nepheline, feldspar and acmitic pyroxene were in equilibrium with a liquid that was becoming more and more sodic. Ns appears in the norm of only the most highly differentiated of the six analysed rock specimens and there can be little doubt that analysis of the zeolite-rich interstitial material of this rock, representing the ultimate liquid fraction, would show notable enrichment in the sodium disilicate molecule.

Origin of differentiation in the Hviddal syenite.

The cause of the petrological variation along the syenite dyke is of considerable interest and it is unfortunate that there is little evidence available on which to discriminate between the several possible mechanisms that may have been responsible. Filter-press differentiation involving mild squeezing of the more westerly part of the dyke at an early stage in the crystallisation may have concentrated the lower melting constituents towards the ENE. However, not only is there very little change in dyke width from one end to the other, but there is no crushing of any of the early minerals in the WSW part of the dyke such as would be consistent with this hypothesis. There is also the possibility that differentiation took place *in situ* due to a thermal gradient extending over the country rocks at the time of intrusion. Had the crustal rocks of the eastern part of the area been cooler than those of the west, water and alkalis might have migrated in an eastward direction and thereby depressed the crystallisation range of the magma in the ENE extension of the dyke. Again there is no evidence of such a process having operated and it is likely that if such a temperature gradient had existed the response would have been for the dyke to chill more rapidly in the eastern end to give a finer-grained, possibly porphyritic rock, without any chemical gradient becoming established along it.

The cryptic variation could be very easily explained if one considers the dyke to be a simple layered intrusion which, after consolidation was tilted and eroded so that the lower zones are exposed in the WSW and successively higher levels preserved towards the ENE. The contention that the Tugtutôq area has been tilted down towards the ENE can be supported by evidence from the adjacent Narssaq-Dyrnæs area where the basal Gardar unconformity and overlying strata dip in this same general direction. Since layered structures due to crystal sinking and accumulation are frequently encountered in the olivine-gabbro dykes which followed the syeno-gabbro — syenite composite dyke (UPTON, 1964), there is nothing inherently implausible in the idea of the syenite dyke representing a cumulitic igneous rock body. Layered intrusions of nepheline syenite are very highly developed in the Gardar province and although as yet cryptic variation with height has not been described from any of these it is reasonable to predict that such descriptions will be forthcoming. It is difficult to visualize, in a dyke-like layered intrusion, the nature of the 'primitive' floor upon which settling of early crystals could commence. However in the case of the associated olivine gabbro dykes it is thought that 'pinch and swell' structure is exhibited by the dyke walls in a vertical as well as a horizontal sense and that blockage by sinking crystals may have occurred in some of the narrower 'bottlenecks' and that subsequent accumulation took place above these. The most serious objection to the Hviddal dyke being grouped among the layered syenite intrusions is the absence of overt or 'non-cryptic' layering features. Mineralogical banding and crystal lamination have been searched for with some diligence but appear to be completely missing. Nevertheless this does not automatically negate the layered intrusion hypothesis. A broad dyke cooling slowly without development of convective circulations and with no sudden variations in vapour pressure could, by fractionation of alkali feldspar, olivine, clinopyroxene, ore and apatite, conceivably yield a layered succession of this type. Nevertheless, in view of the highly perfect feldspar lamination characteristic of the layered foyaite and kakortokite bodies at Grønnedal (EMELEUS, 1964) and Ilímaussaq (USSING, 1912; UPTON, 1961) the notably unlaminated condition of the Hviddal syenite is surprising if it is in fact an intrusion in which crystal settling and accumulation have played a major role.

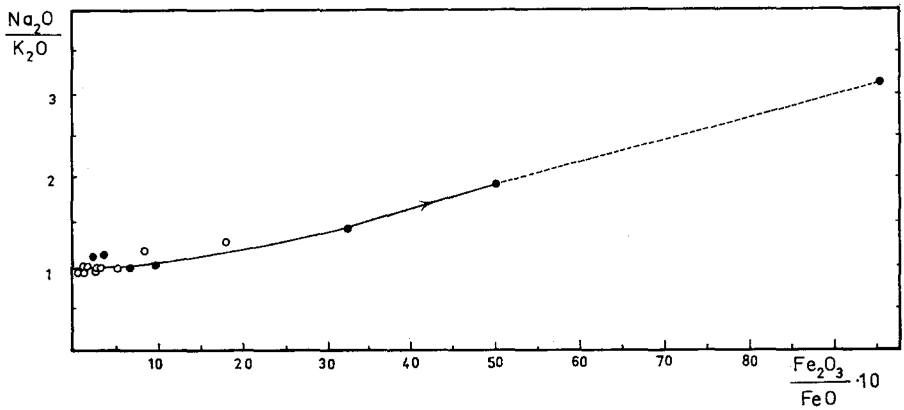

Fig. 7. Alkalic and ferrous/ferric ratios for differentiated Gardar syenite intrusions. Closed circles, values for Hviddal nepheline syenites, except for extreme case (right-hand side) representing mean of three analyses of Ilímaussaq aegirine lujavrites (Ussing, 1912). Open circles indicate syenites, quartz syenites and alkali granites from western Kûngnât (Upton, 1960).

If one concludes that the dyke is a layered intrusion, the syenites should be regarded as 'loosely packed' orthocumulates in which the ratio of intercumulus to cumulus material was relatively high (*vide* Wager, Brown and Wadsworth, 1960; and Upton, 1961).

A further possibility to be considered is that vertical differentiation of the magma took place within the dyke with water and other volatiles becoming concentrated towards the top. Vertical compositional variation of the magma in this manner would entail a depression of the crystallisation temperature range for the upper material and the dyke would have crystallised from the base up. On this hypothesis crystal settling could have been quite unimportant. Again the observed lateral variation would be explicable in terms of a more or less horizontal erosional plane transecting an originally vertical sequence now down-tilted towards the ENE. If the dyke is inferred to be essentially a non-accumulitic body then the analyses of rocks from it should approximate to the composition of the differentiated magma at various levels.

Since there is close similarity in texture, mineralogy and composition between the more basic of the Hviddal syenites and the augite syenites of Ilímaussaq (and also, judging by Ussing's descriptions, close similarity to the Igaliko augite syenite), one may surmise that the parent magma passed through a larvikitic stage whose composition corresponded more or less closely with that of the chilled augite syenite from Ilímaussaq (table 3). Furthermore the Hviddal foyaitic syenites have much in common with the later rocks at Ilímaussaq and Igaliko as well as having similarities to some of the Grønnedal syenites. Highly fractionated residual lujavrite magma was produced during the latest crystallisation stages at Ilímaussaq (Ussing, op. cit.; Sørensen, 1958; Bondam and Ferguson, 1962) yielding rocks largely composed of feldspar, zeolites and either aegirine or arfvedsonite. Sørensen (1962) considers the crystallisation range for the Ilímaussaq lujavrites to have been in the region 400–300° C. It is of interest that the latest crystallising phases in the Hviddal foyaites include abundant zeolites, sodalite and a highly sodic pyroxene; filter-press separation of the latest interstitial residuals would have yielded a small volume of rock reasonably close to the aegirine lujavrites in composition. Nevertheless, in spite of the probability of near identity of the early magmas for the Hviddal and Ilímaussaq intrusions and the overall similarities in their differentiation histories, it should be remembered that a time gap intervened between these two intrusive events, which was long enough to accomodate the emplacement and solidification of the olivine gabbros, the various quartz syenite and alkali granite intrusions in the Tugtutôq-Narssaq district and numerous swarms of small alkalic and basic dykes.

By analogy with sequences in demonstrably layered intrusions in the district the cumulitic hypothesis is tentatively adopted to explain the variations seen in the Hviddal syenites and the following paragraphs are written on the assumption that it is an orthocumulate succession.

The basal Gardar unconformity near Narssaq is gently undulatory but with an overall strike of 100° and a northerly dip of ca. 10°. The trend of the Hviddal dyke is around 60–70° and it is unlikely that the tilting experienced by the dyke exceeds 5°. However a dip of 5° would mean that the present erosional surface reveals a sequence of syenites within the dyke of some 1950–2000 m thickness.

Cryptic and phase layering in the intrusion.

The augite syenites exposed around the central Tugtutôq fjord would, on the above estimations lie around 1200 m below the unconformity. Analyses of 30743 and 30714 (Table 1) show an apparent reversal in the sequence, 30743 coming from lower in the succession but having lower Mg, Ca, Ti and P than 30714. It is not known whether there is a real anomaly in this sector or whether the disparity is explicable in terms of random variation and imperfect sampling. Until further work is done it would be best to regard the composition of the cumulates at this level as the mean of the two analyses. As in the lower accumulitic series of pyroxene-olivine syenites at (western) Kûngnât, the principal cumulus minerals in the lower part of the dyke up to and including those of the central fjord exposures, were alkali feldspar, clinopyroxene, olivine, ilmenomagnetite and small quantities of fluorapatite. Around the 1200 m level the compositions of coexisting feldspar, olivine and pyroxene were very approximately (ignoring intercumulus modification) $Or_{38\cdot5}Ab_{61}An_{\cdot5}$, $Wo_{44}En_{15}Fs_{35}Ac_6$ and $Fo_{11}Fa_{89}$. Compositions of minerals at lower levels are not known. However in the chilled zone of the closely related augite syenite of Kangerdluqssuaq, Ilímaussaq, the coexisting feldspars, pyroxenes and olivines were $Or_{32}Ab_{58\cdot5}An_{8\cdot5}Cn_1$, $Wo_{48}En_{28}Fs_{24}$ and $Fo_{15}Fa_{85}$, and it is likely that a comparable mineral assemblage exists at a lower level in the Hviddal dyke. By the time the cumulus pile had risen to approximately 1000 m. below the unconformity, olivine was no longer precipitating, presumably in consequence of the ever rising oxidation state of the residual magma. The equilibrium feldspar was now more potassic (ca. $Or_{43}Ab_{57}An_0$) and the cumulus pyroxene was a pale green ferrohedenbergite contrasting with the pink-grey ferroaugites and augites of lower levels. From here onward pyroxene, ore and apatite made diminishing contributions to the cumulus until at a level corresponding to 30640 at ca. 550–600 m below the unconformity feldspar was probably the only mineral contributing to the primary mush. During the accumulation of the next 100 m of crystal material the composition of the residual magma is believed to have reached the feldspar-nepheline phase boundary with the consequent precipitation of cumulus nepheline alongside the dominant feldspar phase (ca. $Or_{49}Ab_{51}An_0$). The ratio of cumulus nepheline to feldspar is believed to have been very roughly 1:3. The extent of cryptic variation in the cumulus nephelines is undoubtedly very slight. The compositions of the feldspars from the uppermost rocks available have not been determined although the normative value (for 30676) is $Or_{54\cdot5}Ab_{45\cdot5}An_0$.

In the lower rocks reaction of the cumulus phases with the intercrystal melt gave rise to (a) zonation of the pyroxenes and making over of the feldspars and olivines, (b) production of biotite and amphibole reaction growths around the pyroxenes, olivines and ores and (c) independent and separate interstitial minerals such as nephelines and analcite. The relative lack of unmixing in the feldspars of the lower rocks compared with those of the highest levels may be a consequence of the small amount of water contained by the intercumulus liquid of the early cumulates. Concentration of volatiles in the intercumulus liquid of the upper cumulates probably helped to promote feldspar exsolution.

As the residual liquids became more sodic and hydrous, intercumulus addition to the pyroxenes tended increasingly to be of pyroxene zones progressively enriched in Na and Fe''' rather than of barkevikitic hornblende. Ever decreasing quantities of the amphibole phase were produced in the intercumulus upwards through the succession, the compositions changing from barkevikite towards ferrohastingsite, suggesting continuously decreasing temperatures of formation. In the uppermost rocks the amphibole phase was entirely suppressed, the only Fe''' Na bearing mineral being pyroxene. Amphiboles of the arfvedsonite-riebeckite series were not stable at any stage in the crystallisation of the dyke and it is likely that the latest magma residues produced only rocks comparable to the aegirine lujavrites of the Ilímaussaq, rather than to both arfvedsonite and aegirine lujavrite types as seen at the latter.

The micas in the dyke behave in a comparable manner to the amphiboles. In the lowest rocks examined biotites grow as intercumulus fringes around the ores and as post-amphibole fringes around the olivines (Fig. 1). In successively higher rocks changes in the pleochroism suggest a gradual compositional variation and it would seem that, as in the case of the amphiboles, crystallisation temperatures were being continually depressed. Intercumulus micas persist to slightly higher levels than the amphiboles. A similar situation is reported by YAGI (1953) from the Morotu analcite syenites where biotite became unstable in the residuals enriched in sodium and iron, and gave place to aegirine and potassic feldspar.

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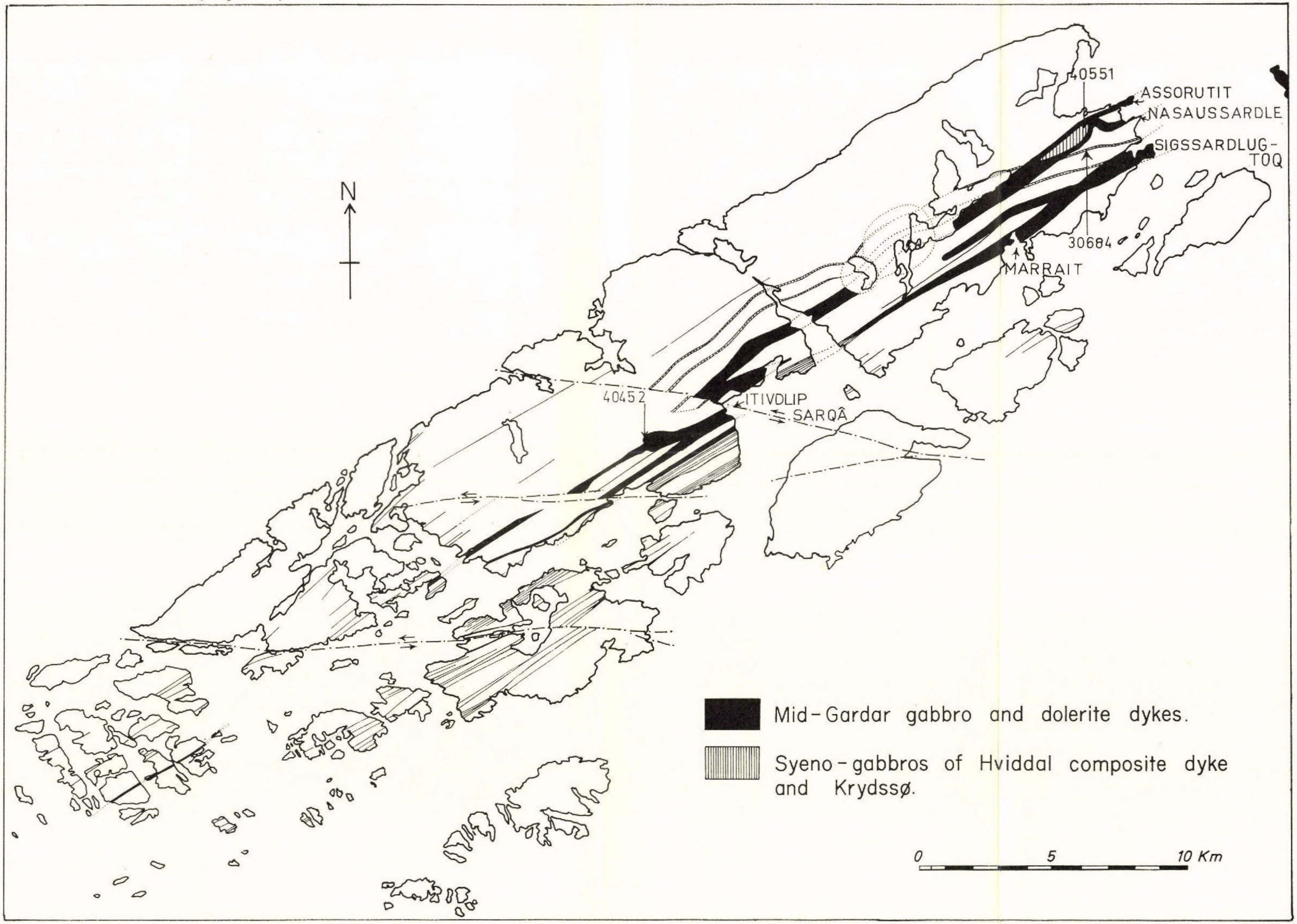
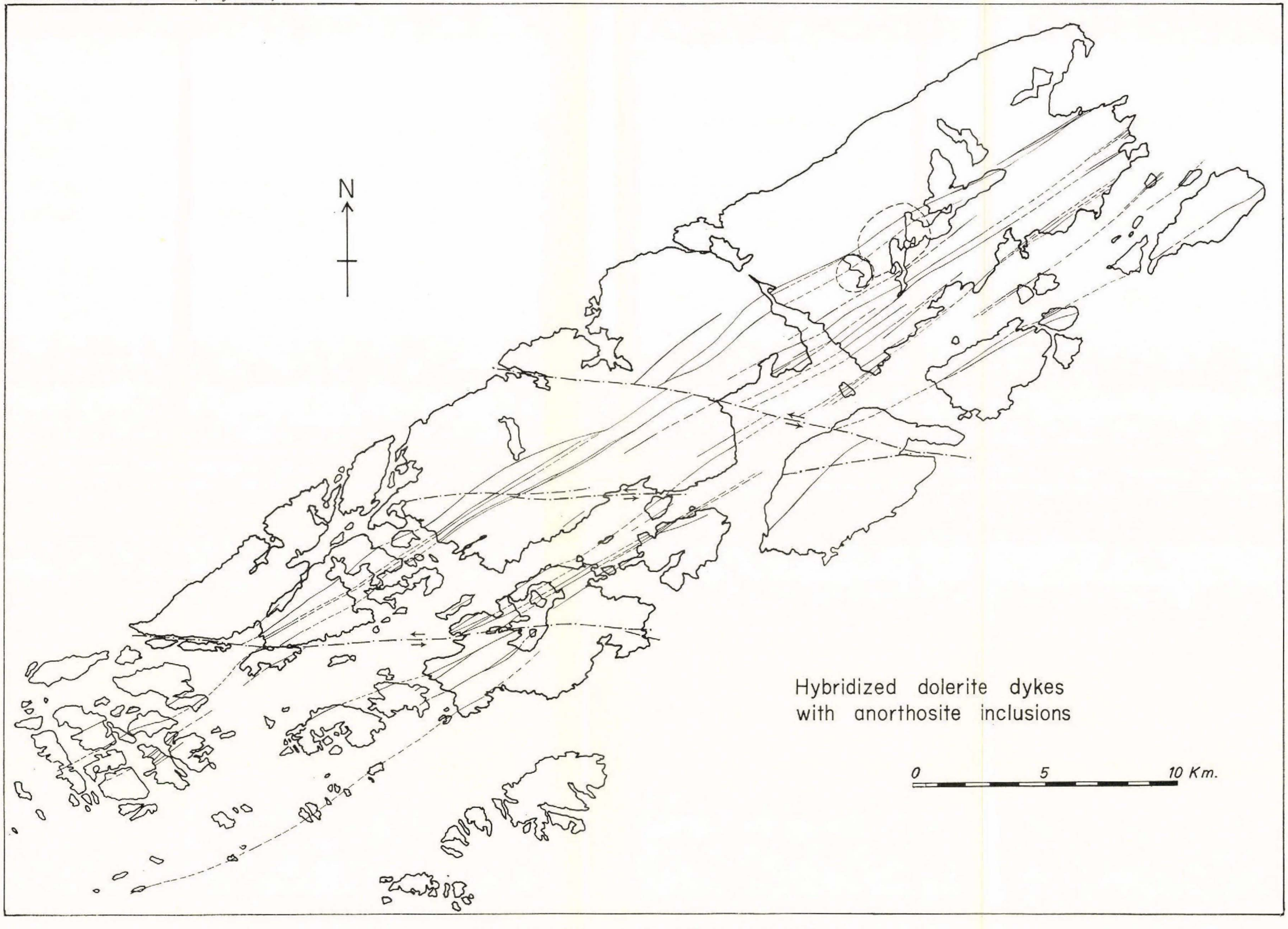
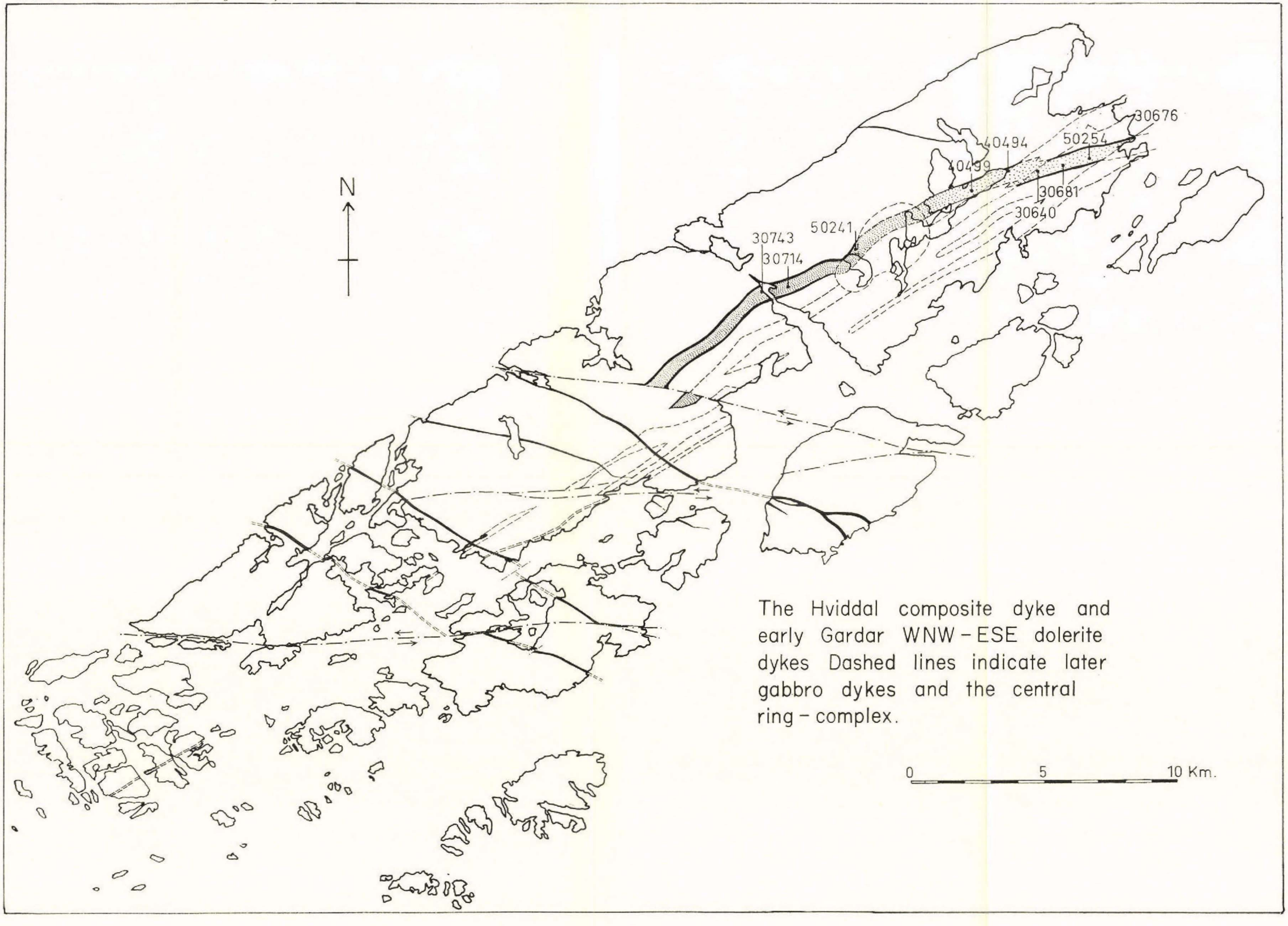


Map of the gabbros and syeno-gabbros of the Tugtutôq-Narssaq area.



Map of the hybridised post-gabbro dolerite dykes of the Tugtutôq-Narssaq area.



The Hviddal composite dyke and early Gardar WNW-ESE dolerite dykes Dashed lines indicate later gabbro dykes and the central ring-complex.