GRØNLANDS GEOLOGISKE UNDERSØGELSE
BULLETIN NO. 27

THE ALKALINE IGNEOUS COMPLEX OF KÛNGNÂT FJELD, SOUTH GREENLAND

BY

B. G. J. UPTON

WITH 57 FIGURES IN THE TEXT
AND 6 PLATES

Reprinted from
Meddelelser om Grønland, Bd. 123, Nr. 4

KØBENHAVN
BIANCO LUNOS BOGTRYKKERI A/S
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ABSTRACT

An intrusive complex of saturated syenites and gabbros near Ivigtut in S.W. Greenland forms the mountain of Kûngnât Fjeld. The rocks were intruded into the basement gneisses towards the close of the Gardar period, thought to be of Pre-Cambrian age. The complex consists of three steep-sided syenite bodies. These were intruded successively with progressive easterly shift of centre and were succeeded by an alkali gabbro intrusion which, occurring as a ring-dyke, almost entirely surrounds the syenites. Emplacement of each of these intrusions is thought to have been by ring-faulting and cauldron subsidence.

The S.W. marginal syenite, regarded as the earliest of the three syenite intrusions, is a small, poorly exposed body. It consists of quartz syenite containing fayalite and aegirine-augite.

The second syenite intrusion formed the western layered syenite stock. This is a larger mass thought to have been originally ca. 2.6 × 3.5 kms. It possesses the characteristics of a layered intrusion of Skærgaard type with inwardly directed rhythmic banding, cryptic layering, feldspar lamination and an overall increase in mafic index from top to bottom. The base of the layered rocks is not exposed. The intrusion is divided horizontally, by a raft-like mass of gneiss blocks, into an upper and a lower layered series. This raft, the "grey-zone", is believed to represent a subsided mass of roofing material which sank only a relatively short distance before coming to rest, suspended in the magma chamber. Differentiation by bottom accumulation of fayalite, clinopyroxene, high-temperature alkali feldspars etc. continued independently above and below this raft. In each case it resulted in pronounced fractionation of the magma. In both series the rocks grade up from quartz-free to quartz-bearing types. The ultimate differentiates of the upper layered series have been lost by erosion, but those of the lower series are represented by transgressive soda-granite dykes and sheets. These latter, which remained unconsolidated until very late in the cooling history of the complex, include riebeckite-astrophyllite granites of close affinity to some of the Nigerian examples. The differentiated sequence of the lower

layered series is analogous to the larvikite-nordmarkite-ekerite sequence of the Oslo region.

The eastern syenite intrusion is also layered in its central part with somewhat higher average dips than in the western intrusion. For the most part it consists of more basic syenites with more magnesian pyroxenes and olivines and more calcic feldspars. However fractionation *in situ* again produced quartz syenites of less basic type. The eastern stock possesses a marginal border group on its eastern flanks. An irregular zone of pegmatite surrounds the eastern intrusion and is thought to have been caused by outward diffusion of volatiles and alkali silicates.

In the syenites partial analyses indicate a range in feldspar composition from $Ab_{59}\,Or_{29}\,An_{10.5}\,Cn_{1.5}$ to ca. $Ab_{59}\,Or_{37.5}\,An_{3.5}$, (mol. comp.). Optical data show a pyroxene range from augites of ca. $Ca_{42}\,Mg_{20}\,Fe_{38}$ through ferroaugites to hedenbergitic types, and with progressive Na enrichment through to aegirine-augites. The olivines range from ca. Fa_{80}—Fa_{100}.

Convection, occurring within the main western and eastern syenite magma chambers, is believed to have been responsible for the steep inclination of the layering by promoting marginal deposition of primary precipitate crystals. Evidence for strong magmatic currents is mainly provided by the trough-banding. Consideration of the feldspars suggests that in the two layered intrusions the magma chambers became filled with accumulated crystal mush over a temperature range between 800—700° C.

The behaviour of the trace-elements is broadly similar to that found in the Skærgaard series, except that at Kûngnât Ba and Sr were progressively removed from the magma. Li and Zr are strongly concentrated in the latest fractionates of the western lower layered series. The syenite melts were continuously depleted in F by the bottom accumulation of fluorapatite.

The ring-dyke consists of a suite of gabbroic and syeno-gabbroic rocks thought to have been derived by the fractionation of alkali-basalt magma at depth. Some contamination by syenitic material is suspected. In places the ring-dyke rocks suffered strong metasomatism from residual syenitic and granitic liquids. Apart from water, this alteration involved the addition of Li and Rb.

Spectrographic analyses of the feldspars from the whole complex showed that there are all gradations from those with severe Rb depletion to those with moderate Rb enrichment. A surprising Ag-Cu content in some of the feldspars is attributed to the presence of submicroscopic sulphide inclusions.

The four Kûngnât intrusions were apparently intruded in order of increasing basicity. A possible explanation is that the four magma portions were tapped off from successively deeper levels of an already-differentiated parental magma. The Kûngnât complex is probably coeval and comagmatic with the alkaline intrusions at Nunarssuit, Ilímaussaq and Tugtutôq. The development of nepheline syenites in this region of south Greenland is considered to be closely linked to that of the saturated syenites such as those at Kûngnât.

Danish Geodetic Institute

Fig. 1. Aerial photograph of Kûngnât Fjeld from the northwest. From the summit of Kûngnât peak towards the bottom right-hand corner are seen the Røverborg-Nisseborg ridge, the ridge of 920 m. Peak and the western ridge. Arsuk Island is seen across the fjord beyond Kûngnât.

PREFACE

The present work was carried out under the auspices of the Grønlands Geologiske Undersøgelse. This, the Greenland Geological Survey, is at present engaged on a programme of field work designed to complete the mapping of Greenland's south-western seaboard within the next few years.

From the economic stand-point the plutonic rocks of the numerous intrusive centres that punctuate the Archaean basement coastal strip between Frederikshåb and Kap Farvel are of particular interest. Several are being mapped for the first time whilst others, like the Grønnedal, Ilímaussaq and Nunarssuit alkaline complexes, which have for long been known in fair detail, are now being reworked.

The mapping of Kûngnât was started in the summer season of 1955 and was completed in 1956. A further brief visit was paid to the area in 1957.

Most of the laboratory investigations were carried out at Oxford where the results were presented as a D. Phil. thesis in 1958. The author

is grateful to the Department of Scientific and Industrial Research for a research grant covering the period 1955—1958.

The author most gratefully acknowledges the assistance and generosity of the Grønlands Geologiske Undersøgelse, and the guidance and interest of Professor L. R. Wager who supervised the work at Oxford. Special thanks are also due to A. Berthelsen, who directed much of the work in Greenland and to Dr. C. H. Emeleus whose company, advice and assistance in the field was much appreciated. The author is indebted to Drs. E. A. Vincent and H. Pauly for their help in interpreting textures in the ore minerals and to Dr. S. R. Taylor who gave his ever-ready supervision to the spectrographic work. Further thanks are due to Mr. B. Collett for making four chemical analyses, to Dr. G. M. Brown for critically reviewing the manuscript, and to Drs. E. Hamilton and W. G. Ernst for many helpful discussions. To the many others who have given assistance and advice the author extends his sincere thanks.

Greenland Geological Survey.
Mineralogical Museum
Copenhagen.

B. G. J. Upton

November 1959.

INTRODUCTION

Kûngnât, a shapely 1420 m. mountain, consisting mainly of resistant syenites, rises high above the surrounding gneisses and is one of the best known landmarks of the S.W. Greenland coast-line. The mountain lies at 61°12′ N. and 48°15′ W. close to the entrance of Arsuk Fjord, and is readily accessible by water from the nearby mining settlement of Ivigtut. There is a wide variety of spellings used for the Greenlandic name Kûngnât, but the form used throughout this paper is that favoured by the names commission of the Greenland Department.

The base maps were prepared from vertical aerial photographs by the Danish Geodetic Institute to a scale of 1 : 20,000. These maps, contoured for every fifty metres, proved accurate and reliable. In view of the small size of the complex, roughly 15 sq. kms., the general high standard of exposure and the ease with which fresh material is available, it proved to be a very profitable area for investigation. The area is magnificiently dissected although the relief is so severe that some parts of the complex are virtually inaccessible.

Being but a few kilometres from the classic mineral locality of the Ivigtut cryolite mine and the nepheline syenite-carbonatite intrusions of Grønnedal-Íka, Kûngnât has been familiar to geologists and mineralogists for the last hundred years or more. However, remarkably little information on its geology has ever appeared in print. Apart from occasional mineralogical references relating to feldspar specimens, the first account to appear was C. E. Wegmann's in 1938. His visit to the area had been a short one and his observations necessarily limited. Wegmann apparently visited the south-eastern contact zone of the intrusion and from the quartz-bearing rocks which are conspicuous in this marginal zone, he inferred a granitic nature for the massif as a whole and compared it to the Finnish Onas granite. Karen Callisen (1943) mentions in passing that the dominant rock type at Kûngnât is augite syenite, but gives no petrographic details. The first hint that alkaline basic rocks may be present as an integral part of the complex was given by R. D. Crommelin (1937), who investigated various sand samples collected by Wegmann in south Greenland. Amongst these were two

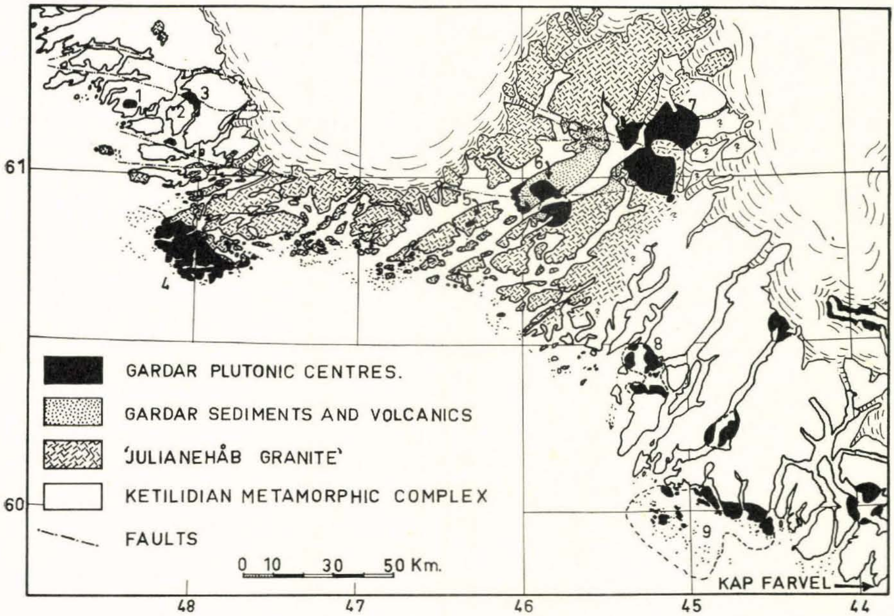


Fig. 2. Sketch map of the S.W. Greenland coast-line, showing localities of the 'newer intrusives'. 1, Kûngnât; 2, Ivigtut; 3, Grønnedal-Íka; 4, Nunarssuit; 5, Tugtutôq; 6, Ilímaussaq; 7, Igaliko; 8, Frederiksdal; 9, Sydprøven. (Map compiled by A. Berthelsen).

samples from "Ekaluit", at Kûngnât. Without doubt the locality refers to Kûngnât Bugt where there is a fine sandy beach. From his study, Crommelin concluded that "... by the side of the granites, basic rocks play a part e.g. diabase or essexite, of which such combinations may expected."

A preliminary determination of the age of the complex was made, using the lead-alpha method on zircons from a syenite-pegmatite (Moorbath, Taylor, and Upton, 1958). This indicated a Cambrian age. However, in view of more recent (as yet unpublished) work at Oxford this estimate may have to be revised. Intrusion at a much earlier date in the Pre-Cambrian now seems more probable.

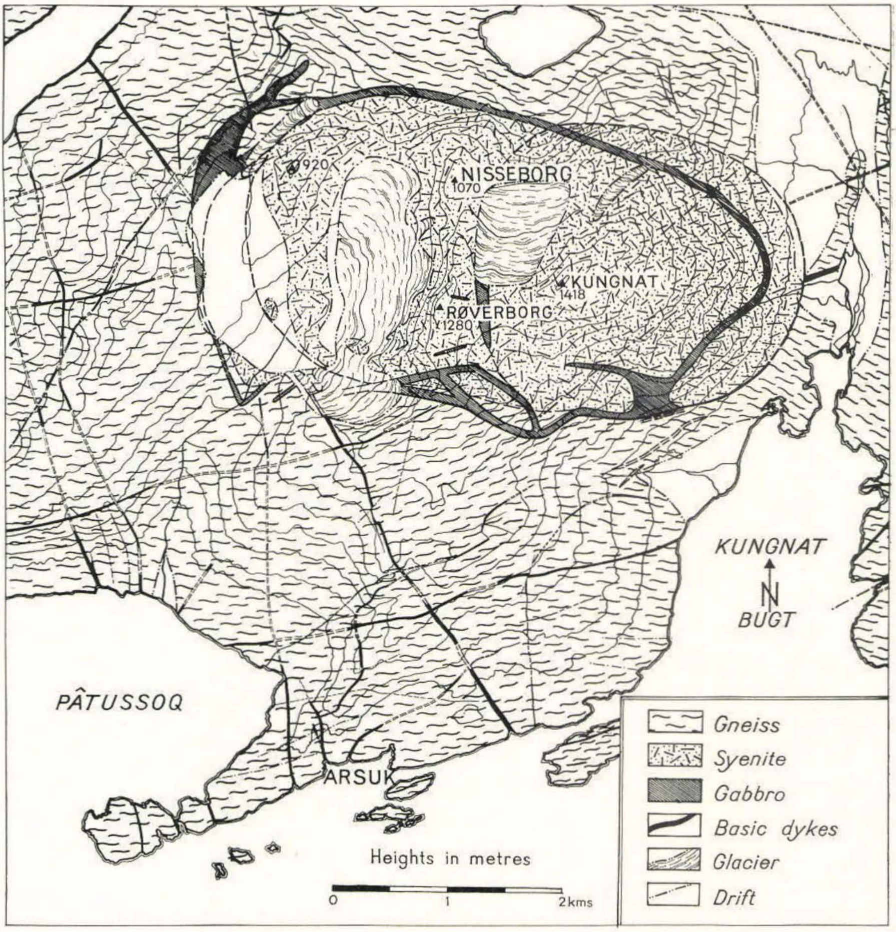


Fig. 3. Map of the Kûngnât complex indicating the extent of drift and permanent ice, and showing the main dykes in the region.

I. GEOLOGY OF THE COUNTRY AROUND KÛNGNÂT

The plutonic rocks at Kûngnât were intruded into a series of ancient, highly folded, regionally metamorphosed rocks which are now regarded as having once been a sedimentary sequence. The folding and metamorphism are attributed to the Ketilidian orogeny which affected a large part of the south Greenland basement in Pre-Cambrian times (Wegmann 1938).

In the immediate environs of Kûngnât are quartzo-feldspathic gneisses which are normally well banded with an overall east-west strike. This series of gneisses is known as the "gabbro-anorthositic" series because certain horizons contain a high proportion of blocks and lenses of resistant feldspathic rock that possesses an unusually calcic plagioclase. The high Ca content of the feldspars confers to these rocks a high degree of resistance towards assimilation or remelting wherever the gneisses became caught up in the later intrusives or were involved in their thermal aureoles.

Isolated strips and thrust masses of less strongly altered rocks of the Sermilik and Arsuk groups, including schists and pillow lavas, are believed to represent not later formations, but parts of the original geosynclinal sequence that escaped the more severe folding of the orogeny. The basement complex can therefore be divided into the banded gneisses, mainly of amphibolite facies, and the less metamorphosed rocks of the Sermilik-Arsuk formation.

Sandstones and lavas of the Gardar period, of post-Ketilidian age, were probably deposited over the whole region although they are now confined to the down-faulted zone of the area around Narssaq some 100 km. to the E.S.E.

Faulting.

There are a few large dislocations in the neighbourhood. One major crush line, the Fortuna Havn fault, with an E.N.E.—W.S.W. trend has controlled the coast-line south of Kûngnât and must run close offshore between the mainland and the islands that lie just outside Arsuk.

Although there is no clear evidence for its existence available within the area under discussion, other workers on the basement rocks to the north and west of Kûngnât consider that an E.S.E.—W.N.W. trending tear fault with a sinistral displacement has its easterly continuation skirting within half a kilometre of the north face of the mountain. This is one of a series of sinistral tears that affect the Ivigtut region and which are known to have been active at least during the early part of the Gardar period. The Kûngnât complex was thus intruded into relatively undisturbed gneisses, bordered to the north by a tear fault and to the south by the Fortuna Havn fault which is probably also a tear.

South of Kûngnât lies the large island Arsuk Ø which is entirely composed of the volcanics, schistose gneisses and dark schists of the Sermilik and Arsuk groups. A thrust zone inclined southwards, running along the line of the fjord which separates Kûngnât from Arsuk Ø, divides the Sermilik-Arsuk rocks from the underlying gneisses.

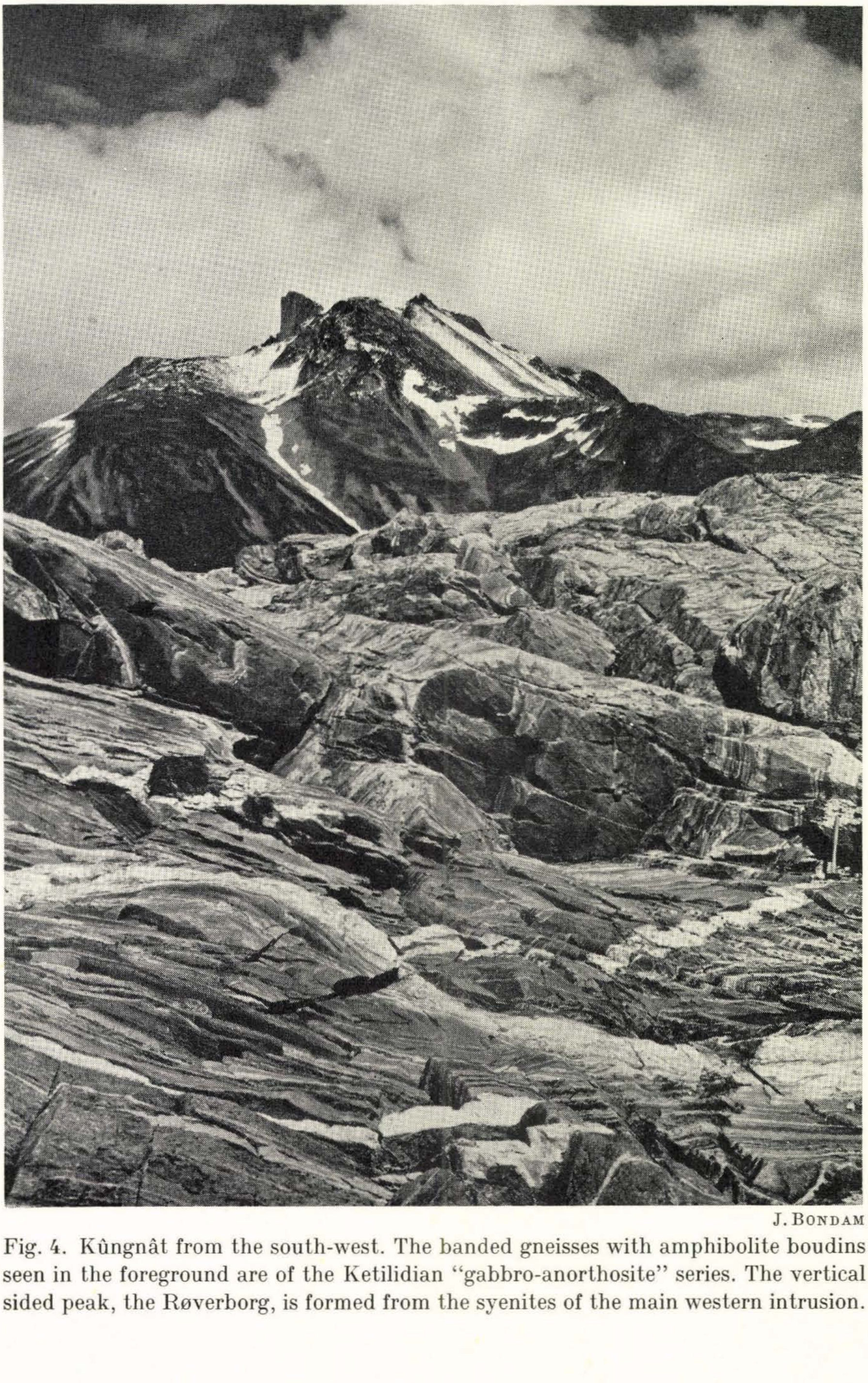
Early (Pre-Gardar) intrusives.

One of the earliest intrusive episodes in the area resulted in swarms of broad dolerite dykes being injected into the basement complex. These subsequently suffered shearing and slight metamorphism which converted them to metadolerites. Around Kûngnât these early dykes are sparsely represented although there is one broad dyke which makes a marked feature in the hillside behind Arsuk village. These early dykes are now referred to the Kuanitic period which in a recent, as yet unpublished, time-sequence proposed by A. Berthelsen, separates the Sanerutian from the earlier Ketilidian period. During the Sanerutian period, (which immediately precedes the Gardar), reactivation of the Ketilidian basement was responsible for the metamorphism of these dykes.

Gardar intrusives.

Probably the earliest Gardar dykes around Kûngnât are the lamprophyric dykes which make up a swarm running E.N.E.—W.S.W. occurring over a belt about 1 km. broad on the south side of Kûngnât. They are well exposed around the coast of Pâtussoq bay and are of dense, fine-grained rock, either black or dark-grey and possessing very marked flow-banding parallel to the walls.

A classification of the mid-Gardar dykes has also recently been proposed by Berthelsen. These dykes are the brown-dykes of Wegmann's accounts, this name now being abbreviated to B.D. Berthelsen divides them into three classes, namely B.D.O.'s, B.D.1's and B.D.2's, with the B.D.O.'s the eldest. B.D.O.'s are probably not



J. BONDAM

Fig. 4. Kûngnât from the south-west. The banded gneisses with amphibolite boudins seen in the foreground are of the Ketilidian "gabbro-anorthosite" series. The vertical sided peak, the Røverborg, is formed from the syenites of the main western intrusion.

represented around Kûngnât but the B.D.1's, with a general trend from W.S.W.—E.N.E., include some of the more conspicuous of the broad alkaline dolerites that weather to a brown rubble, which are to be seen around Pâtussoq and Kûngnât bays. The B.D.2's have a regional trend N.E.—S.W. and may be seen on the peninsula east of Kûngnât, cutting the B.D.1's.

Towards the close of the Gardar, renewal of magmatic activity produced the Kûngnât complex. Probably the syenites, granites and basic rocks of the Nunarssuit area were intruded contemporaneously and the same may well be true of the alkaline rock complexes of Ilímaussaq, Tugtutôq, etc., away to the E.S.E.

Post-Gardar intrusives.

After the intrusion of the Kûngnât rocks the Ivigtut region remained stable and undisturbed except for a further recurrence of dyke injection. These dykes, the youngest rocks of the Ivigtut region, are assigned a post-Gardar age and have a regional trend N.N.W.—S.S.E. parallel to the Greenland coastline. Representatives are well displayed in coastal sections in Pâtussoq bay and along the peninsula to the west of Arsuk. One of these younger dykes cuts the gabbro ring-dyke at Kûngnât and is believed to intrude the syenites also.

Apart from this swarm, small dolerite dykes occupy the crush-zones in the eastern Kûngnât syenites and also traverse the smooth syenite rock face which overlooks Kûngnât Bugt.

II. THE SOUTH-WESTERN MARGINAL SYENITE

In the south west corner of the complex a fairly distinctive quartz syenite occurs. The full extent of this syenite is not known since it is only seen in restricted outcrops appearing through the moraines of the main glacier. Between the layered syenites of 920 m. Peak and the interrupted and patchy exposures of the ring-dyke on its south-western sector, the ground may very well be underlain by this syenite. Much of the debris covering the surface of the desert plain in this area appears to be due to the weathering *in situ* of underlying syenite.

Contacts between the S.W. marginal syenites and the main western centre syenites are never seen. Nevertheless, the S.W. marginal rocks are regarded as the oldest intrusive rocks in the complex, although the evidence for this is more of a negative than a positive nature. The syenites are commonly xenolithic, containing basic blocks thought to

Fig. 5. 920 m. Peak from the south. The mountain is composed of syenite of the western lower layered series. The scarp face is seen here, with the rocks dipping gently from left to right. The foreground is probably underlain by rocks of the south-western marginal syenite intrusion.

be from older dolerites, together with gneiss blocks, mainly of the "gabbro-anorthositic" variety. Dyke-like apophyses are sent out by these syenites into the surrounding rocks. These have only been seen to cut the gneiss and not the gabbros or layered syenites. The gabbro at one locality a little east of the main glacier river is in contact with the S.W. marginal syenite and appears to be chilled against it. On the west side of the river, where it passes through a small gorge formed in the gabbros, small patches of syenite with veinlets leaving them are found within the gabbro. These are probably partially-remobilised xenoliths. A pre-gabbroic age for the S.W. marginal syenite is thus certain whilst the assignment of a pre-western layered syenite age is rather more subjective.

The S.W. marginal syenites are comparatively quartz-rich rocks carrying subsidiary fayalite, aegirine-augite, and soda-hornblende with accessory magnetite, biotite and fluorite. Zircon and apatite are scarce.

A modal analysis of a typical S.W. Marginal syenite is given below (specimen 26473):

Feldspar (coarse perthite)	76 %
Quartz	7.5 -
Fayalite	2.5 -
Aegirine-augite	5 -
Hornblende and biotite	8 -
Accessories	1 -

On the western ridge of the Kûngnât massif some 500 m. to the south of its intersection by the ring-dyke, some irregular sheets of fine-grained quartz syenite occur within the gneiss. In texture and grain size they are similar to the S.W. marginal syenites and it is likely that they are of the same age and that these sheets are offshoots from the syenite which is believed to underlie the plateau to the east of the ridge.

III. THE WESTERN LAYERED SYENITE INTRUSION

A sequence of some 1800 m. of layered syenites is exposed in the western half of Kûngnât. A distinct major stratification of the rocks can be seen from a distance, particularly in the 920 m. Peak and near the summit of the Røverborg. On closer inspection it is found that the lowest exposures in the sequence show a rhythmic banding. (For the layered syenites described in this paper, a terminology will be used similar to that employed by Wager and Deer in their 1939 memoir on the layered Skærgaard gabbros). Much higher in the syenites on the west face of the Røverborg, rhythmic bands can be seen traversing the face at a height of between 1000—1200 m.

Detailed investigation reveals that throughout most of the sequence a high proportion of the tabular feldspar crystals lie roughly parallel. This "igneous lamination" of the feldspars is parallel to the mineral banding whenever this is present. The lamination has to a large extent controlled the weathering and is responsible for the larger scale stratification.

The layering dips in from the intrusion margins towards a focus that lies some way east of the Røverborg at a point now occupied by the younger eastern syenite intrusion. In the lowest rocks the dip is normally around 35°—40° although highly localised dips of up to 70° are to be found. The inclination of any particular layer is believed to decrease inwards from a maximum of ca. 40°, so that the general form is that of a rather steep-sided dish.

Over all its central part the Røverborg presents a near-vertical strike face, with layering crossing it as horizontal bands which dip gently eastwards away from the observer. Banking-up of the layering against the intrusion margins is discernible, if only faintly, near the south end of the Røverborg face and towards the north end of the Nisseborg face. The angle of dip of the marginal banding appears to decrease upwards through the series.

Two conspicuous angular basic inclusions are visible below the Røverborg summit on the west face of the mountain. A third and even

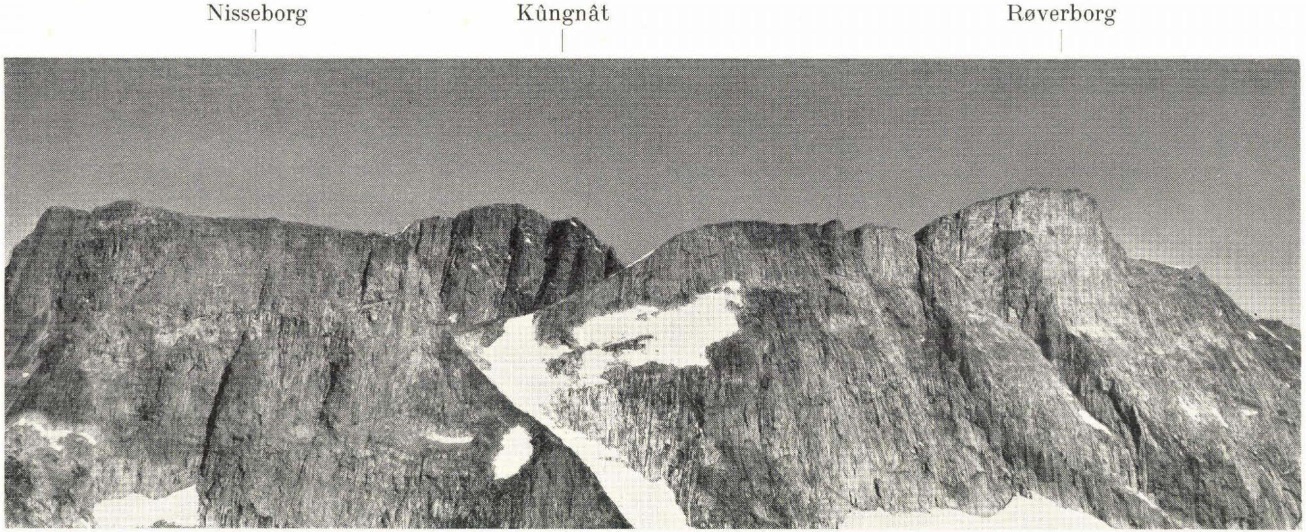


Fig. 6. Panorama of the Kûngnât syenites as viewed from 920 m. Peak. From left to right are: 1) the Nisseborg. 2) Kûngnât Peak, 3) the Røverborg. Irregular banding features can be seen in the Nisseborg face. The grey-zone of gneiss blocks occurs about half-way up the face of the Røverborg.

larger mass, at the same height (1100—1150 m.), caps the ridge a little way north of the Røverborg. These are accompanied by other less well defined grey masses, mostly lying beneath them. In favourable lighting conditions it is clear that the Røverborg wall contains a high proportion of included blocks seen as shadowy grey masses which tend to be concentrated along an apparently horizontal zone lying between 900 and 1000 m. This main grey zone, which has controlled the change of slope about half-way down the face, is virtually inaccessible but is without doubt composed of huge masses of gneiss. The lower blocks that can be reached at the foot of the wall are of banded gneiss. In some cases the margins are diffuse, in others they are quite sharp. Although the grey zone does form a quite well defined horizon, gneiss blocks are not confined exclusively to it. Similar inclusions occur along the crest of the Røverborg ridge and on its eastern flanks. The gneiss capping to the 920 m. Peak, which is more likely part of a former inclusion and not part of the original roof cover, may well be considered as belonging to a westward extension of the grey zone.

The lowest syenites of the intrusion are dark olive-green when fresh. The mafic bands form a large proportion of the whole rock, but on ascending the sequence the mafic layers become thinner and more irregularly spaced. Banding features die out almost completely after a few hundred metres and ultimately the rocks become massive and virtually structureless. However, still higher and above the grey zone a second series of banded rocks appears. The banding in these falls off rapidly in intensity upwards and the highest Røverborg rocks are extremely leucocratic and only slightly banded. Hand specimens can be taken from the highest exposures which are practically monomineralic perthite rocks.

The term "western lower layered series" (W.L.L.S.) will be used for all the syenites up to the grey zone and "western upper layered series" (W.U.L.S.) for those rocks above it. This subdivision is applicable only with difficulty to the Nisseborg succession. The rocks of the Nisseborg summit ridge are clearly of W.U.L.S. affinities and those at the foot of its west face are just as unquestionably of higher W.L.L.S. type, but the zone of gneiss inclusions does not extend this far north as a distinct horizon, as it does below the Røverborg. Hence the division here between the two layered series is rather more arbitrary, although it is believed that there is a real discontinuity occurring at some height between 700 and 950 m.

The W.L.L.S is subdivided into three sub-series. These are arbitrary divisions grading smoothly one into the other and their approximate distributions are shown on the accompanying map.

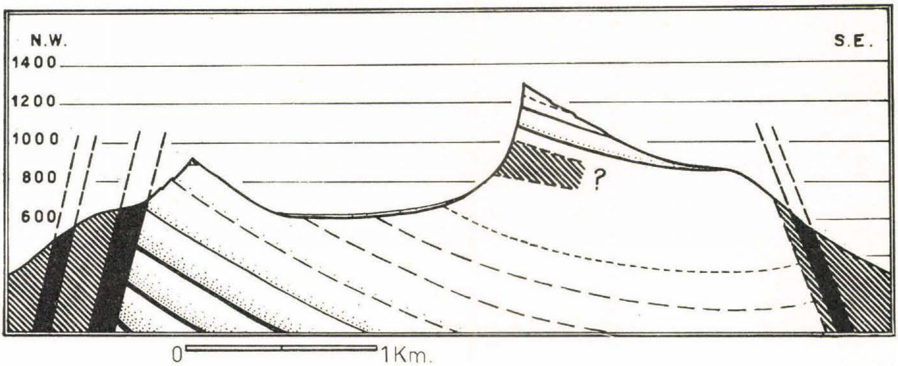


Fig. 7. Section across the western layered series drawn from 920 m. Peak to the Røverborg. Line shading, gneiss; solid, ring-dyke rocks. Density of banding in the syenites is indicated diagrammatically.

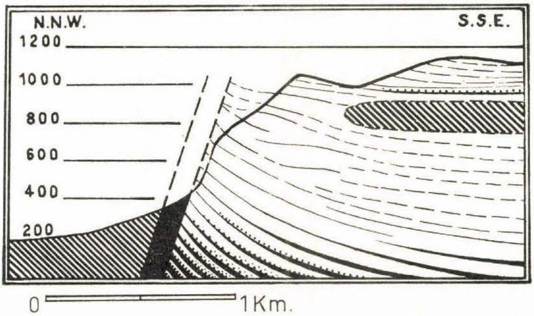


Fig. 8. Section through the Nisseborg. Ornamentation as for fig. 7.

As mentioned above, the lowest rocks seen are rhythmically banded and are comparatively mafic syenites which pass upwards into rocks devoid of obvious banding but generally showing a pronounced feldspar lamination. These in turn grade up into highly feldspathic quartz syenites in which banding features are absent and which normally possess no lamination. The lowest rocks constitute what will be termed here the lower banded group, the middle rocks constitute the lower laminated group, and the highest accessible rocks, the lower unlaminated group.

			Approx. thickness
Western Layered Syenite.	W. Upper Layered Series (grey zone)		300 m.
	W. Lower Layered Series	L. Unlam. Grp.	700 -
		L. Lam. Grp.	400 -
		L. Banded Grp.	400 -

The lower banded rocks are themselves often laminated, although this is usually less obvious than in the laminated group. In the Western

Upper Layered Series there is an ill-defined lower banded group and throughout the series much of the rock shows a comparatively high degree of feldspar lamination.

Contact relationships around the western centre.

The contacts between the W.L.L.S. and older rocks are unexposed. On the north side of the intrusion the later ring-fracturing was guided by the gneiss-syenite contact so that these two rock types are now separated by the gabbro ring-dyke. The syenites immediately inside the ring-dyke are layered rocks with banding dipping in at 30—40°. Prior to ring-dyke emplacement the banding must have dipped in directly from the gneiss wall. Naturally, on account of subsidence within the ring-fault, a lower level of syenites was formerly in contact with these gneisses than those now on a level with them. There can have been no border group of any appreciable thickness developed between the layered syenites and the gneisses.

The gneisses on the north side are poorly exposed but can be seen to have been somewhat homogenised in that they lose the gneissose banding as they near the intrusion. Close to the ring-dyke on the northern slopes of 920 m. Peak, the gneiss has a hornfelsed texture and contains quartz, orthoclase, oligoclase, orthopyroxene and a little hornblende. These rocks have been thermally metamorphosed by both the syenite and the later gabbro.

On the south side of the intrusion, ice covers the contact between the layered syenites and the gneiss slabs that appear through the main glacier to the south of them. These gneisses are probably enclosed on their south side by gabbro (again obscured by ice) and they appear to have suffered extensive metasomatism and remobilisation. Such relict gneissose banding as remains has the same strike as that of the gneisses outside the complex and there has been no relative movement between them. There has been much partial melting and most of the gneiss is seen as agmatite or auto-brecciated material. Again a high proportion of the least altered blocks are of the "gabbro-anorthositic" variety. There is intensive pegmatite development which probably owes its origin at least in part to metasomatism by volatiles from the syenite. Granitic and syenitic veins and dykes are locally abundant, some with quite diffuse margins and others with sharp contacts. In the east, the upper layered series is cut off against the younger eastern syenites. At the south end of the Røverborg ridge, the upper syenites come into contact with the gneisses but the relationships are difficult to interpret on account of the steepness of the ground, rather poor exposure and the additional complication of the gabbro dykes outcropping here. The syenites lose banding and lamination as they approach the gneiss and there is a transition zone ca. 10—15 m. broad where it is difficult to tell whether the rock should be regarded as marginal facies syenite or transformed gneiss. Close to this zone there is also a loss of banding in the gneisses.

IV. THE WESTERN LOWER LAYERED SERIES

The lower banded group.

The main glacier river emerges from the terminal moraine at a little over 500 m. and runs south westwards at right angles to the strike of the syenites exposing slabs of rhythmically banded syenite. At around 450 m. the stream course levels out and passes through a stretch of sand and gravels. The stream here is hemmed in by steep river cliffs and by moraines. The syenite comprising these river cliffs must lie within 100 m. of the southern contact and forms the lowest exposures in the layered series. North of the river cliffs are four or five syenite ribs or terraces leading down from 920 m. Peak. These are of the more resistant feldspathic rock and they are separated by sand and snow-filled gullies. These gullies are underlain by mafic horizons, ca. 1 m. thick, which have been preferentially eroded. On the north side of the intrusion the lower banded group rocks are exposed around the lower part of the north sides of 920 m. Peak and the Nisseborg.

Typically, a dark band in these syenites, rich in olivine, pyroxene and ilmenomagnetite, grades upwards from a sharply defined base into a more feldspathic layer. The gradation from mafic to leucocratic is usually quite a rapid one and is effected within the lower half of a band unit. The differentiation within such a unit is not extreme and whilst the feldspar content is seldom less than 30 $^0/_0$ in the basal layers it rarely exceeds 90 $^0/_0$ in the most leucocratic upper parts. Generally the feldspathic part of a band unit constitutes 75 $^0/_0$ or so of the whole. The more uniform feldspathic layers will be referred to as standard rock since, as a rough approximation, they probably contain an unsorted assemblage of primary precipitate material.

The banding is seen throughout a thickness of some 300—400 m. There is wide variation in unit thickness but in some parts of the sequence the banding is regularly repetitive with similar rhythmic units repeated fifty or more times. Banding is normally continuous in the available exposures and may be inferred to have considerable areal extent. In the lowest rocks even the smallest units are comparatively massive, being one or two metres in width, and in these the rock may be conspicuously mafic for as much as half the total thickness. The band units are regarded as being gravity stratified and as displaying a form of

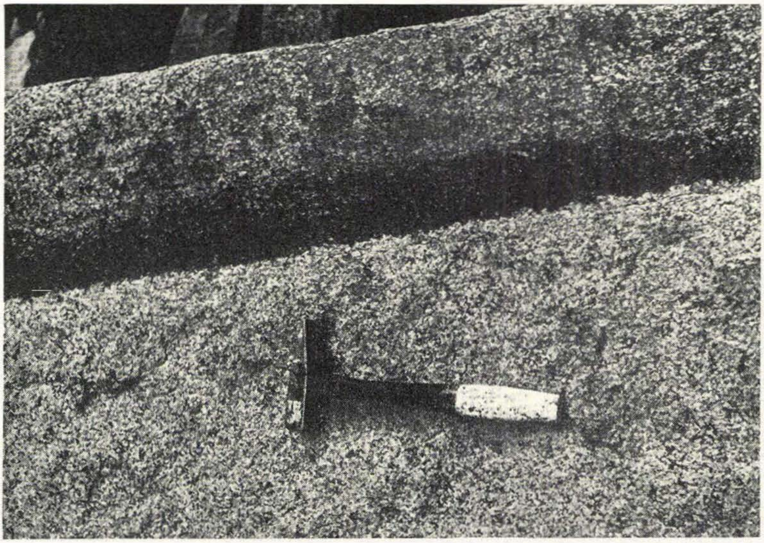


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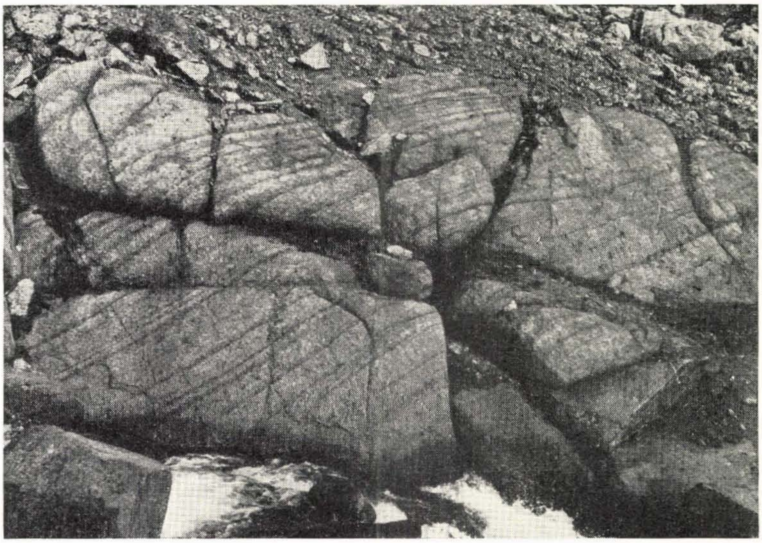
Fig. 9. Extreme mafic banding seen in the lowest exposed syenites of the western lower layered series.

J. Cooke

Fig. 10. Polished surface of a hand-specimen from a mafic band, taken from the banded syenites shown above in fig. 9. The specimen shows the leucocratic top of one rhythmic unit overlain by the mafic base of another. × $^3/_4$.



C. H. EMELEUS

Fig. 11. Rhythmic banding in syenites exposed alongside the main glacier river, western Kûngnât.

graded bedding. In general the rhythmic banding is comparable to that described from Skærgaard (WAGER and DEER 1939) and from Stillwater (Hess 1938, p. 265).

Slight discordances in the attitude of the layering occasionally give rise to an appearance of current bedding. Rocks showing such structures are thought to have been deposited under conditions of turbulence on the floor of the intrusion. Evidence of this sort, for the presence of small magmatic currents, is widespread.

Strong evidence for magmatic flow is provided by the "wash-outs", sets of trough-bands which occur fairly high in the lower banded group. The troughs are typically bilaterally symmetrical and have their long axes perpendicular to the intrusion margins. They slope down towards the centre of the intrusion at the same angle as the rest of the layering. The largest examples are 10—12 m. in width. Rhythmic layering is seen in the trough-bands and the trough-like form may be preserved through twenty or thirty band-units. The basal trough-bands appear suddenly in the syenite succession, often amongst rocks which are otherwise unbanded. The basal units of a major trough-set show the most extreme crystal sorting and are correspondingly more clearly defined. The strength of the banding diminishes upwards through the trough-set. Trough-banding is at its best in Kûngnât in the glaciated slabs lying between 450 and 500 m., which are exposed in the southern part of the main glacier. Here, four trough-sets are exposed within a stretch of ca. 150 m., all commencing at the same horizon. Trough-sets are also well displayed

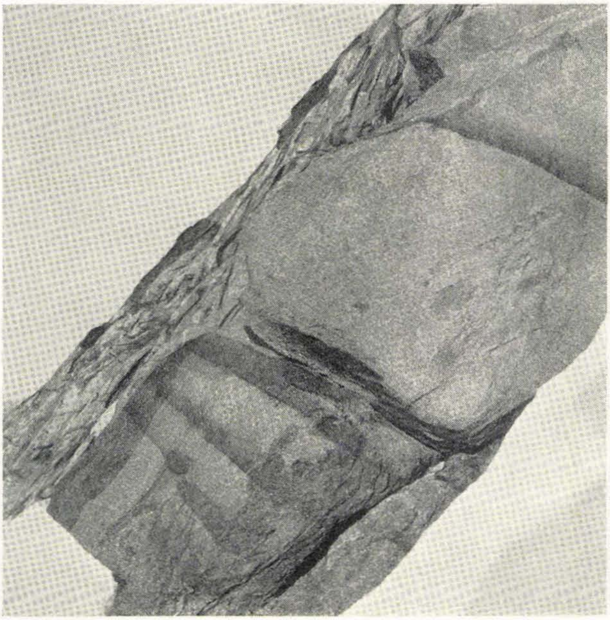


Fig. 12. Banding in syenites on the west face of the 920 m. Peak, showing mafic horizons passing upwards into more feldspathic rock.

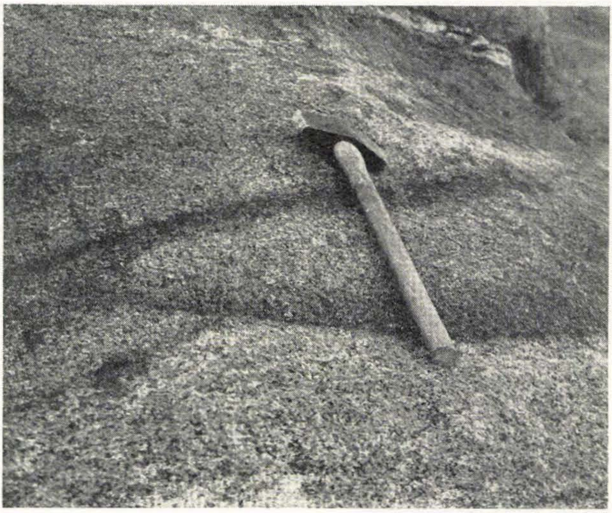


Fig. 13. Current bedding effects in syenites on the west face of the 920 m Peak.

around the lower parts of the north-western and northern slopes of 920 m. Peak and the Nisseborg. The axial plane through the trough-sets is usually vertical but at some localities, especially on the N.W. face of 920 m. Peak, a series of trough-sets is seen where the axial plane is

Fig. 14. Small trough in banded syenites on the west face of 920 m. Peak.

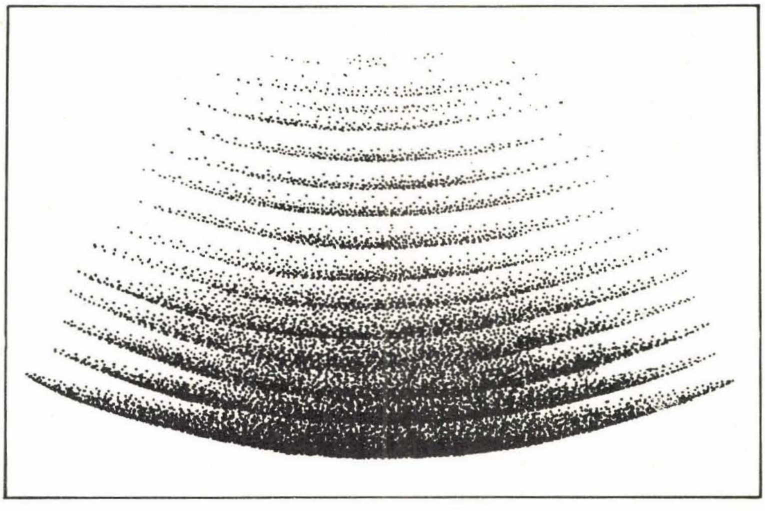


Fig. 15. Diagramatic representation of a typical large trough-band set from the lower banded group.

inclined. Each succeeding trough-band unit is a little offset from the one beneath it, always in the same sense. Thus whilst each unit is itself bilaterally symmetrical, the whole set is not and looks in cross-section like a pile of saucers heeling over. Often, small trough-sets cut across other small trough-bands beneath them and produce a false-bedded effect. There is every gradation from major trough-banding, through minor troughing and current-bedding to the regular planar bedded rocks. The troughs are almost always seen in cross-section although incomplete longitudinal sections have been found. On account of the topography the lower banded group with its trough-bands is only exposed near the intrusion margins, but it is unlikely that the troughs continue with the same intensity for an appreciable distance down dip. The Kûngnât trough-band sets are broadly similar to those described from Skærgaard. Trough-banding is also known in south Greenland from Nunarssuit where it is magnificently developed in fayalite-syenites and from Tigssalug where it is seen in layered granitic rocks¹).

The lower laminated group.

920 m. Peak with its arcuate ridge provides the most easily accessible outcrops of the laminated syenite. The steep western and northern sides of the mountain are stepped scarp faces while the dip slopes fall away on the east to enclose the main glacier. The average gradient of the dip slope is a little greater than the dip of the layering giving this side of the mountain a slightly roof-tiled appearance.

Probably on account of their relative fissility these laminated syenites are difficult to obtain in a fresh green condition and they are typically white or creamy coloured, with iron staining around the feldspars.

The lower unlaminated group.

Although generally structureless it was occasionally possible to take dips and strikes from poorly laminated rocks and from sporadic and ill-defined schlieren. These observations are approximations and it is possible that the comparatively high dips marked on the map may in some cases be erroneous.

The weathering is very superficial and gives a golden-brown tint to the rock surfaces. Beneath the weathered skin the syenites are a rich blue-green when newly broken. The rocks are exposed along the lower and central part of the Røverborg-Nisseborg face. The highest rock collected *in situ* from the W.L.L.S. (No. 27654) was taken at 745 m. at the foot of the face about 200 m. north of the Røverborg summit, and there is a considerable thickness of rock above this point up to and including the grey zone. Knowledge of these higher rocks is confined to loose blocks which have fallen onto the glacier from this inaccessible part.

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¹) Unpublished G.G.U. reports. i) Pulvertaft, T. C. R. 1958. The Geology of the Nunarssuit Area. ii) Emeleus, C. H. 1958. The Granites of the Tigssalug Area, south-west Greenland.

Modal analyses of syenites from the unlaminated group.

	1	2	3	4	5	6	7
Feldspar	86.7	88.4	88.2	89.9	87.3	90.3	89
Quartz	4.7	..	.5	1.1	2.3	3.4	6
Fayalite	2.6	..	..	1.3	3.1	.7	..
Pyroxene	5.2	4.3	5.3	5.5	6.1	3.8	3.2
Hornblende and biotite	.3	5.5	3.8	1.2	.3	1.4	1.3
Accessories	.5	1.8	2.2	1	.9	.4	.5

1. No. 26443, Foot of Nisseborg west face.
2. No. 26446, Foot of Nisseborg west face.
3. No. 26477, Foot of Nisseborg west face.
4. No. 27647, Exposure in main glacier, west of Røverborg.
5. No. 27648, Foot of Røverborg west face.
6. No. 27654, Foot of Røverborg west face.
7. No. 30633, Loose block from Røverborg face.

Pegmatites of the W.L.L.S.

It appears to be general behaviour for the western syenite to become drusy and coarsely pegmatitic as it approaches the gneisses. The lower part of the Nisseborg north face, for example, rises vertically from the contact zone and the debris-slopes beneath it are rich in pegmatitic feldspars and quartzes, together with well formed soda-hornblende prisms several centimetres long. Much of the face must be highly pegmatitic.

The layered syenites are locally riddled with pegmatite and aplite veinlets, the pegmatite veins often possessing schillerised feldspar and black hornblendes grown perpendicular to the vein walls. These veinlets were emplaced after the consolidation of the syenites and cut across the banding, often with displacement. Pegmatitic patches in the lower banded rocks are frequently seen where the bladed feldspars have grown out from a central point. Some at least are thought to have developed around well digested gneiss xenoliths.

The W.L.L.S. pegmatites have a greater tendency to be complex than those of the other Kûngnât syenites and among the minerals of the pegmatite patches in the higher syenites are riebeckitic amphibole, fluorite, siderite, zircon, white-mica (taeniolite), astrophyllite and molybdenite. The last named is extremely scarce and has only been observed in one loose block. The astrophyllite occurs as slender brown crystals, up to three or four centimetres long. Fluorite can be found as small, deep violet crystals.

One pegmatitic vein, found at the base of the Røverborg, consists of feldspar, mica, and abundant euhedral zircons. The zircons are dark brown and are up to two centimetres long. In section the zircons are patchy and clouded, but not zoned. Late stage greisen veinlets ramify through the rock carrying albite (ca. An_4—An_6) together with white mica. The mica is conspicuously replacive towards the perthitic feldspar. The zircons were collected and subsequently used for a preliminary age determination (MOORBATH, TAYLOR and UPTON, 1958), the results of which have been referred to in the introduction.

V. THE LATE STAGE SODA-GRANITE SUITE OF WESTERN KÛNGNÂT

Towards the close of the magmatic cycle at Kûngnât a large number of acid sheets and dykes were injected into the rocks of the west Kûngnât region. These minor intrusives comprise a distinctive suite of sodic rocks ranging from riebeckite granites through to aegirine-bearing microgranites. The period of injection postdated the solidification of the ring-dyke and occurred when the consolidation of the lower parts at least, of the W.L.L.S. was complete. These minor intrusives fall roughly into three classes: a) coarse soda-granites, mostly riebeckite granites, b) striped aegirine-riebeckite microgranites and c) the "grey-dykes", consisting of more evenly textured soda-microgranites.

The coarse soda-granites outcrop as sheets in the gneiss just south of the western syenite centre and also as a small sheet in the ring-dyke rocks on the western ridge. Towards its southern end, the Røverborg ridge swings to the westwards to enclose the southern lobe of the main glacier and the ridge then divides into two on either side of a high corrie at about 800 m. Some half-a-dozen soda-granite sheets intersect the arrête on the north side of the corrie and are inclined eastwards at angles of between 30°—40°, varying in width from 1—20 m.

The granites are quite white or cream coloured but are peppered with blue-black amphibole and, in some cases, with golden brown bundles and rosettes of astrophyllite. The contacts with the gneisses are normally straight and firm although they can be gradational over a zone of 1—2 cm. as a result of marginal remobilisation of the gneiss. Fine grained chilled margins are entirely lacking. Some xenoliths of the "gabbro-anorthositic" gneiss are present, the less calcic blocks presumably having been better assimilated.

The sheet which cuts the ring-dyke on the western ridge is of interest in that it proves that these granites are among the youngest intrusives in the complex. It is more astrophyllite-rich than any from the high corrie and furthermore it is notably drusy, with astrophyllite being the most prominent of the druse minerals. Astrophyllite is con-

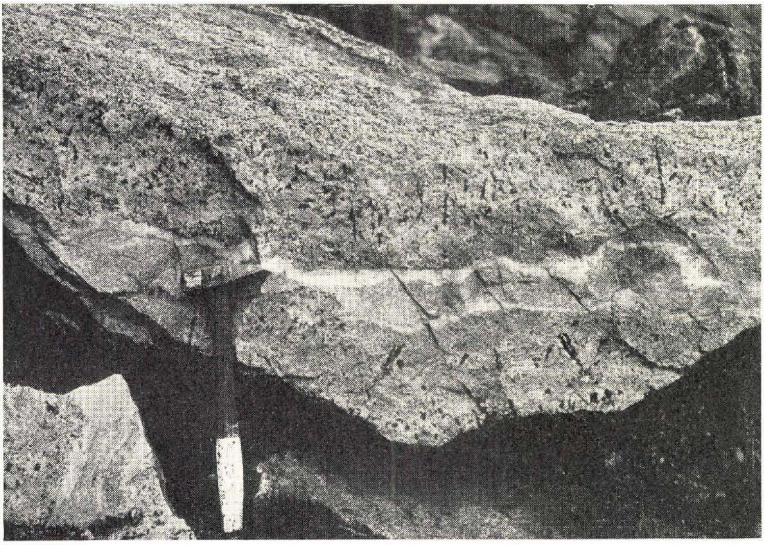

Fig. 16. A zoned and pegmatitic microgranite sheet in the western centre.

centrated close to the contacts, a feature also observed in some Nigerian riebeckite granites (Jacobson, Macleod and Black, 1958, p. 18).

In the larger sheets seen in the corrie there is some flow-banding. This is sub-parallel to the roof and floor of the sheets and results from local concentrations of riebeckite and astrophyllite. Beer (1952) describes similar riebeckite granites occurring at Darowa, Nigeria, which exhibit "... a peculiar banded appearance due to alternating layers of mesotype and leucocratic granite." In the mesotype material at Darowa the riebeckite prisms are arranged in eddy-patterns, believed to have been caused by movements in the cooling magma.

Besides the more homogeneous granites, there is a multitude of irregular sheets of pegmatitic microgranite which are best seen in the syenite exposures in and around the main glacier. In width these sheets range from a few centimetres to over ten metres and they characteristically show a marked banding roughly parallel to their cooling walls. In detail, this banding or zoning can be highly irregular and convoluted. (Fig. 16). It is due not only to variation in the proportion of light to dark minerals but also to wide variation in grain size. One of these sheets cuts the ring-dyke on the spur below the Nisseborg north face, providing proof that these too were intruded very late in the history of the complex.

At about 500 m. in the upper reaches of the main glacier river, typical microgranite sheets can be seen dipping gently upstream. The V-shaped outcrop on either side of the stream is conspicuous, the grey colour contrasting with the red-brown sand from the syenites. The contacts are knife sharp and the angular disorientated chips of syenite commonly found in these rocks show little or no sign of reaction. The disorientation is clearly apparent in the case of xenoliths of the well-laminated syenite.

Pegmatite development is characteristic and a large proportion of any single sheet may be of quartz, feldspar and soda-hornblende pegmatites. It is often not easy to clearly distinguish the "syenitic pegmatites" from these banded and often highly pegmatitic soda-granite sheets. The latter are very clearly intrusive rocks whilst the "syenitic pegmatites" and aplites may often equally well be replacement bodies. As a class, the acid intrusives are rich in quartz whereas the pegmatite-aplite veins (as opposed to drusy pegmatites) are not noticeably so. All are considered as late fractionates from the same magma, but there is some field evidence that the soda-granite suite is later than the pegmatite-aplite veining. Probably the pegmatites and aplites are derived from the interstitial liquid of the lower rocks, particularly the lower banded group, and the later acid transgressive rocks may have been the result of filter-pressing the larger volumes of inter-crystal liquid from the unlaminated group syenites.

The banded structure of the sheets commonly shows a crude bilateral symmetry which suggests that they may have originated as channels for circulating hydrothermal fluids, which were progressively filled up by precipitation on the walls. The latest and most central zone is frequently occupied by finer grained blue-grey rock, rich in amphibole. This may vein and brecciate outer layers of its parent vein. Such auto-brecciation is common. The lack of reaction with the country rocks suggests a low temperature of emplacement, although the inclusions, which are locally abundant, testify to the violent intrusion of the magmatic fluids. The zoned pegmatites present in the Quincy, Mass., riebeckite granite, which were described in great detail by Warren and Palache (1911), are evidently of the same type as these pegmatitic microgranites.

The grey-dykes are closely related to the intrusions described above. They have none of the coarse banding, although they usually show flow-structures and mineral lineation. They are not normally pegmatitic. The grey-dykes are of limited extent but have straight courses and sharp contacts. They are small, rarely exceeding 1 m. across, and usually possess a greenish tint imparted by their content of fine aegirine crystals. One has been found cutting a riebeckite granite sheet and they may as a class be later than the coarse granites and represent the final magmatic fraction of the western syenite intrusion.

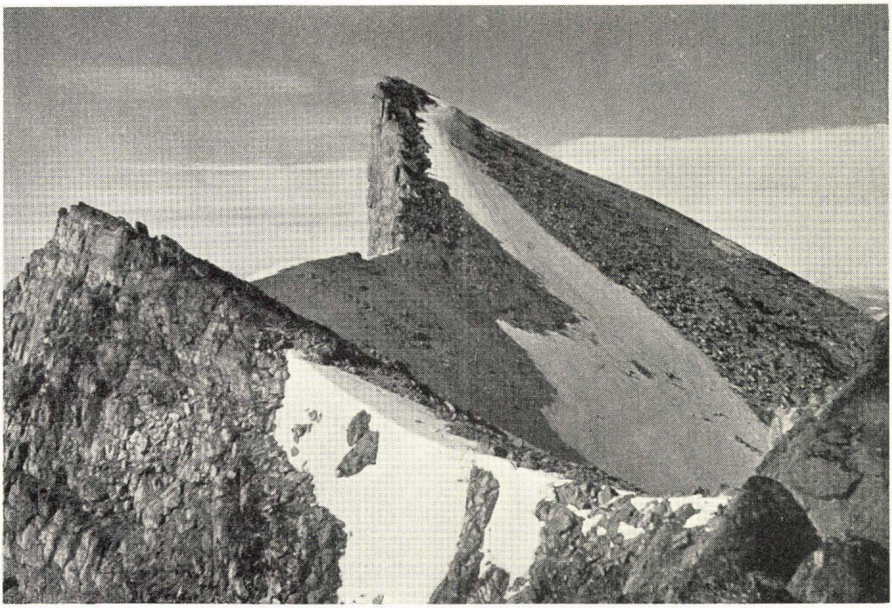

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Fig. 17. The summit of the Røverborg viewed from the south. Rocks of the upper layered series are seen dipping gently from left to right.

VI. THE WESTERN UPPER LAYERED SERIES

Although perfectly exposed on the near-vertical west face, the western upper layered series is only accessible on the eastern slopes of, and along the crest of, the Nisseborg-Røverborg ridge. Several large rhythmic band units can be followed by eye across this west face. They may be up to 10 m. thick and appear to display a high degree of sorting. In the Røverborg-Nisseborg col at ca. 980 m., some of the banding can be examined. The mafic rock outcrops as iron-stained zones. On the eastern slopes of the Røverborg differential weathering of the light and dark horizons creates in some crags the effect of a sedimentary sequence such as of alternating shales and limestones (Fig. 18).

Faint mafic banding is detectable up to the summit of Røverborg. Lamination appears best in the middle parts of the sequence and is often developed to a high degree. However, lamination is lost in the uppermost rocks and this can be correlated with a change in habit of the feldspars. The Røverborg summit rocks mainly contain blocky feldspar crystals that do not lend themselves to parallel orientation. Near the summit, textures are very variable and there is a marked influx of pegmatitic material. The rocks are coarsely drusy with feldspar,

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Fig. 18. Layering in the western upper layered series syenites.

quartz and carbonate crystals in the druses. The W.U.L.S. rocks, though thought of as being floor cumulates and not part of a down growing "upper border group", are believed to have been deposited not far below the intrusion roof, which may have lain within 200 m. of the present summit. The reason for so thinking is that the drusy and variable nature of the highest rocks is closely comparable to the behaviour of many granitic or quartz syenitic bodies close to their margins. Rocks of a similar facies occur along the summit ridge of the Nisseborg, 150—200 m. below the horizon of the analogous Røverborg summit rocks. A tentative explanation is that the roof of the intrusion was, over the Nisseborg region, materially lower and that upper marginal facies rocks developed here earlier than they did in the central Røverborg area.

Irregularities in the banding are found on the Nisseborg ridge and are also observable on its west face and there would seem to be firm ground for concluding that the Nisseborg rocks had a rather localised and individual cooling history which, though closely paralleling that of the Røverborg, had some peculiarities of its own.

The W.U.L.S. contains many fine-grained basic inclusions. One mass, just north of the Røverborg-Kûngnât col, shows intensive net-veining by feldspathic veinlets. Other large masses are visible in the Røverborg face. Xenoliths of gneiss are locally abundant and may have aureoles of pegmatite around them.

VII. THE EASTERN SYENITES

The eastern syenite stock is divisible into two parts- an eastern border group and a layered series. The eastern border group is a marginal belt of syenite possessing steeply dipping fluxion structures, which lies around the eastern periphery of the mass. The layered syenite series comprises most of the stock and has given rise to Kûngnât Peak itself. Mineralogically the syenites are of a more basic type than those of the western centre although they share many features in common with the lower banded group of the W.L.L.S. A trend towards soda enrichment of the pyroxenes and amphiboles, which is well seen in the south-western marginal syenites and in the main western intrusion, is reduced to a minimum in the eastern syenite intrusion. These syenites are not strongly differentiated although there is a tendency to produce rocks with a higher FeO/MgO ratio and with some SiO_2 enrichment. The rocks are mainly composed of alkali feldspar with subordinate olivine, ferroaugite or hedenbergite, ilmenomagnetite and apatite. Hornblende and biotite are normally present.

A tentative division of the eastern layered series into an upper and a lower sub-series is made solely on petrographic grounds. No obvious change in rock type occurs in the field and there is certainly no separation by any such raft of foreign material as there is in the western centre.

It has not been possible to demonstrate the age relationship between eastern and western centres in the field. There is no marginal chilling nor veining of one syenite by the other and recognisable inclusions of one syenite in the other have not been found. There is marginal development of pegmatite by the eastern mass, but if only the contact zone itself were studied it would not be clear which syenite had given rise to the pegmatites. The age relationship only becomes apparent after mapping the whole of the syenites, when it can be seen that the roughly circular eastern stock was intruded transgressively, cutting across the structures of the older western centre. It is inferred that the eastern syenites were emplaced after a ring-fracture had cleanly cut across the recently solidified but still hot western rocks and that the new syenites became welded against the older syenites.

The eastern border group.

The eastern border group involves those rocks forming the smooth mountain face that rises out of Kûngnât Bugt, and all the rest of the syenites lying outside the gabbro ring, together with a zone, probably less than 200 m. wide, inside the ring. This zone forms much of the east face of Kûngnât, rising above the terrace feature made by the ring-dyke (fig. 22).

The shrub and grass covered slopes that lead up to the base of Kûngnât's S.E. face overlie banded gneisses. Ascending these slopes from the shores of Kûngnât Bugt, and approaching the rock wall, the gneissose banding becomes fainter whilst patches of feldspar pegmatite become more prominent. Eventually, close to the foot of the wall, at about 160 m., a contact zone of intensive brecciation is encountered. Because of the loose rock and vegetation of the upper part of the slope and the steepness of the slabs above, it is not possible to make a precise estimate of the width of this breccia zone, but it is probably never broader than 20 m. Within this zone there is a disordered array of gneiss blocks, many of the more angular of these being of the "gabbro-anorthositic" variety. Much of the matrix material is medium grained acid rock which is believed to represent remobilised gneiss, so that, to a large extent, this is a zone of autobrecciation. Many of the contact phenomena of this zone have been described by WEGMANN (1938, p. 96).

Moving inwards, gneiss blocks become increasingly scarce and green syenite appears as the dominant rock type. Pegmatite is abundant in the marginal zones and aplitic veining is also widespread. The pegmatitic patches, occurring up to half a metre across, are composed mainly of feldspar but with subsidiary quartz and hornblende. It is conceivable that the eastern syenite body initially possessed a chilled marginal facies, such as is sporadically preserved in the contact zone of the closely allied augite syenite of Ilímaussaq, but that this was subsequently lost during recrystallization in the later stages of the cooling history. The extensively developed pegmatites have probably formed largely at the expense of the earlier consolidated and finer grained syenites.

The sequence across the contact zone can also be examined around the east face of the north-east shoulder of Kûngnât. Here again, tough green syenite passes outwards into more and more pegmatitic rock and the contact zone itself consists of a narrow belt of brecciated gneiss with an abundance of pegmatite and aplite. Beyond this, the gneiss shows loss or reduction of banding for some 30 to 40 m. At this locality, the syenite-gneiss contact is seen to be almost vertical through a distance of some 400 m.

The border group syenites are characterised by the possession of steep angled fluxion-banding. This takes the form of rather wispy mafic bands, seldom thicker than 2 cm., normally dipping steeply into the intrusion and striking approximately parallel to the contact. In detail, however, the course of these bands is highly irregular and there is a strong tendency for them to fork and rejoin. Straggly trough-like features are also developed in the marginal banding. The fluxion-banding of the border group syenites is earlier than the pegmatite and is frequently obliterated by the latter.

The syenites just inside the gabbro ring around the east side of the mountain do not differ appreciably from the syenites just outside and so, whatever the throw of the ring-fault may have been, it did not have the effect of bringing different rock types into juxtaposition.

The material comprising the mafic bands in the border group is noticeably finer grained than the 'standard' intervening feldspathic syenites. This melanocratic and finer grained variant, apart from sporadically forming distinct bands, occurs as irregular and ill-defined patches which are intricately bound up with and inseparable from the coarser and more leucocratic syenite. The grain size averages 2—3 mm. There are often no hard and fast distinctions between the fine melanocratic syenite, the coarser feldspathic syenite and the syenite pegmatite, either in terms of their physical boundaries or of their respective times of crystallization. The melanocratic rock is dark olive-green and is more nearly equigranular, than the feldspathic syenite. The latter, with feldspars 5—10 mm. long, forms the bulk of the rocks away from the pegmatitic marginal zone. Small veinlets of the coarser syenite can be found cutting the finer grained darker rock. In none of the syenite types comprising the border group is feldspar lamination observed.

The eastern layered series.

The layered series is exposed through a vertical thickness of about 800 m. There is little variety in these rocks, apart from the fact that they are intermittently well banded, the banding dipping towards the centre of the intrusion rather more steeply than in the western centre. Poorly developed feldspar lamination is occasionally distinguishable.

The contact between eastern and western syenites is either obscured by drift and ice, or occupied by the later intrusions of gabbroic rocks, or else is only exposed on the precipitous north face of the mountain. On their south side, the layered syenites pass laterally into more structureless rocks which in turn grade outwards into contact-altered gneiss. This gneiss is found as a screen-like mass enclosed between the syenites and the ring-dyke rocks. Near the top of the waterfall at 700—800 m., which marks the lip of the Røverborg-Kûngnât valley, marginal-facies syenite is exposed, crowded with semi-digested xenoliths of gneiss and basic igneous rock and criss-crossed with veins of pegmatite and aplite. There is no border group between the layered syenites and the gneiss here, in the sense that there is on the east, although the two are separated by a transition zone of perhaps 100 m. width.

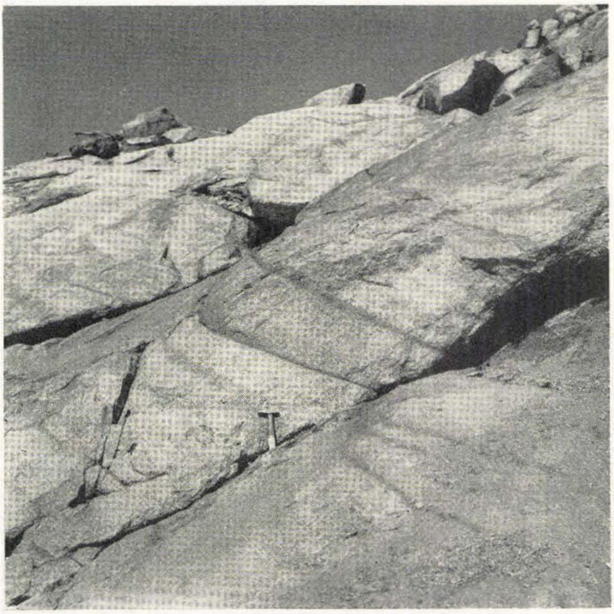
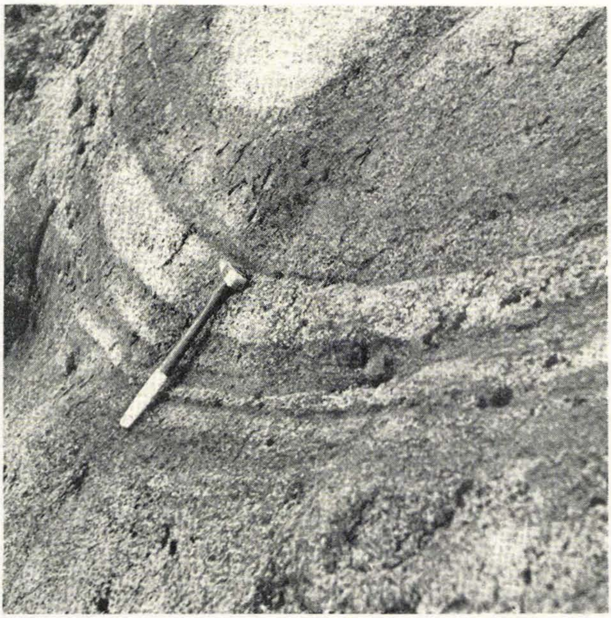


Fig. 19. Banding in the eastern layered series of syenites, seen on the west ridge of Kûngnât peak.



C. H. Emeleus

Fig. 20. Small scale trough-banding in the eastern syenites. South side of Kûngnât, ca. 600 m. above sea-level.

Rhythmic banding, seen on the south and west sides of Kûngnât peak and on the N.E. shoulder of the mountain, dips inwards at inclinations of 40—50°. Well-pronounced banding is not always immediately apparent since the more rapidly eroded mafic layers are often covered with detritus and the majority of outcrops are of the thicker feldspathic horizons. Banding is also visible on the north face of Kûngnât peak and it is inferred that the banding dips inwards away from the border group at similar angles on the eastern side also. The focus towards which the banding is directed apparently lies to the east of the geometrical centre of the intrusion.

J. Cooke

Fig. 21. Specimen from the belt of pegmatite marginal to the eastern syenites, collected below the east face of Kûngnât. The pegmatite consists of feldspar, hornblende and siderite. × $^1/_2$.

Trough-banding is scarce in the eastern syenites although well formed trough-sets occur in otherwise poorly banded syenites on the south side of the mountain (fig. 20).

The eastern pegmatites.

As already indicated, feldspathic pegmatite forms an irregular fringe around the eastern intrusion. Most of it occurs in the form of massive rock or drusy patches although there are abundant late pegmatites as well-defined veins. Aplitic material is normally associated and it is common to find veins with aplitic centres and coarse pegmatitic margins.

Most of the pegmatite consists of feldspar crystals 2—20 cm. long, which often display a striking schiller in mauves, blues and, more rarely, greens. Hornblende and quartz are important constituents; the

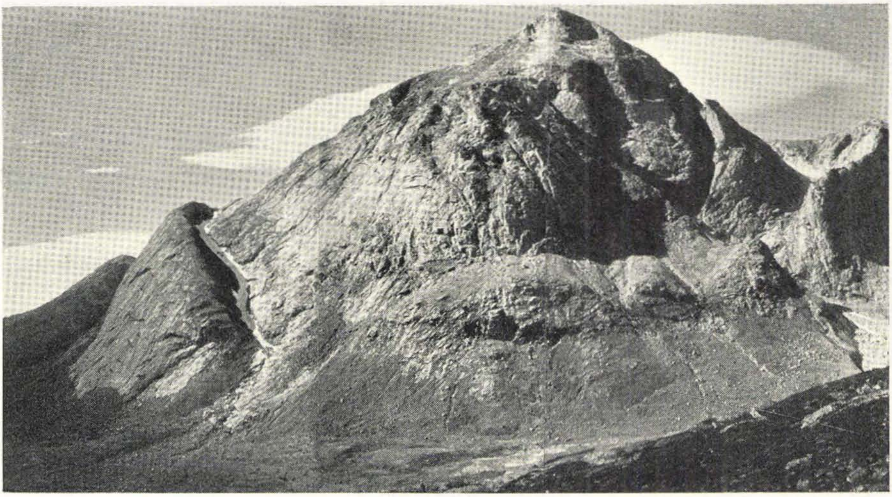


Fig. 22. Panorama of Kûngnât from the east. The outcrop of the ring-dyke forms the terrace feature on the lower part of the face and is also responsible for the snow-gullies on the north and south sides of the mountain.

quartz occurring interstitially or in vugs, usually as clear but occasionally as opaque, smoky crystals. Carbonate approaching pure siderite in composition also occurs interstitially and forms well-shaped rhombs in the drusy cavities (fig. 21). The siderite normally has an outer coating of haematite. An approximate analysis of the carbonate gave the manganese content as 2.0 $^0/_0$ MnO. Together with these minerals, zircon is often present, forming euhedral prisms of up to 1 cm. long, enclosed in the feldspar.

Late stage acid intrusives of the eastern centre.

A suite of quartz microsyenites and microgranites occurs as small intrusive bodies in and around the eastern syenite stock. This suite appears to be entirely analogous to the late stage intrusives of the west in their relationships to the syenites and in their very late (post-gabbro) period of emplacement. They occur as cross-cutting veins and inclined sheets and, less often, as sills more or less concordant with the layering of the syenite. Like those of the western centre, their contacts are sharp. Lamination of the feldspars and occasionally lineation of amphiboles may be present and some small-scale layering also has been seen in microgranite sills on the west ridge of Kûngnât Peak.

In spite of the analogies between this suite and that of the western centre, the contrast in mineralogy between the two is striking. The astrophyllites, riebeckites, aegirines, microclines and late albite of the western rocks are conspicuously lacking. These late eastern intrusives are typically light coloured and often pinkish. They contain coarse perthites, quartz, hornblende and biotite. Iddingsite after fayalite occurs in some of the more syenitic types. Apatite, ore and zircon are the normal accessories, but in one quartz syenite dyke from the shores of Kûngnât Bugt, colourless fluorite and white mica appear. This is quite exceptional and is the only known occurrence of these minerals in rocks associated with the eastern centre.

VIII. THE RING-DYKE SUITE

Following the consolidation of the syenites, a new episode of ring-fracturing occurred which admitted an iron- and alkali-rich gabbroic magma. This gave rise to a complete ring-dyke together with apophyses and side-branches which probably resulted from the further disintegration of the central block of gneiss and syenite on foundering (cf. many of the Nigerian ring-dykes, and the Ossipee ring-dyke, New Hants. (Kingsley, 1931)).

The Kûngnât complex must have been emplaced in a series of events following each other in rapid succession. Not only was the ring-dyke emplaced and crystallized whilst the residual granitic and pegmatitic fluids of the eastern centre were still mobile, but even before the late stage residuals of the earlier western centre had been injected. Whereas with the syenites there had been a progressive easterly shift of centre, at this stage the centre of fracturing reverted to a more westerly point and the ring-dyke cuts well out into the gneisses on the west but transects the eastern syenites in the east. On the north and south sides of the complex the ring-fracture followed closely along the contacts of syenite and gneiss.

The crystallization of the new magma resulted in a rather complex rock suite, consisting of feldspar, olivine (mostly hyalosiderite-hortonolite), Fe-Ti oxides, clinopyroxene, biotite and apatite, with subsidiary amounts of sulphide. Lateral variation in rock type is tentatively ascribed to mild filter-pressing at an early stage in the cooling history. However, the possibility of a certain amount of contamination by the cooling syenites cannot be excluded. Some of the rock types are undoubted fractionates from gabbroic magma and others are due to hydrothermal alteration of the solidified gabbros.

Field relationships.

The ring-dyke rocks are relatively rapid weathering and the deep gullies on the east side of Kûngnât owe their origin to the deep excavation of the gabbros by ice. Generally the gabbros weather to a brownish sand such as that covering most of the terrace feature on the east face (fig. 22).

The attitude of the ring-dyke is variable. Around much of the south and east it is dipping outwards at an estimated angle of 50°. In the extreme south-west the outward dip appears to be much shallower, possibly as low as 20°, and the topographical influence on the outcrop is considerable. At the south end of the Røverborg face two branches of the dyke are exposed through a height of some 300 m. with the contacts approximately vertical. A vertical outer contact is also clearly exposed on the western ridge. Here the ring-dyke contains large angular masses of gneiss and it is apparent that the greater thickness of the dyke in part derives from its having stoped its way into position. This is a further similarity in behaviour to many of the Nigerian and New England ring-dykes. "As in New Hampshire, most of the Nigerian ring-dykes are either vertical or dip steeply outwards, and they often provide clear evidence of emplacement by piecemeal stoping". (JACOBSON *et al.* 1958, p. 69).

Over most of its course the ring-dyke does not exceed 100 m. in width. In the southern and eastern sectors, assuming an outward hade of 50° to be normal, the subsidence of the inner mass required for the intrusion would have had to be of the order of 100 m. Narrow dykes of ring-dyke suite rocks are uncommon but occur in places within the W.L.L.S.

Evidence of the supposed ring-fault required for the intrusion is scarce. In the deep gully on the N.E. of the mountain at ca. 700 m. alongside the outer margin of the gabbro the syenites are sheared and severely crushed for a zone of less than 1 m. out from the contact. The gabbro margin itself is uncrushed. However crushing is not normally seen alongside the ring-dyke and it is likely that any mylonitisation the syenites may have possessed at the time of faulting would have been lost as a result of the rheomorphism caused by the newly-intruded magma.

Uncontaminated rock from the marginal chill zones is probably extremely scarce and was not found for collection. Thus there are no specimens of rapidly-chilled rock that might be taken and analysed to form an estimate of the original magma composition.

Broken-up fragments of fine grained basic rock, often partially hornfelsed, are commonly found in the strongly back-veined and brecciated marginal zones of the ring-dyke (fig. 25). These probably represent the metasomatised and partly-reacted chilled margin.

The north face of the Nisseborg is one huge breccia zone, apparently caused by intensive back-veining of the syenites. The net veining seen

Fig. 23. Sketch showing the course of the ring-dyke on the north side of 920 m. Peak. The amphitheatral disposition of the layered rocks can be seen in 920 m. Peak. The foreground is composed of gneiss.

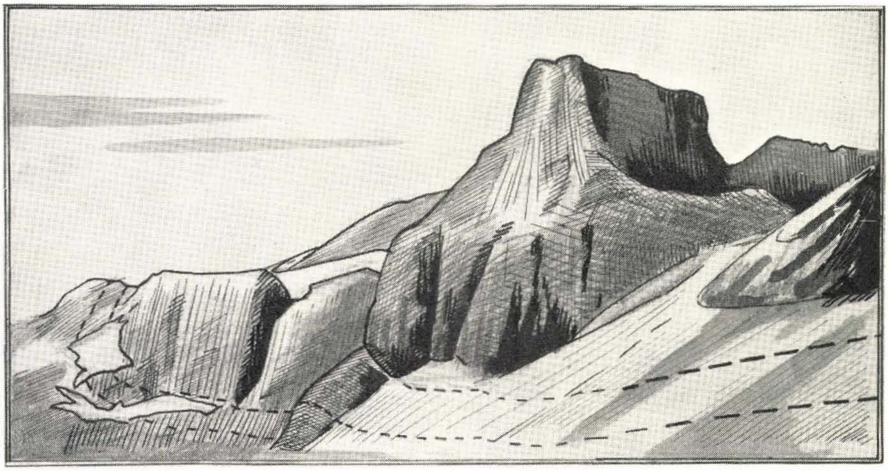


Fig. 24. Sketch showing the course of the ring-dyke below the northern precipice of the Nisseborg, a little to the east of the view shown in fig. 23.

in the outer branch of the ring-dyke on the south part of the Røverborg face is also impressive and is ascribed to the same cause. The amount of rheomorphism characteristically associated with the ring-dyke is further evidence that the gabbros were injected at a time when the syenites, though consolidated, were still at a high temperature.

Faulting, for which, admittedly, scant evidence was found in the field, is believed to be responsible for the interruption of the ring-dyke

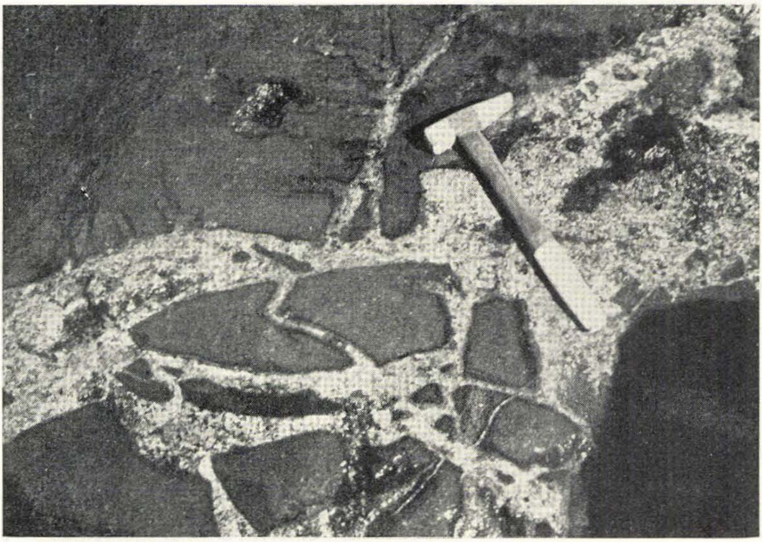


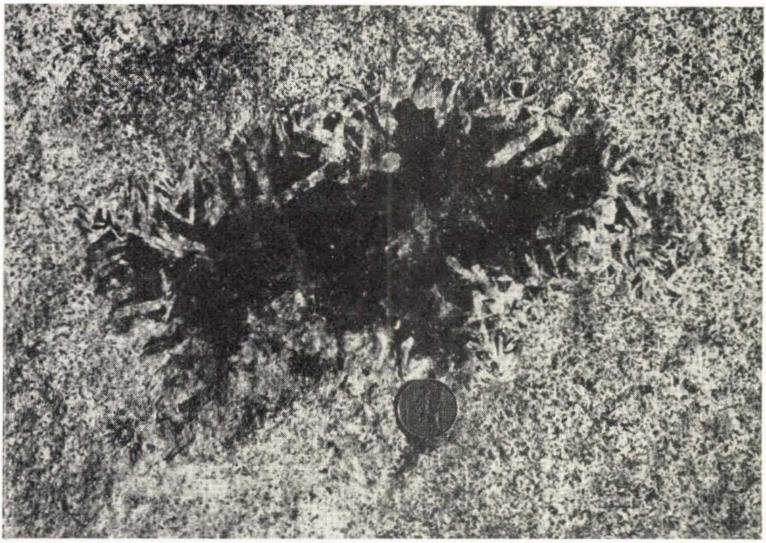
Fig. 25. Detail of the marginal brecciation of the ring-dyke rocks, believed to be due to remobilization of the basement gneiss. South side of Kûngnât.

outcrop in the south west sector. Two postulated faults are shown on the map.

The more basic rocks of the ring-dyke (e.g. no. 26040) are light coloured gabbros with clean white plagioclase. They are speckled with rusty stains around the honey-coloured olivines and with purple-black ophitic augite. The more alkaline rocks are generally greyer in colour. The ring-dyke rocks are more fine grained than the syenites, with a grain size rarely exceeding 3 mm. Biotite is almost invariably present and apparent in hand specimens. Feldspar lamination is most unusual, but is occasionally seen poorly developed. Layered structures are also scarce and never strongly developed. On the western ridge, and in the ring-dyke north of 920 m. Peak, there are suggestions of synclinal layering.

In the dyke body lying between the eastern and western syenites there are occasional cognate inclusions of another gabbroic variety. In the same area a rock having features in common with the Oslo region sørkedalites, appears alongside a gabbro dyke and probably represents a further pulse of magma.

Xenoliths are unusual in the ring-dyke but, apart from the large included blocks of gneiss in the western sector, referred to above, small xenoliths of "gabbro-anorthositic" gneiss are present in the gabbro dyke between Røverborg and Kûngnât Peak. These may have been carried up from depth from a subsided gneiss mass that had been partly brecciated by the ring-dyke magma.



C. H. Emeleus

Fig. 26. A typical pegmatitic patch occurring in otherwise homogeneous olivine gabbros. North-west sector ot the ring-dyke.

Many of the strikingly coarse pegmatite pockets in the gabbro (fig. 26), contain poikilitic pyroxene and schillerised alkali feldspar together with some olivine, ore and biotite.

In the north-west sector of the ring-dyke, immediately below the snout of the small western glacier, a slightly younger gabbro intrusion forms the inner (southern) part of the dyke. Its contact with the outer olivine gabbro is exposed over a distance of some 30 m. The contact is sharp, the later gabbro having a chilled zone of dense gabbro-picrite up to 5 cm. wide. This passes inwards into a zone, 20—30 cm. wide, of mafic gabbro studded with conspicuous and elongate plagioclase blades which lie perpendicular to the contact. These crystals, which show a high degree of parallelism, are slightly curved with the ends deflected downwards so that the crystals are convex on their upper surfaces. In length they range from 2—7 cm. (fig. 27). This perpendicular feldspar zone passes gradually into coarse olivine gabbro similar to the slightly earlier gabbro, but with a tendency to be pegmatitic. This behaviour is extraordinarily similar to that of the marginal border group rocks of Skærgaard where "reefs" of perpendicular feldspar rock occur. Wager and Deer (1939, p. 144) describe the Skærgaard example as ". . . an olivine gabbro somewhat similar to the chilled gabbro except for the lath shaped feldspars, 2—5 cm. long. . . . These form gently curved and sometimes branching crystals which are set with their length roughly perpendicular to the nearby wall of the intrusion . . .". The Skærgaard reefs are 10—100 cm. wide, parallel to the intrusion walls. In these,

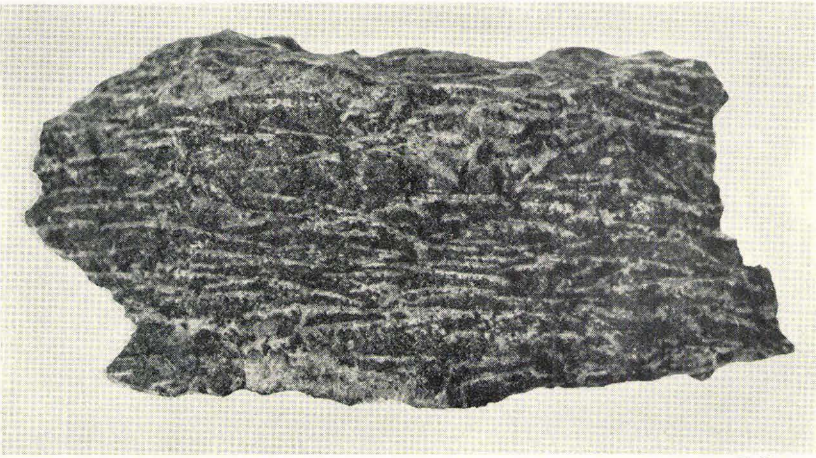


Fig. 27. Specimen of 'perpendicular feldspar gabbro' showing the typical curved and elongate feldspars which grow outwards horizontally from the vertical cooling wall. × 1/2.

according to the 1939 memoir, the feldspars, though oscillatorily zoned, are ninety percent An_{65}. (More recent determinations have shown the most basic zones in each crystal to be An_{77} (BROWN, G. M., Personal communication, Oct. 1959)). The Kûngnât analogues are not more basic than An_{60}.

WAGER and DEER conclude that the long feldspars grew inwards from the temporary cooling wall and that their extended growth was helped by circulatory magma currents. This explanation would apply equally well to the Kûngnât rocks.

A peculiar rock type occurs in the same general area as the perpendicular feldspar rock and also in the central branch of the ring-dyke. The rock consists of olivine-rich and feldspar-rich portions occurring in alternating ill-defined lenses, these lenses being arranged more or less horizontally (fig. 28). Such "ripple-marked" gabbros occur as localised patches or reefs in the ring-dyke. Mineralogically, these rocks are identical to the standard gabbros around them and differ only in their peculiar heterogeneity. These reefs, to generalise from one case where the base was exposed, overlie the standard-textured gabbros approximately horizontally. The basal contact was sharp and had plagioclase crystals 1—2 cm. long growing vertically up from it. Thus the ripple-marked gabbros appear to start growth as a variety of perpendicular feldspar rock, perhaps analogous to a harrisitic growth (BROWN 1956).

At two localities in the ring-dyke, one in the N.W. sector and the other on the south face of the mountain, a schistose variety of rock is found. The schistosity is imparted by the common orientation of the biotites. Lying between the mica plates are strings of small olivines and

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Fig. 28. 'Ripple-marked gabbro', outcropping in the north-western sector of the ring-dyke.

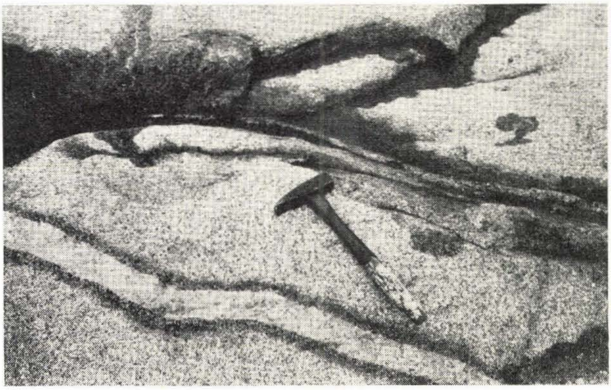

Fig. 29. Even-grained olivine gabbros transected by a feldspathic vein. The dark rims on either side of the vein are of contact-altered metasomatised gabbro.

zoned plagioclases. The crystals are unbroken and the rock texture is not obviously hornfelsic. Possibly these rocks completed their growth under stressed conditions. Apart from the olivine, feldspar and biotite, there is occasional development of orthopyroxene probably developed at the expense of the olivine.

Local areas of hydrothermal alteration are common in the ring-dyke. There is good field evidence that the alteration was caused by residual liquids from the two main syenite bodies. In the rocks affected, only the ore and apatite remain unaltered. The plagioclase is heavily sericitised, the olivine and augite altered to amphibole (in some cases a red-brown barkevikite zoning out to a pale green hastingsite), and the biotites are selectively bleached to a chloritic material, leaving opaque or darkly pleochroic strips parallel to (001). Fig. 29 shows the metasomatised rims of gabbro alongside a late stage veinlet derived from the western syenite. The riebeckite granites, when in contact with the gabbros, effect a similar marginal alteration.

IX. THE PETROGRAPHY OF THE SYENITES

Much of eastern Kûngnât and also the lower parts of the western layered sequence consist of comparatively basic syenites which have relatively high CaO/Na_2O and low FeO/MgO values together with smaller SiO_2 contents. These syenites are closely comparable to the "augite-syenites" of Igaliko and Ilímaussaq and to the type locality larvikites from the Oslo region. (The similarity between the Igaliko "augite-syenites" and the Oslo larvikites was stressed by USSING (1912)).

Compared with these rocks, the basic Kûngnât syenites are somewhat deficient in sodium and aluminium. This is reflected in the fact that these other syenites are often nepheline bearing whilst nepheline has not been recorded from Kûngnât.

In spite of the overall similarity between the more basic syenites in the Kûngnât complex and the larvikites the name larvikite has not been adopted here and the ponderous, but more accurate, name of ferrohortonolite-ferroaugite syenite has been thought preferable.

In accordance with the concept introduced by WAGER and DEER in 1939, the layered rocks will be considered as being composed of primary precipitate material which settled out from the magma to accumulate on the floor of the intrusion together with interprecipitate material formed from the liquid retained interstitially between the primary precipitate crystals. Some of the interprecipitate liquid would yield discrete crystals whilst the rest would simply enlarge the primary precipitate grains.

L. R. WAGER, in a personal communication, suggested that the term "cumulate" be used for those rocks which have been formed through the accumulation of primary precipitate crystals. In the case where the interstitial liquid has crystallized in place with little or no change in the bulk composition, i.e. with diffusion effects restricted to a small range, he suggests that the resultant rock be distinguished as an "orthocumulate". These contrast with the "adcumulates" in which larger scale diffusion effects have produced significant changes in the composition of the interprecipitate, e.g. in some of the ultrabasic rocks on the island of Rhum (BROWN 1956 p. 14). In general the layered syenites of the Kûngnât complex come under the definition of orthocumulates.

SHAND (1949 p. 272) concluded that the mechanical accumulation of crystals probably played a part in the genesis of certain syenites, "... particularly those with a prominent banded structure and parallel texture." He cites the case of the Plauen syenite which EBERT believed to have been formed through feldspar accumulation (from the Meissen granite magma), with the interstitial matter representing the trapped liquid.

The primary precipitate minerals in the layered syenites are believed to have included; a) a high temperature alkali feldspar of the sanidine-anorthoclase series, close to the minimum melting point composition, b) fayalitic olivine, c) iron-rich clinopyroxene, d) a high temperature solid solution of Fe and Ti oxides and e) fluorapatite.

These collected on the intrusion floor as a crystal mush which may at first have contained a volume of interstitial liquid approximately as great as that occupied by the crystals themselves. The mafic layers with 25—30 % of dark minerals may possibly have been more closely packed and may have held less interprecipitate liquid than the feldspathic layers. Primary precipitate packing was probably better in those syenites with more tabular feldspars where there was good lamination than in the poorly laminated syenites. At the time of writing the Skærgaard memoir, WAGER and DEER believed that only ca. 20 % of each layered gabbro was derived from interprecipitate liquid.

Any zoning in the feldspars and ores after the crystallization of the interprecipitate magma was subsequently lost when these minerals underwent unmixing. However, the perthites and antiperthites do carry thin extra-perthitic fringes of sodic feldspar. The fayalites tended to be made over to the changing equilibrium composition more readily than the pyroxenes, and whilst there is usually vigorous zoning in the latter, this is not seen in the olivines.

With the increase in water vapour pressure as the temperature fell, the pyroxene zoning gave place to hornblende formation. The hornblende can be regarded as playing a treble rôle in that it *a*) effectually continues the zoning of the pyroxenes but now as a hydroxylated phase, *b*) of replacing or making-over the pyroxene already present and *c*) of crystallizing interstitially as an independent mineral. Throughout the Kûngnât syenites it appears that no more pyroxene was formed after the start of hornblende separation.

The western lower layered series exhibits cryptic layering, with small changes in the compositions of the constituent minerals occurring upwards through the sequence. The feldspars change in habit and in perthitic texture and there is a corresponding compositional change. The olivines become more iron-rich upwards and the pyroxenes grade from grey augitic varieties up into aegirine-augites.

The Fe-Ti oxides, which, together with apatites, are important primary constituents in the lower rocks, become increasingly scarce in the upper rocks. Apatite is virtually eliminated by the time the unlaminated group syenites are reached. Sulphides, of minor importance in the mafic layers of the lower banded group, also decrease upwards. Quartz, fluorite and siderite are normal constituents of the higher rocks. The appearance of these minerals is never abrupt and is too subtly accomplished to be of use in mapping.

In the mafic layers of some of the trough-bands, large poikilitic knots of hornblende occur as black spots in the rock. Their formation probably involved considerable ionic diffusion in the interstitial liquid towards the crystal nucleii.

Lepidomelane reaction fringes around the ilmenomagnetite crystals are present wherever the ore grains were exposed to the increasingly hydroxyl-rich residual liquid. Higher up the sequence these mica fringes are lost, presumably on account of the lower Ti content of the ores in the later rocks. A new biotite phase appears as an interstitial mineral in the upper syenites. This variety of biotite is also found in the south western marginal syenites and in the W.U.L.S.

It is doubtful whether the rocks of the unlaminated group of the W.L.L.S. should be regarded as cumulates. The residual magma at this stage may have crystallized more or less *in situ* with a minimum of crystal sinking and it is more proper to speak of the crystals as early or late phases rather than to try to distinguish between primary precipitate and interprecipitate. Of the late phase minerals, quartz, fluorite and siderite occur anhedrally but zircon and thorite(?) assume euhedral forms.

In several ways the upward changes in the W.U.L.S. parallel those found in the W.L.L.S. Again there is an upward gradation from quartz-deficient types to rocks in which quartz is an essential constituent. Olivine, and to a lesser extent pyroxene, is rare in the higher rocks, being virtually confined to the thin and sporadic mafic horizons.

A hastingsitic amphibole (with an associated biotite species), is present throughout the W.U.L.S., together with a less sodic hornblende. In the uppermost rocks, riebeckitic material is also present.

Fe-Ti oxides are scarce in this upper syenite series and lepidomelane fringes are generally absent. Zircons and minute apatites are constant accessories and a small amount of interstitial carbonate and fluorite appears in the uppermost rocks of the series.

The feldspars.

The syenites are composed mainly of alkali feldspar which occurs, for the most part, as coarse perthite and antiperthite. However, all gradations are to be found between coarsely exsolved feldspar and almost optically homogeneous material that is only slightly unmixed. The bulk feldspar from ten syenite specimens, taken from various parts of the complex, was separated and partially analysed. The observed composition range was from $Or_{32} \rightarrow Or_{41.5}$, and from $An_{11} \rightarrow An_4$, (wt. $^0/_0$).

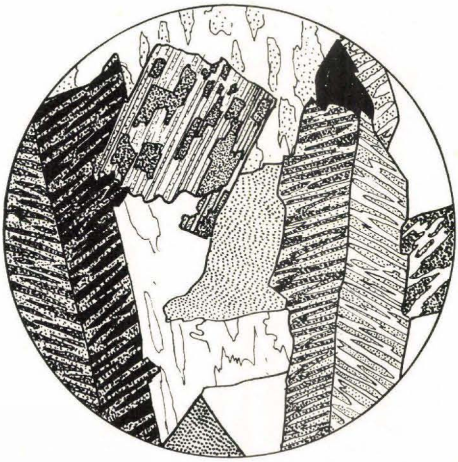

Fig. 30. Feldspar from a typical south western marginal syenite. A perthite crystal is seen in approximately (100) section together with two twinned crystals exhibiting the herring-bone pattern. These are seen in approximately (010) sections. The feldspar is accompanied by interstitial quartz. Specimen No. 26016. Crossed nicols. ×20.

By analogy with similar feldspar from Norwegian larvikites, whose cooling history has been discussed in detail (Muir and Smith 1956, Smith and Muir 1958), it is likely that the feldspar in most, if not in all, of the Kûngnât syenites commenced growth as homogeneous, high-temperature, monoclinic feldspar, i.e. as soda-rich sanidine. The perthitic and antiperthitic feldspars present in most of the syenites are members of the orthoclase-microperthite series as defined by Tuttle (1952) and subsequently modified by MacKenzie and Smith (1955). However, those feldspars showing least exsolution have high optic axial angles and these, plotted on the diagram relating 2V and composition (fig. 32), lie between the curves representing the sanidine-anorthoclase series and the orthoclase-microperthite series, although nearer to the latter curve.

Feldspars of the south west marginal syenites: These are characteristically well formed and up to 2—3 mm. long. Microscopically they possess complex intergrowths along the boundaries of adjoining crystals. Most, if not all, are twinned on the Manebach law, usually once, but not infrequently two or three times. The perthite lamellae are developed along ($\bar{1}502$), so that on (010) faces the lamellae are distributed along either side of the twin composition plane, giving the crystal a distinctive herring-bone appearance. The perthites contain approximately equal amounts of sodic and potassic phases. The latter is normally clouded to a greater or lesser extent with decomposition products and appears to be monoclinic. The albitic lamellae possess very fine scale polysynthetic twinning parallel to (010).

Feldspars of the western lower layered series: In these syenites the average length of the feldspars is ca. 6—7 mm. and they only exceptionally exceed 1 cm. In the laminated group the feldspars are usually not more than 1—2 mm. thick. The feldspars normally possess complex textures which result from twinning, unmixing and late deuteric effects. However, clear and almost homogeneous crystals devoid of these complications are present in, and apparently restricted to, the mafic parts of the banded rocks. They are always accompanied by a certain amount of perthitic (or antiperthitic) material and there are all gradations between this and the nearly homogeneous material. These clear feldspars are cryptoperthites in which exsolution has been arrested at a relatively early stage, most probably as a result of low concentration of water and other fluxes in the surrounding liquid. Tuttle and Bowen (1958, p. 50) came to wonder how such cryptoperthites manage to persist in nature at all, when unmixing can be induced in the laboratory by heating them in the presence of water vapour under pressure. They concluded that the natural cryptoperthites must have cooled in an extremely dry environment in order to have remained in the metastable condition. On the (100) faces the cryptoperthites show straight extinction and hence appear to be monoclinic.

In the lower syenites the feldspars are mainly antiperthitic and consists of patches of cloudy orthoclase set in a plagioclase matrix. The plagioclase displays a combination of albite-ala twinning (determination by K. Heier) together with multiple pericline twinning. Proceeding upwards through the lower layered series there are subtle changes in the appearance of the feldspars. The multiple twinning of the plagioclase becomes finer and less obvious and the pericline twinning becomes scarcer. The orthoclase patches become better ordered into regular lamellae and ultimately, in the unlaminated group rocks, finely developed lamellar perthites are dominant. Manebach-twinning also appears and increases in importance upwards and the higher rocks possess herring-bone perthites similar in appearance to those of the south western marginal syenites.

The partial analyses of five feldspars from the W.L.L.S. show a range from $Or_{32.5}Ab_{60}An_{7}Cn_{0.5}$ (mol. comp.) in the lowest exposed rocks, to $Or_{39.5}Ab_{56.5}An_{4}$ in the lower rocks of the unlaminated group. These analyses suggest that the trend followed by the primary precipitate feldspars was towards enrichment in potassium and depletion in calcium and barium. Barium is at its maximum in some rocks of the lower banded group where the molecular percentage of barium feldspar (Cn) rises to 1 %.

An antiperthite from the lowest rocks (specimen No. 26003), consists mainly of oligoclase and orthoclase. The oligoclase has a composition of ca. An_{14}, as estimated from its 2V (84°+) and from its refractive indices, using TSUBOI's curves (α' close to 1.535). The bulk composition of this antiperthite is $Or_{32.5}Ab_{60}An_{7}Cn_{0.5}$ (mol. %). In rather similar feldspar from higher in the series (in the laminated group), a stereographic plot of the angles between the twin axes and α, β, and γ indicated a composition between An_{10}-An_{14}. Here the orthoclase fraction had a $2V\alpha$ of 36—42° (data kindly supplied by K. HEIER).

Optic axial angles of cryptoperthitic material from the W.L.L.S.: The compositions are of the bulk feldspar, obtained through partial analyses on the assumption of ideal formulae.

Specimen No.	Composition, wt. %	$2V\alpha$
27648	$Or_{40.5}Ab_{55}An_{4.5}$	87—71°
26261	$Or_{41.5}Ab_{53.5}An_{5}$	76—39°
26470	$Or_{39}Ab_{55}An_{5}Cn_{1}$	73—65°
26467	$Or_{40.5}Ab_{55}An_{4}Cn_{0.5}$	87—60°
26003	$Or_{34.5}Ab_{57.5}An_{7.5}Cn_{0.5}$	83—79°

Feldspars of the western upper layered series: The average crystal size is slightly less than in the underlying syenites, the average length being ca. 5 mm. In the laminated syenites the crystals are ca. 0.75—1 mm. thick. However, in many of the poorly laminated rocks they are approximately square in cross-section with a side length of up to 2 mm. As a generalisation, the feldspars of the W.U.L.S. are more euhedral than those of the W.L.L.S. This is tentatively correlated with the better lamination in the W.U.L.S., which may have permitted better packing. Better crystal packing would have meant less intercrystal liquid and hence less subsequent growth of the primary precipitate crystals to spoil the more nearly perfect shape acquired before settling.

The feldspars are similar to those of the lower series in their microscopic features. Feldspars in the mafic layers are often quite free from twinning and scarcely exsolved. In all the W.U.L.S. sections examined there are occasional crystals with almost clear cryptoperthitic centres and more coarsely perthitic margins. The lower rocks contain antiperthitc feldspars with the orthoclase patches more or less defined by pericline and albite twin-lamellae in the plagioclase. These twin lamellae do not intersect and a mosaic or chequer-board texture results. The albite twinning seems to be generally simple without the combination albite-ala. This facilitates use of extinction angle measurements in estimating feldspar compositions. There appears to be a small range in composition of the plagioclase component from the bottom of the series to the top, from ca. $An_8 \rightarrow An_4$. The perthites from the upper rocks generally show more regular lamellar textures, often with Manebach twinning giving herring-bone patterns on (010). These are less perfectly developed than those in the south west marginal or the unlaminated group syenites. The orthoclase component of these perthites has an extinction of α onto a of ca. 8°. The intercrystal boundaries between the feldspars are highly complex with intricate dovetailing and interlobing of adjacent crystals. Untwinned albite, not in optical continuity with the plagioclase of the perthites, occurs as intercrystal material. On the other hand, perthitic crystals are commonly surrounded by homogeneous or scarcely perthitic plagioclase which *is* in optical continuity with the albite of the central parts, and which has broader twin lamellae than the latter. The plagioclase rims are reminiscent of those seen around the antiperthitic feldspars in the riebeckite granites (see p. 76).

Analyses of feldspars from two rocks, one low in the series and the other from the highest point in the sequence, indicate a slight overall change in molecular composition from $Or_{37}Ab_{58}An_5$ to $Or_{37.5}Ab_{59}An_{3.5}$.

Feldspars of the eastern syenites: In the mafic bands and schlieren, unmixing of the feldspar was slight and clear, untwinned, unzoned and nearly homogeneous feldspars are again found, precisely as they are in similar situations in the western layered series. Feldspars of this type occur in the more basic border group rocks as anhedral, interlocking crystals, seldom exceeding 1—2 mm. diameter. The feldspar extracted from such a rock, (no. 26118), had a molecular composition of $Or_{33}Ab_{58}An_8Cn_1$, but this probably does not represent the most calcic of the border group feldspars. Again, there are all gradations from the optically homogeneous feldspars to the coarsely antiperthitic types characteristic of the standard rocks. A feldspar separated from the higher (feldspathic) part of a rhythmic unit in the more basic syenites occurring high in the eastern layered series had a bulk composition $Or_{29}Ab_{59}An_{10.5}Cn_{1.5}$ (no. 27696a). This feldspar consisted of both coarse antiperthite and slightly unmixed cryptoperthite. Antiperthite from the standard rock in a rhythmic unit from the lower part of the layered series had a composition $Or_{33.5}Ab_{62}An_{4.5}$ and, as anticipated, this feldspar from a more fractionated rock is poorer in Ca and Ba than the other two, but shares in common with them a relatively low K content compared with the feldspars from western kûngnât.

The antiperthites tend to be tabular parallel to (010), although the crystal form is usually poor and the crystal margins are complex with a suggestion of replacement textures. There is never the development of the fine lamellar perthites which occur in the western intrusions, and the Manebach twinning which is normally associated with these perthites is seldom seen in the eastern syenites.

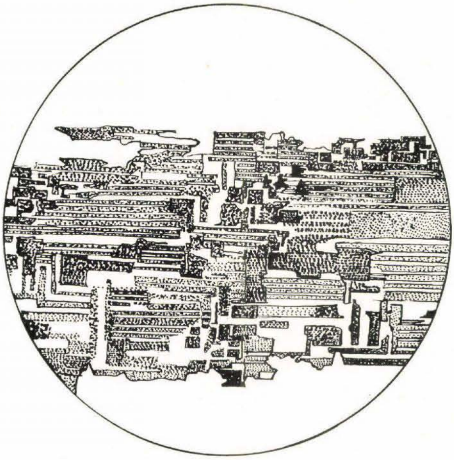

Fig. 31. Part of the (100) face of a typical antiperthite from the eastern syenites, showing typical chequered or mosaic appearance. Crossed nicols. × 20.

Feldspar apparently closely similar to much of that in the eastern syenites is described from the Oslo larvikites by Muir and Smith (1956). Their specimen no. 1 is taken from a larvikite that is mineralogically very similar to the more basic eastern syenite types. They describe this larvikite as a dark irridescent rock containing Ti-augite, lepidomelane, iron-ores, large crystals of apatite, olivine pseudomorphs and some barkevikite. The blue schillerised feldspar was sub-microscopically perthitic and consisted of three components *a*) almost optically homogeneous alkali feldspar, *b*) exsolved plagioclase, ca. An_{18}, and *c*) a minor amount of exsolved Or of composition ca. $Or_{85}Ab_{15}$. The optically homogeneous phase had an angle α onto a of 7—9° and had refractive indices and 2V which are set out below in comparison with those measured on the two more basic of the analysed eastern syenite feldspars from Kûngnât:

Refractive indices.

Specimen:	α	β	γ	2V
S. and M. No. I	1.527	1.532	1.536	76 —82°
Kûngnât No. 26118	1.527	n.d.	1.534	80 —83.5°
Kûngnât No. 27696a	1.529	1.530	1.534	78.5—84°

The optic axial plane was perpendicular to (010) in all three.

By single crystal X-ray analysis, Muir and Smith found that the optically homogeneous material from the larvikite consisted of an intergrowth of Ab-twinned soda-feldspar and a weaker monoclinic potash phase. The α^* and γ^* lattice angles corresponded to a low temperature plagioclase of ca. An_{18}, or to a plagioclase of lower An content which was in a transitional thermal state. From analogy with this larvikite feldspar and with those from the base of the W.L.L.S., the plagioclase content of the eastern syenite antiperthites is thought to have a composition of around An_{15}—An_{18}.

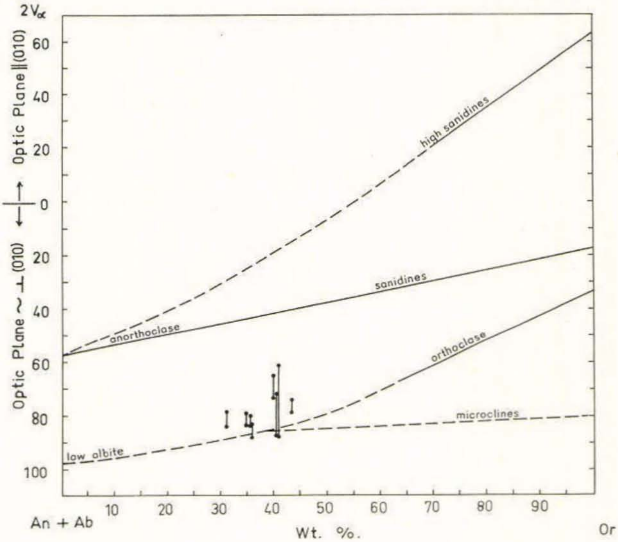

Fig. 32. 2V and composition of feldspars from the Kûngnât syenites, plotted on a modification of Tuttle's diagram (MacKenzie and Smith, 1955).

Feldspars from the eastern pegmatites: The large and beautifully schillerised 'moonstone' feldspars from these pegmatites are often glassy clear. Bøggild (1905 p. 442), is evidently describing one when he writes of a pegmatitic feldspar from "Kunak" as being extraordinarily clear and free from inclusions or any microscopic structure.

A partial analysis of one such feldspar, which presumably commenced growth as a sanidine, indicated a molecular composition of $Or_{45}An_{51}An_4$. The refractive indices were α 1.525, β 1.528, and γ 1.532. The extinction angle of α on the trace of (010) is 12°. This, together with the high $2V\alpha$ (74—79°), suggests a close similarity to some feldspars from the Oslo region, described by C. Oftedahl (1948a). These, from syenite-pegmatites and nordmarkites, he attributes to late stage magmatic hydrothermal stages and he places them in the orthoclase-cryptoperthite series. Oftedahl concludes that the schiller in the Norwegian examples is due to some sort of internal reflection from the boundary planes between the two feldspar phases. In the case of those showing blue and violet colours, he says that the internal reflection in some cases has the character of a selective reflection, with a higher reflection power for the blue and violet colours than for the others.

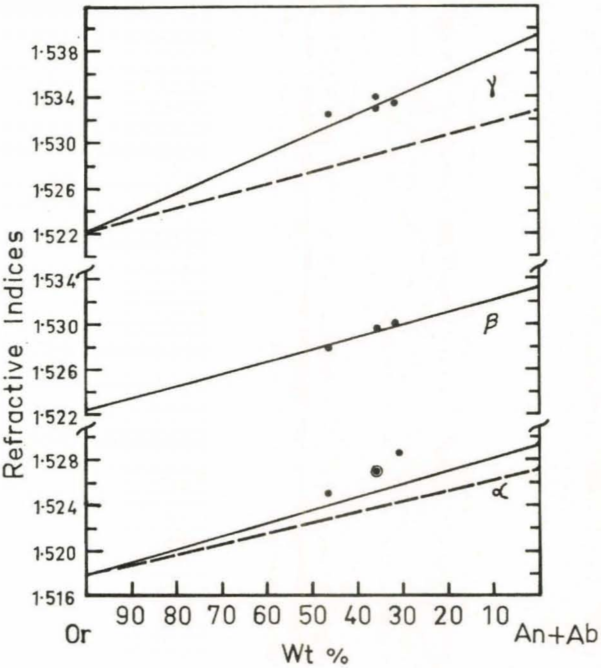

Fig. 33. Kûngnât orthoclass-cryptoperthites plotted on Tuttle's diagram relating refractive index to composition (Tuttle 1952).

Oftedahl has also examined a feldspar from Kûngnât (spelled "Kunait"), the precise locality of which is unknown. This was a coarse microperthite, the phases extinguishing at 5° and 10° on (010), (Oftedahl, 1948b).

Cooling history of the feldspars: Muir and Smith considered that the data on their larvikite feldspar, specimen no. 1, were consistent with the primary crystallization of a single lime-rich anorthoclase of composition $Or_{28.5}Ab_{61.5}An_{10}$ (wt. $^0/_0$), which underwent subsequent unmixing and inversion. (In a more recent publication, however, (Smith and Muir 1958) they revised their nomenclature, calling the primary single-phase (monoclinic) feldspar a lime-bearing soda-rich sanidine, rather than an anorthoclase). The compositions of the comparable Kûngnât cryptoperthites from nos. 27696a and 26118 were respectively $Or_{30.5}Ab_{57}An_{11}Cn_{1.5}$ and $Or_{35}Ab_{56}An_{8}Cn_{1}$ (wt. $^0/_0$s), and these are similarly considered to have once been single phase soda-sanidines. Since it is likely that the rock from which Smith and Muir's specimen no. 1 was taken must have had a rather similar cooling history to that of the eastern Kûngnât syenites, their deductions regarding the successive changes in this feldspar may well be applicable to the basic oligoclase antiperthites from Kûngnât. These authors suggested that, on reaching the solvus, the disordered and monoclinic soda-sanidine unmixed into two components, namely a Na-rich sanidine and a K-rich sanidine. On further cooling the Na-rich sanidine inverted to anorthoclase. As Al-Si ordering proceeded with lowering temperature the anorthoclase gave way to oligoclase and the K-rich sanidine was converted to orthoclase, this resulting in the formation of an oligoclase-antiperthite. Continued ordering could yield an antiperthite containing microcline and oligoclase in a lower structural state. In the absence of X-ray data, the structural state of the plagioclase and K-feldspar within the Kûngnât antiperthites is unknown. However, there is a strong probability that microcline could be detected in them. The probability is even stronger in the case of the feldspars from the quartz syenites. Relevant information is provided by Woodard (1957) who describes the feldspars from the fayalite-bearing nordmarkites occurring in the Mt. Agamenticus ring-complex in Maine. Here, the typical nordmarkite contains anti-

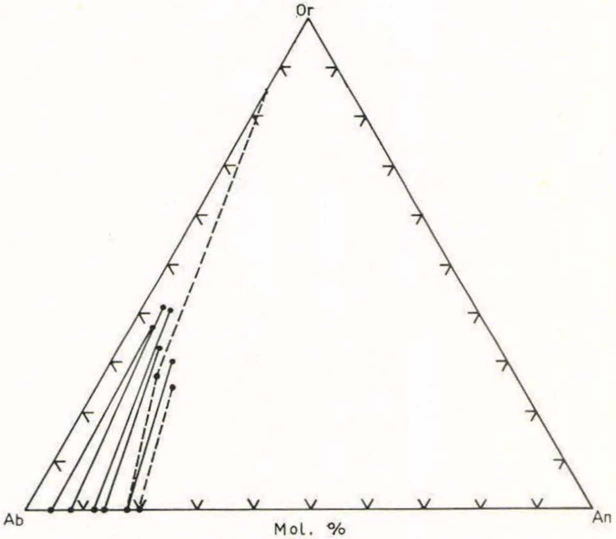

Fig. 34. Compositions of antiperthitic feldspar shown together with the compositions of their exsolved plagioclase. Continuous tie-lines refer to feldspars from the Kûngnât syenites. Broken lines refer to antiperthites from Oslo larvikites, in one case also indicating the composition of the exsolved orthoclase. (Larvikite data from Muir and Smith 1956).

perthitic feldspar consisting of albite and 'orthoclase-microcline', the latter referring to a K-feldspar with the Al-Si ordering in an intermediate stage. Only in his quartz-rich syenites where all the feldspar shows coarse and microperthitic structure does the K-phase appear as cross-hatched microcline. Woodard writes that, accompanying the introduction of SiO_2 in the rocks, there is a tendency for the feldspars to develop a triclinic K-phase as a result of Al-Si ordering. In the sequence basic syenite → quartz syenite → soda-granite at Kûngnât, cross-hatched microcline does not appear until relatively late in the evolution of the soda-granites. Here again, the inversion could be correlated with the quartz enrichment, but it seems more probable that it is simply a response to slowly lowering temperatures. Undoubtedly, much of what appears microscopically to be orthoclase in the Kûngnât quartz syenites and early soda-granites, is in fact microcline which has not deviated far from the monoclinic state, i.e. is, in Woodard's sense, 'orthoclase-microcline'.

Twinning in the feldspars: Smith and MacKenzie (1954) have shown that the soda-phase of perthites may show both pericline and albite twinning whether it be high or low temperature material. In the Kûngnât syenites, the plagioclase constituent is probably all of intermediate or low temperature type. The more calcic feldspars from the western layered series and from the eastern syenites characteristically possess pericline and albite twinning in the plagioclase component. Pericline twinning is normally absent in the perthites from the more fractionated rocks which are somewhat more K-rich. Ito and Sadanaga (1952), in a study of unmixed Na-K feldspars, showed that when there is less than 70 % potash phase present, pericline twinning appears in the plagioclase in addition to the albite twinning and that the preponderance of albite over pericline twinning increases as the feldspar becomes more potassic. Manebach twinning of the whole feldspar tends to appear in the Kûngnât syenites as pericline twinning is lost in the plagioclase constituent.

Textural zoning in the feldspars: It was frequently noticed that whereas the cores of the feldspars were micro- or cryptoperthitic the marginal zones were more coarsely exsolved. This appears to be a common feature in many syenites. It is, for instance, noted by Woodard (1957) in the Mt. Agamenticus nordmarkites, and also by Stringer *et al.* (1956) in the quartz syenites from the outer ring of the Chambe complex in Nyasaland. The explanation may lie mainly in the concentration of volatiles in the fractionating intercrystal liquid inducing fuller unmixing in the later growth zones. At Kûngnât, it seems less likely that this textural change is connected with normal compositional zoning in the feldspars. Although in the case of 'normal-zoned' pure Na-K feldspar the marginal parts of the crystals should approach the minimum melting point composition more closely than the inner zones and hence should reach the solvus curve at a higher temperature than the cores, (thus giving the margins a greater chance to exsolve than the cores), this effect would be counteracted to some extent by the higher Ca content to be expected in the cores of the Kûngnât feldspars—if in fact they *do* possess significant compositional zoning. This would follow since the solvus curve would be correspondingly higher for the material richer in Ca.

Temperatures of perthite exsolution: BOWEN and TUTTLE (1950), determined the peak of the Or-Ab solvus curve under a vapour pressure of water of 1000 bars and found it to lie at 660° ± 10°C and at a composition of $Ab_{55}Or_{45}$ (wt. $^0/_0$). These authors stated that "660° is the minimum temperature of stable existence of a feldspar of this composition". YODER, STEWART and SMITH (1957), say that at 5000 bars total pressure the solvus maximum is at 715° ± 5°C, corresponding to $Ab_{55}Or_{45 \pm 3}$, and that the effect of pressure is to raise the maximum by ca. 14° per 1000 bars. The feldspars in the Kûngnât syenites range from Ab_{53}-Ab_{59} wt. $^0/_0$, and, assuming the bulk of the perthite textures in the Kûngnât syenite feldspars to be the result of exsolution then, according to these data, the perthites and antiperthites should have commenced exsolving between 660° and 715° since it is likely that they were subject to partial pressures of water between 1000 and 5000 bars. It is assumed here that the partial pressure of water was roughly equivalent to the total pressure. This estimation, however, ignores the influence of calcium on the solvus curve. Concerning this, ORVILLE (1957) remarks that "the presence of a few percent An in the melt raises the crest of the ternary solvus by a large amount and the solvus intersects the liquidus within a short distance of the Or-Ab side line". In the case of the Kûngnât feldspars it would appear that in spite of An contents of up to 11 $^0/_0$ by weight, the feldspar always crystallized from the melt as an homogeneous phase which subsequently unmixed. Since furthermore, SMITH and MACKENZIE (1956) suggest that the solvus peak in the system Ab-Or lies substantially lower than the 660° determined by BOWEN and TUTTLE, the precise temperatures at which unmixing commenced in the different syenite feldspars cannot be estimated. It seems certain, however, that the unmixing of the more calcic antiperthites started at a considerably higher temperature than did the more highly fractionated feldspars from the quartz syenites.

Crystallization temperatures of the syenite feldspars: The fact that over a wide range of the syenites, including nearly all the exposed western layered series and the more fractionated eastern syenites, the feldspar composition is fairly constant around a mean value of $Or_{56}Ab_{39.5}An_{4.5}$ (wt. $^0/_0$), suggests that they had reached a minimum melting point composition. This is substantiated by the fact that such a composition plots close to the cotectic curve in the projection of the Ab-Or-An system at 5000 bars water vapour pressure, presented by Yoder *et al.* (1957). The point falls close to the 725° isotherm. The three more calcic feldspars analysed fall further away from the low temperature trough indicated on this diagram. The presence of Ca raised the solvus whereas the effect of the complex ion assemblage in the syenite magmas would have been to depress the minimum melting point. This, taken together with the fact that the effect of increase in pressure is also to increase the temperature of the solvus peak and lower the minimum melting point, must indicate that the water vapour pressure on the feldspars during the early part of their cooling history was relatively low, perhaps in the region of 1000 bars. Had it not been fairly low it is highly likely that the solvus curve would have intersected the solidus-liquidus in which case a "two-feldspar" syenite (or monzonite) would have resulted. When unmixing commenced, the water vapour pressure on the feldspars would have been higher than it was when the high temperature feldspars began to crystallize from the melt as a result of the rise in vapour pressure which would normally accompany a fall in temperature in a closed system.

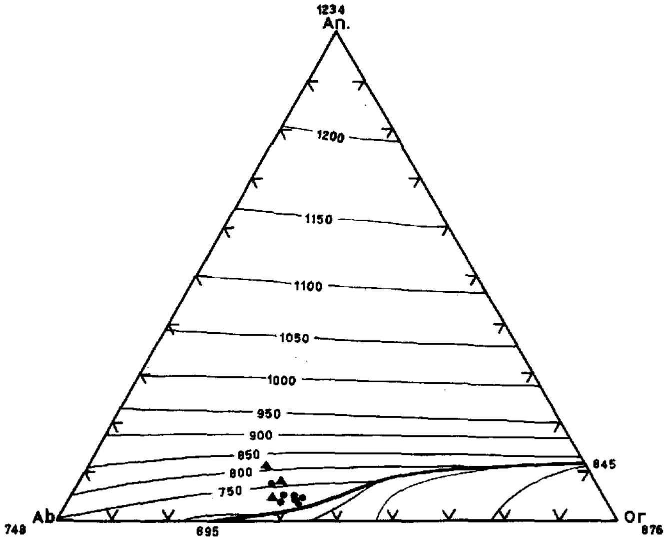

Fig. 35. Bulk feldspar compositions plotted on the Ab-Or-An diagram, redrawn from Yoder Stewart and Smith 1957.

- ● Feldspars from the western layered series.
- ▲ Feldspars from the eastern syenites.

In view of the probabilities that the vapour pressures were substantially below 5000 bars during the growth of the primary precipitate feldspars, the Yoder, Stewart and Smith ternary projection cannot be used directly as an indicator of the crystallization temperatures. However, it may be inferred from the diagram that the high temperature syenite feldspars precipitated over a temperature range of ca. 100°, and that this was probably in the region of 800—700°[1]).

Other minerals.

The olivines: Olivine is present throughout the syenites and it is usually found fresh or only slightly altered. The total composition range, estimated from 2V's and Poldervaart's curves (Poldervaart, 1950) is from Fa_{80}—Fa_{100}. (Wilkinson (1956, p. 445) reminds petrologists of the errors involved in relying too much on the optical properties of olivines and he regards it unwise to quote compositions to 0.5 molecular percent Fa if they are based only on optical measurements.)

The olivines are commonly found in clusters of several crystals, which often include pyroxene and ore. It is likely that much of the olivine of the layered rocks settled out in such clusters rather than as separate crystals. The fayalitic olivines are often pale yellow and may sometimes be mildly pleochroic with α pale yellow-grey and β and γ pale greyish.

Olivines of the south western marginal syenites: Small crystals up to 1 mm. constitute one or two percent of these rocks. Although growth continued late to produce anhedral and partly interstitial crystals, crystallization probably commenced early. They are pale yellow and commonly show two sets of cleavage, parallel to (010) and (100). The cores have a 2V of 50° indicating a composition of Fa_{95} although probably most is close to pure fayalite. In some rocks, especially those with scarce amphibole, the fayalites are virtually unaltered but in others there is partial replacement by yellow-brown iddingsite and ore.

Olivines of the western lower layered series: There is an upward change in composition from ca. Fa_{89} to Fa_{100} in the highest rocks.

Fayalite is surprisingly scarce in the laminated group, although usually present in sections of the unlaminated group rocks. The explanation may be that after deposition of the lower banded group, fayalite was only a very minor component of the primary precipitate and that with the still significant gravity sorting that was operating during the formation of the laminated group, the standard syenites of this group are almost olivine free. The overlying unlaminated group, being almost completely unsorted, has a more even distribution of fayalite which constitutes 1—2 $^0/_0$ of these rocks.

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[1]) McCulloh, writing of comparable nordmarkitic rocks of the Oslo area, (1952), arrived by similar arguments at the tentative suggestion that the main crystallization occurred between 800—700° and that feldspar unmixing commenced at ca. 650°.

(McCulloh, T. H., 1952. Studies on the Igneous Rock Complex of the Oslo Region. X. Geology of the Grefsen-Grorud Area. Oslo. Norske Vid. Akad. Oslo I. Mat. Naturv. Kl.)

In the mafic bands the olivines are very fresh and may be idiomorphic. However, in the more feldspathic standard rocks they commonly show alteration to iddingsite with or without some accompanying ore, probably secondary magnetite.

In the unlaminated rocks, just as in the south western marginal syenites, fayalite growth has continued late to give subhedral or even interstitial anhedral crystals. Pseudomorphing is widespread in these upper rocks.

Fig. 36. Primary precipitate fayalite and pyroxene, slightly modified by interprecipitate growth, in the basal part of a rhythmic unit from the lower banded group. These are accompanied by feldspar, apatite, biotite and anhedral ilmenomagnetite. Uncrossed nicols. × 20.

Olivines of the western upper layered series: In sections of twenty six standard syenite specimens sampled from over the whole area occupied by the Nisseborg-Røverborg W.U.L.S., eighteen were entirely free from any trace of olivine. The greater part of all the olivine in the series is concentrated in the comparatively thick mafic layers low in the sequence. Hand specimens from these may contain up to 40 $^0/_0$ fayalite. The scarce thin bands and schlieren of the higher rocks are similarly fayalite bearing, but they are separated by considerable thicknesses of olivine-deficient rock.

A small range in composition from Fa_{95} upwards to $Fa_{99\text{-}100}$ occurs within a vertical distance of ca. 250 m. The grain size is normally from ca. 0.5—4 mm. across although the crystals are frequently markedly elongate. One olivine from a thin mafic band was ca. 7 mm. in diameter and is the largest olivine of any composition found in the complex. The olivines show alteration to iddingsite accompanied by opaque ore material, possibly secondary magnetite. Often ore is the only alteration product forming heavy black rims around the olivines (fig. 37).

Olivines from the eastern syenites: Olivine is sparsely scattered throughout the eastern centre syenites, being absent only from the derived pegmatites and microgranites. It forms up to 40 % of some of the mafic horizons.

In the basic syenites of the upper rocks in the layered series the composition range is from Fa_{80}—Fa_{88}, mostly due to zoning. Differences in composition between olivine in a mafic horizon and in its associated feldspathic rock are suspected but not yet demonstrated. In the underlying syenites the range is from Fa_{85}—Fa_{94}, with one Fa_{100} found in an atypical quartz-bearing marginal facies rock. In the border group the observed range is Fa_{82}—Fa_{88}, rising to Fa_{90} in the feldspathic standard syenites where the progressive "making-over" of olivines to less magnesian types had proceeded further. Olivines from the more mafic portions are not only generally more magnesian but are much less prone to alteration to iddingsite.

Fig. 37. Fayalite crystals in a syenite from the western upper layered series, partly pseudomorphed by ore and poikilitically enclosed by hornblende. Uncrossed nicols × 20.

Olivine is a normal constituent of syenites of the Kûngnât type and is widely reported from the "augite syenites" and nordmarkites of South Greenland (USSING 1912 and unpublished G.G.U. annual reports). References to olivine-bearing syenites from other parts of the world are common in the literature. Thus the larvikites of the Oslo region are normally olivine-bearing according to BARTH (1954). JACOBSON *et al.* (1958) state that fayalite may have formerly been present in the N. Nigerian syenites although it is now pseudomorphed, and fayalite syenites have long been known from New England and Wisconsin, U.S.A. The fayalite in the "ridge syenites" of the Okonjeje complex, S.W. Africa, is given as Fa_{87} by SIMPSON (1954).

The pyroxenes: The classification of the clinopyroxenes followed here is that of POLDERVAART and HESS (1951). The pyroxene compositions were estimated by means of their 2V's and β refractive indices, using HESS's curves (HESS 1949).

The pyroxenes of the syenites present a continuous trend from augite (titaniferous), through ferroaugite and ferrohedenbergite to aegirine-augite. WILKINSON (1956) states that the continued fractionation of pyroxenes of alkali basalt parentage, at compositions more iron-rich than ca. $Ca_{44}Mg_{36}Fe_{20}$, may result in enrichment in the acmite molecule, and it is likely also in the Kûngnât syenites that there is significant addition of sodium to the pyroxenes after this point is reached. This is particularly so in the case of the W.L.L.S. pyroxenes. Rather similar clinopyroxene trends have been described by IWAO (1939) and by YAGI (1953) for alkalic rock suites in the Nayosi and Morotu districts of Sakhalin. SIMPSON (1954), points out that the course of clinopyroxene crystallization in the Okonjeje tholeiitic series (of which the "ridge-syenite" is the culmination) involves very little variation in lime content. (This is inferred mainly from the pyroxene optics). However, this is in marked contrast to the clinopyroxene trends established for other tholeiitic basalt magmas (BROWN 1957). The trend shown in the Kûngnât rocks appears to be similar to that at Okonjeje and to involve very little change in the Ca content (figs. 38 and 39).

The most magnesian pyroxenes for which β r.i. and 2V data are available are ferroaugites of ca. $Ca_{42}Mg_{25}Fe_{33}$ from the eastern syenites. However, the most magnesian pyroxenes seen in the eastern syenites had a 2V of ca. 52.5° and, by extrapolation of the pyroxene curve shown in figure 38 back to more magnesian compositions, it is cautiously suggested that these have a composition of ca. $Ca_{42}Mg_{31}Fe_{27}$.

In the W.L.L.S. the pyroxenes range from ca. $Ca_{43}Mg_{8}Fe_{49}$ through to $Ca_{44}Mg_{1}Fe_{55}$ and, with increasing Na enrichment, into aegirine-augite. By contrast, in the W.U.L.S. and eastern syenites, the end member of the sequence seems to be practically pure hedenbergite.

The extent to which Na enrichment could proceed in the western syenites may have been partly dependent upon the water concentration in the liquid phase. With falling temperature and rising P_{H_2O}, the pyroxene normally gave way to hornblende, and only in localized and exceptional instance was the Na enrichment prolonged in the pyroxene phase.

Twinning, either simple or multiple on (100), is occasionally present in the ferroaugites from the eastern border group but, apart from these, twinning appears to be absent.

Pyroxenes from the south west marginal syenites: These probably started separating early although the crystals are seldom well formed.

Zoning is conspicuous, with progressive deepening of the green colour from centre to margin. The cores, which are free from sagenitic material, are of pale green, scarcely or non-pleochroic, ferrohedenbergite. The marginal zones are often of pleochroic aegirine-augite, with α blue-green and β and γ green. The zoning involves a continuous increase of 2V outwards. The full range observed is from 61° to 71° (+ve), although most of the material has a 2V between 66 and 71°. The pyroxenes are normally strongly corroded and associated with hornblende.

Pyroxenes from the western lower layered series: Distinct colour zoning is nearly always present and, in the lower rocks, the cores are of pale pinkish-brown colour, grading out to light green margins. In the higher rocks from the unlaminated group, zoning is from green ferrohedenbergitic cores to deeper green pleochroic outer zones of aegirine-augite. Individual crystals are generally limited in zonal range to only a part of the entire range. The range of zoning in any particular crystal has presumably been controlled by such factors as a), the amount of interstitial liquid immediately available to supply the requisite ions and b), the partial pressure of water vapour and hence the concentration of OH^-. Above a certain vapour pressure of water, amphibole and not pyroxene became the stable phase, a situation that is probably general in syenitic rocks. YAGI (1953) for example, considers that in the alkalic rocks of the Morotu district, Sakhalin, the aegirine-augite gradually became unstable and was replaced by arfvedsonite as the magma became more and more water rich. As a result of irregularities in the zoning, the change upwards in the composition of the pyroxene cores is of greater significance than any changes in the bulk composition. However, with strongly zoned and partly reacted pyroxene it is often difficult to determine the composition of the cores. The outer zones of the upper pyroxenes are commonly, but not invariably, more Na-Fe rich than those of lower horizons.

The optic axial angle is a useful measure of the changing composition since it increases constantly through the series, reaching a maximum in the aegirine-augites. A survey of the 2V's from sixteen rocks from the W.L.L.S. showed that, from the lowest syenites up to the unlaminated group, the 2V of the cores increases from 58° to ca. 62°, and that the rims show a corresponding increase from ca. 66° to 77°.

The pyroxenes of the lower banded group tend to retain their idiomorphic habit in spite of their irregular late growth zones and the raggedness caused by hornblende reaction. In the laminated group they are markedly elongate up to 3 mm. long. In the higher rocks the pyroxenes are entirely anhedral and frequently show an interstitial habit, thus resembling the aegirine-augites of the south western marginal syenites.

	2Vγ	βr.i.	Composition
1) No. 27648 (green, scarcely zoned)....	ca. 62°	1.737 (∓ .001)	$Ca_{44}Mg_1Fs_{55}$
2) No. 26261 (greenish margins)	ca. 60°	1.733 (∓ .001)	$Ca_{43}Mg_5Fe_{52}$
3) No. 26003 (Pale green margins)	ca. 59°	1.729 (∓ .001)	$Ca_{43}Mg_8Fe_{49}$

1) from the lower part of the banded group, 2) from the laminated group, and 3) from the lower part of the unlaminated group. Probably the pinkish cores in the lowest syenites are as magnesian as $Ca_{42}Mg_{20}Fe_{38}$.

Pyroxenes from the western upper layered series: The pyroxenes are of light green hedenbergitic varieties and are usually only slightly pleochroic. Normally they are idiomorphic although they have frequently suffered some reaction to hornblende. The crystals tend to be smaller than those of the W.L.L.S. although they have a size range from ca. 0.25—3 mm. in length.

Unlike the fayalites, they have not been efficiently sorted from the more feldspathic rock and small pyroxenes are an accessory in practically all the thin sections examined. However, in some rocks, effective separation of pyroxene from feldspar has been achieved and in rocks such as that shown in fig. 51, the mafic horizons are composed chiefly of euhedral hedenbergites.

As with the olivines, late (interprecipitate) growth was generally slight and the crystals are, as a result, more homogeneous and less zoned than their counterparts in the W.L.L.S. Apart from the restricted composition range of individual crystals, there would seem to be very little cryptic variation with height. The 2Vγ throughout, lies between 60—64°.

The trend towards soda enrichment, so conspicuous in the W.L.L.S., is surprisingly limited considering that, as a whole, these rocks are more sodic than the W.L.L.S. and have slightly higher Na/K ratios than the latter. However, alkali pyroxene does occur occasionally as in one thin mafic horizon where it is found as bright green interstitial aegirine-augite strongly pleochroic, (α blue-green, β green, γ yellow-green), and closely associated with hornblende to which it is partly made over. A high extinction angle, γ onto c, of over 70° indicates a composition more Na-rich than $Aeg._{40}$ (Winchell 1951). The occurrence of late soda-pyroxene instead of the normal soda-hornblende is rare and suggests peculiarly dry conditions during its crystallization. Generally the pyroxenes of the Nisseborg are more sodic (greener and more pleochroic) than those of the Røverborg succession.

Pyroxenes from the eastern syenites: Although in the more feldspathic syenites the pyroxenes are severely corroded to hornblende, there are all gradations from this condition to the fresh idiomorphic state in which they occur in the amphibole-free mafic portions.

Sodic pyroxenes are conspicuously absent from the eastern syenites. The pyroxenes range from pinkish ferroaugites to bottle-green hedenbergites, the former being found in the basic syenites of the higher part of the layered series and in the melanocratic border group rocks. The pyroxenes have cores with 2Vs of 50—54° increasing outwards to as much as 61° in the more extreme outer green zones which are present in the pyroxenes from the more feldspathic rocks.

	$2V\gamma$	β R.I.	Composition
1) No. 27696a	ca. 55°	1.711 (± .001)	$Ca_{42}Mg_{25}Fe_{33}$
2) No. 26118	55°	1.711 (± .001)	$Ca_{42}Mg_{25}Fe_{33}$

1) is from the basic syenites of the layered series, and 2) is from a mafic portion of the border group.

More iron-rich pyroxenes are characteristic of the higher zones in the lower part of the layered series. These are strongly coloured, dull green but non-pleochroic hedenbergites, with 2Vs from 62—64°. They tend to be unzoned. Pyroxene from No. 28324b. had $\beta = 1.739$ (± .001) and $2V\gamma = 62.5°$ indicating a composition on the He-Fs join at ca. $Ca_{45}Mg_{0}Fe_{55}$.

The pyroxenes of the eastern rocks have an average length of 1—2 mm. As in the more basic rocks from the W.L.L.S., the cores of the ferroaugites are normally filled with sagenitic grills of fine opaque rods. The more augitic varieties have a tendency to develop a subophitic habit, a feature that relates them rather to those of the ring-dyke rocks than to those of the western syenites.

The amphiboles: Hornblendes, ranging from barkevikitic to hastingsitic are present throughout the syenites, commonly interstitial and always of relatively late formation. They are characteristically found fringing the pyroxenes. The amphibole phase is most nearly suppressed in the basic syenites from the eastern border group, where only subordinate amounts of barkevikitic hornblende are to be found.

The amphibole relationships are complex and there appear to be at least two separate series, a common hornblende series, primarily associated with the pyroxenes, and a hastingsitic series that is more closely associated with the olivines. These hastingsitic types, which are found in the south western marginal syenites, the upper part of the W.L.L.S., and in the W.U.L.S., are frequently found together with an unusual biotite variety. Where the amphiboles are in contact with the olivines, it is not uncommon to find a "bleached" zone of pale or colourless (monoclinic) amphibole separating the two. These pale amphibole fringes grade rapidly out into the usually strongly coloured hornblende or hastingsite. The colourless material is thought to belong to the cummingtonite—grünerite series. (In one case the 2V was found to be

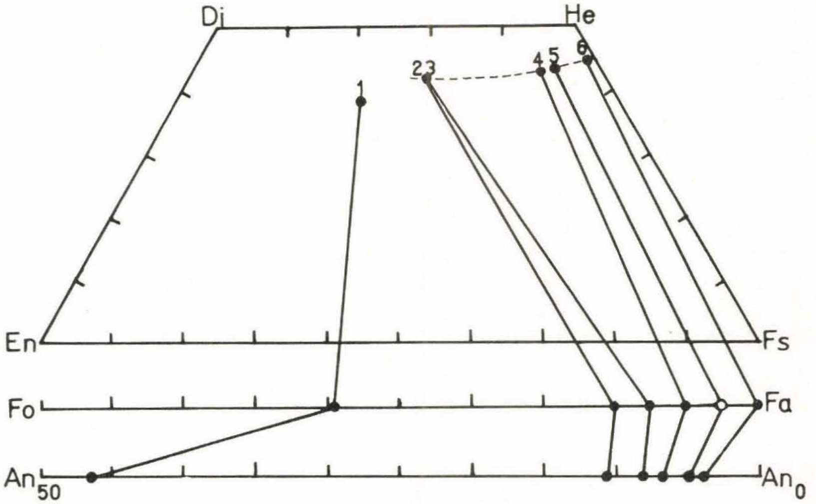

Fig. 38. Soda-poor pyroxenes from Kûngnât, with tie-lines to olivines and feldspars present in the same rock. The An content of the feldspars is that of the bulk feldspars, obtained by analysis. The composition of the olivine present together with pyroxene 5 is hypothetical, olivine being scarce or absent from rocks of this horizon. The compositions of the olivines and pyroxenes are estimated from optical measurements. 1, Ti-augite from the ring-dyke; 2 and 3, ferroaugites from the eastern syenites; 4, 5, and 6, ferrohedenbergites from successive horizons in the western lower layered series.

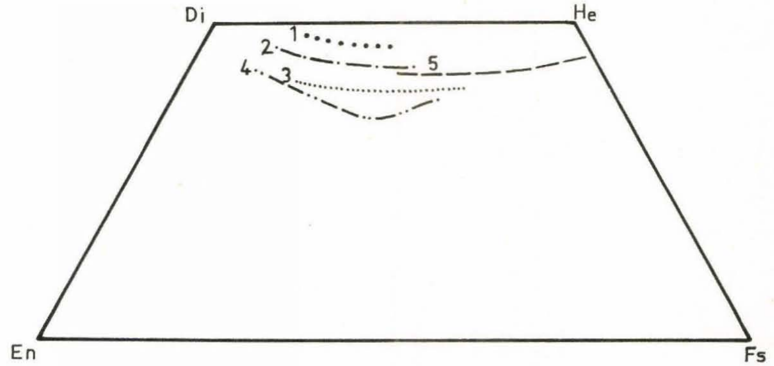

Fig. 39. Comparison of the pyroxene trend in the Kûngnât syenites with trends in differentiated sequences of alkali-olivine basalts (curves 1 and 2), and of tholeiitic rock suites (curves 3 and 4). 1, Black Jack sill (Wilkinson, 1956); 2, Garbh Eilean sill (Murray, 1954); 3, the Okonjeje tholeiitic series (Simpson, 1954); 4, the Skærgaard and other tholeiitic suites (Brown, 1957) 5, Kûngnât syenites.

ca. 82°, suggesting an iron-rich member). Zones of this kind may have been produced by diffusion effects operating between the primary olivine and amphibole.

In the south western marginal syenites, hornblende appears interstitially, sometimes poikilitically and also as reaction product of the pyroxene. Typically associated with the fayalites and often rimming them is a pale blue-green amphibole which has only a very slight pleochroism. The grünerite is often developed where the two are in contact. This blue-green variety also occurs as interstitial patches and irregular platy aggregates[1]).

The hornblende in the lower part of the western lower layered series is generally of a less sodic variety than that of the south western rocks. In the upper rocks of the W.L.L.S. patches of intensely blue pleochroic riebeckitic material, again in connection with grünerite, are intimately associated with the fayalite-rich areas but not with the aegirine-augites.

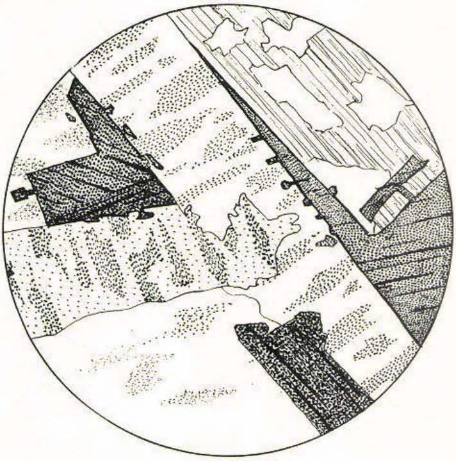

Fig. 40. Interstitial hornblende occupying spaces between primary precipitate feldspar in a syenite from the laminated group. The small peg-like growths of hornblende growing into the feldspar are a common feature. Crossed nicols, ×20.

Sodic-hornblende is the dominant ferromagnesian mineral of the W.U.L.S. Most appears as interstitial wedges between the feldspars, and it is normally strongly zoned, becoming more blue-green in colour outwards and with an increase in the extinction angle of γ onto c. The hornblendes are strongly pleochroic with α pale olive-green, β dull green and γ deep blue-green. Just as in the south west marginal rocks, hastingsitic material occurs interstitially or as irregular sheaves and bundles. This is only faintly pleochroic. In the higher rocks of the W.U.L.S. the hastingsite becomes increasingly important, and here there is often considerable doubt as to its late formation. While most remains definitely

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[1]) Warren and Mckinstry described in some detail the reaction relationships between fayalite, ferroanthophyllite and grünerite in some similar nordmarkitic granites from Massachusetts. (Warren, C. H. and Mckinstry, H. E. 1924. The granites and pegmatites of Cape Ann. Massachusetts. Proc. Amer. Acad. Arts and Sciences v. 59. 315—357).

interstitial, some occurs as more nearly idiomorphic prismatic crystals up to 4 mm. long. These to not appear to be pseudomorphs after pyroxene and it may be that in these late high rocks the temperature was sufficiently low and the partial pressure of water vapour such that Na-Fe amphibole was stable and could join the primary precipitate assemblage. In some of these higher rocks, the hastingsites zone out towards riebeckite fringes and riebeckite strips and flakes become abundant within the crystals. This riebeckite has virtually straight extinction, and an intense pleochroism from deep Prussian blue to light blue-greys. CHAPMAN and WILLIAMS (1935), in their discussion of the origin of the White Mountain magma series, note that riebeckite appears later than hastingsite and may be marginal to it and, again, a similar relationship between hastingsite and members of the arfvedsonite- riebeckite series has been described by IWAO (1939) in monzonite-syenites from Sakhalin. Strips of yellow-brown serpentinous material, developed parallel to the c. axis, are common in these sodic-amphiboles.

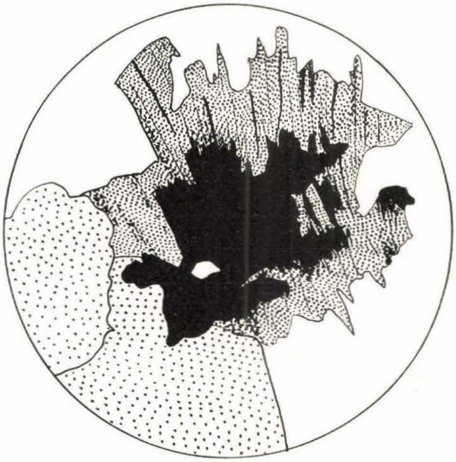

Fig. 41. Typical reaction fringe of lepidomelane around an ore grain in the eastern syenites. Ferroaugite is shown in the S.W. sector of the field. Uncrossed nicols, × 30.

In the eastern syenites common olive-green hornblende is quantitatively the most important ferromagnesian mineral. It has formed interstitially and mainly at the expense of the pyroxene.

Hornblende development was inhibited in the mafic bands, both in the layered rocks and in the border-group. Hornblende and biotite tend to be mutually exclusive in the eastern syenites, the biotite being able to develop in the mafic environments whereas hornblende development was at an optimum in the more feldspathic rocks.

The micas: Biotite micas occur in all of the syenites. White-micas are scarce and are restricted to the pegmatites of the western centre.

In syenites, e.g. larvikites, carrying ilmenomagnetite it is a common feature for the ore grains to have reaction fringes of lepidomelane around them. Such reaction fringes are well developed in the lower rocks of the western lower layered series and in the eastern syenites. In the latter, lepidomelane is normally seen surrounding the oxides except where these have been protected from reaction by being enclosed at an early stage by another mineral. Thus, ores enclosed in pyroxene may show little or no reaction to mica and may retain their idiomorphic habit. Pleochroism is extreme in the lepidomelanes, with α pale straw, β and γ red-brown to dark sepia.

In the south western marginal syenites, the unlaminated group of the W.L.L.S. and in the W.U.L.S. another biotite phase appears which is associated with the hastingsites. It is typically present as interstitial wedges and the crystals are commonly elongate parallel to the *c* axis. The pleochroism is rather variable from reddish-browns to dull green. In extreme cases the pleochroism is from α bright red-brown to β and γ olive-green. The absorbtion parallel to β and γ is not noticeably greater than that parallel to α[1]).

Quartz: Quartz is present as interstitial wedges in all the south western marginal syenites, the upper parts of the two western layered series and in the more feldspathic rocks of the eastern border group. In the south western syenites it is present up to 8 $^0/_0$.

In the lower banded group of the W.L.L.S. quartz is normally absent but it does appear in some of the marginal facies rocks on the north side of the intrusion. It comes in as a normal accessory in the laminated group and occurs up to 4 $^0/_0$ in the highest unlaminated rocks reached *in situ.* However, quartz comprises ca. 6 $^0/_0$ of some of the fallen blocks from higher horizons and there is thought to be every gradation from these rocks through to soda-granites containing up to ca. 30 $^0/_0$.

Quartz in the upper W.U.L.S. rocks appears to have replaced the feldspar to a small extent. It is not possible to state at what precise level in the series quartz makes it appearance, but it may be expected in any thin section of average syenite from above 1100 m.

Iron-titanium oxides: There is less than 1 $^0/_0$ ore present in the south western marginal rocks, although ore is an important constituent of the lower W.L.L.S. and eastern syenites. In these it may constitute up to 10 $^0/_0$ of the rock in the mafic horizons. The average grain size is ca. 1 mm.

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[1]) This mineral may well be the lithia-mica, cryophyllite. Warren and McKinstry described this mineral from the fayalite-bearing granites of Cape Ann (Mass.) as pleochroing from apple-green in basal section to brown in prismatic section. (Warren, C. H. and McKinstry, H. E. 1924. The granites and pegmatites of Cape Ann, Massachusetts, Proc. Amer. Acad. Arts and Sciences v. 59. 315—317.

A high temperature Ti-Fe oxide is believed to have been a primary precipitate mineral in the layered Kûngnât rocks. Although crystallization of this mixed oxide undoubtedly commenced early, growth continued late and there was subsequent unmixing and oxidation. In the W.L.L.S. the content of ore decreases upwards and by the time the unlaminated group is reached, the rocks contain 1 % or less. A similar situation exists in the W.U.L.S. where the ore content again decreases upwards. In the lower rocks of this series idiomorphic crystals occur although the ore is more usually seen as shapeless grains.

The ores in one rock from a mafic horizon low in the banded group of the W.L.L.S. have been examined in a polished section. Most consists of anhedral ilmenite although coarse ilmenite-magnetite intergrowths are plentiful. These intergrowths lack the very regular lamellar relationships seen in the eastern syenites. Four rocks from the eastern centre, two from the border-group and two from the layered series were also examined in reflected light and the ores in these show highly complex relationships between ilmenite, magnetite and ulvöspinel. For the most part these are probably due to unmixing phenomena, but are also probably complicated by later oxidations, particularly of ulvöspinel to ilmenite. Thus, in specimen no. 26118 from the border-group, the grains commonly consists of broad alternating lamellae of ilmenite and magnetite. The magnetite strips, on closer inspection, are found to consist of a very fine ulvöspinel-magnetite lattice, with later ilmenite lamellae that may have arisen through oxidation of the ulvöspinel. Relationships of this kind may be due to two episodes of exsolution; *a.* from a homogeneous high temperature oxide into lamellae of ilmenite and titanomagnetite, and *b.* subsequent unmixing of the latter into magnetite and ulvöspinel. (VINCENT and PHILLIPS 1954).

Grill patterns of ilmenite-magnetite lamellae as a result of twinning are very common. As a generalisation the ilmenite lamellae in the more basic syenites are somewhat broader than in the more highly fractionated types.

The sulphides: Sulphides are a minor constituent of the lower W.L.L.S. and the eastern syenites and may have been among the primary precipitate minerals. Pyrrhotite is the dominant sulphide mineral, normally containing blebs and grains of chalcopyrite. H. PAULY, who was kind enough to examine some of the polished sections, remarked on the tendency for the two phases to have straight mutual boundaries. Very small amounts of pentlandite occur as minute 'sparks' in the pyrrhotite.

It is possible that there were two separate episodes of unmixing, one involving the exsolution of the chalcopyrite from a high temperature Cu-bearing sulphide, and another producing the pentlandite from the Ni-bearing pyrrhotite. The pentlandite sparks, according to PAULY, are of the normal kind to be expected from unmixing of nickeliferous pyrrhotite, possibly in the temperature range 300—400°C. Pyrites is occasionally present in small amount. In one of the eastern syenites a myrmeckite-like intergrowth of chalcopyrotine and chalcopyrites was observed.

The phosphates and fluorides: Accessory fluorite, often associated with the hornblendes, occurs as irregular patches in the south western marginal syenites. It sometimes shows a pale-lilac colouration. Apatite is very scarce in the south western rocks but occurs as minute stubby prisms.

From its distribution in the W.L.L.S., apatite is considered to have settled out along with the other primary precipitate minerals. It cannot be regarded as a late crystallizing accessory which attained its euhedral form through its relatively greater power of crystallization. The apatite is a conspicuous accessory in the lower banded group rocks and is relatively concentrated in the mafic layers. With the magma suffering continuous phosphorus depletion, the proportion of apatite crystals in the syenites decreases rapidly upwards and although minute crystals are sometimes found, apatite is commonly absent from specimens of the unlaminated syenite group.

Analysis of the rocks for P and F reveals a striking parallelism in their behaviour and there can be little doubt that in and below the laminated group practically all the phosphorus and the greater part of the fluorine are present together in the primary precipitate fluorapatite. The two elements were fractionated out at much the same rate throughout the period corresponding to the formation of the lower banded group and the laminated group but, by the time of the unlaminated group formation, the P concentration had been reduced to such an extent that there was insufficient fluorapatite forming to accommodate all the F remaining in the interstitial liquid. As a result, the fluorine crystallized out as interstitial fluoride (CaF_2) rather than, as formerly, the fluorophosphate. Thus there was continual fractionation and removal of fluorine for most of the cooling history and only a secondary enrichment in the late stage differentiates, (see p. 108). A surprising result of this process is that the fluorite-bearing rocks are among those most impoverished in fluorine. The fluorite frequently possesses deep violet patches and markings. Przibram (1956), remarks that the radiation colour of fluorite is violet and suggests that splits and cracks in the mineral may contain radioactive materials (probably U compounds) which produce these coloured halos.

Apatite is only present in very limited quantity in the W.U.L.S. rocks and there is no obvious tendency for it to be concentrated in the mafic layers. It appears to be as abundant in the upper rocks as in the lower.

Fluorite, associated with the amphiboles, seems to be restricted to the uppermost rocks.

Stout euhedral prisms of apatite up to 2 mm. long are always present in the more mafic assemblages of the eastern syenites, where they often form 1—2 % of the rock. In the more feldspathic syenites also, apatite is a constant accessory mineral. Fluorite, however, has not been found in any of the syenites or pegmatites of the eastern centre.

The zircons: Zircon is, rather surprisingly, only a scarce accessory in the south western marginal syenites.

In the W.L.L.S. the distribution and variety of zircons presents some puzzling features. In the lower banded group zircon is extremely scarce but it does occur sporadically as comparatively large crystals of 1 mm. or so diameter. These show a very pronounced oscillatory zoning, with an alternation of thin colourless and yellow-brown zones (Plate 1). In the laminated group, zircon, whilst still rather uncommon is sometimes seen as anhedral and elongate crystals up to 4 mm. long.

There was a tendency for Zr to become concentrated in the residual magma and, in the unlaminated group, clear and usually unzoned zircons are a characteristic accessory. In spite of their perfect crystal form they are believed to have crystallized late. Unlike the zircons of the W.L.L.S. acid intrusives they are never obviously metamict and halo formation in the surrounding micas and amphiboles is not very pronounced.

Small zircons, often slightly zoned and frequently of rather dirty appearance, occur throughout the W.U.L.S. syenites. In the eastern syenites zircons are mainly associated with the coarser and more feldspathic syenite varieties of the border group.

Other accessory minerals: Carbonate, probably siderite, is a minor constituent in the south west marginal syenites, the W.L.L.S. unlaminated group, the W.U.L.S., and in the coarser feldspathic eastern border-group syenites.

An accessory that occurs in the south western syenites and in the upper part of the W.L.L.S. is possibly metamict thorite. The mineral occurs as very small prismatic crystals which are orange or red-brown in colour. These are generally anisotropic, with straight extinction. The crystals are length slow and they are occasionally pleochroic in browns. Orthite has been recorded from the W.U.L.S. as euhedral dark brown pleochroic crystals, sometimes showing strong zoning, simple twinning and well developed halos in the surrounding hornblendes. Pyrochlore has been noted as a scarce accessory in a loose block of quartz syenite that is believed to have been derived from the Nisseborg face. A small quantity of ænigmatite was seen in a section of syenite from the laminated group of the W.L.L.S.

X. THE PETROGRAPHY OF THE LATE STAGE SODA-GRANITE SUITE OF THE WESTERN CENTRE

Soda-granites are fairly abundant in the south Greenland alkaline province and occurrences are known from the Ilímaussaq complex, the southern part of the Nunarssuit complex, and also in the central complex on Tugtutôq island. These granites are closely related to those at Kûngnât and contain arfvedsonite, riebeckite and ægirine, with astrophyllite, fluorite (and ænigmatite) among the common accessories. There is also a close petrographic resemblance between the Kûngnât soda-granites and those occurring in the White Mountain magma series (New Hants.) and particularly to the potassic phase riebeckite granites of northern Nigeria.

The feldspars.

In those soda-granites showing the most resemblance to the upper W.L.L.S. syenites, the dominant feldspar is a lamellar perthite which is normally Manebach twinned. However, even in these granites, there is a considerable amount of antiperthitic material, this frequently possessing rims of more coarsely twinned albite.

Most of the granite sheets contain abundant microcline and microcline-microperthite, and this is taken as an indication that crystallization was prolonged into lower temperatures than in the case of those rocks where lamellar perthite is the principal feldspar. However, relict and badly corroded lamellar perthite is often present in these "lower temperature" granites, probably representing early formed feldspar which escaped total recrystallization in the later cooling stages. The albite-rimmed antiperthites are also present in these granites, the albite rims being not more calcic than An_5. Late stage albitisation has frequently been severe, and a large amount of albite, ca. An_4, appears to have grown at the expense of the earlier formed feldspar and amphibole. The deuteric albitisation (and the presence of albite rimming) in the Kûngnât soda-granites is a feature shared in common with many of the Nigerian riebeckite granites and may be a characteristic feature of soda-granites in general. For instance, Warren (1913) described extremely similar textures, resulting from recrystallization and albitisation in the Quincy riebeckite granite.

The normative feldspar, calculated from the analysis of one of the albitised granites was $Or_{35}Ab_{65}$ (mol. $^0/_0$). It is of interest that Barth (1944) remarks of the Oslo ekerites that the feldspar is an albite orthoclase patch-perthite low in Ca and that the calculated bulk composition is always close to $Or_{35}Ab_{65}$, approximately corresponding to the minimum melting point in the Or-Ab system. The ekerites, appearing late in the Oslo plutonic sequence, play a part analogous to that of the soda-granites in the Kûngnât W.L.L.S.

The zoned and pegmatitic microgranites of western Kûngnât contain a complex feldspar assemblage resembling that in the coarser granites and consisting of antiperthite, microcline-microperthite, late-stage albite and subordinate lamellar perthite.

The 'grey-dykes' generally have a feldspar content of albite and microcline. An attempt was made to extract the bulk feldspar from a 'grey-dyke' specimen which had a groundmass of apparently untwinned feldspar laths showing a pronounced flow pattern. Occasional corroded phenocrysts of microcline-microperthite (up to 1 mm. across) were also present. The feldspar could not be adequately cleared of minute ægirine and riebeckite needles, but a partial analysis of the impure feldspar indicated a molecular composition of ca. $Or_{57}Ab_{39}An_4$. It is of interest that this rock, characterised by its strongly sodic coloured minerals, should have a feldspar content considerably more potassic than seen in any of the syenites.

Other minerals.

Quartz: The coarse granites contain up to ca. 30 % of quartz, present as clear, anhedral, and not infrequently strained crystals. Much or all is of late formation and frequently appears to have partially replaced the microcline-microperthites and lamellar perthites.

The amphiboles: In the coarse soda-granites it is probable that neither pyroxene nor fayalite ever crystallized and that soda-iron-rich amphibole was the first ferromagnesian mineral to separate. In the higher temperature granites, i.e. those rocks intermediate between the quartz syenites and the (extensively recrystallized) riebeckite granites, somewhat zoned soda-hornblende occurs as irregular crystals, often interstitial to the perthites. The margins show the budding or buttoning into the perthites which is also found in the soda-hornblendes of the W.U.L.S. and upper W.L.L.S. These hornblendes have an extinction of γ onto c of ca. 27°, and have a pleochroism; α, olive-green, β slaty blue-green, and γ intense blue-green.

In the lower temperature granites, the amphibole loses its interstitial habit and, although usually seen as ragged crystals as a result of partial albitisation, it may have originally been as idiomorphic prismatic crystals. These have the configuration of riebeckite, with an extinction α onto c of 7—8°, and a strong pleochroism; α intense blue-black, β slaty blue-green, and γ dull yellowish-green. Although the term 'riebeckite' is used here, it is very likely that the mineral has a composition intermediate between arfvedsonite and riebeckite. The amphibole from the Ilímaussaq soda-granite was described by Ussing as 'arfvedsonite with slight tendencies towards riebeckite' whereas here the mineral might be described as tending towards arfvedsonite. The riebeckites are up to 3 mm. long and constitute up to 4 % of the rocks.

The mafic zones of the microgranites can contain up to 20 or 30 % of amphibole. In some, the mineral is a soda-hornblende (with an angle γ onto c of up to 34° and a pleochroic formula of; α yellow-green, β dull green and γ deep blue-black), whereas in others it is a riebeckite apparently identical to that described from the coarser granites.

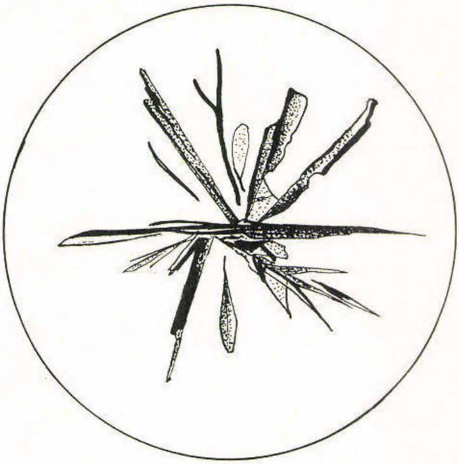

Fig. 42. Radiating cluster of astrophyllite crystals in a riebeckite granite. Uncrossed nicols. × 60.

Astrophyllite: Astrophyllite is a common accessory, especially in the coarser granites where up to 3 % may be present. It is found as bundles or as radiating clusters of acicular golden-brown crystals up to 1 mm. across. In places, the astrophyllite grows as orientated needles in the perthites and sometimes as intergrowths with the soda-amphiboles, parallel to the c axis. A perfect (100) cleavage is seen and a pleochroism; α deep orange, β yellow, and γ lemon-yellow. The optic orientation is a parallel γ, b parallel α and c parallel to β. The refractive indices are: α 1.695, β 1.715 and γ 1.751. These astrophyllites are closely similar to those of Nigeria and New Hampshire, whose optical properties were listed by Beer (1952, p. 30).

The pyroxenes: Whilst pyroxenes are normally absent from the coarser soda-granites, acmitic ægirine is present in the striped microgranites and in the grey-dykes, occurring either as the sole ferromagnesian mineral or alongside riebeckite. The microgranites and grey-dykes are considered to be of slightly later date and of lower temperature formation than the coarser granites. The aegirine is commonly seen as ragged prismatic crystals showing only a mild pleochroism, α being rather more a bluish-green than β and γ. The crystals have virtually straight extinction. The grey-dykes, however, often contain euhedral aegirine crystals up to 3 mm. long although in addition to occurring as phenocrysts, the aegirine is also found forming narrow hydrothermal veinlets in these dykes. One grey-dyke, bearing aegirine and riebeckite, which cuts an earlier riebeckite-granite has caused some interesting marginal effects in the granite. Aegirine, absent from the main body of the granite, is developed as radiating bunches associated with riebeckite in a narrow zone alongside the contacts of the grey-dyke.

Other accessory minerals: Biotite, of a type similar to that found in some of the quartz syenites of the western Kûngnât, is seen as an accessory mineral in the higher temperature soda-granites. The occurrence of small magnetite grains is also an indication of affinity between these granites and the quartz syenites. In these perthite-bearing granites, small yellow prismatic crystals occur which, when not isotropic, show high polarisation colours. They may represent either metamict thorite or orthite.

Zircon is invariably present, usually as small dull brownish and often metamict crystals that produce halos when surrounded by riebeckite. Fluorite is sporadic accessory, and pyroclore and lithia-mica are rare minor constituents of the striped microgranites.

	1	2	3	4	5	6
Quartz	93.6	36.3	39.4	38.5	31.4	34.7
Feldspar		57.7	54.0	54.5	63.2	60.9
Riebeckite (or other soda amphibole)	3.9	1.8	5.5	5.8	2.7	2.9
Aegirine	...	...	...	...	0.2	1.2
Biotite	...	...	...	0.7	...	...
Cryolite	...	...	...	...	2.3	...
Zircon	0.1	+	...	0.5	0.2	0.1
Astrophyllite	2.4	2.7	1.1	...	...	0.2
Ore	...	1.5	...	...	...	...
Apatite	...	+	...	...	...	...

1. No. 26025, granite from southern corrie, Kûngnât.
2. Astrophyllite ekerite. Bø chappel, Luksefjell, Norway.
3. Riebeckite granite, North Conway Quadrangle, New Hampshire.
4. Riebeckite granite, Percy complex, New Hampshire.
5. Albitic riebeckite granite, Kigom, Nigeria.
6. Potassic riebeckite granite, Liruei, Nigeria.

No. 2, taken from Barth 1944, nos. 2 and 3 from Chapman and Williams 1935, and nos. 5 and 6 from Beer 1952.

In each case quartz and feldspar together constitute ca. 94 % of the entire rock.

In the Nigerian riebeckite granites, astrophyllite, fluorite, zircon, white-mica, pyrochlore and thorite are common accessory minerals. Cryolite, thomsonolite and related fluorides, though associated with the soda-granites of Nigeria and the Pike's Peak district, Colorado, have not been identified from Kûngnât in spite of the fact that the world's major occurrence of such minerals lies but a few kilometres away at Ivigtut.

XI. PETROGRAPHY OF THE RING-DYKE SUITE

The more basic of the ring-dyke rocks are composed mainly of feldspar and olivine. The feldspar commenced crystallization as labradorite but usually possesses strong zoning. The olivines which are also somewhat zoned are mostly of Fa_{35}-Fa_{40}.

The rocks are relatively rich in aluminium and alkalis, a fact reflected in their high feldspar content. The low Ca and high Al content gives a relative paucity in clinopyroxene and an abundance of intermediate plagioclase. Neither nepheline nor analcite appears in the ring-dyke rocks although they possess variable amounts of interstitial alkali feldspar. The lack of nepheline distinguishes them from the original essexites of Salem Neck although they bear resemblance to the Oslo-essexites (or kauaiites) of the Oslo region. In particular an analogy can be drawn between the more olivine-feldspar-rich types and the "apotroctolites" described by BARTH (1944). BARTH defines his sørkedalite-apotroctolite series as being of troctolite-like rocks with alkaline affinities. The series draws away from true troctolites as the alkalinity increases: Olivine gabbro (= troctolite) → olivine diorite → olivine syeno-diorite → olivine syenite. The olivine diorite members of this series were named sørkedalites by BRØGGER.

There is likewise an overall similarity to the basic rocks of the Narssaq region, S.W. Greenland, which were called "essexites" by USSING (1912) but "essexite-gabbros" by WEGMANN (1938), and, for example, to the gabbroic rocks described from N. Nigeria, New Hampshire and the Okonjeje complex in Damaraland. In many features there are close comparisons to be drawn between the more basic Kûngnât ring-dyke rocks and the rocks of Skærgaard layered series. This is particularly so as regards the iron enrichment and the low state of oxidation in the two instances. In the lowest rocks of the Skærgaard layered series, olivine and plagioclase were the dominant primary precipitate minerals. Pyroxene (augite and pigeonite) apparently formed entirely from the interprecipitate liquid (BROWN 1957, p. 514). Olivine, Fa_{37} occurs alongside plagioclase An_{62}, and a little higher in the sequence Fa_{43} is found together with An_{56}. In the more basic facies of the Kûngnât ring-dyke olivine of ca. Fa_{41} appeared early in the company of An_{60}. However the composition of the interstitial pyroxenes differed widely in the two cases.

The ring-dyke suite is characterised by a high Ti and P content and such minerals as titanaugite, ilmenite, lepidomelane and apatite are normal constituents.

In view of the general confusion surrounding the nomenclature of the basic alkaline plutonic rocks it is difficult to give names to the various rock types that comprise the Kûngnât ring-dyke. However since most of the ring-dyke rocks bear normative andesine it is proposed to call these rocks olivine diorites, these grading one way to olivine gabbros and in the case of the more alkalic members, to olivine syeno-diorites.

The ring-dyke rocks can be regarded as a suite of rocks which differ amongst each other in the relative proportions of early high temperature minerals and later lower temperature phases. The "lower temperature rocks" are the dioritic and syeno-dioritic rocks with more alkaline feldspars, particularly iron-rich olivines and with much clinopyroxene and biotite. The more extreme rocks are virtually syenites. Although crystal settling was probably operative during the cooling of the ring-dyke magma, the rocks are, for the most part, not obvious cumulates. The minerals therefore cannot normally be treated as primary precipitate, but rather as primary phase and interstitial.

Modal analyses of rocks of the ring-dyke suite.

	1	2	3	4	5	6	7	8	9	10	11
Feldspar	42.1	59.6	63	70.3	68.4	63.8	64.0	59.9	69.0	64.6	35.8
Olivine	36.2	31.1	21	12.2	11.0	13.5	13.6	9.9	8.5	6.7	9.1
Pyroxene	1.6	2.3	5.0	5.8	7.8	8.3	8.8	12.6	9.4	17	19.8
Biotite	2.7	3.4	5.3	4.0	7.7	8.4	9.0	8.2	4.3	3.4	7.3
Ore	17.3	4.6	4.0	6.9	4.7	5.0	3.3	8.1	7.4	8.3	17.2
Apatite	.1	..	1.7	.8	.4	1.0	1.3	1.3	1.4	..	10.8

	Spec. No.	Rock type and locality:
1.	30630	Gabbro-picrite; marginal to perpendicular feldspar rock.
2.	27630	Troctolitic gabbro; N.W. sector of ring-dyke.
3.	26271	Olivine gabbro; western ridge.
4.	26040	Olivine gabbro; eastern sector of ring-dyke.
5.	26196	Olivine diorite; southern sector of ring-dyke.
6.	26233	Olivine diorite; southern sector of ring-dyke.
7.	27323	Olivine syeno-diorite; central branch of ring dyke.
8.	26209	Olivine diorite; southern sector of ring-dyke.
9.	27687	Olivine diorite; central branch of ring-dyke.
10.	27316	Olivine diorite; eastern sector of ring-dyke.
11.	27685	Olivine ferrodiorite; central branch of ring-dyke.

The feldspars.

The rocks are characteristically highly feldspathic with a normal content of 60—70 % feldspar. The first feldspar to crystallized was generally ca. An_{57}-An_{58}.

In the more basic types the bulk of the broad feldspar laths is unzoned or very slightly so. However, marginally and interstitially zoning is severe. The zoning is normal and often ranges down to ca. An_{20}. It is difficult to assess the lower limit of the zoning since the albite twinning is lost as the feldspar becomes more alkaline. The final products of the zoning are small interstitial patches of clear untwinned cryptoperthite. In some rocks the early feldspar is slightly more calcic, at around An_{60}.

In the analysed rock, No. 26040, the earliest feldspar has a composition of An_{60} and considerable zoning is present. The bulk feldspar was extracted and a partial analysis indicated a wt. % composition of $Or_6Ab_{46}An_{48}$. The most calcic plagioclase yet found was an oscillatorilly zoned phenocryst in a fairly fine grained rock, which had a core of ca. An_{63}. The composition, the oscillatory zoning, and the fact of its being a phenocryst, set this aside as abnormal.

Apart from the albite twinning, the feldspars commonly show Carlsbad and, in the more basic types particularly, pericline twinning. Baveno twinning is occasionally present. In the more alkaline rocks the plagioclase occurs as more elongate laths and more of the crystals are involved in the vigorous zoning. The cores are generally ca. An_{54}. The quantity of interstitial Na-K feldspar is correspondingly greater. As the quantity of interstitial alkali feldspar increases microperthitic structures become microscopically visible. In extreme cases the content of perthite or cryptoperthite rises so that the plagioclase is only seen as strongly zoned cores. In the most extreme case the rock is quite syenitic and cryptoperthite ($2V\alpha$ 84°-86°) is the sole feldspar. In some rocks from the south-west sector of the ring-dyke, the strongly zoned and slender plagioclases show twin-lamellae tapering and wedging out. Slight clouding is also present and these two factors are possibly connected with the faulting that is thought to have occurred nearby.

Other minerals.

The olivines: Olivine is an essential mineral, present throughout the ring-dyke suite. 10 % to 20 % olivine is normal for the more basic varieties and the olivine content is rarely less than 7 %.

Olivine precipitation commenced early and finished early in the more basic rocks. In these, the olivines typically occur in small clusters

(Plate III). Their mutual boundaries are smooth and often curved. The crystals are idiomorphic although there are slight tendencies to form embayments and they are remarkably free of any serpentinisation or other alteration.

In the most basic rocks the olivines have limited zoning and generally have compositions in the range Fa_{35}-Fa_{40}, although compositions down to Fa_{33} occur in the chilled picritic margin of the perpendicular feldspar rock. With increasing alkalinity and progressively higher content of low temperature interstitial material the period of growth became longer relative to the feldspar and an anhedral or sub-ophitic habit results. In these rocks there is an increase in the range of zoning. Since the amount of zoning and of "making-over" of early olivine is dependent upon the length of exposure to the fractionating interstitial liquid, it follows that whilst one olivine crystal enclosed fairly rapidly by feldspar and/or pyroxene may escape reaction and remain moderately magnesian, another, not so protected, will be partly made over and also zoned to a greater extent. Thus, not only may a single crystal be zoned, but it may have quite a different overall composition from another olivine a short distance away. Olivine composition ranges of up to 20 $^0/_0$ Fa are known in single thin slices, e.g. a range of Fa_{42}-Fa_{62} in a rock from the south side of Kûngnât. The extent of zoning in the ring-dyke olivines is comparatively slight when compared with that found in various other alkaline-olivine basaltic rocks, for example in olivines from the Garbh Eilean sill (JOHNSTON 1953) or from the Black Jack sill (WILKINSON 1956). The most iron-rich composition recorded from the ring-dyke suite is from a rock in the north-west sector where the range is from Fa_{59}-Fa_{78}.

In the main glacier river valley there is a small dyke of porphyritic dolerite which, from its mineralogy is obviously a member of the ring-dyke suite. Its olivines are unique in the complex in being densely schillerised and in being zoned from surprisingly basic cores, Fa_{22}-Fa_{40}. Thus the full composition range in the suite is from ca. Fa_{22}-Fa_{78}, with the great mass of the rocks carrying hyalosiderite or hortonolite.

The pyroxenes: The pyroxenes show a trend from titanaugites to ferroaugites. The more basic rock types bear richly coloured titanaugites, pleochroing in rosy-pinks and creamy-greys, and occurring sub-ophitically among the olivines, ores and feldspars. In these rocks pyroxene is of subsidiary importance.

Crystallization appears to have commenced at a time when most of the feldspar and olivine had already precipitated. However, with increasing alkalinity the rôles tend to be reversed and as the growth period of olivine and feldspar was prolonged to lower and lower temperatures, the pyroxenes tended to assume a more idiomorphic habit. This behaviour is precisely analoguous to that in the early stages of fractionation in the more basic syenites.

The titanaugites display uneven patchy zoning. The "core" material is more strongly coloured and is normally crowded with sagenitic rods. This patchy zoning is probably due to irregular exsolution phenomena (BROWN 1957, p. 535). The 2V increases with fractionation from ca. 40° in the titanaugites to ca. 57° in the more iron-rich pyroxenes. Normal zoning in the pyroxenes from the alkalic rock types is often apparent from the colouring, pale pinkish-grey cores grading out to light greenish-grey margins. The titanaugite from the analysed rock no. 26040 has a β R.I. of 1.701 ($\pm$ .001), and a $2V\gamma$ of 48° indicating a composition of ca. $Ca_{39}Mg_{35}Fe_{26}$.

Orthopyroxene, normally absent from the ring-dyke suite rocks, does occur in the brecciated and contaminated rocks near the outer contacts of the ring-dyke. It appears alongside clinopyroxene and has almost certainly arisen as a reaction product from olivine as the result of some silicification. Orthopyroxene is well developed in some of the marginal facies rocks below the north face of the Røverborg where hypersthene En_{69} is found ($2V\alpha$ 69°).

The amphiboles: Amphiboles are very scarce in the ring-dyke rocks, being virtually confined to the hydrothermally altered rocks. Occasionally in the more alkalic types thin hornblende rims appear around the olivines.

The micas: Lepidomelane is an essential constituent and develops almost exclusively as a reaction fringe around the ore minerals. As a generalisation, the fringes are at their widest in the more alkalic types and are reduced to a minimum in the more basic rocks from the western sector of the ring. Reaction between ore and interstitial liquid did not commence until relatively late in the cooling history, occurring after most of the pyroxene had precipitated. Consequently all crystal surrounded by feldspar, olivine, or pyroxene and so insulated from the corrosive late magma fraction did not develop the biotite zones. Occasionally the biotite displays a poikilitic habit.

The pleochroism is from α pale-straw, β and γ deep red-brown and sepia tints. The 2V is large, ca. 30°. Sometimes the biotites zone outwards to paler green and much less pleochroic chloritic material, probably the result of late stage alteration.

Iron-titanium oxides: A homogeneous high temperature Ti-Fe oxide is thought to have commenced crystallization at an early stage, alongside olivine and plagioclase. Well-formed octahedral ore crystals are common. However, the growth period was extensive and much of the ore tends to be interstitial. Opaque minerals generally account for some 5 % of the rocks.

The opaque minerals in four of the ring-dyke rocks have been briefly examined in reflected light. Two of these, Nos. 26040 and 26271, are representative of the more basic rocks, believed to have formed under strongly reduced conditions. No. 26015 is a moderately alkalic type, thought to have cooled from a slightly more water-rich and more highly oxidised magma portion, and No. 27685 is an olivine ferrodiorite, much enriched in Fe, Ti and P.

The ore in the olivine ferrodiorite is all relatively early homogeneous titano-magnetite with little evidence of unmixing. This rock is finer grained than most of the ring-dyke rocks and the homogeneity of the ore is probably attributable to rapid chilling of the ferrodiorite magma, which appears to have been intruded after that of the main ring-dyke.

The ores from 26040 and 26271 are complex, with ilmenite-magnetite intergrowths. The intergrown lamellae are generally less broad than those in the more slowly cooled ilmenomagnetites of the syenites. Under higher magnifications, in oil immersion, it was found that much of the "magnetite" consists of intergrowths of magnetite and ulvöspinel. Ulvöspinel is relatively scarce in 26040 compared with 26271, and the intergrown fretworks are also on a coarser scale in the latter. The relative proportions of magnetite and ulvöspinel differ from grain to grain (Plate V). Hence the relationship is unlikely to be a eutectic one but is more probably one of exsolution (see: VINCENT, WRIGHT, CHEVALLIER and MATHIEU 1957). Since 26271 was taken from the ring-dyke in one of its wider parts, the coarseness of its ulvöspinel frets compared to those of 26040 may be due to slower cooling below the ulvöspinel-magnetite solvus. VINCENT and PHILLIPS (1954) point out that the presence or absence of ulvöspinel is dependent upon the oxidation state obtaining within the cooling magma and on whether there was subsequent oxidation of the rock. The differences in oxidation state of the various ring-dyke rocks are thought to be dependent on the proportions of interstitial liquid to the early formed ore. The more basic varieties of the suite are believed to have had a high proportion of early ore to interstitial liquid as a result of mild filter-pressing early in the cooling history. As a result of removal of H_2O-bearing interstitial liquid the ore cooled under a lower partial pressure of oxygen and ulvöspinel exsolved and remained unoxidised. On general petrographic grounds it is considered that 26040 had a greater ratio of interstitial liquid to early phase minerals than 26271 (more biotite, more augite and more strongly zoned plagioclase). This would account for the scarcity of ulvöspinel in 26040 and for the relatively large quantity of ilmenite, probably derived from ulvöspinel oxidation.

Ulvöspinel is quite lacking in the more alkalic rock 26015. Rocks of this type are believed to have had a much higher interstitial liquid to early phase mineral ratio.

Minute spindle-shaped lamellae of a translucent spinel are also found in the more basic rocks and remnant wisps of titano-magnetite are usually present in the lepidomelane fringes, lying parallel to the mica's cleavage.

The sulphides: Sulphides are a minor accessory in the suite and are usually seen together with the oxide grains. In their mineralogy they resemble the sulphides in the basic syenites and again pyrrhotite is the principal sulphide, occurring together with subsidiary chalcopyrite. The latter is sometimes seen as distinct lamellae within the pyrrhotite. Pentlandite "sparks" are again present in the pyrrhotite and, as in the syenites, it is probable that there were two phases of exsolution from a homogeneous sulphide; one of these involving the separation of chalcopyrite and the other yielding the pentlandite. A little pyrite is also present in very small amounts.

In the Skærgaard layered series the association pyrrhotite-chalcopyrite is only seen from the fayalite ferrogabbros upwards (Wager, Vincent, Smales and Bartholomé 1957). Bartholomé considered that in the early Skærgaard liquids the original sulphide was a high-temperature bornite which subsequently broke down. After a brief period in which high temperature chalcophyrite may have been forming, Cu-bearing pyrrhotite separated from the later liquids which, by unmixing, gave rise to chalcopyrite. As far as the sulphides are concerned, the Kûngnât rocks roughly correspond to the later Skærgaard rocks where, as a result of extensive Cu removal in the early fractionation stages, iron-sulphides were dominant. Later alteration of the pyrrhotite to marcasite, widespread in the later Skærgaard rocks, is not seen in Kûngnât.

Apatite: Apatite is seldom, if ever, absent from the ring-dyke and was among the earliest phases to crystallize. Interstitial apatite, as in some of the alkali-iron-rich gabbroic rocks of the Narssaq region and in the lower Skærgaard gabbros, is not found. The habit in the ring-dyke suit is slender and acicular, this contrasting with the condition in the syenites where the apatite occurs in stouter prisms.

Apatite becomes a major constituent in the Fe-Ti-P-rich olivine ferrodiorite associated with the central branch of the ring-dyke between Røverborg and Kûngnât peak, where it comprises ca. 11 °/₀ of the rock (Plate IV). The very high fluorine content of the ferrodiorite suggests that the mineral is a fluorapatite. In its high primary apatite content the ferrodiorite may be compared to the Oslo sørkedalites. The Skye fayalite quartz diorites and some of the Skærgaard ferrogabbros, may represent an analogous stage in the differention of tholeiitic basalts.

Comparison of the modes of a Kûngnât "ferrodiorite" and a sørkedalite from the Oslo district.

	1	2
Feldspar	35.8	42.5
Olivine	9.1	23.3
Clinopyroxene	19.8	...
Biotite	7.3	7.5
Ore	17.2	14.0
Apatite	10.8	12.5
Calcite	...	.2
Olivine composition	Fa_{60}	Fa_{40}

1. Hortonolite ferrodiorite, No. 27685, Kûngnât.
2. Sørkedalite (olivine diorite) Kjelsås, Oslo (Barth 1944).

XII. ANALYSES OF THE KÛNGNÂT ROCKS

In addition to four rocks chemically analysed by B. Collett at Oxford using classical methods, approximate analyses were made of a further twenty-four rocks[1]. The following methods were employed for these approximate analyses (some details being given in the appendix at the end of the paper):—

Na_2O K_2O	Flame-photometrically.
Al_2O_3 Fe_2O_3 FeO	Volumetrically. (Aluminium determinations by Miss E. A. Hughes, Mineralogical Museum, Copenhagen).
SiO_2	Colourimetrically.
P_2O_5	Colourimetrically, except in the case of No. 27685 where the determination was made by D. Curran, Oxford, using a tracer isotope dilution method).
MnO TiO_2	Determined colourimetrically for twelve of the rocks and in all twenty-four by quantitative spectrographic methods. Where the two methods were used on the same rocks, agreement between the results was reasonably good, (difference of the results normally within 10 % of the mean value).
CaO MgO	Spectrographically.
H_2O	Penfield method.

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[1] Of the 23 of these in which all the major elements were determined, the summations of 10 fall between 98 and 102 %, the summations of another 10 fall between 102—103 % and, for the remaining 3, between 103—104 %. The principal errors are thought to lie in the Al, Ca and Mg determinations.

Quantitative spectrographic analysis was also made for the following elements:— Li, Rb, Cs, Ba, Sr, Ga, Sc, La, Zr, V, Cr, Ni, Co, Cu, and F. Details of the spectrographic techniques employed are also given in the appendix.

Nb was determined colourimetrically in two rocks. (Determinations by Miss E. A. Hughes.)

Table 1. Analyses and approximate analyses of syenites from the western lower layered series and the south western marginal intrusion.

	1	2	3	4	5	6	7	8
G.G.U. nos.	26004	26005	26470	26255	27647	27648	27654	26473
SiO_2	55.3	55.9	59.9	60.5	63.0	66.6	66.8	69.6
Al_2O_3	12.8	14.2	15.1	15.5	16.5	16.2	16.4	15.2
Fe_2O_3	2.0	1.6	2.5	1.1	1.1	.5	.9	1.2
FeO	12.5	10.4	7.8	7.4	3.7	4.2	3.1	4.4
MgO	.89	.75	.60	.45	.11	.06	.13	.06
CaO	5.7	3.8	3.9	3.5	2.5	2.2	2.7	1.7
Na_2O	4.5	5.0	5.2	5.4	5.9	5.9	5.9	5.6
K_2O	4.4	4.9	5.2	5.7	6.1	6.2	5.9	4.7
H_2O^+	.46	.54	.63	.51	.40	.49	.53	.73
H_2O^-		.13			.26			
TiO_2	2.2	2.2	1.1	.75	.38	.34	.39	.22
P_2O_5	.44	.54	n.d.	.13	.05	.02	.03	n.d.
MnO	.32	.29	.19	.18	.09	.11	.08	.12
BaO	.18	.18	.46	.09	tr.	tr.	tr.	tr.
F	.37	.22	.17	.09	.07	.05	.05	.06
		100.65			100.16			
F = 0		.09			.03			
		100.56			100.13			

Analyses 2 and 5 by B. Collett (except for BaO and F). Specimens 2 → 7 represent an ascending sequence in the W.L.L.S. Nos. 1 and 2 are from approximately the same horizon in the lower banded group (two samples being taken because of the difficulty of selecting a representative standard rock from a strongly banded locality).

No. 3 from the lower banded group.
No. 4. from the lower laminated group.
No. 5 from the lower unlaminated group.
No. 6 from the lower unlaminated group.
No. 7 from the lower unlaminated group.
No. 8 from the south western marginal syenites.
n.d. = not determined. tr. = trace amounts only.

Table 2. Approximate analyses of rocks from the soda-granite suite associated with the western syenites.

G.G.U. nos.	9 26025	10 26272	11 26498
SiO_2	74.6	76.8	68.7
Al_2O_3	12.2	12.4	10.5
Fe_2O_3	1.2	.87	4.4
FeO	2.3	1.2	2.3
MgO	.01	.01	.01
CaO	1.1	1.36	1.2
Na_2O	5.2	5.1	6.0
K_2O	5.2	4.0	4.2
H_2O	.36	.28	n.d.
TiO_2	.32	.22	.33
P_2O_5	n.d.	tr.	n.d.
MnO	.05	.02	.12
ZrO_2	.29	.22	.97
Li_2O	tr.	tr.	.19
F	.27	.03	.45

No. 9. Soda-hornblende granite.
No. 10. Riebeckite astrophyllite granite.
No. 11. Aegirine riebeckite microgranite ('grey-dyke').
n.d. = not determined. tr. = trace amounts only.

Table 3. Approximate analyses of syenites from the western upper layered series.

G.G.I. nos.	12 27692	13 26094	14 27677	15 27700	16 27699	17 26231	18 27683
SiO_2	63.0	64.1	62.9	64.6	66.0	67.4	66.3
Al_2O_3	15.8	17.0	15.2	15.8	11.9	17.4	15.8
Fe_2O_3	1.5	1.3	3.1	2.4	2.0	1.5	1.4
FeO	5.9	4.0	4.5	4.6	3.6	1.0	5.1
MgO	.16	.21	.12	.10	.11	.03	.08
CaO	2.2	2.1	3.2	2.2	2.2	1.2	1.9
Na_2O	5.8	6.4	6.1	6.4	6.6	7.1	6.4
K_2O	5.7	5.9	5.3	5.5	5.5	6.2	5.4
H_2O	.73	.61	.70	.53	.69	.55	.52
TiO_2	.25	.23	.28	.26	.15	.20	.33
P_2O_5	.07	n.d.	.06	n.d.	.10	n.d.	n.d.
MnO	.24	.17	.15	.14	.16	.04	.18

Nos. 12—17. Ascending sequence.
No. 18. Syenite from the top of the Nisseborg succession.
n.d. = not determined.

Table 4. Analysis and approximate analyses of syenites from eastern Kûngnât.

	27696a	27324	26042
G.G.U. nos.	19	20	21
SiO_2	57.1	61.6	62.8
Al_2O_3	13.5	16.1	16.8
Fe_2O_3	1.6	2.3	.97
FeO	7.1	4.4	3.8
MgO	1.3	.24	.19
CaO	4.1	2.7	2.5
Na_2O	5.2	5.9	5.8
K_2O	5.1	5.9	5.8
H_2O^+	.37	.47	.56
H_2O^-			.17
TiO_2	1.6	.51	.43
P_2O_5	.49	.07	.09
MnO	.19	.09	.10
BaO	1.1	tr.	tr.
F	.07	tr.	tr.
			100.01

Analysis no. 21 by B. Collett (except for BaO and F).

No. 19. Basic syenite from the upper part of the eastern layered series.
No. 20. Syenite from high in the lower part of the eastern layered series.
No. 21. Moderately leucocratic quartz syenite from the eastern border-group.

tr. = trace amounts only.

Table 5. Analysis and approximate analyses of rocks from the ring-dyke suite.

	22	23	24	25	26	27	28
G.G.U. nos.	26271	26040	26490	26169	26277	26152	27685
SiO_2	45.8	45.4	47.9	46.4	44.7	51.6	34.2
Al_2O_3	17.2	18.0	17.6	17.1	18.8	n.d.	10.0
Fe_2O_3	2.6	3.1	2.8	3.1	2.5	3.2	4.2
FeO	15.0	11.9	12.0	12.2	9.7	11.2	18.7
MgO	6.9	5.1	4.4	7.8	6.0	3.4	4.8
CaO	5.3	7.6	6.7	5.5	6.3	6.7	9.8
Na_2O	3.3	3.7	4.2	3.9	3.8	4.1	2.3
K_2O	1.1	.91	2.0	1.9	2.0	2.3	.78
H_2O^+	.65	.35	.52	1.8	1.7	.46	.92
H_2O^-		.05					
TiO_2	2.5	3.5	3.8	2.3	2.5	2.5	8.8
P_2O_5	.47	.25	n.d.	n.d.	n.d.	n.d.	3.1
MnO	.21	.19	.21	.22	.15	.19	.20
BaO	tr.	.10	.16	.14	tr.	.45	.10
F	.23	.03	.29	.22	.45	.45	2.4
		100.13					
F = O		.01					
		100.12					

Analysis No. 23 by B. Collett (except for BaO and F).

Nos. 22, 23 and 24 are gabbroic varieties of the ring-dyke suite from, respectively, the western, eastern and south-western sectors of the dyke.

Nos. 25 and 26 are metasomatically altered rocks from the southern and western sectors.

No. 27, olivine syeno-diorite from the northern sector.

No. 28, olivine ferrodiorite, from the central branch of the ring-dyke.

n.d. = not determined. tr. = trace amounts only.

Table 6. Analyses of syenites from other districts compared with the approximate analyses of the basic syenites from Kûngnât.

	1	2	3	4	5	6	7	8	9
SiO_2	55.92	57.09	55.79	58.17	53.71	55.0	54.8	57.46	58.77
Al_2O_3	14.22	13.52	15.76	16.07	15.37	20.0	19.2	18.50	15.78
Fe_2O_3	1.60	1.60	1.60	1.30	3.28	.9	1.8	3.12	2.33
FeO	10.36	7.12	7.56	5.04	5.72	2.9	2.0	4.80	6.03
MgO	.75	1.26	.41	1.20	1.58	1.7	2.2	.99	.24
CaO	3.83	4.06	3.70	3.42	5.20	4.2	3.3	3.68	3.55
Na_2O	4.98	5.15	7.72	7.41	6.84	9.7	10.0	4.86	4.47
K_2O	4.86	5.13	4.34	4.65	4.11	4.4	6.0	4.63	5.29
H_2O^+	.54	.37	.18	.41	.45	..	..	.10	1.22
H_2O^-	.13		.34	.19	.33	..	..	.22	.29
TiO_2	2.18	1.58	1.18	2.09	3.40	.8	.6	1.38	.94
P_2O_5	.54	.49	.36	.42	.52	.3	..	.38	1.45
MnO	.29	.19	.14	.07	.14	.1	.1	.04	.10
BaO	.18	1.1	..	..	..	..	..	..	..
F	.22	.07	..	..	..	..	..	..	..
	99.16	96.30	99.08	100.44	100.65	100.00	100.00	100.16	100.37

No. 1. (No. 26005) Lower banded group. W.L.L.S. Kûngnât.
No. 2. (No. 27696a) Upper part of layered series, east Kûngnât.
No. 3. Augite-syenite, Nunasarnausaq, Ilímaussaq (Ussing 1912).
No. 4. Nordmarkite, Narssaq (Ussing 1912).
No. 5. Augite-syenite, Qôroq, Igaliko (Ussing 1912).
No. 6. Larvikite, Undrum, nr. Oslo. (Barth 1944)[1].
No. 7. Larvikite, Gjertrudkollen, Oslo (Barth 1944).[1]
No. 8. 'Ridge-syenite' (O.K. 66) Okonjeje (Simpson 1954).
No. 9. Rhomben porphyry, Quincy, Mass. (Warren 1913).

[1] Calculated anhydrous to 100 %.

Table 7. Comparison of analyses of quartz syenites.

	1	2	3	4
SiO_2	62.98	62.80	62.24	63.54
Al_2O_3	16.45	15.69	15.82	15.30
Fe_2O_3	1.07	.97	1.94	1.34
FeO	3.73	3.81	4.69	4.44
MgO	.11	.19	.07	.72
CaO	2.52	2.52	2.65	2.34
Na_2O	5.94	5.80	4.80	5.12
K_2O	6.09	5.82	6.26	5.12
H_2O^+	.40	.56	.56	.62
H_2O^-	.26	.17	.07	.26
TiO_2	.38	.43	.87	.52
P_2O_5	.05	.09	.14	.24
MnO	.09	.10	.24	..
CO_2	..	..	..	.15
	99.71	98.95	100.35	99.71

1. Quartz fayalite syenite, no. 27647. Unlaminated group. W.L.L.S.
2. Quartz fayalite syenite, no. 26042 eastern Kûngnât.
3. Quartz syenite. North Conway Quadrangle New Hants. U.S.A. (CHAPMAN and WILLIAMS 1935).
4. 4 Syenite, Zaranda, Nigeria (JACOBSON *et al.* 1958).

Table 8. Comparison of the approximate analysis of a Kûngnât riebeckite granite with analyses of soda-granite from some other regions.

	1	2	3	4	5	6	7	8
SiO_2	76.8	75.26	76.65	70.59	73.59	75.29	73.82	72.4
Al_2O_3	12.4	11.88	11.66	12.38	12.50	13.33	10.59	12.3
Fe_2O_3	.87	.91	.80	1.61	2.04	.52	2.18	1.2
FeO	1.2	.90	1.14	3.33	1.12	1.40	2.98	.9
MgO	.01	.19	.10	none	.07	.22	.04	.1
CaO	1.36	.70	.34	.93	1.22	.64	.28	.2
Na_2O	5.10	4.45	4.53	6.95	4.56	3.80	4.20	8.3
K_2O	4.01	4.53	4.44	3.74	5.05	3.97	4.57	4.3
H_2O^+	.28	.52	.10	.21	.09	.30	.39	..
H_2O^-		.29	.18	.20	.12	.40	.49	..
TiO_2	.22	.08	.16	.44	.22	tr.	.13	.2
P_2O_5	tr.	.01	.01	tr.	.02	.03	.02	..
MnO	.02	.01	.02	.08	.04	none	none	..
ZrO_2	.22	n.d.	n.d.	n.d.	n.d.	tr.	none	.1
F	.03	.25	.12	n.d.	n.d.	n.d.	.06	..
	102.52	100.25	100.25	100.46	100.64	99.90	99.75	100.00

No. 1. Riebeckite-astrophyllite granite. No. 26271. Kûngnât.
No. 2. Butra riebeckite biotite granite Rop complex Nigeria (Jacobson *et al.* 1958).
No. 3. Ruku riebeckite granite porphyry. Rop complex Nigeria (Jacobson *et al.* 1958).
No. 4. Arfvedsonite granite. Ilímaussaq (Ussing 1912).
No. 5. Potassic-phase riebeckite granite Liruei. Nigeria (Beer 1952).
No. 6. Riebeckite granite, Kadaru. Nigeria (Beer 1952).
No. 7. Riebeckite granite, Rosemount, Pike's Peak, Colorado (Beer 1952).
No. 8. Astrophyllite-ekerite, Bø chappel, Luksefjell (Barth 1944)[1].

[1] Calculated anhydrous to 100 %.

Table 9. Comparison of mean analysis of the ring-dyke gabbro with analyses of gabbros and essexites from other districts.

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	45.75	48.15	45.65	48.04	45.78	43.76	46.10	48.99	46.99	47.91	46.24
Al_2O_3	17.35	18.02	15.08	20.10	14.29	17.07	18.59	18.00	17.94	16.42	17.21
Fe_2O_3	2.80	2.52	3.41	2.32	2.74	1.75	2.63	2.94	2.56	4.51	2.89
FeO	12.79	9.50	14.86	6.13	13.35	10.18	6.68	7.86	7.56	7.60	12.19
MgO	5.40	5.25	6.35	4.68	4.41	5.81	3.23	2.95	3.22	4.33	5.01
CaO	6.46	10.17	9.18	11.52	8.74	10.94	9.86	6.58	7.85	9.16	9.60
Na_2O	3.67	3.46	2.48	3.01	3.08	2.66	6.22	4.63	6.35	3.73	3.18
K_2O	1.32	.14	.28	.79	1.66	.56	.63	2.59	2.62	2.00	.28
H_2O+	.51	.20	.22	.42	.37	.88	.80	.77	.65	1.0	.42
H_2O-		.02	.08	..	.08	.20	.11	.16			.56
TiO_2	3.22	2.64	2.59	2.56	3.24	5.97	3.34	2.30	2.92	2.53	2.08
P_2O_5	.35	.05	.08	.15	2.22	.15	1.41	2.02	.94	.74	.28
MnO	.20	.12	.15	.09	.27	..	.07	.13	tr.	.23	.22
F	.18	..	..	..	..	..	..	..	..	..	..
	100.00	100.24	100.23	99.81	100.23	99.93	99.67	99.92	99.60	100.16	100.16

No. 1. Kûngnât ring-dyke. Mean of three analyses of the gabbroic varieties, recalculated to 100 %.

No. 2. Middle gabbro E. G. 3662. Skærgaard, east Greenland (Wager and Deer 1939).

No. 3. Middle gabbro E. G. 3661. Skærgaard, east Greenland (Wager and Deer 1939).

No. 4. Gabbro, Tripyramid Peak, New Hants. (Chapman and Williams 1935).

No. 5. Ferrogabbro. O. K. 106, tholeiitic series, Okonjeje (Simpson 1954).

No. 6. Jinni Valley gabbro, Nigeria (Jacobson *et al.* 1958).

No. 7. 'Essexite', Narssaq, S. Greenland (Ussing 1912).

No. 8. 'Apotroctolite', Kjelsås, Oslo (Barth 1944).

No. 9. Essexite, type-locality, Salem Neck (Barth 1944).

No. 10. Average of twenty-three Oslo-essexites (Barth 1944).

No. 11. Olivine gabbro, Camas Mhôr, Muck (Tilley 1952).

Table 10. Comparison of the approximate analysis of a Kûngnât ferrodiorite with analyses of iron, phosphorus, titanium-rich rocks from other districts.

	1	2	3
SiO_2	34.2	33.3	44.61
Al_2O_3	10.0	13.1	11.70
Fe_2O_3	4.2	4.5	2.05
FeO	18.7	14.0	22.68
MgO	4.8	9.3	1.71
CaO	9.8	11.0	8.71
Na_2O	2.3	5.0	2.95
K_2O	.78	1.3	.35
H_2O^+	.92	..	.22
H_2O^-		..	.20
TiO_2	8.8	3.6	2.43
P_2O_5	3.1	4.7	1.85
MnO	.2	.2	.21
F	2.4	1.1	n.d.
CO_2	n.d.	.1	.04
S	n.d.	n.d.	.31
	100.02	101.20	100.02

No. 1. Hortonolite ferrodiorite No. 27685, Kûngnât.
No. 2. Sørkedalite (olivine diorite) Kjelsås, Oslo (Barth 1944).
No. 3. Ferrohortonolite ferrogabbro, No. E.G. 4145 Skærgaard, east Greenland (Wager and Deer 1939). n.d. = not determined.

Table 11. Spectrographic trace elemen

	1 26473	2 26004	3 26005	4 26470	5 26255	6 27647	7 27648	8 27654	9 26025	10 26272	11 26498	12 27692	13 260
Li	11	26	24	9	9	8	12	6	59	75	900	5	
Rb	153	68	110	130	97	200	180	180	290	270	375	130	17
Cs	2	*	*	*	*	*	*	*	1.6	8.5	2	*	*
Cu	n.d.	20	19	16	5	3	3	4	1	2	15	3	
Sr	25	105	130	140	105	53	40	65	49	38	25	34	3
Ba	32	1600	1650	4100	800	165	94	200	120	71	48	44	7
Ga	40	19	22	25	24	21	23	26	34	44	56	17	2
Sc	*	56	48	31	25	20	*	*	*	*	*	*	*
La	*	*	*	*	*	*	(150)	(150)	(200)	*	*	*	*
Zr	555	680	780	220	130	680	2050	1850	2150	1600	(7000)	80	12
V	14	63	54	37	33	26	30	59	*	*	15	41	3
Cr	*	*	*	*	*	*	*	*	*	*	*	*	*
Co	*	5	4.5	4	3	2	*	*	*	*	*	*	*
Ni	*	1	2	*	*	*	*	*	*	*	*	*	*
F	590	3700	2200	1700	870	735	490	470	2700	310	4500	305	27

1. South western marginal syenite.
2—8. Western lower layered series syenites.
9—11. Soda-granite suite associated with the W.L.L
12—18. Western upper layered series syenites.

All figures as parts per million. Those values in brackets are semi-quantitative only.

The totals of the approximate analyses are poor compared with normally accepted classical analyses. WASHINGTON (1930) wrote deploring the attitude of chemists and petrographers who are prepared to accept analyses with summations above 101 % or below 99 %, but in the present instance a relatively large number of analyses were required to determine the trends of differentiation in the complex and circumstances did not allow for complete classical analysis in every case. It is contended that the approximate (and in some cases incomplete) analyses of the twenty-four rocks, presented above do serve their intended purpose in establishing the rock trends in spite of the fact that individually they are not to be considered as accurate classical analyses. It is important to stress that the Mg and Ca values were not determined chemically and that the aluminiums were determined by a relatively untried method.

In spite of an overall similarity to the larvikites of the Oslo region, the more basic Kûngnât syenites differ in having a considerably lower Na_2O/K_2O ratio and in having a higher FeO/MgO ratio. The relatively low sodium content of the Kûngnât syenites also seems to distinguish them from the otherwise similar tock types (augite-syenites and nordmarkites of Ussing's nomenclature) in the Ilímaussaq complex. The ferrohortonolite-ferroaugite syenite from Okonjeje in Damaraland, which SIMPSON regards as the ultimate product of the differentiation of a tholeiitic magma, is also broadly similar in composition to the basic

data for the Kûngnât rocks.

14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
27677	27700	27699	26231	27683	27696	27324	26042	26271	26040	26490	26169	26277	26152	27685
5	3	7	8	10	7	5	9	6	1	19	31	25	10	3
150	160	160	215	210	62	110	145	34	14	50	64	200	30	14
*	*	2	*	2	*	*	*	*	*	*	*	*	*	*
3	5	2	4	6	11	12	4	32	17	38	40	5	35	110
45	35	43	35	37	310	51	120	230	435	460	660	430	620	350
70	31	100	46	89	9700	77	460	530	880	1450	1250	350	4000	870
19	22	30	32	37	16	20	23	12	15	20	(58)	18	29	25
*	*	*	*	*	41	*	*	41	41	30	48	*	57	61
*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
145	190	130	180	210	230	99	52	210	80	245	195	38	205	200
40	59	52	41	44	50	37	*	142	290	180	120	160	100	150
*	*	*	*	*	*	*	*	820	390	460	*	540	*	*
*	*	*	*	*	8	*	*	77	46	36	88	48	23	76
*	*	*	*	*	(.5)	*	*	135	40	48	80	43	4	3
320	260	120	*	480	710	130	210	2300	350	2900	2200	4450	4450	(24000)

9—21. Syenites from the eastern centre.
2—28. Olivine diorites etc. from the ring-dyke suite.

= below the detection limits. n.d. = not determined.

Table 12. Spectrographic analyses of feldspars (Na and K determined flame-photometrically).

	1	2	3	4	5	6	7	8	9	10	11	12	13
% Na	4.04	5.02	4.87	5.02	5.02	4.86	4.88	4.63	4.75	4.96	5.01	4.21	(2.46)
– K	.79	4.32	4.87	4.79	4.85	5.60	5.50	5.69	5.49	5.29	5.29	6.38	(6.25)
– Ca	6.8	1.59	1.07	.63	1.12	.61	.71	.61	.58	.63	.40	.56	(.47)
ppm Li	.7	1	2	2	5	4	7	10	10	4	3	2	..
– Rb	5	60	94	150	100	160	170	205	205	170	240	142	(710)
– Cs	*	*	*	*	*	*	*	1	.5	1	*	*	(1.6)
– Ag	41	8	35	2	5	2	30	23	1	5	2	2	(8)
– Cu	27	6	31	8	9	3	40	33	8	4	7	3	(3)
– Ga	39	29	25	29	29	27	27	27	28	29	37	20	(20)
– Tl	19	*	5	3	4	12	14	4	2	1	*	*	(2)
– Sr	1250	550	64	20	105	85	200	34	19	16	7	72	(8)
– Ba	1150	6750	3250	165	2000	2300	4450	400	320	120	115	310	(97)
– Pb	*	9	5	*	7	8	8	6	6	10	5	5	(8)

Specimen		Rock type	Calculated weight composition.
1.	No. 26040	Olivine diorite from ring-dyke	$\mathrm{Or}_{6}\mathrm{Ab}_{46}\mathrm{An}_{48}$
2.	– 27696	Basic syenite, eastern layered series	$\mathrm{Or}_{32}\mathrm{Ab}_{57}\mathrm{An}_{11}$
3.	– 26118	Basic syenite, eastern border group	$\mathrm{Or}_{36}\mathrm{Ab}_{56}\mathrm{An}_{8}$
4.	– 27324	Syenite from eastern layered series	$\mathrm{Or}_{36}\mathrm{Ab}_{59}\mathrm{An}_{5}$
5.	– 26003	Syenite from lower banded group. W.L.L.S.	$\mathrm{Or}_{35}\mathrm{Ab}_{57.5}\mathrm{An}_{7.5}$
6.	– 26467	Syenite from lower banded group. W.L.L.S.	$\mathrm{Or}_{41}\mathrm{Ab}_{55}\mathrm{An}_{4}$
7.	– 26470	Syenite from lower banded group. W.L.L.S.	$\mathrm{Or}_{40}\mathrm{Ab}_{55}\mathrm{An}_{5}$
8.	– 26261	Syenite from lower laminated group. W.L.L.S.	$\mathrm{Or}_{41.5}\mathrm{Ab}_{53.5}\mathrm{An}_{5}$
9.	– 27648	Syenite from lower unlaminated broup W.L.L.S.	$\mathrm{Or}_{40.5}\mathrm{Ab}_{55}\mathrm{An}_{4.5}$
10.	– 26094	Syenite from lower part of the W.U.L.S.	$\mathrm{Or}_{38}\mathrm{Ab}_{57}\mathrm{An}_{5}$
11.	– 26231	Syenite from highest part of the W.U.L.S.	$\mathrm{Or}_{38}\mathrm{Ab}_{58}\mathrm{An}_{4}$
12.	– 26237	Eastern syenite pegmatite	$\mathrm{Or}_{46.5}\mathrm{Ab}_{49}\mathrm{An}_{4.5}$
13.	– 26498	Aegirine-riebeckite 'grey-dyke'	$\mathrm{Or}_{59}\mathrm{Ab}_{37}\mathrm{An}_{4}$

(ferrohortonolite and ferroaugite-bearing) Kûngnât syenites but here, the chief difference appears to be in the state of oxidation, the Kûngnât rocks having cooled in a more reduced environment.

Whilst chemically similar to the W.L.L.S. quartz syenites, those from the eastern border group differ in their mineralogy. For example, they lack the sodic pyroxenes and hornblendes which are found in the upper W.L.L.S. rocks. The Kûngnât soda-granites are chemically similar to soda-granites from many other parts of the world, in particular to some of those from Nigeria. The Bø chappel astrophyllite ekerites in the Oslo district, analogous to the Kûngnât astrophyllite granites in their position in the differentiation sequence, differ in their higher Na_2O/K_2O, lower FeO/MgO, and in being more highly oxidised.

As it was not possible to get an approximation of the composition of the undifferentiated ring-dyke magma by analysis of uncontaminated chilled margin, an average was taken of the analyses of three of the more basic ring-dyke rocks. Since the ring-dyke magma chilled relatively quickly and probably with little sinking of early phase minerals, this average analysis (recalculated to 100 %) is considered to approximately represent the original composition of the magma.

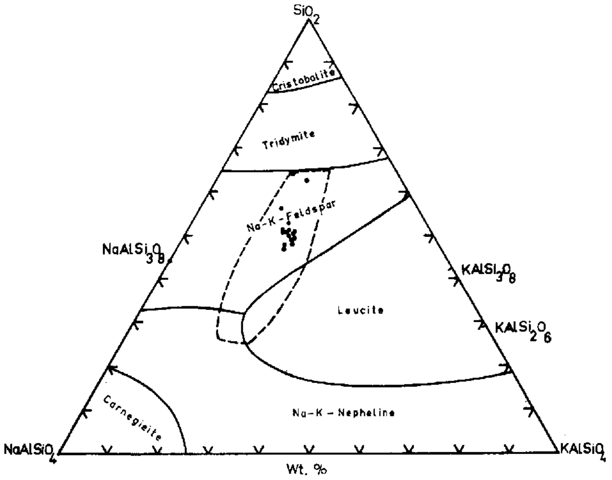

Fig. 43. Compositions of the Kûngnât syenites and soda-granites plotted on the $NaAlSiO_4$-$KAlSiO_4$-SiO_2 diagram. (Bowen 1937).

XIII. GEOCHEMISTRY OF THE KÛNGNÂT COMPLEX

1. The syenites and their derivatives.

The alkali elements.

Lithium. The lithium content of the Kûngnât syenites is uniformly low at around the 5—10 ppm. level. Since the Li content of the constituent feldspars is generally less than 5 ppm. there is probably mild enrichment in the hornblendes and micas. There are indications of some Li enrichment in the W.L.L.S. above the level of the lower laminated group where the lamellar perthites themselves contain ca. 10 ppm. of Li.

The lowest rocks of the lower banded group seem to be exceptional in having a Li content of ca. 25 ppm. The feldspars in these rocks contain only ca. 5 ppm. and the inference is that the lepidomelanes are the primary host.

The lithia-mica taeniolite appears in some of the W.L.L.S. pegmatites, and in the late stage soda-granite suit there is a marked Li enrichment. In the coarser soda-granites, the content is around 60—70 ppm. More extreme enrichment is seen in the aegirine-riebeckite 'grey-dyke' (no. 26498) where the Li content approaches 0.1 $^0/_0$.

Sodium and potassium. The Na/K ratio varies little within the syenites and has a value close to unity. However, the western upper layered series rocks tend to have relatively higher sodium contents than the syenites of the lower series. The south western marginal syenites also show slight enrichment in sodium relative to potassium and the same tendency is present in the late stage soda-granite suite of the W.L.L.S.

Syenites of the W.L.L.S.

Sample no.	$\frac{Na_2O.100}{Na_2O + K_2O}$
27654	50
27648	49
27647	49
26255	49
26470	50
26005	50
26004	50

Syenites of the W.U.L.S.

Sample no.	$\frac{Na_2O.100}{Na_2O + K_2O}$
27683	54
26231	54
27699	55
27700	54
27677	53
26094	53
27692	50

Rubidium and caesium. A general rise in the value of the ratio Rb/K is apparent in both the W.L.L.S and W.U.L.S. Maximum rubidium enrichment is found in the late soda-granite suite, and it is of interest that Jacobson *et al.* remark on the high Rb/K ratios of the Nigerian soda-granites.

In the years since Ahrens *et al.* (1952) drew attention to the close association of potassium and rubidium in igneous rocks, it has been widely recognised that anomalously high Rb/K ratios are common in rocks derived from highly fractionated residual magmas. Recently, Taylor and Heier (1958 and 1959) have demonstrated the phenomenon of rubidium depletion in some igneous rocks formed from magmas relatively rich in calcium and/or barium. Anomalously low Rb/K ratios are found in the lowest rocks of the W.L.L.S. and this is also suspected to be the general case throughout most of the eastern syenite centre. The rubidium depletion in certain of the Kûngnât rocks is considered in more detail in the later section dealing with analyses of the feldspars (p. 112).

Caesium is just detectable in the one south western marginal syenite analysed and in two of the syenites from the W.U.L.S. The highest concentration of caesium found was in the riebeckite granite no. 26272, where it reaches 8.5 ppm.

Sample no.	Cs ppm.	Rb ppm.	Rb. 10^4/K
1) The south western marginal syenites.			
26473	2	150	39
2) Western lower layered series syenites.			
27654	..	180	37
27648	..	180	35
27647	..	200	40
26255	..	97	21
26470	..	130	31
26005	..	110	27
26004	..	68	19
3) Western upper layered series.			
27683	2	210	47
26231	..	215	42
27699	2	163	36
27700	..	160	35
27677	..	150	34
26094	..	170	35
27692	..	132	28
4) Soda-granite suite associated with the W.L.L.S.			
26498	2	375	108
26272	8.5	270	81
26025	1.6	285	66
5) Syenites from the eastern centre.			
27696 A	..	62	14.5
27324 A	..	110	23
26042	..	145	30

The alkaline earth elements.

Calcium, strontium and barium. The calcium content of the rocks in the western layered series decreases upwards, as would be expected in a layered intrusion where not only feldspar but calcium-rich clinopyroxene and apatite were among the primary precipitate minerals.

Strontium and barium show a certain parallelism in their behaviour. The syenites containing the most of these two elements are the basic eastern syenites and the rocks of the lower banded group of the W.L.L.S. Both elements decrease with height in the western layered series and this behaviour contrasts with that in differentiated basic rocks where there is generally a build up of Ba and Sr in the residual liquids.

The strontium is probably not primarily associated with calcium in the syenites. Analysis of the feldspars shows that it is in these that the bulk of the strontium resides. Turekian and Kulp (1956) remark that strontium is not only found in Ca-rich minerals but to an equal or lesser extent in high temperature K-rich minerals. Referring to the work of Wager and Mitchell on the Skærgaard and of Hess on the Stillwater intrusion, they comment that in both of these intrusions subtraction of calcium during fractionation is accompanied by a corresponding enrichment of the residual magma in Sr, i.e. the plot of Ca against Sr has a negative slope. They compare this state of affairs with that in the Oslo suit of alkali rocks where differentiation of a syenitic magma has given rise to increasingly silicic rocks along with a falling off in Ca content. In these Oslo rocks, which are comparable in a broad way to those at Kûngnât, there is also a decrease of Sr in progressively more differentiated rocks.

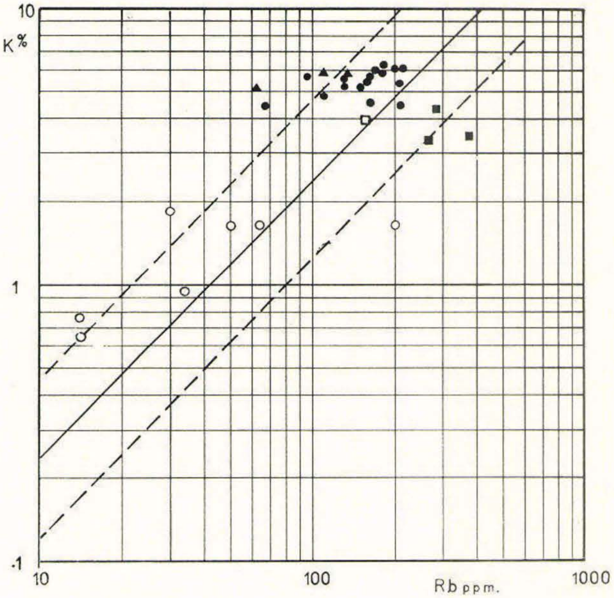

Fig. 44. Rb/K relationships in the Kûngnât rocks superimposed on the Rb/K curve of Ahrens, Pinson and Kearns (1952). Broken lines indicate normal limits of scattering. ▲ Eastern syenites. ● Syenites of the W.L.S. ■ W.L.L.S. soda-granite suite. ○ Rocks of the ring-dyke suite. □ South western marginal syenite.

Turekian and Kulp, as one explanation of the contrasted behaviour in the basic layered intrusions with that of the Oslo syenitic rocks, suggest "— that normal crystallization of a magma is such as to give a negative slope for the Sr-Ca relationship for the early segregates (as in the Stillwater complex) and a positive slope for the late segregates (as in the case of the Oslo rocks)". In other words, when plagioclase is the dominant feldspar precipitating, the Sr content in the residual liquids will increase, but in fractionating liquids where a high temperature Na-K feldspar is crystallizing out, Sr will be rapidly removed from solution. At Kûngnât, however, even in the latest differentiates, the Sr content never falls below 30 ppm.

Feldspar again is the main host for barium in most of the syenites although the high Ba values obtained in some of the lower banded group syenites of the W.L.L.S. and in the basic eastern syenites strongly suggest Ba enrichment in the lepidomelanes, this mineral being an important constituent in these rocks. There is no regular pattern observable in the Ba/K ratios.

Other elements.

Scandium. This element was detectable in the more undifferentiated eastern syenites and in the lower part of the W.L.L.S. The detection limit was around the 15—20 ppm. level.

Scandium preferentially enters early ferromagnesian minerals, occupying the Fe″-Mg″ positions (Ringwood 1955). This is borne out by the observations at Kûngnât where the ferromagnesian-rich basic syenites have a higher Sc content than the more highly fractionated and more leucocratic rocks. The fall off in scandium content in the W.L.L.S. rocks is seen to be fairly regular up to the unlaminated group of syenites where the content passes below the limits of detection. A plot of Sc content against SiO_2%$_0$ is given in fig. 47.

Lanthanum, yttrium and cerium. Lanthanum is just detectable at about the 150 ppm. level in the higher quartz syenites of the W.L.L.S. and in the "higher temperature" soda-granite No. 26025. Apart from this La has not been detected in the Kûngnât rocks. Cerium and yttrium were sought after but were not detected.

Aluminium and gallium. In the W.L.L.S., the aluminium at first increases as the modal percentage of feldspar rises and subsequently decreases as quartz becomes an increasingly important constituent.

It is to be expected that the gallium will be primarily associated with the aluminium bearing minerals, particularly with the feldspars. However, a subsidiary association of Ga with the ore minerals is known to occur in igneous rock suites, with the gallium substituting for Fe^{3+}.

The gallium content rises slightly throughout the W.L.L.S. syenites and is considerably higher in the late stage soda-granite suite. Throughout the series there is a steady increase in the Ga/Al ratio. A plot of the Ga/Al ratio against SiO_2 is presented for these rocks in fig. 53.

In view of the small range in the Ga and Al contents of the syenites the absolute values for these elements require accurate determination before a significant Ga/Al ratio can be quoted and for this reason it is more satisfactory here to use the intensity ratio of the spectrographic lines Ga 2944 Å and Al 2652 Å. The value of these ratios is independent of the various errors involved in the determinations of actual Al and Ga contents. The chief errors in the Ga determinations probably arise from using a working curve based only on G_1 and W_1 standards. The aluminium figures, determined separately by a volumetric method may be too high and may show a systematic error.

Sample no.	Al_2O_3 %	Ga ppm	$I.Ga_{2944}.10^3/I.Al_{2652}$
1) The south western marginal syenites.			
26473	15.2	40	30.5
2) The western lower layered series syenites.			
27654	16.4	26	27
27648	16.2	23	24
27647	16.5	21	23
26255	15.5	24	22.5
26470	15.1	24	22.5
26005	14.2	22	22
26004	12.8	19	22
3) Soda-granite suite associated with the W.L.L.S.			
26498	10.5	56	53
26272	12.4	44	53
26025	12.2	34	35.5
4) The western upper layered series.			
27683	15.8	37	30
26231	17.4	32	31
27699	(11.9)	30	27
27700	15.8	22	26
27677	15.2	19	27
26094	17.0	25	21
27692	15.8	17	22
5) The eastern syenites.			
27696 A	13.5	16	15.5
27324 A	16.1	20	21.5
26042	16.8	23	21

GOLDSCHMIDT and PETERS (1931) showed that in igneous rocks the Ga/Al ratio increased in the later differentiates. An increase in the Ga/Al ratio with increasing differentiation in the Antrim lavas and in the Skærgaard rocks is commented on by SHAW (1957). SHAW points out that since Ga^{3+} is a slightly larger ion than Al^{3+}, Goldschmidt's camouflage principle would suggest that the Ga content of aluminous minerals might increase during differentiation, and furthermore that an increase in the Ga^{3+}/Fe^{3+} is also to be expected. RINGWOOD (1955) considered that the Ga might be present in igneous magmas as GaO_4^{5-} and that the relative enrichment in later magma residuals was the result of this complex ion being slightly larger than the corresponding aluminate ion, AlO_4^{5-}.

Fig. 45 relates the Ga/Al and Rb/K values for the Kûngnât rocks. Since there was a concomitant increase in both these ratios during the fractionation of the syenite magmas this curve could be used to define the stage in differentiation reached by a particular rock type in the complex. In this respect it would be more useful than a plot relating Fe″/Mg″ to Ca/Na.

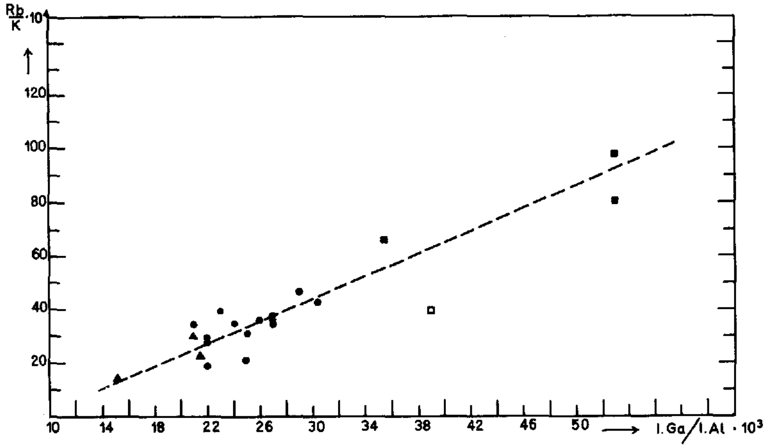

Fig. 45. Rb/K ratios for Kûngnât syenites and granites plotted against the ratio of the spectrographic line intensities, I.Ga 2944/I.Al 2652, showing the tendency for both to increase with increasing fractionation, from eastern syenites to the soda-granite differentiates of the W.L.L.S. ▲ Eastern syenites. ● Western layered syenites. □ south-western marginal syenite. ■ Soda-granite-suite.

The I.Ga/I.Al ratios are comparatively low in the three syenites analysed from the eastern centre, having values of 15·5, 21·5 and 21. Out of the eighteen varied syenites and granites from the western part of Kûngnât only one had a ratio as low as 21. Relative impoverishment in Ga may well have been characteristic of the eastern syenite magma.

Titanium. Titanium shows a moderately steady upward decline through the western lower layered series, its early removal being mainly attributable to the early crystallization of ilmenomagnetite and, to a lesser extent, of titaniferous pyroxene. In the basic syenites at the base of the series the lepidomelanes are undoubtedly strongly enriched in this element. The titanium remaining in the latest magma residuum which formed the soda-granite suite was most likely distributed between the riebeckites, aegirines and astrophyllites. Riebeckites and aegirine commonly contain substantial Ti (e.g. 1.83 % TiO_2 in riebeckite from Pike's Peak Colorado (LACROIX 1889) and 0.77 % in aegirine from Nigerian granites (BEER 1952); astrophyllite is quoted by WINCHELL (1951) as normally Ti bearing.

In the western upper layered series there is an overall improverishment in Ti compared to the lower series, with an average value of 0.18 % TiO_2. However, the eastern syenites are believed to be generally high in their titanium content. The highest content recorded for the Kûngnât syenites was 1.58 % TiO_2 in No. 27696A, thought to be representative of the more basic eastern syenites.

Zirconium. The zirconium content, moderately high (700—800 ppm.) in the lowest rocks of the W.L.L.S., falls off to ca. 130 ppm. in the lower laminated group and then increases to values of over 1000 ppm. in the unlaminated group. There is marked Zr enrichment in the late soda-granite suite. The value of ca. 7000 ppm. given for the aegirine-riebeckite microgranite No. 36498 is only semi-quantitative since it was determined using a highly extrapolated working-curve which was based only on G_1 and W_1 standards with their much lower Zr contents.

The relatively high Zr content of the lowest W.L.L.S. rocks may be due to the greater concentration of pyroxene, ore and apatite in these rocks. WAGER and MITCHELL (1951) showed that Zr is a significant trace constituent in the more basic pyroxenes and suggest that in the Skærgaard the Zr partially replaces the Ca in early pyroxene and apatite. DEGENHARDT (1957) comments that practically all rock forming minerals contain small quantities of Zr and that whilst pyroxenes and amphiboles are preferred hosts, Zr may also be concentrated in magnetite, ilmenite, and apatite. The high zirconium content of the upper W.L.L.S. rocks is reflected in the abundance of small zircon crystals in these syenites. In the residual liquids that produced the soda-granite suite the Zr was possibly present as ZrO_4^{4-} or even as ZrO_6^{2-}, as suggested by RINGWOOD (1955 p. 251). RINGWOOD supposes that because of the large size of these complex ions they accumulate in the final magmatic residues.

In the Zr-rich 'grey-dykes' this element is presumably distributed between the aegirines and riebeckites and, to a lesser extent the astrophyllites and small zircons. DEGENHARDT records up to 0.5 % Zr in aegirines and comparable concentrations are common in riebeckites.

Zirconium values for the W.U.L.S. syenites are conspicuously lower than those for the lower series, but there is a slight tendency towards enrichment in the latest rocks.

The eastern syenites also appear to be generally low in Zr.

1) The south western marginal syenite.

Rock no.	Zr ppm.
26473	555

2) The syenites of the lower and upper western layered series.

W.L.L.S.		W.U.L.S.	
Rock no.	Zr ppm.	Rock no.	Zr ppm.
27654	1800	27683	210
27648	2100	26231	180
27647	680	27699	130
26255	130	27700	190
26470	220	27677	145
26005	780	26094	120
26004	680	27692	80

3) The soda-granite suite at the W.L.L.S.

26498	(7000)
26272	1600
26025	2100

4) The eastern syenites.

27696 A	230
27324 A	99
26042	52

Tin and lead. These two elements were not found above the detection limits in the Kûngnât rocks. Lead was determined, however, in the feldspars from some of the syenites (see p. 113).

Niobium. Niobium was determined colourimetrically in the riebeckite granite No. 26272, where the content was 275 ppm. This value is probably high in comparison with the Nb values of the syenites.

Iron, magnesium and manganese. In the W.L.L.S. all three elements show a decrease up through the sequence on account of their subtraction from the magma in early olivines, ores and pyroxenes.

The lowest FeO/MgO values for the syenites are those of W.L.L.S. lower banded group rocks and in the basic eastern syenites. In general however, the ratio of FeO to MgO is a poor indication of increasing differentiation in the syenites.

Wager and Mitchell (1951) showed that the tendencies for Mn″ and Fe″ to enter crystal lattices are about equal and the absence of any fractionation of Mn″ relative to Fe″, in the Kûngnât syenite magmas was therefore to be anticipated. However, the rate of removal of Mn″ from the melt, relative to Fe″, appears to have been greater in the W.U.L.S. than it was in the W.L.L.S., and in both cases the rate appears to have been greater than that shown during the formation of the Skærgaard layered sequence. Plots of the MnO and FeO contents for the

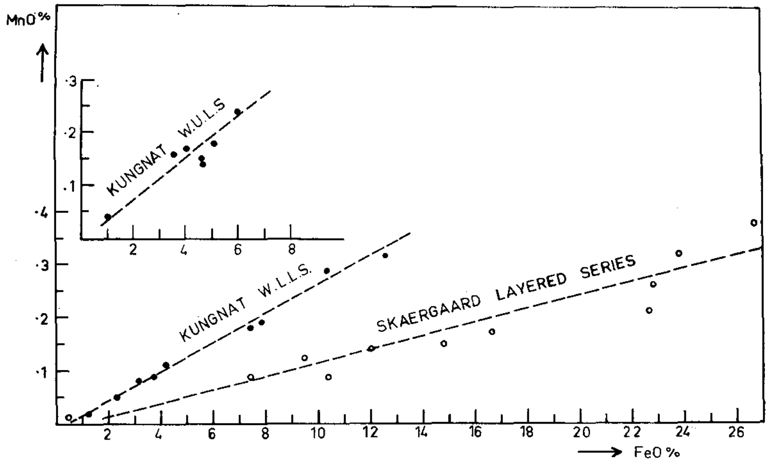

Fig. 46. Diagram showing the relationship at FeO and MnO values in the layered rocks at western Kûngnât and Skærgaard.

layered rocks of western Kûngnât and the Skærgaard are presented in fig. 46. The slope of the MnO-FeO curve for the eastern syenites is approximately coincident with that of the W.L.L.S.

Cobalt, nickel and copper. In the W.L.L.S. nickel had already been extensively removed from solution by the time of deposition of the lower banded group. The lowest exposed rocks, with their relatively high content of olivine, pyroxene and ore, contain only ca. 5 ppm. of Ni. Cobalt, removed from the melt at a slower rate, remains detectable up into the lower unlaminated group syenites.

Subtraction of copper was slower still and this element is present in detectable amounts throughout the series. A graph showing the lowering copper content as the SiO_2 content of the syenites increased is given in fig. 47.

The principal host minerals for Cu in the syenites are probably the sulphides and the early ferromagnesian minerals. In the W.U.L.S. Co and Ni are both below the detection limits and the Cu content remains at around the 3 ppm. level. Surprisingly, nickel was barely detectable in the more basic variety of the eastern syenites, No. 27696, although ca. 8 ppm. of cobalt was present.

Phosphorus and fluorine. The behaviour of phosphorus and fluorine in the W.L.L.S. has been briefly discussed on p. 74. Fluorapatite precipitation was undoubtedly the primary cause of F and P depletion in the later syenites of this series. In the soda-granite suite there is some tendency to fluorine enrichment.

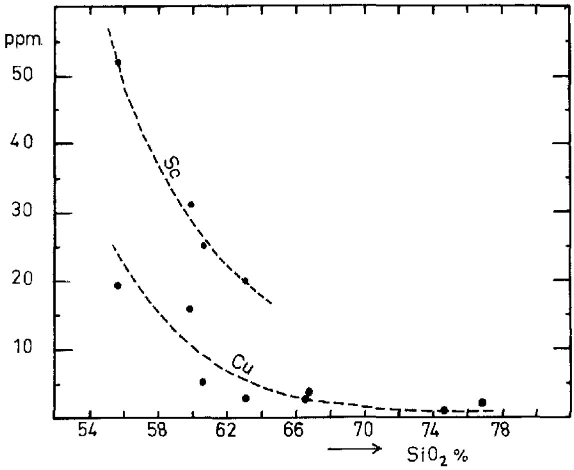

Fig. 47. Scandium and copper contents of the W.L.L.S rocks plotted against SiO_2 content.

Fluorine is present in small amount throughout the W.U.L.S. showing an irregular upward decline and passing below the limits of detection (ca. 100 ppm.) in the highest rocks preserved. F and P appear to have also been progressively removed from the eastern syenite magma as differentiation proceeded. These results contrast with those obtained by Barth and Bruun (1945) for the igneous rocks of the Oslo region, where they demonstrated a very even distribution of fluorine through the various rock types and showed that there was no obvious relationship between phosphorus and fluorine.

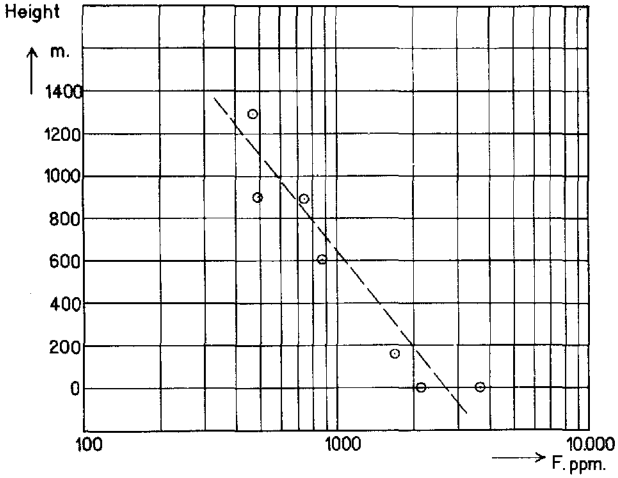

Fig. 48. Plot of F. content against height in the W.L.L.S. syenites. Zero level on the height scale is taken as the level of the lowest exposed rocks.

2. The Ring-dyke suite.

In the two altered amphibolitised gabbros, Nos. 26277 and 26169, lithium and rubidium contents are higher than in any of the other ring-dyke rocks. There is strong field evidence that the alteration was due to hydrothermal activity from syenitic feldspathic veins and from the late granitic bodies. The enrichment in Li and Rb was almost certainly the result of metasomatic processes. There is, however, no evidence for any complimentary passage of Na or K. The water content of these rocks is conspicuously high whereas the fluorine content is not abnormal.

In the more alkalic representative of the suite, specimen No. 26152, the high Ba value may indicate that differentiation of the ring-dyke caused Ba to be concentrated in the residual magma.

The small body of ferrodiorite associated with the ring-dyke is thought to have cooled from a late magma fraction extremely rich in Fe, Ti, P and F. Among its trace elements the Cu content is notably high. In this rock the Ga/Al ratio is surprisingly high (I.Ga/I.Al, 40.5) although the Rb/K value is relatively low. This may be an instance of Ga following Ti^{4+}, the possibility of which was suggested by Sandell (1949). Niobium was determined (colourimetrically) in this rock as 460 ppm. This element is probably primarily associated with the titanium.

XIV. SPECTOGRAPHIC ANALYSES OF KÛNGNÂT FELDSPARS

The total feldspar was extracted from thirteen rocks by means of bromoform flotation and magnetic separation. In two cases, feldspars from 26231 and 27648, quartz is a minor contaminant and in the feldspar from 26498, minute intergrown crystals of aegirine and quartz constitute a serious contamination.

Na and K were determined flame photometrically: Ca, Sr, Ba, Li, Rb, Cs, Ga, Cu, Ag, Pb and Tl were determined spectrographically. The spectrographic proceedure followed was essentially the same as that used by Taylor and Heier in their investigations of trace elements in some alkali feldspars from Norway (Taylor and Heier, 1958, and Heier and Taylor 1959). The composition of the bulk feldspars was calculated from Na, K, Ca and in some cases Ba determinations, assuming the feldspars to possess nearly ideal formulae. For the twelve feldspars, excluding that from 26498, the summation of the calculated Or, Ab, An, and Cn percentages fell between 96.1 and 101.5 %. (The Sr feldspar percentage, where significant, was added to the An percentage).

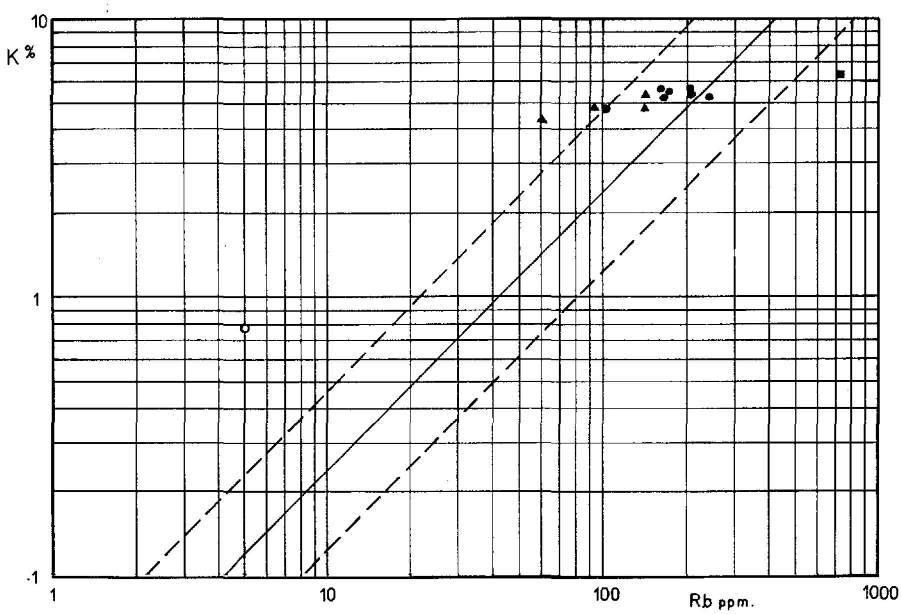

Fig. 49. Potassium-rubidium diagram for Kûngnât feldspars, showing the trend from Rb deficiency to Rb enrichment. ■ Late stage soda-granites. ● western layered syenites. ▲ eastern syenites. ○ Gabbro suite.

Of these, half fell between 99—101.5 % and of the remaining six, three fell between 98—99 %, two between 97—98 % and one at 96.1 %. The fact that the summation for eight of the twelve fell between 96 and 100 % suggests minor contamination of the feldspar samples. The weight percentage of Ab remains approximately constant at ca. 56 % in the perthites, antiperthites and cryptoperthites from the syenites. These plot on the Ab-An-Or diagram in the field which WINCHELL describes as being stable at high but unstable at low temperatures (WINCHELL 1951, p. 264).

The feldspar from the olivine gabbro No. 26040 is zoned plagioclase with interstitial alkali feldspar. The two late stage (low temperature) feldspars, namely a glassy clear moonstone, No. 26237, from the eastern syenite pegmatite belt and the feldspar from a late sodic dyke in the western centre, No. 26498, are both relatively potassic and fall into the K-rich field of the Ab-An-Or diagram. It would seem that whilst the ferromagnesian minerals at Kûngnât showed progressive sodium enrichment with fractionation, the feldspars became increasingly potash-rich.

Lithium, rubidium and caesium. The lithium content of the feldspars rises with increasing fractionation of the magmas, being low in the gabbro plagioclase, remaining low in the eastern syenite feldspars and then showing an increase in the W.L.L.S. reaching ca. 10 ppm. in the higher rocks of the series. The content falls to ca. 3—4 ppm. in the feldspars from the W.U.L.S. An excessively high Li figure recorded for the feldspar from 26498 was without doubt a result of the aegirine contamination. According to AHRENS and LIEBENBERG (1945) concentrations of over 5 ppm. Li are rare in feldspars.

Fig. 49 shows the relationship of rubidium to potassium in the feldspars and is included for the sake of comparison with fig. 44.

Fractionation brought about an increase in the absolute content of rubidium in the feldspars from ca. 60 ppm. in the eastern syenite to ca. 700 ppm. in the feldspar concentrate from No. 26498. As in the case of Li there is a drop from the higher W.L.L.S. feldspars to those of the W.U.L.S.

In a letter to "Nature" (1958), TAYLOR and HEIER, discussing the problem of rubidium depletion in feldspars, state that the 10 % size difference between K′ (1.33 Å) and Rb′ (1.47 Å) only becomes effective on strong fractionation. They point out that feldspars abnormally low in their Rb/K values normally lie within the Ab-An rich-field of the Ab-An-Or diagram, just outside the cotectic curve. This would apply to the feldspars from the eastern syenites and to the lowest W.L.L.S. feldspars of Kûngnât. (See fig. 35 for position of the syenite feldspars on the Ab-An-Or diagram.) In a later paper, (1959), HEIER and TAYLOR showed that of all the alkali feldspars which they investigated, rubidium impoverishment was confined to those with relatively high Ca contents (over 1 %), and a rough inverse relationship was found to exist between Ca and Rb. In the three antiperthitic feldspars from Kûngnât showing the most pronounced Rb deficiency the Ca percentage was between 1 and 1.6 %. Apart from the ring-dyke plagioclase (which also has a very low Rb/K value) all of the other feldspars have a Ca content of below 0.75 %. These authors also remark that, in their Norwegian feldspars, Sr shows no correlation with Rb impoverishment whilst Ba tends to be high in those samples low in Rb. This again is also true in the case of the Kûngnât feldspars.

All the Norwegian feldspars considered were perthitic types believed to have formed through unmixing of an original homogeneous phase and not as a result of replacement phenomena. HEIER and TAYLOR suggest that "In the cases where rubidium is depleted, the system has a composition very close to the point where an independent Or-Ab rich feldspar will appear as the stable phase. Potassium is thus very abundant and may be thought as "forcing" itself into the crystal lattice, which has a restricted number of sites for large ions. Rb, present in much lower amounts and at a size disadvantage in this competition, will be excluded in favour of potassium in this somewhat unusual case." They also consider, (1958(1)), that if much barium is available this smaller divalent ion (Ba″ 1.34 Å) may occupy the high coordination sites to the exclusion of rubidium.

Caesium is only present over 1 ppm. in the feldspar from the aegrine-riebeckite-bearing microgranite dyke. In most of the feldspars Cs is below the detection limits. Caesium appears to become slightly enriched in the feldspars from the more advanced differentiates.

Calcium, barium and strontium. The Ca content declined with advancing fractionation until the An content reached the ca. 4 % level. Barium is an important constituent in the feldspars from the more basic syenites and, during fractionation of the syenite magmas, it was evidently progressively removed by incorporation in the early primary precipitate feldspars.

The anamalously high Ba content of sample No. 26470, (from low in the W.L.L.S.) reflects the high concentration in its constituent antiperthite, ca. 4500 ppm., although the reason for this sudden increase in Ba in the middle of a layered series is a matter for conjecture.

Strontium, like the barium shows a fairly regular decrease in the feldspars from successively more differentiated rocks and shows a sympathetic increase in the feldspar from 26470. Unlike the barium, the strontium reaches its maximum in the basic ring-dyke feldspars and not in those from the more basic syenites.

Lead, thallium, copper and silver. Both Pb and Tl were detectable in nearly all of the thirteen feldspars and, where these have values of less than 10 ppm., it is probable that they are entirely accommodated in the feldspar lattice in sites that would otherwise have been occupied by potassium. (Ionic radii Pb″ 1.20 Å, Tl′ 1.44 Å and K′ 1.33 Å). There is, rather surprisingly, no late stage enrichment in either element.

Ahrens (1948) drew attention to the very close association of Rb and Tl in igneous rocks and minerals; this association is due to the fact that Rb′ and Tl′ have the same ionic radii and rather similar chemistry. Fig. 50 relates the thallium and rubidium content of the Kûngnât feldspars. The crosses represent the potassic feldspars other than hydrothermal pegmatitic microclines and amazonites, which were among the 167 mineral samples used by Ahrens to establish the average slope of the Rb-Tl curve.

The highest thallium concentration found was ca. 19 ppm. in the feldspar from the olivine gabbro No. 26040 and the very high Tl/Rb ratio suggests the presence of Tl‴ rather than univalent Tl′. Shaw (1957) considers that in basic rocks Tl‴ might be camouflaged by Ca″, and regards it as uncertain whether thallium in plagioclase occurs as the trivalent or univalent ion. However, he points out that on account of the strongly reduced conditions in which most basic rocks were formed it is probable that the trivalent form would be unstable. Zlobin (1958), who studied the geochemistry of thallium in the Sandyk massif, Kirgiziya, an alkaline complex roughly comparable to Kûngnât, noted that the Tl entered the biotites in preference to the alkali feldspars. (The Tl content of the two analysed 'orthoclases' from Sandyk was 1.2 and 2.5 ppm. respectively.)

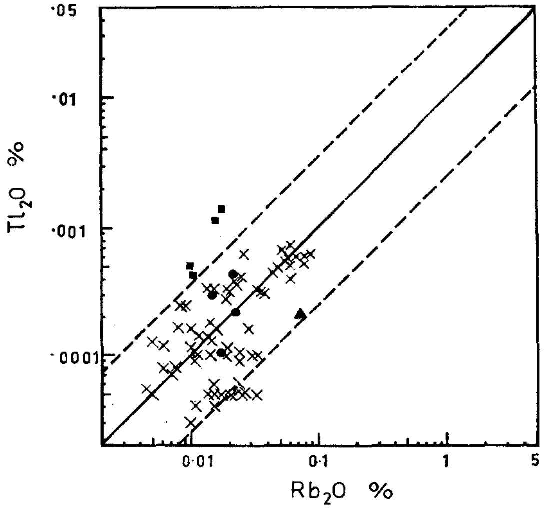

Fig. 50. Rb_2O-Tl_2O diagram. Crosses represent the potash feldspars investigated by Ahrens (1948). Dashed lines represent normal limits of scatter and continuous line is the average Tl-Rb slope as established by Ahrens.

Silver was detectable in all the samples and was determined with the aid of synthetic standards. S. R. Taylor, in a personal communication, suggests that the values of ca. 1—2 ppm. may well be due to electrode blank and should be ignored. However, in four of the samples Ag values in the 20—40 ppm. range were noted, and these coincide with unusually high Cu values, also in the 20—40 ppm. range. Furthermore, there is a tendency for thallium to increase sympathetically with the Ag and Cu although this behaviour is not shown by the lead. Taylor considers that these high Ag-Cu (and Tl) values, which occur apparently randomly in the feldspars, could be attributed to the presence of a sulphide phase, occurring as exceedingly fine inclusions. Alternatively the excess quantities of these elements may be located along minute cracks in the mineral.

XV. THE ORIGIN OF THE BANDING IN THE KÛNGNÂT SYENITES

Various mechanisms have been proposed at different times to explain layering at particular plutonic centres. Any mechanism suggested for the production of layering and banding in the two main Kûngnât syenite bodies should be able to account for such diverse features as the comparatively steep inward dips, the graded and apparently gravity controlled nature of the banding, feldspar lamination and trough-banding.

According to Brown (1956 p. 48), Yoder has suggested that the rhythmic layering of some intrusions might be explained on the basis of variation of water vapour pressure within the cooling magma over a critical range. Explanations of this kind have been given by Ussing (1912 p. 355) to account for layering in kakortokites (eudialyte-rich nepheline syenites), and by Brown in his discussion of some ultrabasic rocks on the island of Rhum. However, the Kûngnât intrusions are thought to represent closed systems with no connection to the surface and with loss of volatiles reduced to a minimum.

Wager (1959) has recently described rhythmic banding in igneous rocks from Rhum and the Bushveld which he thinks may be due to a cyclic process involving the settling of the primary precipitate minerals in a particular order; the order of settling is thought to be dependent upon the relative powers of nucleation of the minerals involved.

However, partly from the field evidence and partly from analogy with the layered sequence at Skærgaard it seems more than likely that most of the banding and lamination in the Kûngnât syenites was caused through the sorting and sifting of crystal material by relatively fast moving magmatic currents.

Evidence for convection currents. The cross-bedding and wedging out of the layers in the lower banded group of the W.L.L.S. provide a strong indication of magmatic currents. Furthermore, the feldspars of the laminated group are not so highly tabular that one may safely suppose that they would have settled with so high a degree of parallelism had they not been orientated by moving magma.

The trough-bands in both syenite centres are regarded as erosion channels carved out of the intrusion floor, comparable with the trough structures of Skærgaard. As at Skærgaard, they provide the strongest single piece of evidence for vigorous magma currents and they indicate the operation of currents which flowed radially and presumably down the slope towards the central part of the chamber floor. This would suggest a convective circulation, with down flowing cooler magma in the proximity of the walls reaching the floor and being directed towards the centre. The regular planar banding resulted from inward moving currents that were evenly disposed over the floor, whilst the trough-banding sets are the products of moving magma that became channelled into localised grooves.

Relatively hot magma rose as a column, more or less centrally, and commenced crystallization on reaching the cooler roof zones. The slightly chilled magma, now charged with growing crystals of the primary precipitate minerals descended laterally and deposited the greater part of its crystal load peripherally at the foot of the wall where its velocity was lessened. Strongly inclined layering resulted from this heavier marginal deposition of the primary precipitate. Field observation suggests that the angle of rest for this material did not normally exceed ca. 40° in the lower banded group of the W.L.L.S. and ca. 50° in the eastern layered syenites. Occasional and localised dips of up to 70° or more in the W.L.L.S. may be due to penecontemporaneous faulting.

The mafic gravity banding itself is ascribed to crystal sorting by currents of varying velocities and the thickness of the band units is a measure of the periodicity of the convection cycles. As Wager and Deer remark, convection currents are by their nature pulsatory and convection is not a smoothly cyclic process. In any one convection cycle, the down flowing magma is thought to have had, initially, a velocity sufficient to retain the feldspar and the smaller crystals of the other primary precipitate minerals in suspension, but not great enough to prevent the heavier ore, pyroxene and olivine particles from settling through and forming the mafic base of a new layer on the inclined floor. Steady deceleration of the current allowed the settling of the feldspar along with the remainder of the suspended ferromagnesian minerals. In the ensuing near quiescent conditions, a mixed assortment of primary precipitate minerals continued to accumulate before the onset of a new convective pulse heralded the formation of another band unit. This normally overlay the previous one quite conformably. There appear to have been slight deviations from this general process, but for most of the banding this explanation seems adequate.

At times during the formation of the lower banded group (W.L.L.S.) rapid pulsatory circulation developed giving perhaps one hundred or more cycles, the time interval between them corresponding to about 10—15 cm. of crystal deposit.

In spite of the complications implicit in there having been both major and minor cycles in the W.L.L.S. formation, it seems clear that there was an overall decrease in convective activity upwards from the lowest rocks exposed. By the time of the deposition of the lower laminated group, activity had decreased and the currents were only sufficient to effect the lamination of the feldspars and to maintain the marginal banking. The faint banding features with their rather diverse low angle dips, that occur over the Nisseborg west face suggest that in the northern part of the western magma chamber turbulence, probably the result of convection, continued much later than in the main central and southern part where the gneiss raft was having a profound effect on the cooling history.


J. Cooke

Fig. 51. Block of laminated feldspathic syenite from high in the western upper layered series. The thin mafic bands are composed of hedenbergitic pyroxene together with some fayalite. × $^{1}/_{3}$

The rhythmic banding which reappears in the upper layered series of the western intrusion is, more by analogy than by direct evidence, also thought to be due to sorting by convection currents. Trough-banding has not been recorded from the W.U.L.S. The lower dips of the upper layered series (10—25°) may mean that the cumulates had a lower angle of repose on account of the magma having a lowered viscosity and possibly a higher volatile content.

Some of the banding features of the W.U.L.S. are believed to have had a mode of formation rather different from that described for the generalised W.L.L.S. and eastern syenite banding. Very thin, excellently sorted, mafic bands or schlieren are common in the highly laminated rocks (fig. 51). These discontinuous and rather trivial banding features are thought to have formed through the re-working of standard mixed crystal mush by magma currents which were faster than most and were capable of winnowing out the feldspar and leaving the olivines and hedenbergitic pyroxenes as miniature *remanié* beds in the sequence. The localised dense mafic lenses seen in the Røverborg-Nisseborg col are also thought to have been formed by winnowing of primary precipitate mush.

Wager and Deer (1939 p. 270) state that convection would be at its optimum in a mass of liquid having a diameter about four times its thickness. At Kûngnât, the shape of the main western chamber at the time of deposition of the lowest exposed rocks appears to have been more nearly equidimensional with a diameter of ca. 2600 m. and an estimated height of around 1600 m. Reckoning that the rocks now capping the Røverborg may have lain within ca. 200 m. of roof of the magma chamber at the time of their deposition, then the magma body which produced the upper layered series was ca. 1600 m. wide and ca. 450 m. deep when bottom accumulation began above the gneiss raft. This magma chamber then may have more nearly approached the optimum size. However it seems possible that more than one circulating system was operating in this upper chamber, the main one operating over the central Røverborg region and a second less regular system in the north, over what is now the Nisseborg area.

Thickness of unconsolidated cumulate mush. Slump structure have not been seen anywhere in the layered syenites even where the banding is steepest although slumping is a common feature in unconsolidated crystal mush on the floors of several layered intrusions. Hess (1938 p. 266) writes of crystal mush deposited on sloping surfaces in the Stillwater intrusion that appears to have been set in motion by earthquakes or increasing tilt. Brown (1956 p. 37 and fig. 34) and Carr (1954 p. 1238), writing respectively of the layered ultra-basics in Rhum and of the layered gabbros of the Isle of Skye, both describe slump structures. In spite of the relatively high dips at Kûngnât, it may be that slumping and sliding down the slopes was inhibited by either the higher viscosities of the syenite magmas tending to stabilize crystal sediment on steeper slopes than would be permissible in a basaltic melt, or by the more rapid fixation of the mush by the crystallization of interstitial liquid, or perhaps by a combination of both these factors.

Hess suggests 10′ to have been the thickness of unconsolidated mush at Stillwater, whilst Brown considers the maximum thickness in the Rhum ultrabasic mushes to have been around 4—5′. In the Kûngnât W.L.L.S. the depth to which banding has been disturbed or erased below the lowest mafic band of some small trough feature was seldom if ever more than 1 m. and this may indicate the approximate depth of unconsolidated material.

The eastern border-group. Initially the border-group must have formed a crescent shaped body, thickest in the east and with the horns directed westwards to taper out against the margins of the western syenites. The eccentric development of the border-group around the eastern layered syenites may have been the result of a temperature gradient in the rocks around the magma chamber, with the coolest zone in the east and the hottest in the west where the western layered intrusion was still cooling. A convection system may have arisen in the eastern centre, with the rising column of hotter liquid situated rather to the west of centre. Where the current in the east swept downwards beside the gneiss wall further cooling occurred. Olivines, feldspars, pyroxenes and ores were precipitated and grew as an incrustation on the cooling wall. The border-group, built up primarily of these minerals, is thought to have grown inwards as an accretion around the eastern sector of the intrusion. This mode of formation is essentially the same as that offered by Wager and Deer to explain the more perfectly developed marginal border-group of Skærgaard.

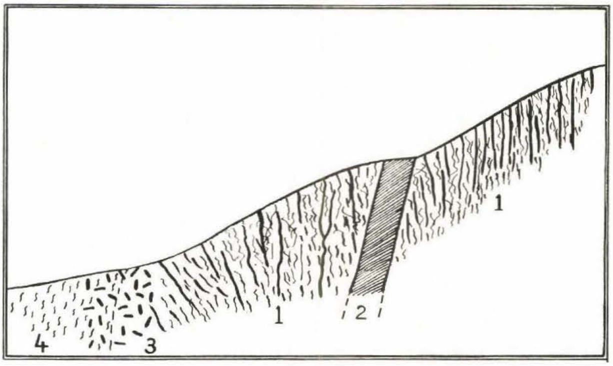

Fig. 52. Diagramatic section across the eastern border-group. 1, border-group syenites, 2, ring-dyke gabbros etc., 3, marginal pegmatites, 4, basement gneiss.

Wahl, (1946) in a re-interpretation of the syenite stock at Almunge in Sweden considers that convective circulation developed during the cooling of the intrusion. He writes "As we have seen from experiences with solid particles in gaseous or liquid mixtures in which thermodiffusion has set in, these solid particles accumulate towards the cooling wall, and this also has occurred in the pipe at Almunge, resulting in a crowding of fragments of foreign country rock along the outer cold walls of the pipe, —". In the Kûngnât eastern syenite stock, it was early crystals rather than xenoliths that accumulated against the cooling wall.

The mafic bands present are to be compared with the "fluxion structures" of the marginal Skærgaard rocks rather than to those formed in more gently dipping floor cumulates, and it is less easy to explain their formation. These bands are consistently found at attitudes only ten degrees or so off the vertical and any suggestion that subsequent tilting has been responsible for their present steepness can be discounted since there is no reason for thinking that there has been any substantial post-intrusive or even penecontemporaneous movements. The form of any of the mafic bands gives local detailed information of the shape of the chamber wall at the time of its deposition. It appears that the temporary cooling wall was at most times intricately scalloped and fluted by the down-flowing melt. A similar occurrence has been described from the Vermilion batholith of Minnesota where the early (syenitic), border phases possess almost vertical banded differentiates. Grout interpreted these as having been formed by a gentle convective circulation flowing past the cooling walls. (Grout F. F. 1925. The Vermilion batholith of Minnesota. Journ. Geol. v. 33 no. 5. 467—487).

XVI. DIFFERENTIATION AND POSSIBLE CONDITIONS WITHIN THE MAGMA CHAMBERS

Partition of the western syenite magma chamber.

The lower and upper layered series represent superimposed piles of stratified rock in which the differentiation trend has been similar.

At a time roughly corresponding to the deposition of the higher rocks of the lower laminated group, a massive roof subsidence occurred with the breaking away of a great raft-like mass of gneiss and, although accompanied by a host of lesser blocks, this raft tended to sink as a single unit. The subsiding gneiss failed to sink to the floor of the magma chamber but apparently remained suspended some 700 m. above it, after having sunk through at least 300 m. of magma. This mass of gneiss which now forms the grey-zone across the Røverborg face thus effectually subdivided the primary western magma chamber into upper and lower secondary magma chambers. The division of the primary magma chamber into two occurred at a time when the magma had already been strongly depleted in early fractionating elements such as Mg, Fe, Ti, Ca, Ba, Sr, Cu, Ni, Sc, F and P. It is the overall impoverishment of the upper layered series in these elements compared with the lower members of the W.L.L.S. that leads to the conclusion that the W.U.L.S. was produced by some of the residual magma left after the formation of the lower laminated group syenites and that it was not due to a separate intrusion of magma. The idea of the W.U.L.S. resulting from the cooling of a second and separate magma pulse of sufficiently strongly fractionated liquid involves too much coincidence and furthermore it would require that some sort of feeder-pipe be postulated. If the grey-zone gneisses had subsided to the full they would merely have provided a temporary interruption in an otherwise continuous layered sequence which would have extended from the lower banded group up to the highest Røverborg rocks. This sequence should have shown a continuous and steady upward increase in SiO_2, Ga/Al, Rb/K etc. and a regular fall off in the content of Mg, Fe, Ca etc. Had this been the case there would have been no reason for Si, Zr, Ga, Rb etc. to become concentrated below the gneiss mass, as in fact they were. As it was, with the suspension of the gneiss raft, the story became complicated. Superimposed on the primary differentiation of the main western syenite magma are the secondary effects of differentiation proceeding independently and simultaneously in each of the two isolated magma portions.

A possible explanation of the failure of the gneiss mass to settle completely is that it encountered a level in the magma at which the density was sufficiently great to arrest further sinking. The field evidence is strongly suggestive that convective circulation was nearly ended at the time of the subsidence i.e. at about the time when the higher levels of the lower laminated group were deposited. There may well have been a density gradient in the magma chamber at this time with relatively dense lower parts overlain by lighter, volatile-rich, upper levels. A volatile enrichment of the upper part of the magma could have been brought about through the upward diffusion of volatiles to levels under a lower confining pressure.

The upper layered series does appear to have formed from a magma that was relatively rich in volatiles compared with most of the W.L.L.S. For example the Fe_2O_3/FeO values tend to be higher in the U.L.S. than in the L.L.S. G. C. Kennedy (1955 p. 496) states that whilst the water content of a melt cannot be calculated from the iron oxide ratios unless the partial pressure H_2 and the requisite equilibrium constants are known, there is nevertheless a relationship between the H_2O content and the value of this ratio. Interstitial carbonate is also more widely present in the W.U.L.S. than in the W.L.L.S. suggesting a higher CO_2 concentration in the higher magma. However, volatiles would in any case be concentrated in residual magma portions through normal crystal fractionation processes.

Since the addition of volatiles of low molecular weight will tend to lower the density of magma, the effect of diffusion towards the cooler and lower pressure roofing zones will be to oppose, and may even reverse, the density gradient due to temperature differences. If, as may well have happened at this juncture in west Kûngnât, such a reverse density gradient was established, with lighter magma close to the roof becoming denser downwards, a convecting system would not be restarted.

The state of near thermal equilibrium following the decline of convection in the primary magma chamber was upset by the foundering of the gneiss raft, possibly because of higher parts of the magma coming into contact with the cooler gneisses of the newly raised 'ceiling'. This gave rise to the new period of convective circulation which was responsible for the sorting and lamination of the U.L.S. There was, naturally, no such revival of the temperature gradient in the magma below the raft and this lower subsidiary magma chamber remained, in contrast to the upper one, in a state of relative tranquillity.

The density of the syenite magmas, throughout most of their cooling histories, could scarcely have been substantially higher than 2.5, inasmuch as the lightest of the primary precipitate minerals was alkali feldspar whose s.g. at room temperature is approximately 2.6.

Differentiation in the two subsidiary magma chambers.

The two separate portions of residual magma differentiated along slightly divergent lines to produce differering end products. Unfortunately the ultimate products of the upper magma body are not preserved but it is likely that the Røverborg top rocks represent the penultimate products formed when perhaps 95 $^0/_0$ or so of the upper magma had already crystallized.

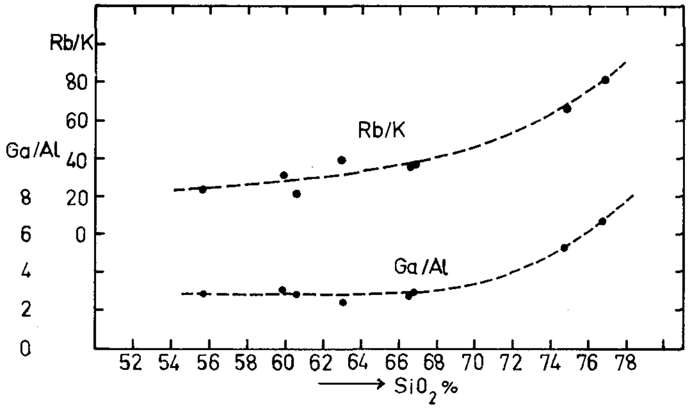

Fig. 53. Diagram showing increase of Ga/Al and Rb/K ratios with increase in silica content of the W.L.L.S. rocks (including the acid differentiates).

Differentiation in each of the two subsidiary magma chambers involved continuation of the primary trends i.e. toward silica enrichment and an increase of Zr, Rb, Cs and also of Na/K and Ga/Al etc.

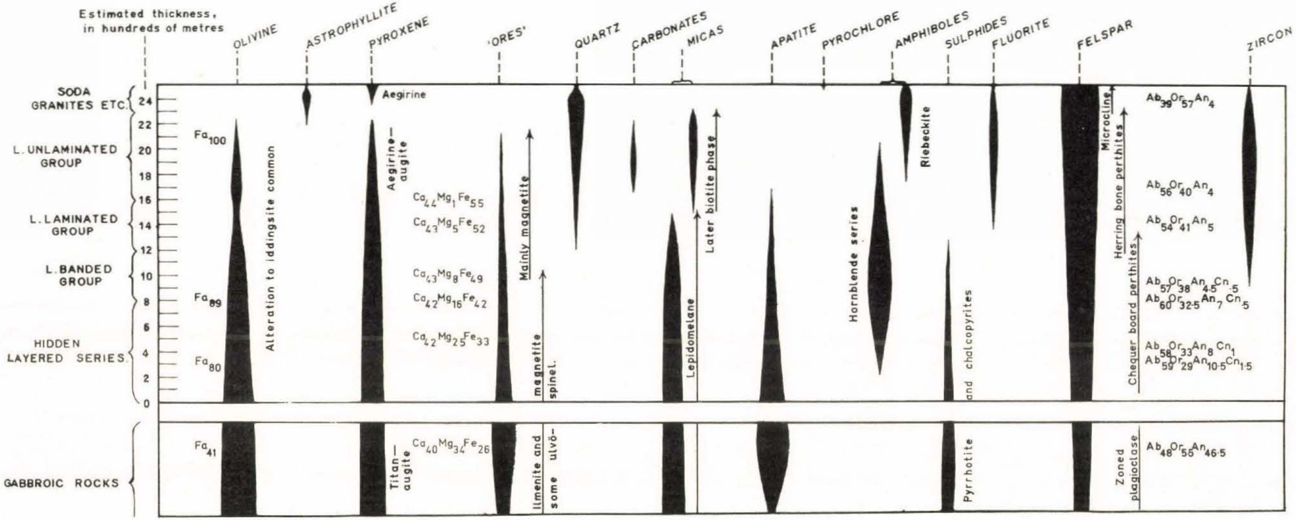

Fig. 54. The mineral variation in the syenites and granites of the western lower layered series shown schematically. The assumptions are made that a) the lower banded group is underlain by syenites mineralogically similar to the more basic eastern varieties. (A thickness of at least 800 m. is suggested for this hidden layered series), and b) that the late stage acid intrusives are equivalent to perhaps 200 m. of layered rock overlying the syenites. The mineral content of the ring-dyke gabbros is included for comparison. It is not suggested that the syenite-granite series is a direct fractionation derivative of the gabbros.

In both sequences iron-rich olivines give way, through Na-Fe-rich hornblende and hastingsite to riebeckite. This change is probably causally connected with an increase in the partial pressure of water in the residual liquids. However the latest riebeckite (and finally aegirine)-bearing products of the L.L.S. are not seen *in situ* as the uppermost members of the succession but are dispersed as a multitude of minor intrusives throughout the underlying and surrounding rocks. Hence the late soda-granite suite is analogous to the transgressive granophyres of Skærgaard and to the granitic veinlets of many differentiated sills. The dispersal and injection may have been due to a filter-press mechanism.

In considering the mineralogical and chemical changes seen in the lower layered series it is convenient to imagine the late granite fractionates as having settled more or less *in situ* to form the uppermost layers and not to have been filter-pressed and dispersed. The soda-hornblende granites (e.g. No. 26025) will be considered as overlying the highest unlaminated group quartz syenites and to be succeeded by the albite-microcline-riebeckite granites. The thin aegirine-bearing 'grey-dykes' will be regarded as if they occurred as the topmost stratum.

The mineral variation in this reconstructed sequence is indicated schematically in fig. 54. Although they are treated here as if they were solely the result of fractional crystallization of the syenite magma, the possibility of some gneiss assimilation in the genesis of the soda-granite suite cannot be entirely ruled out.

The transition from fayalite-bearing rocks to types containing Na-hornblende, riebeckite and aegirine.

The association of riebeckite-bearing rocks with fayalite-hedenbergite syenites and granites is a common occurrence in many igneous provinces. Among the factors that must control the appearance or non-appearance of riebeckite are temperature, partial pressures of oxygen and water vapour, and the compositional changes in the magma other than those involving oxygen and water. The Po_2 will be, to a large extent, dependent upon P_{H_2O} and the latter is thought to have increased more or less steadily with falling temperature and as anhydrous mineral phases settled out from the melt. There is a tendency for the later rocks of both sequences to possess high Fe_2O_3/FeO ratios. Recently W. G Ernst (1957 p. 228) presented stability diagrams for magnesian riebeckites for varying conditions of temperature and pressure. He employed various buffers to maintain a constant P_{O_2} in each particular case, but showed that no matter what buffer was used the form of the stability diagram remained similar.

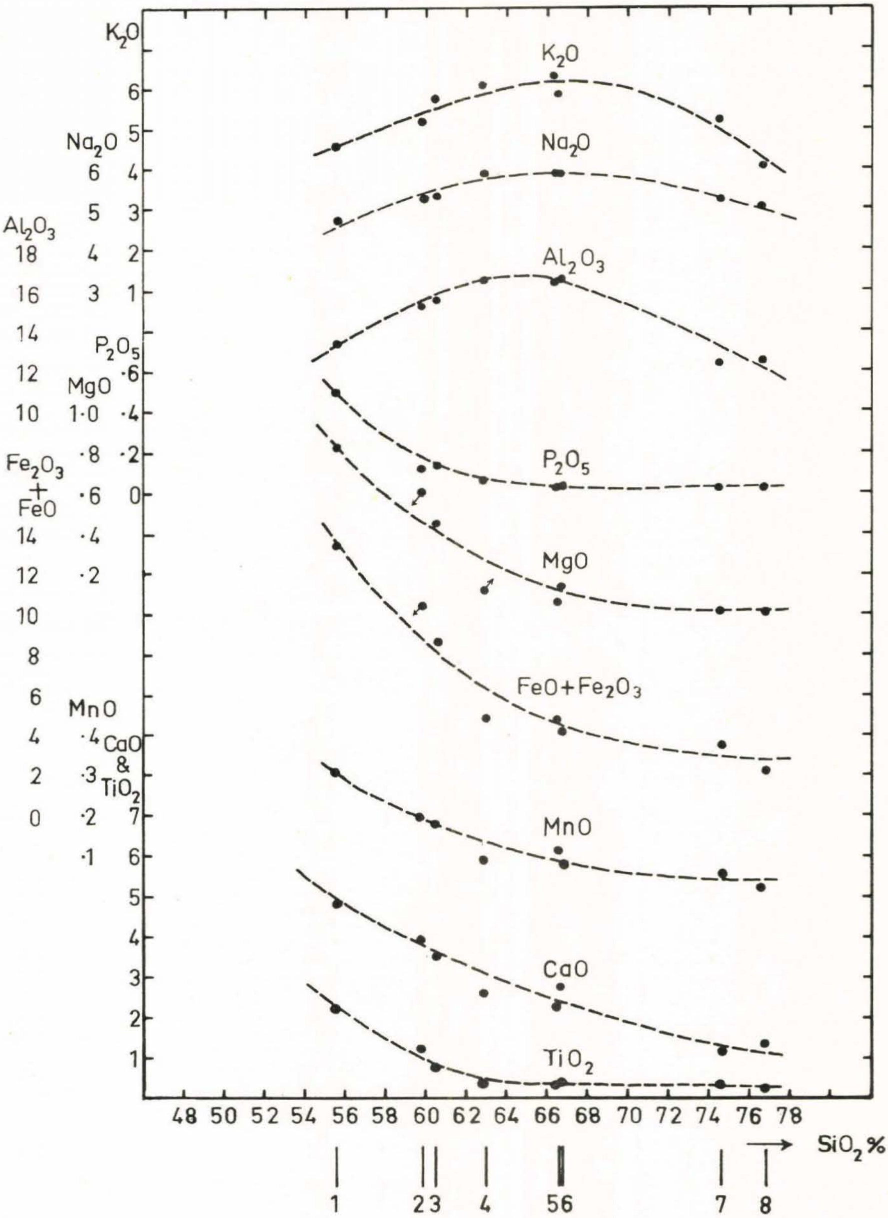

Fig. 55. A Harker variation diagram for the western lower layered series rocks including the soda-granite differentiates. 1. Mean value of analyses No. 26004 and 26005 (same horizon); 2. No. 26470; 3. No. 26255; 4. No. 27647; 5. No. 27648; 6. No. 27654; 7. No. 26025; 8. No. 26272.

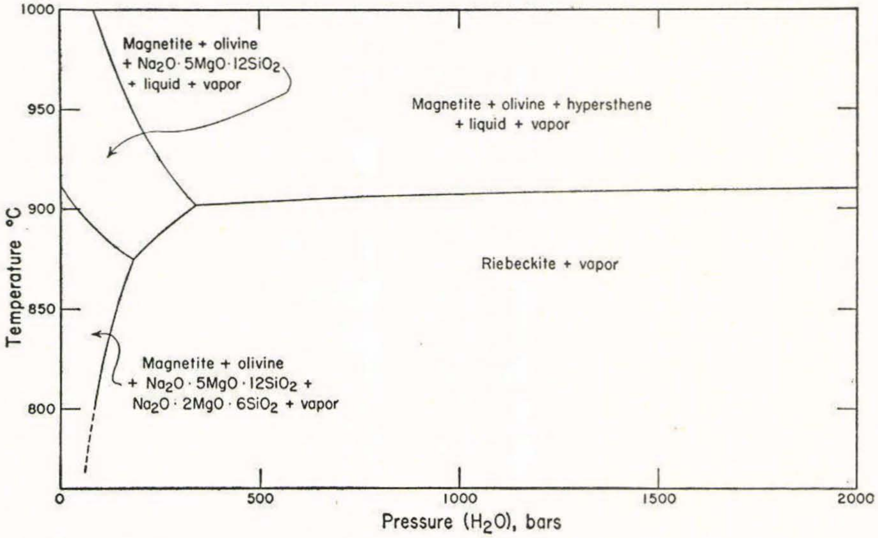

Fig. 56. Stability diagram for magnesian riebeckite using a magnetite fayalite-quartz buffer, reproduced from Ernst 1957.

The high temperature stability limit for riebeckite varies with the P_{O_2} but, under the conditions set by Ernst, i.e. above partial pressures of water vapour of ca. 500 bars, the limit for Mg-riebeckite lies at about 900°C. Below 500 bars water vapour pressure, the high temperature stability limit falls off rapidly but above this pressure further rises in the P_{H_2O} result in only very slight temperature elevation of this limit, and hence only minor enlargement at the Mg-riebeckite field.

Ernst's preliminary investigations with a ferrous riebeckite suggest that the high temperature stability limit lies some 250° lower than for the Mg analogue (Ernst, personal communication 1959). At pressures of ca. 2000 bars vapour pressure (and at a suitable P_{O_2}) ferrous riebeckite breaks down in the neighbourhood of 600°C to acmite, fayalite, magnetite, quartz and vapour. At higher temperatures (ca. 760°C), the acmite melts incongruently and the high temperature assemblage becomes Fa + Q + Mt. + liquid + vapour (Ernst, unpublished data).

It is thought that the riebeckitic amphiboles closely associated with fayalite in some of the quartz syenites of the W.L.L.S. and south western marginal syenites are reaction products partly formed at the expense of the olivine. In these syenites, fayalite and a little magnetite crystallized as early phases, along with an iron-rich clinopyroxene. In the granites there is no evidence of the riebeckite being secondary after fayalite or any other mineral and in some it would appear that the riebeckite precipitated directly from the melt as well-formed crystals. In these granites relicts of fayalite are absent and primary magnetite is not found.

Assuming that a) there are all gradations to be found in the main western intrusion from quartz fayalite syenites to riebeckite granites, and b) that the passage from one to the other involved increase of P_{O_2} and P_{H_2O} in the differentiating magma, then a possible explanation of the mineralogical change may be attempted. On cooling, the less water-rich and less oxidised syenitic melts may have passed through a field in which fayalite and magnetite (together with pyroxene) were in equilibrium with the siliceous melt and that, on crossing the boundary curve of the riebeckite field with further fall in temperature, fayalite became unstable and commenced reaction with the melt. In the case of the quartz syenites this reaction did not normally go to completion. Thus, in the case of the more syenitic rocks, the olivine and clinopyroxene gave rise to different amphibole species by reaction as the interstitial melt around them continued fractionation and became increasingly more oxidised and water-rich. As this process continued with falling temperature, a stage may have been reached when the stability field for clinopyroxene, olivine and magnetite was bypassed and beyond which these minerals were replaced by a single phase Na-Fe-amphibole that crystallized directly from the melt. In the W.L.L.S. probably the soda-hornblende granites, containing lamellar perthite, were an intermediate stage between the quartz syenites and the true riebeckite granites.

In a further personal communication Ernst writes that ferrous riebeckite may appear in equilibrium with a granitic melt under P_{O_2} conditions permitting the existence of fayalite at partial pressures of water vapour in excess of ca. 2500 bars. In the striped micrograntes and 'grey-dykes', believed to represent the last products of the differentiating W.L.L.S. liquid, a pyroxene phase reappears. The aegirine in these rocks probably crystallized from low temperature hydroxyl-rich melts which were strongly oxidised and which had a high sodium content. Yagi (1953) described a similar process, believed to have operated in the alkali rocks of Sakhalin, where arfvedsonite became unstable when the residual magma became soda-rich and gave way to ægirine in spite of the presence of abundant water.

Heterogeneity of the eastern border group syenites.

Although distinct and well formed mafic bands are to be found in the border group at some places, much of the mafic material is distributed in a patchy and irregular fashion or forms poorly defined straggly and bifurcating bands. It seems as if the border group had grown in from the cooler gneisses as a skeletal or spongy growth composed of the finer mafic material and with the occluded spaces containing residual magma enriched in silica, alkalis, carbon dioxide, water and zirconium.

Hence the border group in its early stages may have been analogous to a crystal mush on the floor of a layered intrusion except that it presumably had a certain rigidity and the quantity of interstitial liquid was very greatly in excess of the 'primary precipitate'.

In the early formed finer grained and more mafic rock, where there was fairly close packing and early consolidation, the constituent minerals were to a large extent secured from late magmatic corrosion. Although the ores suffered some reaction with the hydroxyl enriched melt to yield biotite, the pyroxenes mostly show no reaction rims of hornblende. The inference is that here the biotite formation commenced earlier and at a higher temperature than the reaction of pyroxene to hornblende, possibly because biotite formation required a lower partial pressure of water vapour.

Enlargement of the feldspars was prohibited beyond a packing size of ca. 1—2 mm., and possibly because of the limited availability of water and other volatiles, exsolution did not proceed far and the feldspars remained cryptoperthitic. There was, however, no inhibition of unmixing in the ores nor in the augitic pyroxenes where sagenitic rods were formed.

In the coarser feldspathic syenites formed from the trapped magma, feldspar unmixing was much more complete and the feldspars were able to grow larger. Olivines are more altered to iddingsite, the pyroxenes possess more pronounced zoning and reaction to hornblende is often complete. Quartz, carbonate and zircon are common accessories. With increasing vapour pressure in the final cooling stages, small druses appeared containing feldspar, quartz, hornblende, siderite and zircon.

Formation of the pegmatite belt.

The peripheral belt of pegmatite which is irregularly developed around the eastern centre may have been caused by the outward migration of water, carbon dioxide, silica and alkalis from the cooling syenite body. From the abundantly drusy nature of the eastern Kûngnât pegmatites it is evident that the vapour pressure eventually exceeded the confining pressure. WAHL (1946), in a paper on thermal diffusion in magmas, considered in some detail the experimental evidence for the migration of sodium alumino-silicates towards the cooler marginal areas in a rock melt, and gives instances of syenite complexes in which he supposes such a process to have occurred.

An argument used by G. C. KENNEDY (1948) is applicable to this problem. He assumes that at a given height in a magma chamber the pressure is constant and that the margins are cooler than the centre. Water in the melt (in this case particularly in the interstitial melt contained within the border group), will migrate by diffusion to make its free energy equal at every point. This will demand that its partial pressure be constant throughout although the partial pressure of water will, initially, be greater in the hotter parts than near the cooler margins. If diffusion equilibrium is realised and the partial pressures equalized throughout, then there will be a higher concentration of H_2O in the cooler parts. At constant pressure gas is more soluble in cooler than in hot liquid and, if equilibrium conditions held, one would expect a higher marginal concentration of volatiles. (For his theoretical magma, KENNEDY assumes one can apply Goranson's results for Ab-water systems, in particular that the solubility of H_2O will increase by 0.5 $^0/_0$ for each 100° temperature fall.) KENNEDY points out that, owing to the temperature gradient across the contact, 'steady state' rather than equilibrium conditions would occur. He remarks that two effects would follow; i) that the wetter marginal parts would possess a lower freezing point than the drier central parts, since increase of vapour pressure tends to lower the melting point. ii) that outward diffusing water will tend to be accompanied by other volatiles. Discussing the work of MOREY (MOREY and HESSELGESSER 1952) on the water solubility of alkali silicates, KENNEDY refers to the unique feature of these silicates, compared to other common rock forming silicates, of their extreme solubility in super-heated water vapour at high pressure. Under a pressure of 2220 bars, over 40 $^0/_0$ by weight of alkali silicate can be held in solution at 400°C whereas the solubility of the corresponding alkali alumino-silicate under the same conditions is almost negligible. Migration of water should concentrate alkalis into the wetter parts where they would be fixed by precipitation as alkali feldspar. In the east Kûngnât marginal pegmatites, the silica might also have been concentrated by a similar process. The situation may have been comparable to that in the later cooling stages of the Blashke island ultra-basic complex, where M. S. WALTON (1951) thought that perhaps the liquid phase disappeared, leaving only a super-critical gas phase which permeated the intergranular spaces and which permitted a relatively rapid outward migration to occur.

In spite of the stress laid upon water in the foregoing paragraphs, it is possible that, in this instance, the principal carrier was some other volatile material, possibly CO_2. This is suggested by several factors. In the first place, carbonates are an important constituent of the pegmatites. Secondly, the large feldspars are orthoclase-cryptoperthites and not the coarsely exsolved perthites which would have been expected had the water content in the surrounding liquid been high. Possibly CO_2 is less efficaceous in promoting unmixing. A relatively low water content in the Kûngnât syenite magmas during the greater part of the primary crystallization period seems a reasonable inference. TUTTLE and BOWEN

(1958 p. 93) suggested that since most perthite-quartz granites carry amphibole as the principal dark mineral, a likely explanation of the lack of extensive unmixing in the alkali feldspars is that the water content of the magma was low. This, however, involved the assumption that such amphiboles would be unstable in the presence of a high or even moderate water vapour pressure, an assumption which may not be always justifiable. Nevertheless, in the Kûngnât syenites the ratio of anhydrous ferromagnesian minerals to hydrous phases is unusually high and, since the eastern syenites are thought to have crystallized from a magma portion poorer in water than the western syenite magma, it is not surprising that even the residual rocks should show signs of having grown in a relatively dry environment.

Viscosity of the syenite magmas.

Banding features of various forms are present in virtually all of the larger intrusives of southern Greenland so far investigated, whether they be gabbros, syenites, nepheline syenites, or even granites. This may be due to the parental magmas having had an unusually low viscosity which permitted crystal accumulation and, in some cases, convective circulation.

Mason (1952 p. 103) states that the Si(Al) : 0 ratio affects the degree of polymerisation in a silicate melt, this being greatest when the ratio is 1 : 2 and decreasing as the Si is reduced. Alkali metal ions, however, decrease the viscosity by breaking up the polymers. Mason suggests that bivalent ions are even more effective, and considers water to be a great mobiliser on account of its reacting with and breaking down the polymer chains. Probably HF behaves similarly. Wager and Deer, with regard to Vogt's experimental work, believed the richness in ferrous iron to have been a major factor in abnormally increasing the mobility of the Skærgaard magma. At Kûngnât the fairly high Si content of syenite melts may have been effectively countered by the high K, Na, Fe″ and F content. The ever increasing silica content was probably also counterbalanced by the increasing H_2O—CO_2 content of the residual magmas. As a result viscosity may have been kept at a subnormal level throughout the evolution of the layered series.

Temperatures within the syenite intrusions.

As was discussed on p. 62 the syenite feldspars may have crystallized out over a range of ca. 100° from ca. 800—700° according to their composition. Zoning was probably slight in the primary precipitate crystals. Since olivine and pyroxene etc. appear to have crystallized alongside the feldspars it is likely that the filling of the magma chambers by crystal mush was mostly accomplished over a similar temperature range.

The syenite magmas probably had little 'superheat' and it is unlikely that their temperature on intrusion exceeded 900°C.

Crystallization of the soda-granite suite.

The soda-granites represent an essentially low temperature mineral assemblage as compared to the syenites and probably they did not commence crystallization until late in the cooling history of the complex when the syenites were practically consolidated. This is supported by the field evidence inasmuch as the intrusion of the soda-granites postdates the solidification of the ring-dyke and hence also of the eastern syenites.

Some of these late rocks with their complex feldspar contents may have crystallized out under vapour pressures sufficiently high for the Or-Ab solidus-liquidus to have intersected the solvus curve. Re-boiling of the kind envisaged by Bowen and Tuttle (1950) may ultimately have occurred when the vapour pressure was high enough to allow some volume increase. According to these authors, the residual liquid after re-boiling will be present for an excessively long period. By virtue of its high water content, it is a very active liquid and may be expected to effect complete recrystallization of the early formed feldspar, with formation of those with which it is in equilibrium. Possibly the complex replacement textures in the soda-granites and microgranites represents incomplete recrystallization of this sort.

Derivation of the ring-dyke magma.

The final episode of ring-faulting admitted a basic magma which may well have been derived from a large differentiating olivine alkali basalt magma reservoir lying below the complex.

Many features relate the ring-dyke rocks to rocks of known olivine alkali basalt parentage. Neither quartz nor any glassy residuum ever appears and orthopyroxene has only been discovered in the marginal facies where contamination is suspected. Likewise pigeonite is absent. The plot of $K_2O + Na_2O$ against SiO_2 for the average basic ring-dyke rock lies close to the olivine basalt and mugearite field in Tilley's alkali-silica diagram for the Hawaiian lavas (Tilley 1950), and the Na_2O-SiO_2 points lie near the alkali basalt trend for the Hebridean rocks (Wager 1956).

Wilkinson (1956) points out that strong olivine zoning, such as is present in these rocks, is characteristic of derivatives from olivine alkali basalt. Further support is provided by the high phosphorus and titanium contents.

The average analysis of the three more basic ring-dyke samples will be considered as a rough approximation to the composition of the non-porphyritic highly aluminous ring-dyke magma (see p. 95). This analysis differs from the average of the Oslo-essexites (Barth 1944) in having a lower CaO/Na_2O and a higher FeO/MgO ratio, the characteristics of a more highly differentiated magma.

Altogether this magma seems to have had a remarkably low calcium content. The low CaO/Na_2O ratio may have partly arisen by addition of alkalis through contamination by the syenites, but it is likely that fractional crystallization was the prime cause.

With reservations concerning the low Ca and high alkalis, there are some similarities between this magma and the Skærgaard magma at an early stage in its evolution. The liquid admitted to the ring-fault is inferred to have been a portion of olivine alkali basalt magma which had preceeded some way towards enrichment in iron and alkalis.

Wager (1956), in an attempt to find a chemical definition of fractionation stages in basaltic melts, suggested the arbitrary divisions 'early, middle, and late stage basalts', based on the degree of iron enrichment and the composition of the normative feldspar. According to this scheme, the ring-dyke magma falls into the category of an advanced middle stage basalt.

The ferrodiorite is a finer grained rock than most of the ring-dyke rocks and the approximate analysis of it may lie on 'the liquid line of descent'. The very high content of apatite and ore is possibly the result of rapid nucleation in a melt super-saturated with regard to these constituents. The ferrodiorite liquid represented a somewhat more advanced stage in fractionation than the main ring-dyke magma, in spite of it having a rather higher calcium content. The evolution of markedly iron-rich liquids from parental alkali basalt magma may be normal whenever the oxidation state is low enough to inhibit the early separation of magnetite; the iron-rich liquid could give rise to very iron-rich rocks analogous to the ferrogabbroic rocks of tholeiitic suites.

XVII. THE EVOLUTION OF THE KÛNGNÂT COMPLEX

Possible origin of the syenitic and basic magmas.

The four main intrusions, i.e. the south western marginal syenite, the western layered intrusion, the eastern syenites and the ring-dyke, were apparently emplaced in order of increasing basicity suggesting derivation from a deep-level magma source which had already undergone considerable differentiation. The subsequent differentiation *in situ* of the three later intrusions complicates and tends to obscure this relationship.

The south western marginal syenites formed from a magma that had already reached an advanced stage in magmatic evolution. The rocks have high silica content and sodic pyroxenes. The Mg/Fe ratio is low whilst the rocks are relatively enriched in such elements as Cs, Rb and Ga.

The visible western layered series includes much more basic syenites. Nevertheless, differentiation of the lower portion of the magma after partition by the gneiss 'raft' gave rise to quartz syenites similar to those of the south western marginal group. The western layered series undoubtedly continues to increase in basicity downwards below the present level of erosion, probably passing down into rocks mineralogically similar to the most basic syenites of the eastern centre or even into near-monzonitic types. Probably a floor of gneiss underlies the lower banded group.

More basic syenites predominate in the eastern centre, in extreme cases showing strong affinities to the more alkalic ring-dyke rocks. Again it is likely that the stock consists entirely of syenitic rocks overlying a gneissose floor which may be several hundred metres below the present level of erosion.

The possibility of the four intrusions being repetitions of the same sequence merely viewed at different topographic levels has been considered and discounted.

A large body of alkali olivine basalt beneath a thick insulating cover of gneiss is assumed to have initially underlain the area. Such a body would have had only slight heat loss through its roof and may have remained in a quiescent non-convecting state throughout much of the Gardar period. During this long undisturbed spell, diffusion of volatiles, accompanied by silica and alkalis would have ultimately resulted in higher concentrations of these materials in the uppermost portions of the chamber were there was lower confining pressure and a slightly cooler environment. The relatively 'wet' magma produced would have been efficaceous in reacting with, and causing palingenesis of, the gneiss cover.

Such a process could well have become localised and eventually given rise to a subsidiary cupola above the main magma resevoir. This cupola would have contained a 'secondary' syenitic melt composed of materials partly derived from the primary basalt magma and partly derived from remobilisation of the cover. At the same time the basalt magma may have been undergoing slow but steady fractionation by crystal settling.

The embryonic 'secondary' syenite magma, gradational with the underlying basaltic melt, would not have been homogeneous but would itself have possessed a composition gradient dependent upon the temperature and confining pressure gradients of the cupola, and been more siliceous, alkali and volatile-rich in its upper levels.

A subsequent series of disturbances resulting in ring-faulting or stoping of the cover allowed the uppermost magma portion to reach a higher level where it crystallized as the south western marginal syenite. After a relatively brief interval that allowed the first intrusion to consolidate, a renewal of roof fracturing allowed a further portion of syenitic liquid to move up. This was of less siliceous character than the first and on cooling it produced the western layered syenites. Repetition of ring-faulting permitted the still more basic and deeper level eastern syenite magma to invade the higher levels. In each episode of ring-faulting and caudron-subsidence the collapsed gneisses probably never sank to great depth but only to a level in the differentiated cupola melt where the density was sufficiently high to prevent further movement. In the two major syenite intrusions the increased temperature gradient imposed when the magmas came in contact with the cooler freshly exposed roofing rocks, promoted convection.

Hence the mechanism proposed for the emplacement of the syenites involves a) diffusion processes and b) turbulent phases with convection currents, these latter being causally connected with violent disturbances of the *status quo* such as roof-fracturing which allowed for a greater temperature gradient. Convection depends on the higher liquid portions having a greater density than the lower levels. The density gradient after prolonged diffusion in tranquil conditions would be quite the reverse with lighter material at the top and there could be no question of convective circulation restarting unless the system was violently disturbed. Fractionation by crystal settling could continue under either set of circumstances. By the time the syenites had consolidated, the underlying basalt melt had reached a comparatively advanced fractionation stage. The final ring-fracturing caused intrusion of some of this residual magma.

There is a certain measure of agreement between this hypothesis and that offered by BARTH (1954) for the formation of the Oslo magmas. In the case of the Oslo suite, BARTH concluded that there were two sources of magma, one deep seated, responsible for the alkali basalt flows and one, at shallower depth, which provided the trachy-andesites and the main bodies of monzono-syenites and granites. He regards the granitic and syenitic magmas as having been formed through the refusion of the pre-existing crystalline rocks and not as a result of fractional crystallization. However, within these magmas he postulates primary gravitative differentiation and also a secondary differentiation by crystal fractionation.

Barth stresses that a homogeneous magma of great vertical extent is not stable thermo-dynamically and that one should expect accumulation of H_2O, CO_2, HF, HCl, chlorides of P, Ti and Zr etc. in the upper part of such a magma chamber. Together with the volatiles, he maintains that one should normally expect a concentration at the top of the strong bases, Na_2O, K_2O and BaO.

It is of interest in this connection that Simpson considers that similar rock types in the Okonjeje complex were derived through fractional crystallization from a tholeiitic basalt magma.

The relationship of Kûngnât to the other alkaline intrusions of south Greenland and elsewhere.

As remarked earlier, layering of one kind or another appears to be a characteristic feature of all the larger south Greenland intrusives, whether these be basic, intermediate or acid in composition. Cryptic layering, however, has not yet been described from any of the other centres and ring-dyke formation is not typical of the south Greenland province. The rock-types of which Kûngnât is composed are by no means uncommon and all can be matched with varying degrees of exactitude with rocks from the other south Greenland complexes. The Kûngnât intrusions are probably coeval, and comagmatic, with those at the Nunarssuit, Tugtutôq, and Ilímaussaq centres and the petrogenesis of the one must have a close bearing on that of the others. Although nepheline-bearing rocks do not contribute to the Kûngnât assemblage they occur nearbye in the rather earlier Gardar complex of Grønnedal-Ika and there is no doubt that the problem of their genesis, in south Greenland at least, is closely bound with that of the alkali-gabbros and the "augite syenites".

The association of saturated pyroxene and olivine-bearing syenites with nepheline syenites and gabbroic rocks is well known from other parts of the world. Among examples of such provinces could be mentioned New England, central Wisconsin, Damaraland, Oslo Fjord, and the Kangerdlugssuaq region of east Greenland. In New England and the Oslo region, however, nepheline syenites are very much subordinate. The Pre-Cambrian province of south Greenland makes an interesting comparison with the Tertiary province of the Kangerdlugssuaq district where large nepheline syenites occur together with gabbros, fayalite syenites and soda-granites (Wager and Deer 1939, Wager 1947). Besides the well known occurrences of nepheline syenites in the Kola peninsula there are also basic intrusions, together with larvikites, nordmarkites, soda-granite etc. One such intrusion is the Gremyakha-Vyrmes pluton (Polkanov 1944), which contains layered gabbros and syenites and is thought to have been partly formed by gravitational differentiation. The list of intrusive complexes and alkaline provinces showing associations of this kind could be extended almost indefinitely.

Investigation of the system $NaAlSiO_4$-FeO-SiO_2, by Bowen and Schairer (1938) showed that there are two cotectic points, one lying between the silica, albite, and fayalite fields and the other between the nepheline, albite, and fayalite fields (fig. 57). It is possible perhaps that alkaline melts in south Greenland, however derived, pursued their subsequent differentiation trends towards analogous cotectic points and may have given rise either to undersaturated end members roughly corresponding to the nepheline-Ab-Fa point, or to saturated rocks approximating to the SiO_2-Ab-Fa point. (Roedder (1959) suggests the correspondence of the Fa-SiO_2-Ab point (980° C) to a fayalite soda-granite containing about six per cent. of fayalite.) The factors deciding which trend the hypothetical undifferentiated magma would take may have initially been small. In particular, if such a syenitic melt had, at an early phase in its evolution, acquired a higher content of Al, Na, CO_2, H_2O, Cl etc., the subsequent crystal fractionation may have followed an undersaturated trend (perhaps again with gravitational settling of olivine, augite, apatite etc.). On the other hand, with less strongly accentuated concentration of Al, Na etc., allowing no opportunity for feldspathoid formation, a Kûngnât-like trend may have resulted with the ultimate production of soda-granites. In either case fayalitic olivine would have been a stable phase only in the early stages, giving way to various Na-Fe-bearing minerals, in particular to members of the arfvedsonite-riebeckite series and to acmite, in the later stages.

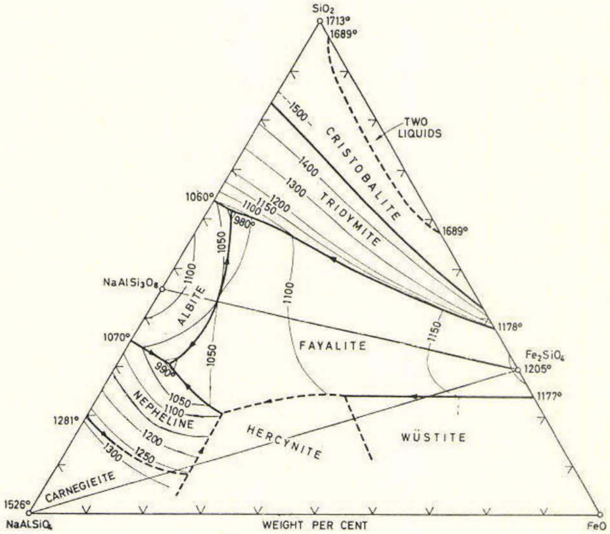

Fig. 57. The system $NaAlSiO_4$-FeO-SiO_2, reproduced from Bowen and Schairer, 1938.

APPENDIX

1. Chemical analyses.

Silica determinations were made by reducing the yellow silicomolybdate complex to molybdenum blue and determining the transmission at 6500 Å on a Beckman spectro-photometer.

Aluminium determinations were made using a method described by H.L.Watts (Analytical chemistry v. 30, p. 967, 1958, 'volumetric determination of aluminium in presence of iron, titanium, calcium, silicon and other impurities.'). In this, the rock is decomposed with HF and H_2SO_4 and the removal of SiO_2 effected. Iron and titanium are precipitated as hydroxides and Al retained in solution as sodium aluminate. KF is added and reacts with the aluminate.

$$AlO_2^- + 2\,H_2O + 6\,F^- \rightarrow AlF_6^{---} + 4\,OH^-.$$

The resulting OH^- is titrated against standard acid. The titration is carried out in the presence of the precipitated hydroxides. Interference by Ca is eliminated by precipitation as oxalate.

2. Spectrographic analyses.

All samples were determined in duplicate, using a Hilger large quartz and glass fully-automatic optical-spectrograph. Spectrographic line intensities were read by means of a Hilger non-recording microphotometer (H. 451).

Conditions for alkali elements (Li, Rb and Cs):

Glass optics. Wavelength range 4600—9600 Å: Kodak I.R.E.R. plates: Lower electrode (anode) of Johnson Matthey 4B graphite, internal diameter 2.4 mm., 3 mm. depth. Upper electrode (cathode) "Ship" carbon 5 mm. diameter: Current 4.4 amps. D.C.: Slit 20 microns: Exposure time ca. 170 secs: Plates developed in Kodak D 19b for 5 mins: G_1 (granite) and W_1 (diabase) were used as primary standards. The following values were used:—

G_1 Li 22.5 ppm., Rb 220 ppm., Cs (2.5 ppm.).
W_1 Li — Rb 25 ppm., Cs —

"LiC", a mixture of alkali feldspar and spodumene (kindly made available by C. BOWLER), was used as a secondary standard for Li. This had a Li content of 84 ppm. (determined flame-photometrically). Secondary standards were also used for the Cs, these consisting of feldspar (with undetectable Cs) mixed with lepidolite whose Cs content had been determined at Harwell by SMALES and CABELL, using a neutron activation method.

The following lines were used:— Li 6707 and 8126: Rb 7947: Cs 8521: Na 5688: K 6939:

Na was used for internal standardisation for Li and Rb, and K was used for Cs standardisation.

Other volatile elements (Pb, Tl, Ga, Cu and Ag).

Quartz optics: Wavelength range 2750—4680 Å: Ilford ordinary (N 30) plates: Anode 2.4 mm int. diam. and 5 mm depth: Johnson Matthey 4B graphite: Cathodes, as for Li-Rb-Cs run: Current 4.4 amps: Slit, 20 microns: Exposure ca. 5 mins., until end of alkali metal distillation: Plate development as above:

G_1 and W_1 were used as primary standards for Pb, Ga and Cu, the following values being adopted:—

G_1 Pb 25 ppm., Ga 20 ppm., Cu 11 ppm.
W_1 Pb — Ga 15 ppm., Cu —

Alkali feldspar standards, kindly made available by Dr. D. M. SHAW, were used as primary standards for Tl. These were "S 98" (6.8 ppm.) and "S 100" (84 ppm.), (see SHAW 1952 p. 128). For want of better standards, two synthetic mixtures (feldspar base) were used as primary standards for Ag. These were "M_2B" (203 ppm.) and "M_2C" (43 ppm.). The M_2 series working curves are generally displaced from the W_1-G_1 working curves and the Ag figures quoted in this publication may well be too high.

The following lines were used:— Ga 2944: Cu 3247: Ag 3281: Tl 3990: and Pb 4057. Na 3303 was used for internal standardisation.

Involatile elements a. (Ca, Ba, Sr, La, Sc, Cr, V, Zr, Mg, Ti, and Mn).

Samples were mixed in a ratio of 1:5 with a powder composed of one part $Pd(NH_3)_4(NO_3)_2$ to nine parts of spec. pure carbon.

Glass optics: Wavelength range 3650—4850 Å (changed to 3800—5300 Å on later runs): Ilford ordinary plates: Anode, int. diam. 2.4 mm.

and 3 mm. depth: Current 6.8 amps: Slit 10 microns: Exposure time 60 secs; Other conditions as above.

G_1 and W_1 were used as the primary standards in all cases, using the following values:—

G_1 Ca 1 %, Ba 1300 ppm., Sr 240 ppm., La 160 ppm., V 18 ppm., Zr 200 ppm., Mg .24 %, Ti .15 % and Mn .021 %.
W_1 Ca 7.9 %, Ba 150 ppm., Sr 180 ppm., Sc 37 ppm., Cr 120 ppm., V 240 ppm., Zr 90 ppm., Mg 4.0 %, Ti .67 %, and Mn .13 %.

The following lines were used:— Mg 2803: Zr 3438: Ti 3990: Mn 4034: Sc 4246: Cr 4254: La 4333: V 4379: Ca 4425: Ba 4554, and in later runs on feldspars, 4934: Sr 4607. Pd 4473 was used for internal standardisation.

Involatile elements b. (Mn, Al, Mg, Ga, Cu, Zr, Ni and Co).

Palladium was again used a an internal standard. The samples were mixed in the ratio of 1:2 with a powder consisting of 10 grms spec. pure carbon and .015 grms $Pd(NH_3)_4(NO_3)_2$.

Quartz optics: Wavelength range 2470—3560 Å: Ilford ordinary plates: Anode int. diam. 2.4 mm. and 3 mm. depth: Current 6.8 amps: Slit 10 microns: Exposure time 75 secs: Other conditions as above.

G_1 and W_1 were again used as primary standards, using the following values:—

G_1 (See above, last section).
W_1 Ni 70 ppm., Co 36 ppm., other values as given above.

The following lines were used:— Al 2652: Mg 2803: Ga 2944: Cu 3247: Ni 3414: Zr 3438 and Co 3453. Pd 3421 was used for internal standardisation.

Fluorine.

No internal standardisation was employed. The samples were mixed in a ratio of 1:2 with a 1:1 mixture of spec. pure graphite and $CaCO_3$.

Glass optics: Wavelength range 4600—9600 Å: Ilford HP_3 plates: Anode int. diam. 4 mm. and 2 mm. depth: Current 5 amps: Slit 20 microns: Exposure time 45 secs.

The primary standard used was G_1 (750 ppm.) together with subsidiary standards.

Use was made of the CaF band-head at 5291 Å.

3. Optical data.

Plagioclase compositions, unless otherwise states, were determined on the universal stage by measurement of maximum extinction angles in the zone perpendicular to (010), or by measurement of extinction angles in combined albite-Carlsbad twins.

Refractive index determinations on pyroxenes were made in sodium d light, using a temperature variation method. The measurements on the alkali feldspars were made using the variable wave-length method at constant temperature.

Optic axial angles were determined on the universal stage by direct measurement about the acute bisectrix and were corrected by means of Fedorow's diagram.

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Færdig fra trykkeriet den 29. december 1960.

PLATES

Plate I.

1. Perthites in a laminated quartz syenite from the western lower layered series, showing the characteristic 'herring-bone' pattern of the twinned crystals. Crossed nicols. × 8.
2. A zoned zircon crystal from a syenite low in the western lower layered series. Crossed nicols. × 100.

Fig. 1.

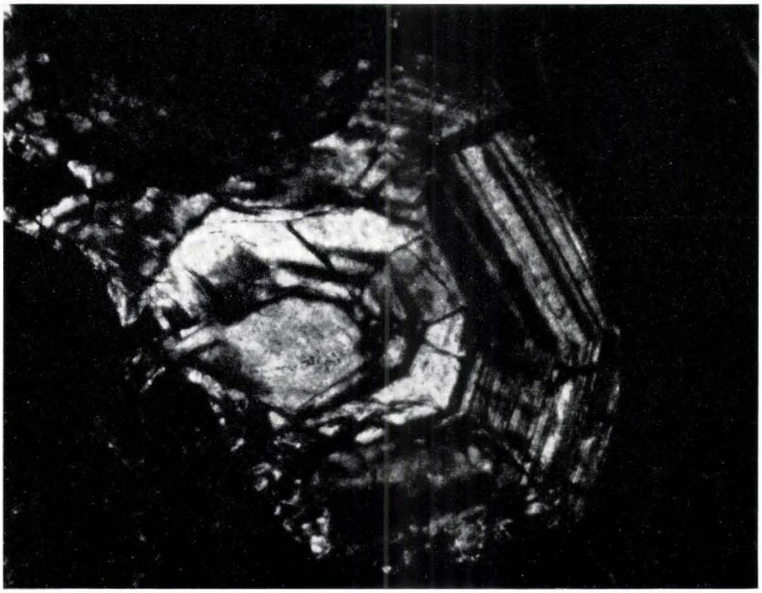


Fig. 2.

Plate II.

1. Photomicrograph of a section of mafic syenite from low in the western upper layered series. Cryptoperthite surrounds the fayalites (partly altered to ore), the hedenbergites and the magnetites. Plane polarised light. × 15.
2. Hedenbergitic pyroxenes from a thin mafic horizon in the layered syenites of the Nisseborg summit ridge. Plane polarised light. × 30.

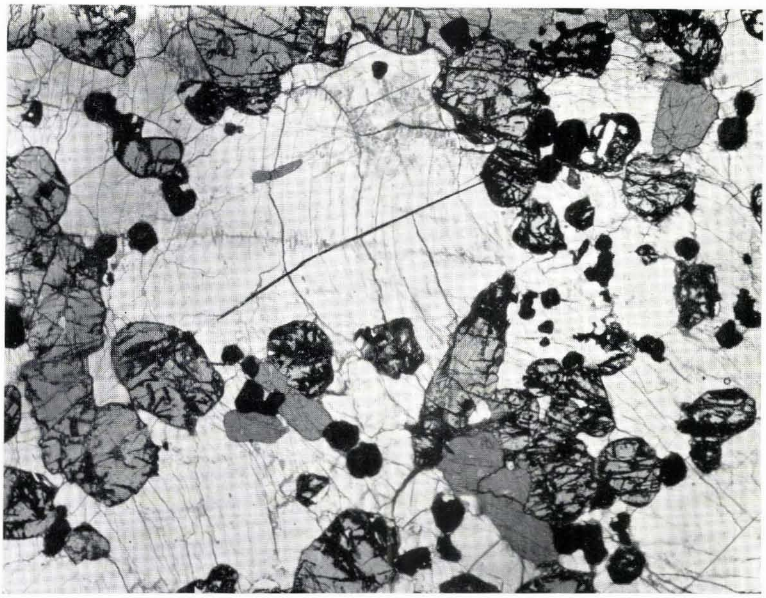


Fig. 1.

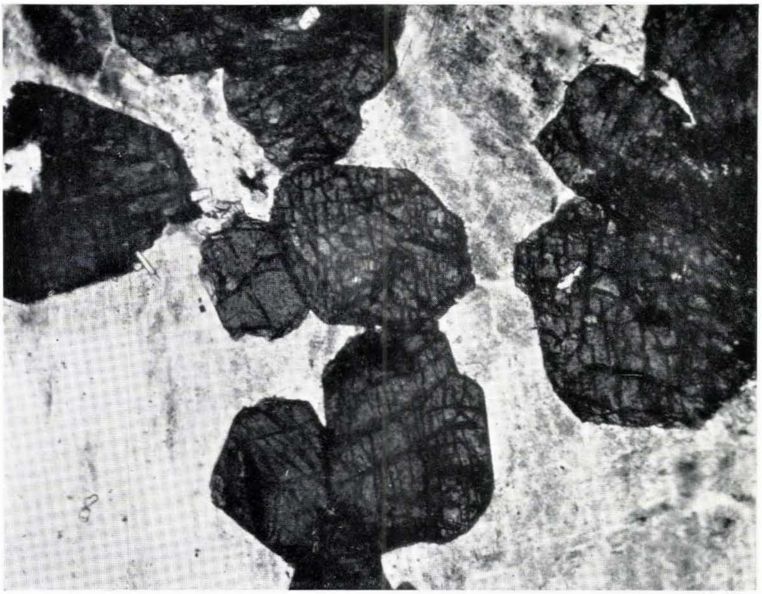


Fig. 2.

Plate III.

1. Photomicrograph showing the texture of a typical olivine gabbro from the ring-dyke suite. Crossed nicols. × 10.
2. A cluster of early olivines in a ring-dyke gabbro, showing the straight or curvilinear sealed surfaces between the crystals. Crossed nicols. × 25.

Fig. 1.

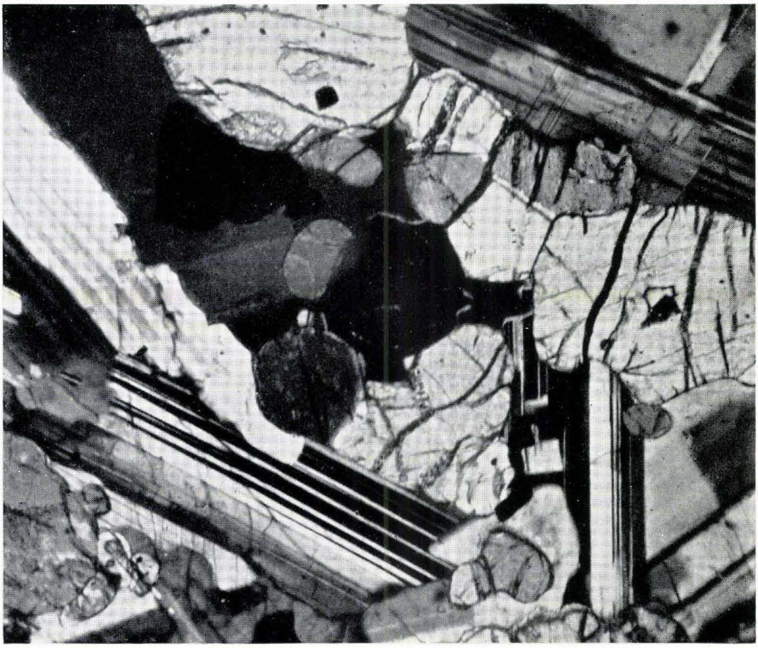


Fig. 2.

Plate IV.

1. Olivine, plagioclase, ilmenomagnetite and biotite in ring-dyke gabbro. The ore, having been enclosed at an early stage by the feldspar, has developed only thin biotite reaction fringes. Crossed nicols. × 50.
2. Abundant apatite crystals in ferrodiorite from a dyke in the Røverborg-Kûngnât hanging-valley. Plane polarised light. × 25.

Fig. 1.

Fig. 2.

Plate IV a.

1. Ulvöspinel-magnetite intergrowth from an olivine gabbro. (Specimen 26271). Uncrossed nicols. Oil immersion. × ca. 300.

2. Another ulvöspinel-magnetite lattice from specimen 26271, for comparison with 1 above. Note the different proportions of ulvöspinel to magnetite in the two instances. Uncrossed nicols. Oil immersion. × ca. 300.

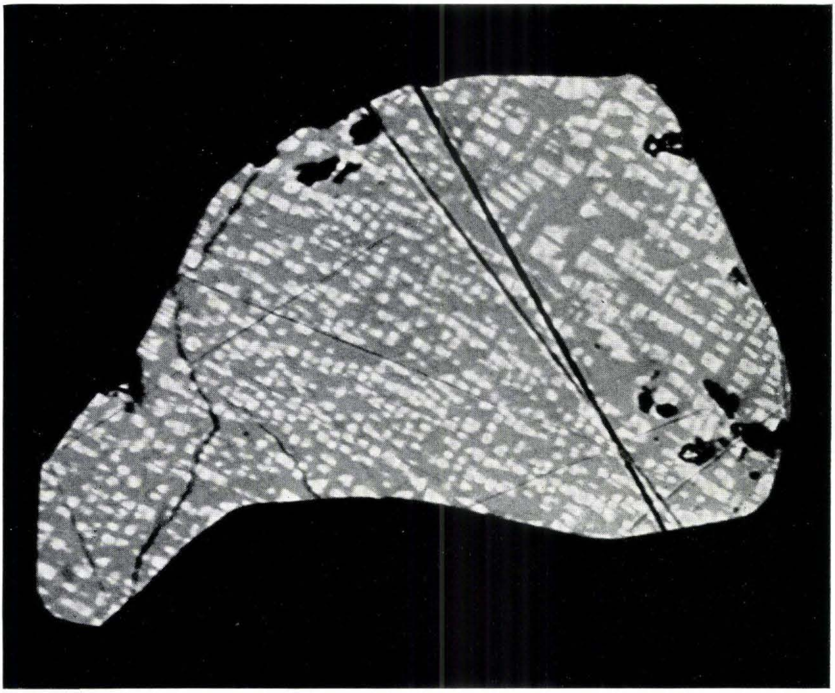


Fig. 1.

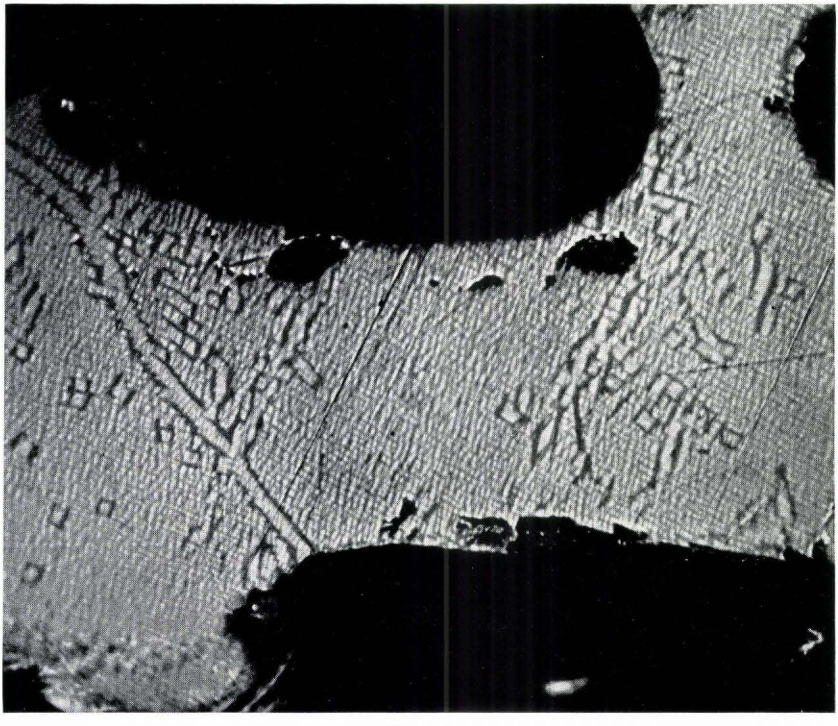
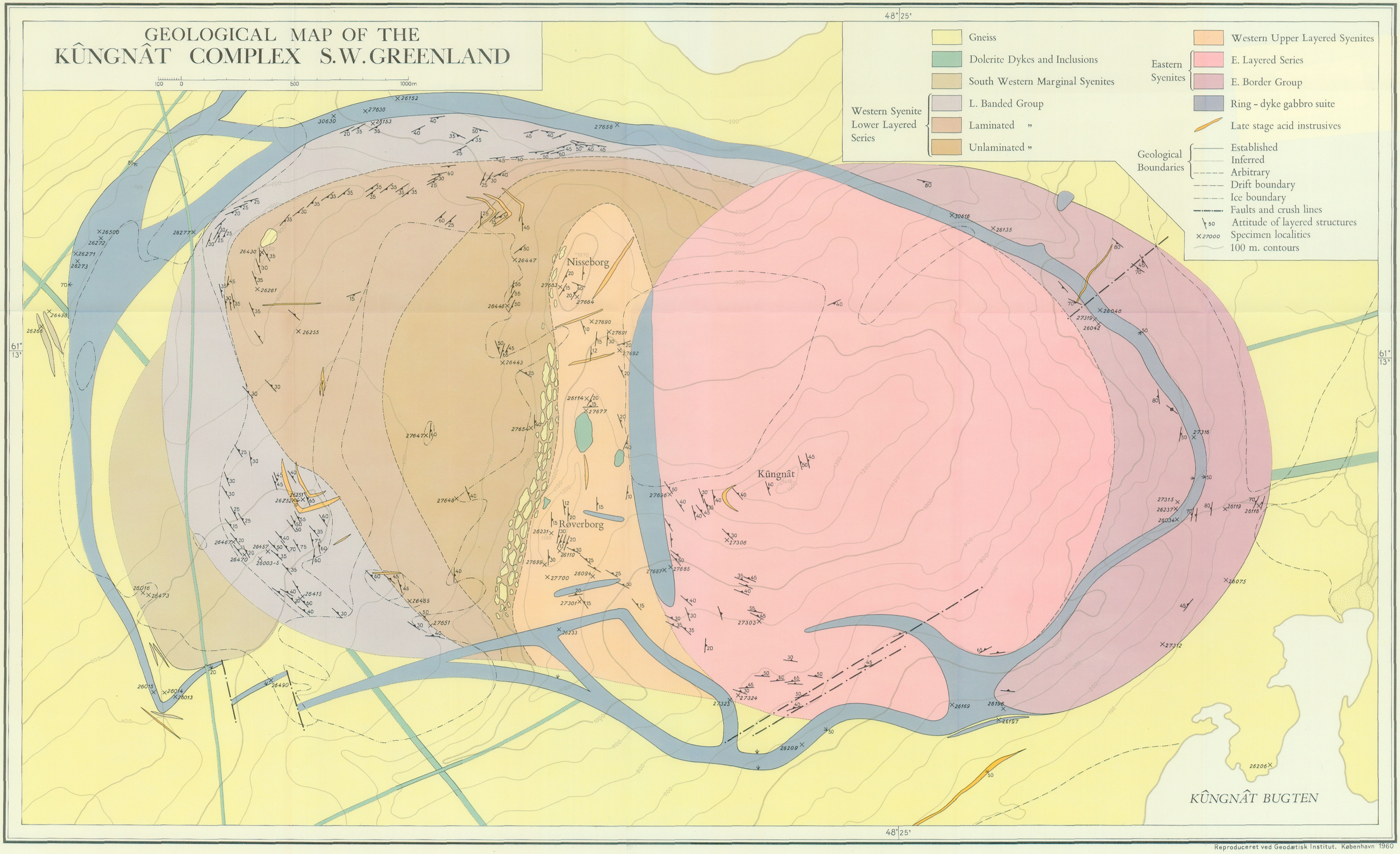


Fig. 2.

GRÖNLANDS GEOLOGISKE UNDERSÖGELSE
THE GEOLOGICAL SURVEY OF GREENLAND

GEOLOGICAL MAP OF THE KÛNGNÂT COMPLEX S.W. GREENLAND



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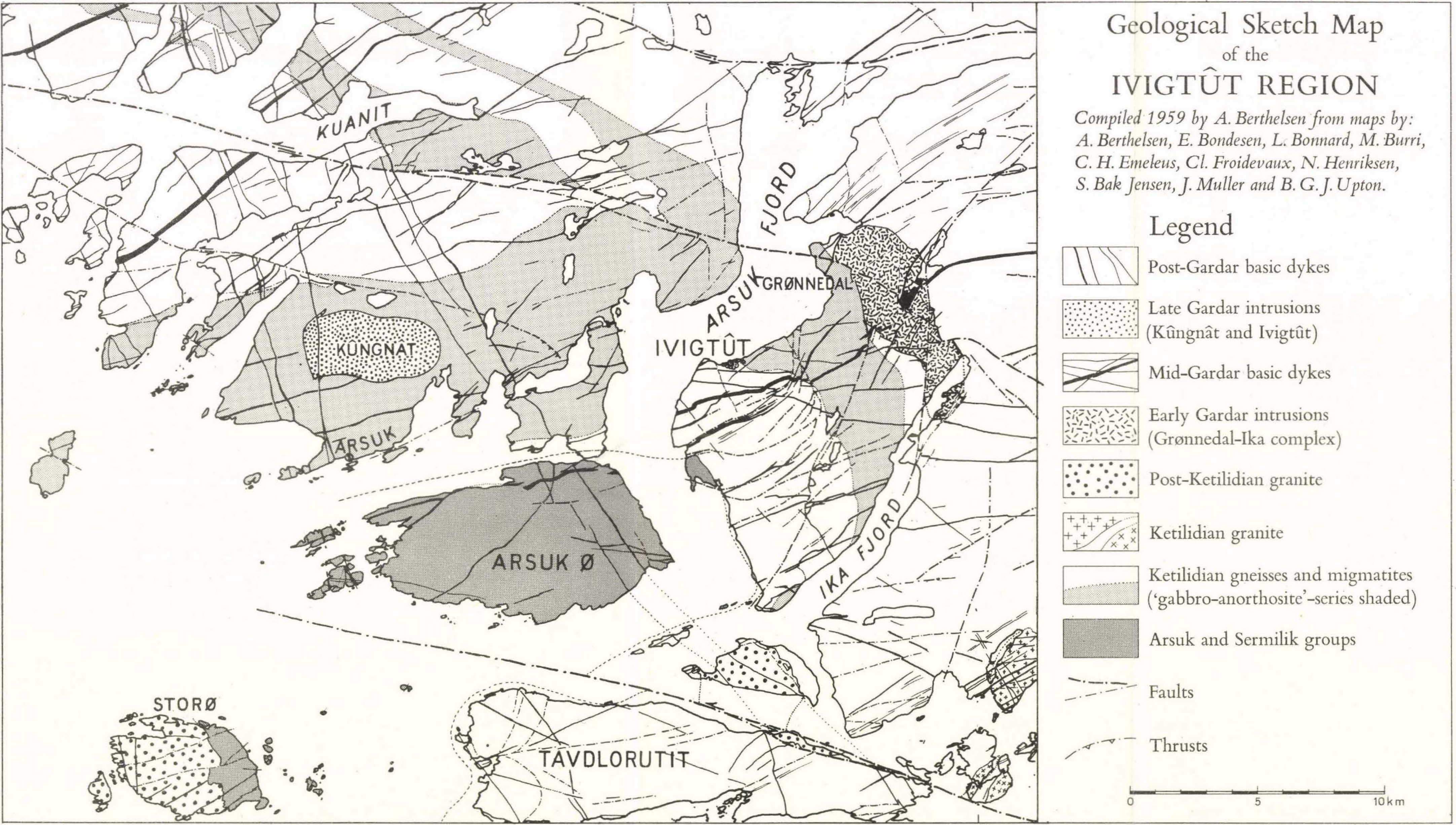
GRØNLAND GEOLOGISKE UNDERSØGELSE
THE GEOLOGICAL SURVEY OF GREENLAND



Geological Sketch Map
of the
IVIGTÛT REGION

Compiled 1959 by A. Berthelsen from maps by: A. Berthelsen, E. Bondesen, L. Bonnard, M. Burri, C. H. Emeleus, Cl. Froidevaux, N. Henriksen, S. Bak Jensen, J. Muller and B. G. J. Upton.

Legend

Reproduceret ved Geodætisk Institut. København 1960

Corrections:

Page 93, Table 7 column 2:

15.69 read: 16.81
98.95 – 100.07