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THE SIGNIFICANCE OF THE KAKORTOKITE IN THE EVOLUTION OF THE ILÍMAUSSAQ INTRUSION, SOUTH GREENLAND

BY

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WITH 44 FIGURES AND 35 TABLES IN THE TEXT,
AND 1 PLATE

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Abstract

The feldspars of the intrusive rocks of Ilímaussaq were subjected to a fairly detailed mineralogical investigation. The K-feldspars from the early augite syenite have an average obliquity of 0.61 compared with the corresponding value of 0.90 for the feldspars of the remaining rock types. In addition, the obliquity values within the augite syenite group show a mildly contrasting variation related to the grain-size of the rock. The co-existing augites and olivines in the augite syenite vary sympathetically with the obliquity values. The structural states and compositions of the Na-feldspars in the major rock groups of the Intrusion indicate that they are all low temperature albites.

Most of the rock types in the Intrusion develop rhythmic layering. Petrofabric analyses of the kakortokite and lujavrites indicate that the cumulus minerals show a marked planarism and, in some cases, lineation.

Six new major element rock analyses of kakortokite together with pre-existing published analyses have been presented in ternary diagrams. In addition, quantitative analyses were carried out on 90 whole rock specimens for the following elements: Na, K, Rb, Li, Cs, Ca, Sr, Ba, Ti, Zr, Nb, Sn, Be, La and Ga. Further results include semi-quantitative analyses for Bi, Pb, Zn, Sb, Sn, Y, Be, Mo, Nb, Cu, Ni, La, Ag, Co and V on 100 kakortokite rocks and 40 minerals. The fractionation trend displayed by the K:Rb ratio shows a remarkably strong correlation with the chronology as determined from the field evidence. Other ratios used include Sr:Ca, Ba:Rb, Ti:Zr, Ti:Nb and Zr:Nb. In general these ratios conform to established behaviour patterns during fractionation; an exception is the Zr:Nb ratio which increases with fractionation. Furthermore, the kakortokite sequence displays a generally progressive variation of these ratios with height, suggesting that they crystallized from the floor upwards.

On the basis of field evidence, petrology and geochemistry it would appear that the earliest magma of the Intrusion had an augite syenitic composition. It is thought that this original augite syenitic magma differentiated along an undersaturated trend and that the heterogeneous syenite represents the roof-development of the innermost differentiate of the augite syenite. It is postulated that by the addition of volatiles the inner augite syenitic magma was converted to a magma of peralkaline composition. The agpaitic (per-alkaline) magma then underwent crystallization which took place from the roof downwards with simultaneous gravity accumulation of the heavier minerals on the floor of the Intrusion. This gave rise to both the sheeted occurrences of sodalite foyaite and naujaite, essentially products of the flotation of sodalite and intercumulus crystallization, and the markedly rhythmically layered kakortokite, a product of gravity accumulation. Finally, a residual liquid, rich in volatiles, was trapped between the downward crystallizing naujaite and the gravity accumulated kakortokite. As a result of faulting and/or slumping the residual mush was injected into the overlying brecciated rocks where it crystallized to form the fissile lujavrites.

The origin of the alkali granite is problematical but it would appear to predate the agpaites and post-date the augite syenite and heterogeneous syenite.

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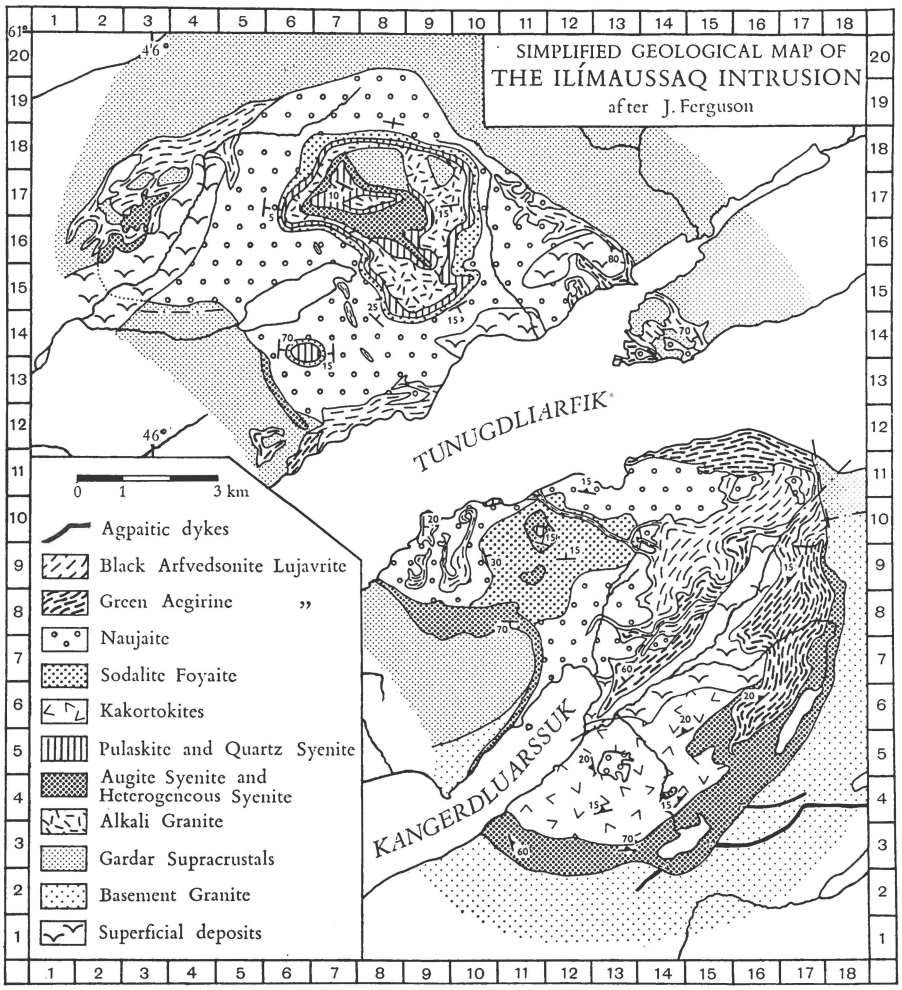

SIMPLIFIED GEOLOGICAL MAP OF
THE ILÍMAUSSAQ INTRUSION
after J. Ferguson
TUNUGDLIARFIK
KANGERDLUARSSUK
46°
0 1 3 km
Agpaitic dykes
Black Arfvedsonite Lujavrite
Green Aegirine ,,
Naujaite
Sodalite Foyaite
Kakortokites
Pulaskite and Quartz Syenite
Augite Syenite and Heterogeneous Syenite
Alkali Granite
Gardar Supracrustals
Basement Granite
Superficial deposits

Fig. 1.

I. INTRODUCTION

The Ilímaussaq Intrusion is one of a number of alkaline plutons of Precambrian age occurring in South Greenland. Of these bodies the Ilímaussaq Intrusion has attracted particular attention due not only to its unusual array of minerals and rock types but also to its position, straddling the comparatively well-known Tunugdliarfik fjord (Figs. 1 and 2); the grey weathering of the friable nepheline syenites contrasts markedly with the darker country rocks making it a landmark of some note.

The Intrusion has an elliptical plan view measuring 17 km along a NW–SE axis and 8 km in a NE–SW direction. From the central point of the Intrusion the town of Narssaq lies some 11 km to the west. The north and west margins of the Intrusion are bounded by the 61° N parallel and the 46° W meridian respectively (Fig. 1).

Ussing (1912, pp. 107–8) divided the Ilímaussaq Complex into three main divisions; the first being the "stratified batholite", the second including a number of more independent bodies occurring in the west and south of the stratified unit, and the third unit comprising a volcanic suite of rocks. The rock types contained within these divisions, as defined by Ussing (op. cit.), are as follows:

1st Division "stratified batholite" (from top to bottom)	2nd Division	3rd Division
arfvedsonite-granite	arfvedsonite-granite	diabase
quartz-syenite	augite-syenite	porphyrites
pulaskite	nordmarkite	porphyries
foyaite	essexite	quartz porphyries
sodalite-foyaite		
naujaite		
lujavrite and kakortokite		

Ussing's original Ilímaussaq Complex has now been subdivided into the Narssaq Intrusion (Stewart, 1964) and the Ilímaussaq Intrusion. The former comprises Ussing's second division minus the augite

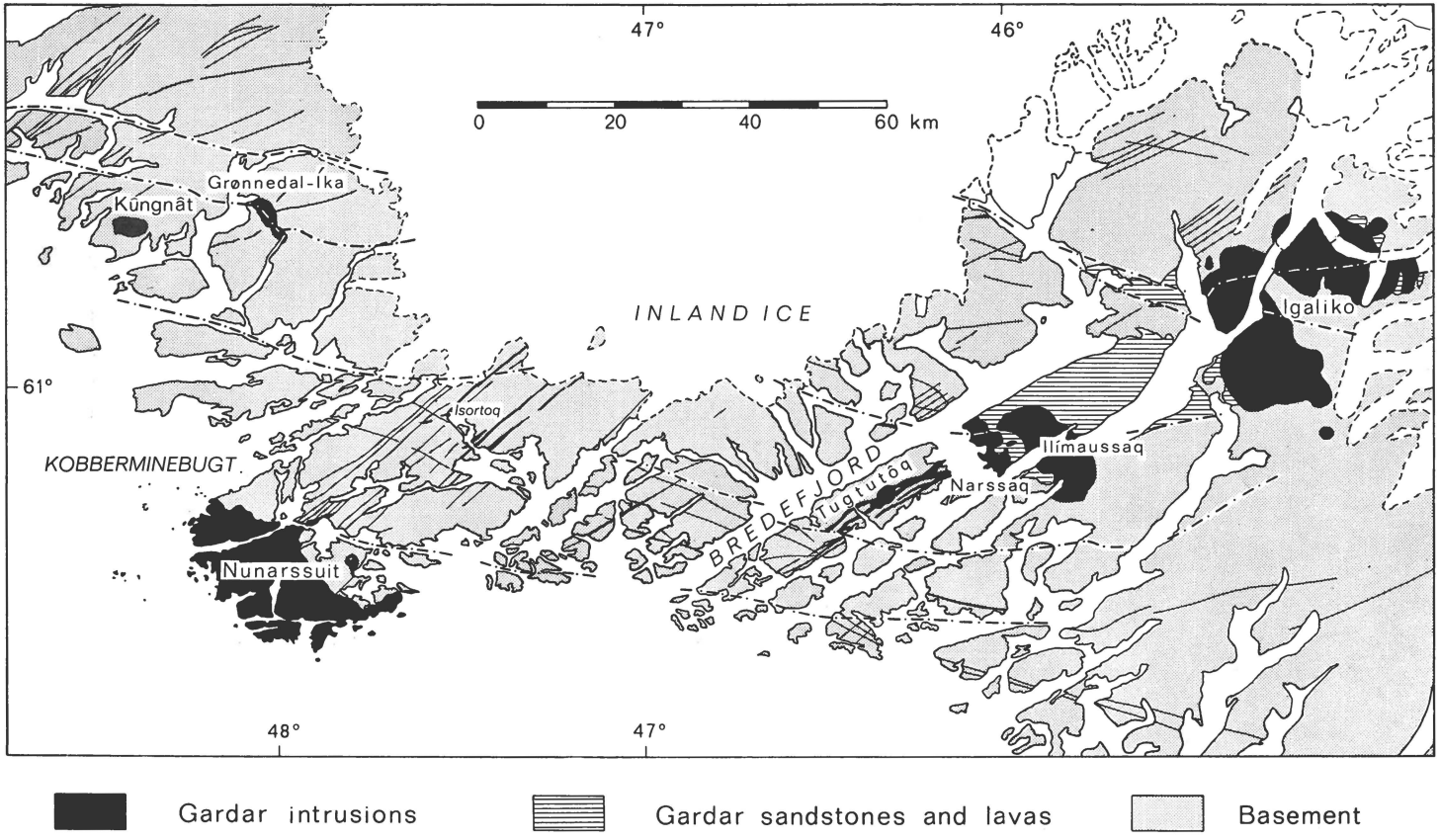


Fig. 2. Sketch map of part of South Greenland showing the main intrusions and dyke swarms of the Gardar igneous province (from WATT, 1966, fig. 1).

syenite occurrence in the south which has now been incorporated in the stratified division as part of the newly defined Ilímaussaq Intrusion. There are, in addition, other occurrences of augite syenite in the Ilímaussaq Intrusion. USSING (1912, p. 306) regarded the "Ilímaussaq porphyry" of the third division to represent an extrusive phase of the Ilímaussaq igneous activity. BERTHELSEN and NOE-NYGAARD (1965, p. 143), however, view these latter rocks of the Eriksfjord Formation as being older than the Ilímaussaq Intrusion, namely of early- and mid-Gardar age (Table 1). The extrusives of this Formation are dominantly basaltic but alteration has obscured the original composition in many cases. However, one trachytic flow has been identified and in addition sills of this rock also occur (STEWART, 1964).

Table 1. *Isotopic age datings of selected Gardar rocks*

Early Gardar	
Dolerite	1435 ± 80 m.y.[1]
Mid-Gardar	
(?) Ivigtut, granite	1260 ± 30 m.y.[2]
(see previous statement)	1250 ± 30 m.y.[2]
Late-Gardar	
Nunarssuit Complex	
Nunarssuit syenite (K/Ar)	1128 ± 30 m.y.[1]
Alangorssuaq Biotite Granite (Rb/Sr)	1150 ± 30 m.y.[4]
Kûngnât Complex	1170 ± 150 m.y.[3]
Ilímaussaq Intrusion	1020 ± 24 m.y.[3]

[1] Determined by Geochron Laboratories Inc; see BRIDGWATER (1965). This date must be regarded as provisional (BRIDGWATER, 1965, p. 33); it was determined by the K/Ar method on augite, a mineral likely to contain excess radiogenic argon (ALDRICH et al., 1962) thereby producing an older "dating" than other minerals from the same rock.

[2] Determined by MOORBATH and PAULY (1962).

[3] Determined by MOORBATH et al. (1960). These Rb/Sr determinations were recalculated (BRIDGWATER, 1965) using the Rb^{87} half life given by FLYNN and GLENDENIN (1959).

[4] Determined by S. MOORBATH, see HARRY and PULVERTAFT (1963, p. 20).

For an account of research on the Ilímaussaq Intrusion the reader is referred to a historical resumé compiled by SØRENSEN (1967). In passing it is of interest to note that the first geological investigation was carried out by K. L. GIESECKE whose first visit to the area was in 1806 (diary publ. 1910). During the field seasons of 1958, 1960, and 1961 the author, as a member of the Geological Survey of Greenland (Grønlands Geologiske Undersøgelse, GGU) mapped the southern half of the Intrusion at scale 1:10 000 and the northern half at 1:20 000. The

result of this work was the publication in 1964 of a 1:20 000 map of the whole intrusion, together with a description of a general nature, completed before the author left Denmark. Subsequently, at the University of the Witwatersrand, Johannesburg, South Africa, a detailed study was made of selected aspects of the petrochemistry of the Intrusion resulting in this additional publication.

The material presented in this paper includes a petrochemical study of the rhythmically layered per-alkaline kakortokite with subsidiary investigation of the other rock units in an attempt to establish the bearing of the kakortokite on the evolution of the Intrusion. Despite the good exposure in the area, various workers have given different interpretations of the chronological order of crystallization. In addition, two rock types within the Intrusion have controversial correlations. It was with these problems in mind that the author undertook a study of the petrochemistry and applied established trace element fractionation trends in an attempt to unravel the differentiation sequence of the rocks and, in particular, the per-alkaline (agpaitic) members.

While this work has been in progress two Russian geologists, V. I. GERASIMOVSKII and E. I. SEMENOV, have undertaken analyses of material collected during their visit to the Ilímaussaq Intrusion in the summer of 1964. The above-mentioned workers and H. SØRENSEN will publish the results of this detailed geochemical investigation but with the minimum of analyses of the kakortokite. This work and that of the author have been carried out independently as a language barrier and distances have made contact almost impossible. It is hoped that the limited geochemical section presented here will neither contradict nor duplicate the work that they have undertaken.

II. DISTRIBUTION OF ROCK UNITS AND CONTACT RELATIONS

General

Ussing (1912) published a very detailed account of the distribution of the rock units of the Ilímaussaq region as well as describing their contact relations. Reference will only be made to this publication when the writer is in disagreement with Ussing's findings. However, new observations presented by Sørensen (1958 and 1962) and Hamilton (1964) will be referred to.

The names introduced by Ussing (1912) for the Ilímaussaq rock types have been largely adhered to in this publication. The petrology of the main rock units has already been published; however, for a better understanding of the contact relations, brief textural and mineralogical descriptions of these unusual rock types are given below:

Augite syenite

This rock has a holocrystalline texture varying from fine- to coarse-grained. The major minerals are alkali feldspars, augite, acmitic pyroxenes, olivine, kaersutite, magnetite and biotite.

Heterogeneous syenite

This rock is characterized by its heterogeneous grain size. Pockets of coarse-grained rock are enclosed in pegmatitic material; there is very little mineralogical difference between the two textural varieties. The major minerals are alkali feldspars, acmitic pyroxenes, soda-amphiboles, olivine and nepheline.

Alkali granite

The rock is coarse-grained and has a hypidiomorphic texture. The major minerals are alkali feldspars, quartz, arfvedsonite, aenigmatite and acmitic pyroxenes.

Quartz syenite

This rock is very similar to the alkali granite with the exception of its lower quartz and higher pyroxene contents.

Pulaskite

This rock is coarse-grained and has a hypidomorphic texture. The major minerals are alkali feldspars, acmitic pyroxenes, arfvedsonite, aenigmatite and nepheline.

Sodalite foyaite

This rock is coarse-grained and does not develop a foyaitic texture. The major minerals are alkali feldspars, acmitic pyroxenes, soda-amphiboles, eudialyte, sodalite and nepheline.

Naujaite

The major minerals are alkali feldspars, acmitic pyroxenes, soda-amphiboles, eudialyte, nepheline and sodalite. With the exception of sodalite the minerals are of pegmatoid dimension and are further characterized by a marked poikilitic texture. Sodalite makes up the inclusions and, on average, forms 35 to 45 per cent, by volume, of the rock.

Kakortokite

The kakortokite comprises a suite of compositionally layered rocks; the rhythmic layering, produced by compositional alterations of black, red and white layers, corresponds to concentrations of arfvedsonite/aegirine, eudialyte and feldspar respectively. The major minerals are alkali feldspars, acmitic pyroxenes, arfvedsonite, nepheline and eudialyte.

Lujavrites

The lujavrites are characterized by being medium- to fine-grained rocks which display a strong preferred orientation of the prismatic minerals, giving the rock a distinct fissility. There are two main varieties in the Intrusion, an arfvedsonite-rich black lujavrite and an aegirine-rich green lujavrite. Other major minerals are alkali feldspars, eudialyte and nepheline; and locally sodalite, "murmanite" and naujakasite.

Augite syenite

Distribution

The augite syenite occurs texturally and compositionally as a highly variable rock type but behaves as a structural unit. To the south of Tunugdliarfik, the augite syenite occurs as an almost continuous marginal shell. This body is of variable thickness and makes a contact which is vertical to steeply dipping outward. On the NE side of Nunasarnaussaq, the contact of the augite syenite sheet with the country rocks dips at 70° under the latter. To the SE in the Laksefjord area, the width of the augite syenite reaches a maximum of 1.7 km but rapidly wedges

out 4 km to the NNE and is absent from here to the coast at Agpat, a distance of 1.6 km. Elsewhere, to the south of Tunugdliarfik, the augite syenite is present as a continuous marginal zone of varying width. In the Laksefjord area, the augite syenite occurs above and below the green lujavrite. The excessive width of the augite syenite underlying the green lujavrite in this area may be due to the fact that the augite syenite here is present as large blocks, or alternatively that these highly altered rocks have, in part, been misidentified by the author (see discussion in kakortokite section).

The augite syenite overlying the green lujavrite at Laksefjeld occurs as two small flat-lying masses forming the uppermost peaks. As also noted by Ussing (1912, p. 38), the contact plane between these two rock types is almost horizontal.

North of Tunugdliarfik, the augite syenite is only sporadically developed as a marginal facies. It is, however, well developed as a sheeted body in the central part.

Approximately 1.6 km to the west of Tugtup agtakôrfia, in a zone extending from sea-level to 200 m, the marginal augite syenite is heavily intruded by lujavrite. Above 200 m the augite syenite occurs as a more distinct belt, 200 m wide and extending in a NNW direction, wedging out 0.5 km S of the western end of Taseq.

The marginal augite syenite reappears again in the Narssaq Elv where it is intruded by lujavrite. Hamilton (1964, p. 16 and Pl. 1) indicates that the marginal augite syenite is continous from a point starting at the 600 m contour SW of Taseq, extending to the Narssaq Elv and being displaced by a fault at the W end of Taseq. The author spent some time in this area sampling and trying to locate the marginal augite syenite but was unable to do so. As described by Hamilton (op. cit.) most of this area under discussion is heavily sheared and iron stained. As far as the writer was able to discern, to the NW of Taseq these rocks were altered porphyritic basalt (GGU 48056) and a rock now represented by perthite, aegirine and an opaque mineral (GGU 48057). To the SW altered naujaite is found (GGU 48040). Immediately to the NW of Taseq, Hamilton (op. cit., Pl. 1) shows a dip symbol within the marginal augite syenite. From its location it would appear to represent a dip of the layering in the augite syenite, yet he clearly states that in this area "the syenite does not appear to be banded" (p. 16).

Scree obscures the area between Narssaq Elv and Kvanefjeld. At the latter locality, the augite syenite is separated from the main country bocks by a zone of lujavrite and xenoliths of country rock measuring up to 800 m wide. To the NE, this zone ends abruptly, being truncated by lujavrite and a large xenolith of basalt. Nowhere else was the marginal augite syenite observed N of Tunugdliarfik.

On the high plateau to the S of Nákâlâq in the north-central part of the intrusion, the augite syenite occurs as a sheet immediately underlying a conformable quartz syenite sheet. Along the NE margin, this augite syenite sheet abuts against a capping of earlier volcanics just to the S of the summit of Nákâlâq. It is uncertain whether the augite syenite continues beneath this capping of volcanics. At a distance of 1 km to the E of Taseq, this sheet is indicated as a tongue-like appendage extending SE (Plate 1) and apparently conformable with the quartz syenite. The texture of the rock making up this extension is identical with that of the medium-grained augite syenite and in addition has the characteristic rusty weathering. Thin section study of this rock (GGU 48013–4) reveals some discrepancies with the augite syenite. The feldspars are similar, being cryptoperthites, and there is an abundance of apatite, which is also typical of the augite syenite. However, the mafic minerals are not olivine and augite, but arfvedsonite, brown amphibole and aegirine. Fenitized products of the mafics in the augite syenite include these latter minerals, as is well shown by the xenolithic occurrences of augite syenite in kakortokite (GGU 24715 and 24764) and in the augite syenite occurring 0.6 km to the NW of Laksefjeld (GGU 24781). Considering then the textural and mineralogical similarities, together with the possible effects of fenitization of the mafics, the classification of these rocks as augite syenite becomes feasible. HAMILTON (1964, Pl. 1) has indicated this tongue-like appendage to be entirely of quartz syenite. The alleged occurrence of augite syenite on the E side of the volcanic capping at Nákâlâq (HAMILTON, op. cit.) was investigated and found to consist of alkali granite (Plate 1).

The dip of the northern contact between the augite syenite and the volcanics is 75° to the SSW. Elsewhere the augite syenite sheet has conformable relations to the quartz syenite and alkali granite sheets, which have the attitude of an inward-dipping remnant basin, the centre of which lies to the S outside the present exposures. Marginally in the north, the sheets are vertical or steeply dipping to the S. Along the western margin the sheets dip east at 5°. Along the E and SE contacts, the sheets dip southerly at 15°; however, 1 km SE of Taseq the dips increase to 25° to the ENE. HAMILTON (1964) has not commented on the form of the augite syenite in this central area or on the under- and overlying alkali granite bodies. He has, however, described detailed traverse sections across parts of this sequence. Along section "A" in the NW the dips are to "the south at an angle greater than 80°" (p. 55) which is in accordance with the writer's measurements. For sections "B" and "D" in the W and SE respectively no dips are given. The dip given for section "C" which is 1 km SE of Taseq is the same as the author's findings. For traverse "E" on the E side the dips are given as "steeply to the south"

(HAMILTON, 1964, p. 60). Using HAMILTON's map for the calculation of the dip for his section, a value of 15° SSE was obtained. This latter measurement is more in accordance with the author's observations made just to the N of this section.

Due to its relative inaccessibility, USSING's traverses did not cover this high central area in much detail, particularly as he was hampered by snow cover from 500 m upwards during the field season of 1908. As a result he was of the opinion that only alkali granite occurred above the foyaite up to the base of the volcanic cappings.

Contact relations

Wherever the augite syenite comes into contact with country rocks a finer grained facies of the augite syenite is developed. In most cases a fine-grained chilled rock is developed in a zone 3 to 10 m wide. Such contacts were noted on the N and S shore of Kangerdluarssuk, in Narssaq Elv and at Nákâlâq. The chill facies then passes into a less fine-grained facies which varies in thickness from 30 to 100 m; this in turn passes into the normal coarse-grained facies of this rock type. At Kvanefjeld, where the augite syenite can be separated from the marginal country rocks by a belt of lujavrites and country rock xenoliths, measuring up to 800 m wide, the augite syenite on the outer side of its occurrence is finer grained than on the inner side. One exception to the general contact conditions was noted, 2 km S of Agpat, where the augite syenite develops a finer grained facies within 100 m of the country granite contact but no actual chill facies has been produced. In addition, apophyses, 2 to 3 m long, of augite syenite are found in the basement granite at this locality. Apophyses of augite syenite, measuring up to 1 m long, occur also in the volcanics 1 km S of the summit of Nákâlâq. The conspicuous augite syenite apophyses mentioned by USSING (1912, p. 59) within the sandstone on the S side of Nunasarnaussaq were not observed by the author; however, those reported on the N side of this mountain by USSING (1912, p. 62) were observed and, as noted by USSING, contain a great amount of quartz in contrast to the usual absence of this mineral, particularly in the coarser facies where nepheline can be present.

A pegmatitic facies is locally developed within the chill and finer grained facies of the augite syenite; particularly well at an elevation of 300 m on the NE slope of Iviangiussaq kangigdleq, where 25 cm wide sinuous pegmatites occur, comprising schiller perthites 6 to 9 cm long. In this area, the country granite is shattered within several metres of the contact with the augite syenite, with quartz-feldspar pegmatites filling the fractures. HAMILTON (1964, p. 14) has reported an example

of back veining by the Julianehåb granite with the augite syenite on the S side of Nunasarnaussaq.

The effects of the Ilímaussaq Intrusion on the Julianehåb granite have been observed by J. H. ALLAART, who has supplied the following information.

The Julianehåb granite has been altered for a distance up to 40 m from the contact with the Intrusion. Near the contact, the granite has been completely fenitized. The plagioclase and microcline have been converted into chess-board albite and the chess-board variety of microcline which is characteristic of most of the potash feldspars found in the Intrusion. The biotite has been converted into soda-amphibole and soda-pyroxene; locally quartz has also been altered to the latter mineral. Quartz and biotite are unaffected 30 m from the contact; the feldspars, however, are clouded. Mylonitic shear zones are found in the granite up to 100 m from the contact. The granite has been completely fenitized for 0.5 m on either side of these mylonites.

The metamorphism of the Gardar diabase by the augite syenite has produced biotite over a width varying from 8 to 10 m. The country rock sandstone has been recrystallized to produce a very compact rock containing numerous quartz veins.

0.4 km N of the summit of Nunasarnaussaq, two small pipe-shaped diatremes of augite syenite, a few metres in diameter, occur in the basaltic country rocks. Along the margins of these diatremes, numerous chips and fragments of sandstone and basalt, measuring up to 1 m wide, are found in a matrix of augite syenite. Towards the centre of these diatremes, fresh fragments of granite occur, resembling that of the underlying Julianehåb granite.

At the NE foot of Iviangiussaq kangigdleq, four sandstone blocks occur in the augite syenite, the largest measuring over 100 m long and 50 m wide. These have been well described by USSING (1912, pp. 51–54). Another large sandstone xenolith of a few cubic metres was noted in the augite syenite, 1.5 km S of Agpat. As pointed out by USSING, the sandstone blocks first described must have sunk a distance of a few hundred metres, as the top of the adjacent Iviangiussaq kangigdleq mountain is below the lower contact of the continental series of sandstones from which these xenoliths have undoubtedly been derived.

Around the margins of these xenoliths the augite syenite has reacted with the sandstone to form alkaline granite. The latter occurs in two distinct forms:

(i) As reaction rims;

(ii) as veins penetrating both sandstone and augite syenite (Fig. 3).

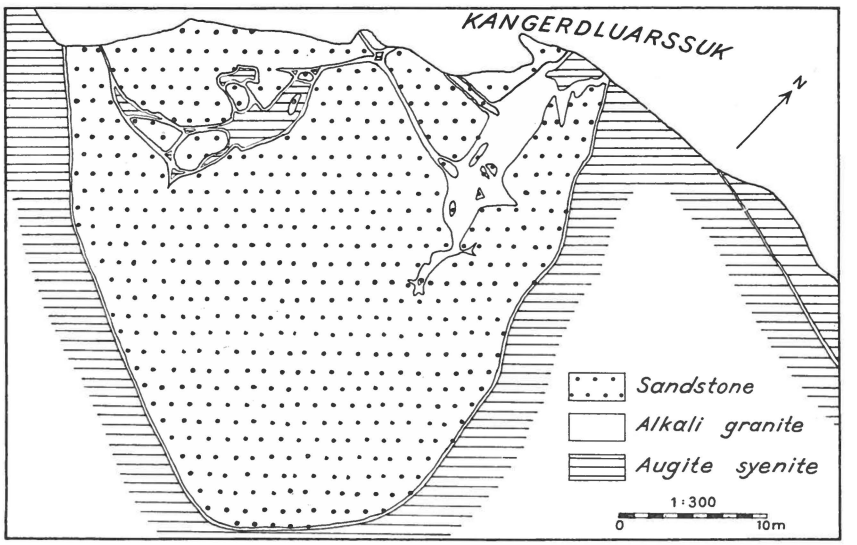


Fig. 3. Plan view of sandstone block in augite syenite at the north-eastern foot of Iviangiussaq kangigdleq.

A well exposed sandstone block occurring at sea-level was mapped in detail (Fig. 3). Reaction *in situ* has taken place both along the main margins of the augite syenite and sandstone block and also where veins of augite syenite invade the shattered sandstone. The alkali granite reaction product achieves widths varying between 10 and 18 cm. Also, a reaction rim of soda-amphibole is present along the alkali granite-sandstone contact with the amphibole prisms aligned perpendicular to the contact.

The alkali granite of the second type intrudes into the augite syenite as fairly large veins, which for the most part are coarse-grained to pegmatitic.

In the area underlying Nákâlâq where the conformable sheets of augite syenite and alkali granite occur, the contact between these two rock types was not noted, partly as a result of scree cover and partly due to the development of a discontinuous quartz syenite sheet having an average thickness of 5 to 10 m with a maximum of 50 m. The contact between these two rock types was, however, observed by Hamilton (1964, p. 23) in an area E of Taseq where the alkali granite has a sharp chilled contact against the augite syenite. Due to the friable nature of the augite syenite, the immediate contact between the augite syenite and the quartz syenite was not observed. Within a few metres of the contact there is no change in grain size in either rock. 1 km to the E of Taseq, a network of quartz syenite and subordinate acid pegmatites penetrate the augite syenite.

The author only observed the contact between the naujaite and the augite syenite at three localities. At an altitude of 400 m on the N slope of Nunasarnaussaq, the augite syenite and naujaite have a sharp undulating contact with no compositional or textural change in either rock. USSING (1912, p. 59) and HAMILTON (1964, p. 14) have made similar observations near sea-level on the N side of Kangerdluarssuk where there is no change in the characters of either rock to within 1–2 m of the scree-covered contact. At two localities to the SW of Taseq, naujaite apophyses were found in the augite syenite with no change in either rock. HAMILTON (1964, p. 19) has also described narrow "naujaite-like" dikes cutting the augite syenite. HAMILTON (op. cit., pp. 18–19) has described a contact, also observed by the author, between these two rock types at Narssaq Elv, which is marked by a 10 cm wide potassium feldspar zone; in addition, the naujaite is fine-grained. A pegmatitic zone is also typically developed near this contact, occurring a short distance within the naujaite. Micro-cracks in the augite syenite, containing eudialyte and aegirine, are also to be found. A contact between augite syenite and naujaite xenoliths observed within the kakortokite is marked by a 20–25 cm wide zone of a feldspar having a grain size similar to that occurring in the augite syenite.

Where the lujavrite has invaded the brecciated augite syenite, the contacts are sharp. This is most noticeable in the areas just west of Tugtup agtakôrfia, Narssaq Elv, Kvanefjeld and Laksefjeld. In most cases there is a slight concentration of dark minerals in the lujavrite along these contacts, but no change in grain size. On top of Laksefjeld, augite syenite blocks occur in green lujavrite; here the immediate contact is marked by a 2 cm wide zone of sugary feldspar. Apophyses of lujavrite occur in the augite syenite. Along the SE margin of the Intrusion, the marginal augite syenite is separated from the lujavrite by an agpaitic pegmatite 50 m wide. HAMILTON (1964, p. 17) has reported a contact between augite syenite and lujavrite veins of the W margin of the Intrusion where "in the actual contact zone green aegirine-analcite-lujavrite predominates".

The contact between the marginal augite syenite and kakortokite is marked by an irregularly-zoned agpaitic pegmatite, 50 to 100 m wide. This pegmatite zone is continuous along the entire contact between these two rock types and also continues a short distance into the augite syenite to the SSW of Laksefjeld. The minerals in this pegmatite zone are of the same variety as those found in the kakortokite and measure from 5 to 20 cm long. Arfvedsonite/aegirine, feldspar and eudialyte tend to concentrate, producing irregular layered pegmatites set in a coarse-grained matrix. There is no change in grain size in the augite syenite as the pegmatitic contact is approached. The immediate contact of

the augite syenite with the pegmatite is marked by vertical veins of fibrous aegirine, up to 15 cm wide, and also 20 cm wide feldspar-arfvedsonite pegmatites, penetrating the augite syenite. A few small augite syenite xenoliths were noted to occur at a few localities in the main pegmatite within a few metres of the contact with the augite syenite.

Further contacts between augite syenite and kakortokite are to be found where xenoliths of the former rock make their appearance in the kakortokite. These xenoliths vary in size from small fragments measuring a few centimetres, to blocks up to 400 m long. These xenoliths usually have a conformable attitude to the layering in the kakortokite. The contact between these augite syenite xenoliths and the kakortokite is usually marked by pegmatitic development of agpaitic minerals. These contact pegmatites measure from 5 cm to 3 m wide, averaging 2 m. The pegmatitic minerals reach a size of 15 cm long but are generally 4 to 8 cm long. Local variations of the above contact conditions occur where a 5 cm wide fine-grained feldspar zone is found and occasionally narrow veins of the feldspar penetrate the kakortokite for distances up to 40 cm. Also noted in one instance was the development of aegirine veins, 1 to 2 cm wide, in the kakortokite paralleling the pegmatitic contact with the augite syenite.

At approximately 2.8 km NE of Iviangiussaq kangigdleq, and at an altitude of 500 m, there occurs a prominent, coarse-grained, melanocratic, cylindrical body in the augite syenite. This body measures approximately 7 to 10 m in diameter and protrudes a few metres above the surrounding augite syenite. This rock is dominantly comprised of arfvedsonite anhedra, measuring 1 to 2 cm in diameter, with a smaller amount of aegirine, small albite laths, zoisite, fluorite and a minor amount of zeolite (GGU 24766, 22623, 21841). An X-ray diffraction pattern revealed the presence of carbonate apatite in this rock. The interference figure showed this mineral to have a small 2 V but was not measurable on the universal-stage.

Agpaitic pegmatite resembling that which occurs between the marginal augite syenite and kakortokite is to be found elsewhere. To the NNE of Laksefjeld, an apgaitic pegmatite occurs of similar dimensions and character as that separating the augite syenite and kakortokite. This pegmatite has a NNE strike and is continuous for a distance of 3 km. This pegmatite occurs mainly as the boundary between augite syenite and green lujavrite but is also transgressive to the former rock type over a short distance. There is a reappearance of agpaitic pegmatite 0.8 km further to the N of the latter pegmatite which is marginal to the Intrusion and continues for a distance of 0.8 km before pinching out 0.1 km S of Agpat. Ussing (1912, p. 71) reported this pegmatitic occurrence as being unlayered kakortokite, rich in eudialyte, which

separates the lujavrite from the downfaulted block of sandstone to the E. SØRENSEN (1958, p. 15) also visited Agpat and, as confirmed by the author, did not see this dike exposed at sea-level; the contact between the lujavrite and sandstone here is brecciated and rich in fluorite. Unfortunately, at the S end of this dike where the lujavrite and sandstone again meet, the contact is obscured by strong pneumotolytic alteration.

Alkali granite and transitional rocks

Distribution and contact relations

The main occurrences of alkali granite are found as two sheets in the north-central part of the Intrusion to the north of Tunugdliarfik. These two sheets occupy positions both above and below the central augite syenite sheet and for the most part have conformable relations (see section on augite syenite for attitude of these sheets). Along the N margin of the lower alkali granite sheet, a portion of the roof capping of volcanics separates the sheets of augite syenite and alkali granite. In this area, the lower alkali granite sheet on outcrop is vertically disposed. The true thickness of the lower alkali granite sheet varies from 60 to 100 m. Along the N and W margins the thickness varies from 80 to 100 m, and along the E and S margins it has a constant thickness of 60 m. The remains of the upper eroded sheet of alkali granite has a maximum thickness of 100 m and has a moderate dip to the S.

To the S of Tunugdliarfik, the alkali granite occurrences are limited to two very small bodies, measuring a few metres in diameter, within the remnant cappings of heterogeneous syenite to the NE of Nunarsarnaussaq. USSING (1912, p. 70) reported that in this area "there are several small, projecting cliffs of a light greenish, coarse-grained arfvedsonite granite", and that each of these masses measures only a few metres in extent. Fairly large quartz syenite masses were found in this area, which are not reported by USSING (op. cit.) but, other than the two bodies of alkali granite mentioned, no further occurrence of this granite rock type was noted by the author.

The contact between the alkali granite and the country rocks was seen on the N slope of a hill, 1 km ESE of Nákâlâq peak. Here, the granite is in contact with the roof-capping of volcanics, and is fine-grained, with the arfvedsonite prisms measuring 1–2 mm long and the feldspar and quartz having a sugary texture. No noticeable alteration was seen in the volcanics.

To the N of Tunugdliarfik in the north-central area, the lower alkali granite sheet has an interesting transitional relationship towards the underlying partially-developed heterogeneous syenite sheet. Pro-

ceeding downward from the alkali granite sheet, the following rock types are encountered: quartz syenite, pulaskite and heterogeneous syenite. Ussing (1912, p. 80) has referred to the quartz syenite, pulaskite and foyaite (heterogeneous syenite) as the transition series. The alkali granite grades down imperceptibly into a conformable quartz syenite sheet which has a fairly constant thickness of 5 to 10 m, with a variable quartz content. At the top of the quartz syenite sheet, the quartz content is less than 15 per cent but, at the lower contact, it grades imperceptibly into a nepheline-bearing pulaskitic rock. The division between the quartz syenite and alkali granite is a fairly arbitrary one in the field, as these two rock types have similar compositional and textural appearances. However, on the whole, the alkali granite is a slightly coarser-grained rock. The petrographic division between these two rock types is taken as 15 per cent quartz; in excess of this amount the rock is classified as an alkali granite and below this quartz content as a quartz syenite. The lower transition of the quartz syenite sheet into pulaskite takes place over a thickness of approximately 4 m before the conformable pulaskite sheet is encountered which averages 5 to 10 m thick. The first indication of this transition is the gradual decrease in the quartz content into a quartz-free zone, which in turn is underlain by a feldspathoidal rock. The quartz syenite and pulaskite have a very similar texture but a moderate colour contrast; the feldspars in the former are green in contrast to the grey of the latter.

Hamilton (1964, p. 58) has reported that at a locality 1 km to the N of Taseq, the quartz syenite contains xenoliths of naujaite, sodalite foyaite and pulaskite and that locally the quartz syenite may in fact be granite. The author has observed a large naujaite xenolith in granite at this locality; the naujaite was only identifiable by its characteristic texture; extreme hematite and fluorite alteration, faulting and scree cover make conclusive recognition of all local rock types very difficult.

Where the heterogeneous syenite is developed and comes into contact with the pulaskite, the contact is gradational over several centimetres with no change in grain size of either rock.

It should be noted here that Hamilton (1964, Pl. 1) does not show the quartz syenite and pulaskite sheets as being continuous in this main sheeted capping of transition rocks. In his text, reference is made to units that may be a variety of pulaskite (p. 54) but they are not shown on Hamilton's map. The continuity of the foyaite in Hamilton's mapping is not known as they have a common symbol with the sodalite foyaite. However, Hamilton has referred to a foyaite or possible variety of foyaite in four of the five sequences that he has investigated. In the fifth sequence "E" (p. 60), alteration and displacement obscure the identification of the rock types.

At a distance of 0.6 km S of Taseq, there is a further occurrence of these transitional rocks in the form of a small capping. The sequence of rocks displayed in this remnant capping is identical with that found in the main occurrence in the north-central part of the Intrusion, with the exception that the normally overlying alkali granite sheet is absent and also that the thicknesses of the rocks units are, for the most part, more condensed. The layered sheets in this capping have a synclinal disposition with dips measuring up to 70° E on the W side and 15° W on the E side. The sodalite foyaite is found as a thin discontinuous sheet having a maximum thickness of 2 m, and it passes transitionally into the heterogeneous syenite over a distance of 0.5 m. Where the sodalite foyaite is absent, the finer grained variety of naujaite occurs, displaying a perfect transition towards the heterogeneous syenite over 0.5 m. The heterogeneous syenite has a maximum thickness of 2 m and passes transitionally upwards into pulaskite, well developed as a sheet approximately 15 m thick. This latter rock grades imperceptibly into quartz syenite which is present as a remnant capping, a few metres thick. USSING (1912) has made no mention of this capping of transitional rocks and HAMILTON (1964, Pl. 1) has given the augite syenite symbol to this capping of rocks but has made no mention of it in his text. It should be noted that this capping of rocks has undergone some alteration, making field identification of some of the units rather difficult.

To the S of Tunugdliarfik, the relationship between the heterogeneous syenite (foyaite), pulaskite, quartz syenite and alkali granite is more complicated. To the NE of Nunasarnaussaq, there occur three small cappings of heterogeneous syenite which overlie the sodalite foyaite. The largest of these cappings is found approximately 1 km SW of Tuperssuatsiait, mostly confined to the 200 and 300 m contours and measuring 0.8 by 0.5 km.

Surrounding the aforementioned two alkali granite bodies occurring within the heterogeneous syenite, are narrow zones of first quartz syenite and, outermost, pulaskite. As usual, a perfect transitional relationship exists between these rock units. Pulaskite and quartz syenite are also present as small separate plug-like bodies, frequently displaying small-scale layering having low dip angles. The pulaskite and quartz syenite bodies have vertical and conformable sill contact relationships towards the heterogeneous syenite. On the NE slope of Nunasarnaussaq, an elongate body of pulaskite separates, for the most part, the marginal augite syenite from the heterogeneous syenite. Contact relations towards the augite syenite are obscured by scree, and in the only instance noted, the contact between the pulaskite and heterogeneous syenite was a vertical one and transitional over a few centimetres.

Ussing (1912, p. 69) observed two of the cappings of heterogeneous syenite (foyaite) to the NE of Nunasarnaussaq, which he regarded as being overlain by sheets of pulaskite varying from 20 to 50 m thick. Extensive pulaskite sheets, however, were not observed by the author; furthermore, Ussing failed to identify quartz syenite in these remnant cappings. The occurrence of the thin pulaskite body on the NE side of Nunasarnaussaq was observed by Ussing (1912, p. 341), but because of the lack of contacts he drew no conclusions regarding its form or age relationships.

Sodalite foyaite

Agpaitic rocks make up the bulk of the rocks occurring within the Ilímaussaq Intrusion. The major rock units in this group include sodalite foyaite, naujaite, lujavrites and kakortokite.

Distribution

The sodalite foyaite occurs in three areas, two of which are to the N of Tunugdliarfik and one to the S of this fiord. In all three localities this rock unit has the disposition of a remnant sheet overlying the naujaite. To the N of Tunugdliarfik, the largest sheeted occurrence of sodalite foyaite is to be found underlying conformably the transition series in the main north central capping. The sodalite foyaite also makes its appearance in the small capping of transitional rocks, 0.6 km S of Taseq. For a description of the dispositions of these sheets the reader is referred to the augite syenite section. The large occurrence of sodalite foyaite in the north central part of the Intrusion averages 15–20 m thick, with a maximum of approximately 100 m near the 1334 m peak of Nákâlâq and a minimum of 1–2 m immediately to the E of Taseq. Hamilton (1964) makes no reference to the form of the sodalite foyaite in the N central capping; however, on Pl. 1, where the generally unnumbered dip symbols are shown, there is a general agreement with the author's observations.

In the small capping of transitional rocks to the S of Taseq, the sodalite foyaite has a maximum thickness of 2 m and pinches out locally on the SE side. This occurrence of sodalite foyaite was not observed by Hamilton (1964) or Ussing (1912).

To the S of Tunugdliarfik, the sodalite foyaite sheet straddles the water divide between Tunugdliarfik and Kangerdluarssuk. This sheet has a dominantly E–W strike and dips 15° to the N; however, along the west contact with the naujaite, this sheet strikes NNW and dips easterly at 30°. Calculations of the thickness of this sheet indicate an average

of 40 m and a maximum of 120 m. USSING (1912, p. 68) ascribes a greater thickness to this sheet: "At places the thickness is considerably over 150 meters". This is not in keeping with the author's findings, but it must be remembered that these are calculated and not observed thicknesses.

USSING (1912, p. 68) regards the two main occurrences of sodalite foyaite as a whole being a formerly continuous thick sheet with a basin-shaped disposition. This view is also held by the author. It would appear that USSING (1912) did not see the vertical attitude of this sheet near the 1334 m peak of Nákâlâq.

Contact Relations

Where the heterogeneous syenite is not present, the sodalite foyaite comes into contact with the pulaskite. This contact was observed at only two localities. Along the northern margin of the main sheeted body this contact shows two contrasting styles. In the one case these rock types have a sharp contact with no textural or compositional change in either rock type. In the second occurrence, the sodalite foyaite and pulaskite contact is marked by a 20 cm wide nepheline-bearing pegmatite which is characterized by the development of stellated aegirine crystals.

The sodalite foyaite normally has a transitional contact with the overlying heterogeneous syenite over a width of 20–50 cm; however, in one instance a sharp contact was observed. The normal relationship is marked by a decrease in the grain size of the sodalite foyaite over a zone approximately 20 cm wide; the feldspar and aegirine anhedra decrease from 1.5 cm to 0.5 cm in diameter. This is followed by a perfectly transitional zone with the heterogeneous syenite over a width of 20–50 cm. On the E contact of the capping of heterogeneous syenite immediately to the NE of Nunasarnaussaq, a sharp undulose contact between these two rock types was noted, the sodalite foyaite having a finer grain size than usual and showing an increase in olivine content within 20 cm of the contact with the heterogeneous syenite.

USSING (1912, pp. 69 and 79) makes reference to the perfect transition of sodalite foyaite into foyaite (heterogeneous syenite) but makes no mention of the width of this zone. HAMILTON (1964, p. 40) remarks on the increase of olivine in the sodalite foyaite near the contact with the foyaite.

Naujaite

Distribution

The naujaite makes up the main bulk of the exposed rock in the Ilímaussaq Intrusion and directly underlies the sodalite foyaite. The naujaite also has a layered structure which shows a concordancy with

the overlying sodalite foyaite sheet. The upper part of this naujaite "sheet" is relatively undisturbed; however, its possibly sheet-like nature is obscured in the lower exposed parts due to brecciation and the presence of lujavrite. The upper part of the naujaite is relatively free of lujavrite. The breccia zones are well exposed along the NW margin at Kvanefjeld, in the cliffs behind Tugtup agtakôrfia and Igdlúnguaq, within the peninsula of Nunasarnaq and in the cliffs to the N of Lakseelv.

To the N of Tunugdliarfik the naujaite underlies the two occurrences of sodalite foyaite and in most cases extends to the borders of the Intrusion. Along the W contact HAMILTON (1964, Pl. 1) shows the augite syenite as a buffer between the naujaite and country rocks along its entire length. The author's findings contrast with HAMILTON's in that the augite syenite is found to be absent from 0.6 km S of Taseq to Narssaq Elv so that the naujaite is free to make contact with the country rock (see discussion in augite syenite section).

In the Kvanefjeld area the naujaite has only limited contact with the country rocks as this part of the Intrusion is rich in lujavrites and the remnant augite syenite shell is present sporadically. However, E of Kvanefjeld along the N and E contacts on the Intrusion the naujaite is in almost continuous contact with the country rocks except for minor interruptions caused by intervening lujavrite.

The naujaite extends down to sea-level along the N shore of Tunugdliarfik with interruptions caused by brecciated zones rich in lujavrite, particularly along the W and E margins.

To the S of Tunugdliarfik the naujaite is mainly confined to the area between the latter fiord and that to the N of Lakseelv. S of Lakseelv only minor inclusions of naujaite are found in the lujavrites and kakortokite. Within the main naujaite area to the S of Tunugdliarfik this rock type underlies the sodalite foyaite sheet. Along the W contact the naujaite is separated from the country rocks by a buffer of marginal augite syenite. To the N the naujaite extends down to sea-level with minor lujavrite interruptions along the W margin and extensive development of lujavrite along the E margin. Immediately to the N of Lakseelv the naujaite is heavily brecciated and enclosed by lujavrites.

The thickness of the naujaite "sheet" is difficult to assess due to brecciation and the fact that its base is nowhere exposed. Calculations made from the main exposed breccia zones to the upper contact with the sodalite foyaite indicate a thickness between 600 and 800 m. This figure is similar to that given by USSING (1912, p. 143) who states that "The naujaite reaches its maximum thickness, about 600 meters, at the inner end of Kangerdluarsuk".

Contact relations

For the most part there is a complete transition between the naujaite and sodalite foyaite. In the main occurrence of sodalite foyaite to the N of Tunugdliarfik this transition takes place over a zone approximately 2 m wide. The normal 5–10 cm diameter poikilitic phenocrysts in the naujaite decrease to 0.5–2.0 cm in diameter and the included euhedral sodalites decrease from 3 mm to less than 1 mm in width. Progressing upwards, the sodalite tends to collect interstitially until finally the transition into non-poikilitic sodalite foyaite is complete. To the S of Tunugdliarfik this transition zone can be up to 7 m thick.

In two areas there are notable exceptions to the transitional nature of this contact. S of Tunugdliarfik over a strike distance of 0.5 km, the western contact of the sodalite foyaite and naujaite sheets is knife sharp. Here both rock types have normal development right up to the contact. In the small capping of rocks to the S of Taseq the contact between the naujaite and sodalite foyaite is also sharp; the sodalite foyaite has only minor development, having a maximum thickness of 2 m, and pinches out locally. The naujaite at this locality, whether in contact with sodalite foyaite or heterogeneous syenite, has decreased in grain size (GGU 48044), the poikilitic anhedra being only 1 cm in diameter and the included sodalite 1 mm in diameter. Naujaite showing a decreased grain size has also been noted elsewhere, notably in the Tuperssuatsiait area (GGU 21953).

USSING (1912, p. 67) has noted the dominant transition of naujaite into sodalite foyaite. However, HAMILTON (1964, pp. 40 and 50) refers to this contact as being sharp. The latter author has also reported inclusions of sodalite foyaite in naujaite to the S of Tunugdliarfik (p. 45, Fig. 21).

The contact between the naujaite and country rock basalts was seen along the NE boundary of the Intrusion at an altitude of 800 m. This contact is marked by a 5 m wide agpaitic pegmatite. This pegmatite makes sharp vertical contacts with both the naujaite and basalt and in addition, small apophyses of agpaitic pegmatite also project into the basalt. Heavy natrolization of the agpaitic pegmatite has taken place.

The contact between the naujaite and kakortokite is seen where blocks of the former occur in the kakortokite. This contact is variable but is usually marked by a pegmatitic zone ranging from 12–50 cm wide, averaging 20 cm. The composition of the pegmatites is agpaitic and can show a zoning with eudialyte concentration towards the kakortokite and arfvedsonite concentration along the naujaite contact. The textures and compositions of the naujaite and kakortokite are unaffected in these cases. A felted aegirine vein 5–10 cm wide was also observed forming the

contact between these two rock types. In one instance the contact between the naujaite and kakortokite was seen to be knife-sharp, with the naujaite being free of sodalite within 3 cm of the contact and the kakortokite containing a series of en echelon zeolite veins parallel to the contact. At a locality 0.6 km SSE of Lakseelv mouth the contact between the kakortokite and a naujaite xenolith is marked by an apophysis of naujaite measuring 1 m wide × 5 m long in the kakortokite.

On the N shore of the small lake on Kringlerne a naujaite xenolith contains a steeply dipping fracture which is filled by a 1.5 m wide body having kakortokitic composition. This latter body has narrow layering developed parallel to the contacts. An 8 to 15 cm wide concentration of eudialyte often marks the contact; however, narrow arfvedsonite layers are sometimes to be found in conjunction with the eudialyte on the naujaite side of the contact.

Kakortokite

Kakortokite has been defined by Ussing (1912, p. 43) as the group name for the petrographically variegated sheets of Kringlerne, in the southern portion of the Intrusion, which may be regarded as varieties of one rock-type. The high plateau of Kringlerne owes its name to the layered kakortokite sequence resembling "ring-twisted cakes".

Distribution

This mass of rocks is found in the southern portion of the Intrusion to the south of Kangerdluarssuk and occupies an area extending 5 km along a NE axis and 2.1 km along a SE axis. The kakortokite extends from a point approximately 2 km NE of the peak of Iviangiussaq kangigdleq, north eastwards to a point approximately 2.2 km up the Lakseelv, where it disappears under alluvium and augite syenite beneath the NW flank of Laksefjeld. The kakortokite is separated from the country rocks by a rather thick marginal augite syenite shell and an agpaitic pegmatite buffer occurring between the kakortokite and augite syenite.

The definition of kakortokite has produced some confusion, as Ussing (1912, p. 49) has referred also to the pegmatite found to the NE of Laksefjeld as kakortokite. As this rock is coarser grained, generally unlayered and, in part, unconnected with the type area, application of the name would appear a misnomer. The author would like to limit the name kakortokite to a layered sequence of rocks having the mineralogical composition and textural features characterized in the type area of Kringlerne, possibly including occurrences of unlayered rock that occur in continuation with the main layered series of Kringlerne.

USSING (1912, p. 38 and Fig. 5, p. 39) and SØRENSEN (1958, pp. 18–19, Fig. 9) have reported the presence of black lujavrite underlying the kakortokite in a tributary of the Lakseelv to the NW of Laksefjeld. SØRENSEN (op. cit.) described the occurrence of "lujavrite" which "is black and resembles a fine-grained black kakortokite". In the field the author could not establish the presence of black lujavrite in these areas but only what appeared to be unlayered kakortokite. This controversial sequence of rocks will be granted a separate status in the later petrochemical sections and for convenience be termed "hybrid" rocks. A rock, part of which resembles green lujavrite, was found in dike form cutting these "hybrid" rocks at a locality 1.3 km upstream from Lakseelv mouth and situated on the south bank (specimens GGU 21855–6). This ENE-striking dike dips steeply to the SSE, measures 5 m wide and has sharp contacts. This rock type will be treated as a special variety of "hybrid" and be termed "aegirine dike" during the subsequent petrochemical investigation. Thereafter an attempt will be made to place this rock in its correct category.

Other findings of the author in the area to the NW of Laksefjeld indicate that directly overlying the kakortokite is what appears to be very altered "augite syenite" rather than green lujavrite reported by USSING (1912, p. 38). The latter rock type is found a little higher up in the sequence. It must be pointed out that from approximately 300 m upwards, the rocks in the Laksefjeld area are very altered, making differences between unlayered kakortokite and augite syenite very difficult to distinguish. In these altered rocks, the felsic minerals are generally completely zeolotized or albitized, grossularite garnet is present, and the ferromagnesian mineral(s) are altered to a brown amphibole. However, a rock type to the NW of Laksefjeld has still retained enough characteristic properties to be identified as augite syenite in that cryptoperthite, olivine and augite are present (GGU 24781). A distinct occurrence of layered kakortokite (GGU 24908–10) in very altered "augite syenite" is found at 550 m to the SW of Laksefjeld peak.

Examples of kakortokite being included in other agpaitic rocks are mentioned by USSING (1912, p. 47); occurring at 70 m up the tributary of Lakseelv to the NW of Laksefjeld are very small flat lenses of karkotokite included in "lujavrite" ("hybrids") measuring 0.2–2.0 cm thick and rich in eudialyte and paralleling the parting planes. At 80 m in the same river bed, SØRENSEN (1958, p. 18, Fig. 9) reports vein-like inclusions of kakortokite in "lujavrite". The author, as mentioned earlier, regards the "black lujavrite" in this area as possibly being unlayered kakortokite; the occurrences of "kakortokite", just referred to, were seen by the author; by virtue of their small size they defy accurate

correlation with kakortokite. It should be remembered that the mineralogical difference between some of the agpaitic rocks is very minor and that unless the inclusions are large enough to enable recognition of characteristic layering, one should approach identification of the rock type with caution.

Similar criticisms can be levied at other occurrences of "kakortokitic" rocks as reported by SØRENSEN (1958, pp. 15–16) who mentions that F. L. JACOBSEN and J. BONDAM found inclusions of kakortokite in lujavrite and a dike of kakortokite in naujaite respectively. SØRENSEN (op. cit.) also reports conformable inclusions of kakortokite in lujavrite at the head of Kangerdluarssuk where there is evidence of gravitative crystal accumulation. The author studied these "inclusions" in some detail together with a number of rock bodies present in lujavrites that were problematical and not unlike the unlayered kakortokite.

Of these occurrences, four were observed on the peninsula of Nunasarnaq as plug-shaped masses several metres in diameter (GGU specimens 22526, 22541, 22550 and 22554), a thick lens measuring 6 × 12 m was seen between Lilleelv and Lakseelv at 200 m (GGU 24954), irregular lenses up to a few metres long were noted at the head of Kangerdluarssuk at 100 m (GGU 21851) and finally a 60 cm wide sill was recorded at sea level 1.2 km NW of Agpat (GGU 21979). At this stage the generally unlayered nature of these bodies and the lack of detailed petrographic and geochemical evidence casts suspicion on attempts at correlation with the kakortokite. In further discussion of this problem, these rocks will be regarded as a separate entity and be termed "kakortokitic" rocks. They are then distinguishable from the "hybrids" in that the latter are rock occurrences of "lujavrite/unlayered kakortokite" habit that underlie the layered kakortokite sequence to the NW of Laksefjeld, whereas the "kakortokitic" rocks are from outside of this area and constitute small separate bodies.

Contact relations

Intrusions of feldspar porphyry syenite are found in the kakortokite, and sparingly, in the green lujavrite. They have both dike and sill form. In the SW and NE portion of the kakortokite there is a sill of this rock type underlying a red layer of the kakortokite. Sills are generally connected by a series of NE striking dikes. A few minor bodies occur also as small plugs in the green lujavrite on top of Laksefjeld. The plugs are usually over 3 m in width and have a 10 cm wide chill zone showing a concentration of dark minerals. Where they decrease in width to less than 0.5 m, there is a complete reaction with the kakortokite marked by a pegmatitic zone, 1 to 2 m wide, containing large spherulitic aegirines.

At 350 m, towards the SW margin of Kringlerne, a 75 cm thick pegmatite was found occurring concordantly with the layering of the kakortokite and containing fibrous aegirine, feldspar, eudialyte, rinkite and white mica.

The occurrence of distinctly layered kakortokite in augite syenite at 550 m to the SW of Laksefjeld has been interpreted by the author as being an inlier of kakortokite surrounded by giant blocks of augite syenite. However, on further reflection it is possible that the augite syenite has been misidentified in these very altered rocks and that the area of augite syenite that is shown in the map to underlie the green lujavrite at Laksefjeld, is in fact very altered kakortokite. If this latter interpretation is correct, GGU specimen 24781 would have to represent an inclusion and the area shown as augite syenite on the map (FERGUSON, 1964, Plate 1) should be reduced to the locality of this sample. This idea would be in keeping with USSING's view (1912, p. 38), namely, that the kakortokite is overlain by green lujavrite in this area; however, the author has doubts that the kakortokite is underlain by black lujavrite.

Where the kakortokite approaches the marginal agpaitic pegmatite, which separates the former from the augite syenite, the layers wedge out to within 50 to 100 m of the contact. Within the latter zone a rock is present having the mineralogy, texture and fabric of a homogeneous kakortokite. As these rocks are in lateral continuity with the main mass of kakortokite and have the average mineralogy of the latter rock, the author sees no reason to exclude them from the definition of kakortokite as they can still be regarded as varieties of one rock type.

Lujavrites

General

The lujavrites are finer grained than the other agpaitic rocks of the Intrusion, and are texturally further contrasted by developing a strong fissility, so much so that earlier travellers described them as "chlorite schist" or "a kind of gneiss" (GIESECKE, 1910).

There are two primary varieties of lujavrite, a black arfvedsonite-rich variety and a green aegirine-rich variety. These two types occur in approximately equal amounts. Aegirine and/or arfvedsonite make up a total of 22–58% (average 37%) of the rock and interchange with one another, producing black or green lujavrite depending on the occurrence of either arfvedsonite or aegirine enrichment.

A pegmatitic rock which is particularly well developed between Tuperssuatsiait and Agpat has also been classed as a variety of green

lujavrite. Here the mineralogy is essentially that of the green lujavrite but local facies comprise crystals of pegmatitic dimensions of feldspar, arfvedsonite and aegirine; which can measure up to 50 cm long. In addition there are minor occurrences of black lujavrite. There is no definite trend to the pegmatitic development which forms irregular masses within the subordinate normal green lujavrite. Irregular compositional layering emphasises the heterogeneity of this rock. The identification, by the author, of this expanse of rock between Tuperssuatsiait and Agpat as a local variation of the green lujavrite, is open to question, as the pegmatitic facies are in excess of the fine- to medium-grained green lujavrite. On the coast, at approximately 1 km to the E of Tuperssuatsiait, occasional black lujavrite dikelets can be seen cross-cutting the irregular pegmatitic rocks.

Another area of pegmatitic development in lujavrite occurs near the western extremity of Nunasarnaq peninsula. Here, irregular pegmatites of the order of 1 to 2 m wide are found, containing feldspar phenocrysts, 16 cm long and 3 cm in diameter, as well as radiating clusters of aegirine; eudialyte, nepheline and sodalite occur as 1 to 2 cm diameter phenocrysts. The sodalite and nepheline frequently have white analcime veins cutting through them.

To the east of Igdlúnguaq, brown nodules measuring 3–4 cm long × 1 cm wide are found in the black lujavrite. These nodules comprise analcime and acmite; the latter is sometimes homoaxially grown on a small arfvedsonite core. The fissility of the rock passes through these nodules and there is no textural change between the nodules and host lujavrite (GGU 48094).

At Idglúnguaq, Tugtup agtakôrfia and Kvanefjeld, a peculiar nodular texture is present in the black lujavrite. These nodules average 4–8 cm in diameter (range 2–20 cm). They are ellipsoidal, being slightly flattened parallel to the fissility. A pale corona of acmite and analcime, 1 cm wide, surrounds these readily weathered nodules, the cores of which are dominantly analcime with minor arfvedsonite. Ussing (1912, pp. 82–83) and Sørensen (1962, p. 34) have also made reference to the occurrence of these orbicular structures at two localities along the N coast of Tunugdliarfik.

Another type of mottling occurs in the black and green lujavrite. This is particularly well developed E of Nákâlâq near the border of the Intrusion, where spheroids of feldspar 10–15 cm in diameter are set in the normal black lujavrite. The lamination of the rock passes directly through them without deviation. Spheroidal feldspar nodules were also seen in the green lujavrite at two localities in the area 2.4 km SSW of Agpat. These nodules are roughly spherical, having an average diameter of 8 cm (range 2–14 cm), and are confined to a single horizon. They have

a more massive habit than the former type and with no vestige of the lamination of the rock passing through these spheroids.

On the S side of Taseq, in the river bed, an augen texture was encountered in black lujavrite dikes. This is caused by grey-black nodules of acmitic-rich lujavrite set in a fine-grained network of black lujavrite. There is heavy shearing parallel to the walls of the dikes.

SØRENSEN (1958, p. 43, Fig. 18) has described a lujavrite occurrence of small pillow-shaped "balls" from an area immediately to the W of Tugtup agtakôrfia. The "balls" consist of green lujavrite and the thin "veined" matrix comprises black lujavrite.

Distribution

The lujavrites have a wide distribution in the Ilímaussaq Intrusion. The largest exposed development of lujavrites is found to the south of Tunugdliarfik. The green and black lujavrites are frequently intimately associated, with the exception of the area extending from Laksefjord NNE to Agpat and westwards of the latter locality to Tuperssuatsiait, where green lujavrite predominates. A further characteristic of this extensive development of green lujavrite is the relative scarcity of naujaite inclusions which are usually ubiquitously present in these rocks.

Immediately to the N of Lakseelv, in an area extending from Kangerdluarssuk northeastwards to Agpat and approximately 1.4 km wide, there is extensive development of a breccia zone, where naujaite xenoliths are enclosed in lujavrites. Such breccia zones are common in lujavrites; in the lujavrites near the margins of the Intrusion additional xenoliths can include augite syenite and country rock. In addition to the Lakseelv area, other zones of breccia development include the hinterland area of Naujakasik, Tuperssuatsiait, the peninsula of Nunasarnaq, the western and eastern margins of the Intrusion along the N coast of Tunugdliarfik, particularly around Tugtup agtakôrfia and Igdlúnguaq, the Kvanefjeld area in the NW part of the Intrusion and in the Narssaq Elv.

In all the occurrences of lujavrites to the N of Lakseelv there is in general a preferred distribution of the black and green varieties. The main occurrences of green lujavrite are found in the lowermost exposed portions of the naujaite sheet and of the black lujavrite in higher zones. USSING (1912, p. 158) also made this observation, with the difference that he cited an additional arfvedsonitic sheet as underlying the green lujavrite at the mouth of Lakseelv (refer to kakortokite section for a discussion on this locality). There is a marked decrease of lujavrites in the uppermost parts of the naujaite. The black lujavrite is found in minor amounts at the top of the naujaite zone and cuts the sodalite

foyaite in the areas to the S of Tuperssuatsiait and to the SW of Nákâlâq at an altitude of 770 m. No lujavrites were found in horizons higher than the sodalite foyaite.

The marginal syenite is penetrated by lujavrites along the W contact of the Intrusion at approximately 1.6 km W of Tugtup agtakôrfia and in the Narssaq Elv and Kvanefjeld areas. In the Laksefjeld area, the green lujavrite is found to be under- and over-lying the augite syenite with near-horizontal contacts. There are two occurrences of lujavrite entirely within country rocks. On the W side of the Intrusion on the N shore of Tunugdliarfik, green lujavrite is situated within earlier volcanic rocks. Ussing (1912, p. 55) has described an ellipsoidal occurrence of black lujavrite on the E side of Iviangiussaq kangigdleq at about 500 m, which is entirely surrounded by country rock granite. The author spent a brief time in this area but did not observe this rock.

It is difficult to make thickness estimates for the lujavrites as most of these zones are masked by the presence of naujaite blocks. An additional difficulty is the fact that the base of this zone is not known with absolute certainty. In the case of the Laksefjeld occurrence of green lujavrite overlying augite syenite, where there is an almost complete absence of naujaite blocks, the calculation of the thickness is a comparatively easy matter if one assumes a constant dip of 20° north-westwards, as indicated by primary layering in a few localities. This calculated figure is of the order of 140 m true thickness. The difficulty now arises as to whether the green lujavrite to the N of Lakseelv can be correlated with the green lujavrite of Laksefjeld. If this is a valid correlation, then it would appear from the area 1.5 km to the S of Agpat, where black lujavrite overlies green lujavrite, that the black lujavrite sheet(s) would occur at a short distance above the exposed green lujavrite at Laksefjeld. The thickness of the black lujavrite is particularly difficult to calculate, as these rocks contain a very high percentage of naujaite xenoliths. If these black lujavrite units were free of xenoliths they would be of the order of 150 m to 250 m thick. Combining this figure with that obtained for the green lujavrite from Laksefjeld the total thickness would then be about 350 m. It must be remembered that this figure will be erroneous if correlation of the green lujavrite to the N with that to the S of Lakseelv cannot legitimately be made. These calculations should not distract from the fact that, together with the minor intrusions of lujavrites, this unit can be present through a vertical thickness of the order of 1 km in the exposed part of the Intrusion. Ussing (1912, p. 157) estimates that, in the area between Lakseelv and Agpat, the thickness of the lujavrite, measured perpendicularly to the parting, exceeds 600 m. Bearing in mind that the primary layering in

this area dips 40° NW and rapidly flattens out to the NW, the author's calculated value of the thickness is no greater than about 350 m.

Contact relations

The main contact between the black lujavrite of the breccia zone and the lower green lujavrite can be studied over a strike length of 6 km, and is completely gradational over a true thickness of approximately 3 m. The transitional rock is characterized by a colour tonal variation from black to grey to green corresponding to the change from arfvedsonite to aegirine enrichment. Away from this main contact, sharp conformable compositional layers, measuring from 1 cm to 1 m thick, can be seen in the black and, to a lesser extent, in the green lujavrite zones. The layers are lens-shaped, having an average lateral extent of 20 to 40 m before wedging out into the more homogeneous lujavrites.

To the N of Lakseelv, at a point approximately 3 km upstream, a large sheet of black lujavrite is present in the green lujavrite. The contact between these two rock types was noted at the western extremity of this sheet where at a point 1 km ENE of Lilleelv mouth there is a highly sinuous but sharp contact, with minor green lujavrite apophyses in the black lujavrite.

At the W end of Nunasarnaq peninsula, the contact between the green and black lujavrite is marked by a 2 to 5 cm wide analcime-rich light-coloured zone where arfvedsonite is absent and the aegirine is present as very fine needles; the eudialyte is fresh whereas the feldspars, nepheline and sodalite show strong analcime replacement.

Auto-intrusion was noted at sea-level near the eastern margin of the Intrusion at a point 2.2 km E of Nordre Siorarssuit, where alternating green and black lujavrite layers are truncated by cross-cutting inhomogeneous black lujavrite. To the N of Lakseelv, both the black and green lujavrite can be seen truncating one another.

Quite frequently "knots" of felted aegirine occur in the black lujavrite; sometimes these "inclusions" are entirely mono-mineralic and on other occasions have more or less the mineralogy of green lujavrite. SØRENSEN (1962, pp. 44–45 and Fig. 19) refers to a green vein, parts of which resemble green lujavrite, which is fragmental and enclosed by "dark" lujavrite. SØRENSEN (1958, p. 38 and Fig. 17) also refers to inclusions of green lujavrite in black lujavrite at Tugtup agtakôrfia. At a point 1 km E of Tuperssuatsiait in a ravine at sea-level, ptygmatic aegirine veins occur in green lujavrite.

At the W end of Nunasarnaq peninsula, lenses of a black rock, measuring a metre or two long, occur in green lujavrite. Thin section study of these xenoliths indicates a rock rich in arfvedsonite and having the approximate composition of a black lujavrite except for the absence

of eudialyte and the presence of a poikilitic non-acmitic clino-pyroxene (GGU 48087). An X-ray diffraction pattern of this mineral closely resembled diopside. Surrounding these inclusions is a light-coloured mantle, 1.5 to 4.0 cm wide, comprising a rock devoid of arfvedsonite and in which the aegirine only occurs as very fine needles; analcime is plentiful, eudialyte is present in average amounts whereas nepheline, feldspar and sodalite are sparingly present in this rock. A few centimetres away from this analcime-rich rim, there are 1.3 cm wide arfvedsonite concentrations in the green lujavrite over a width of 12 cm.

Naujaite xenoliths in lujavrites range from blocks measuring 0.6 km long to chips measuring a few centimetres. These xenoliths are generally conformably enclosed by the lujavrites; however, disconformable relationships are by no means uncommon. SØRENSEN (1962, p. 39) has described such a disconformable relationship from Igdlúnguaq. The size of the zenoliths has no influence on the contact relations. In a few cases, the contact between these rock types is sharp, showing no alterations. However, the contact is usually marked by veins or pegmatites and minor alterations in the lujavrite and naujaite. The usual effect produced at this contact, whether the rock is black or green lujavrite, is the concentration of felted aegirine and, in some cases, arfvedsonite prisms in a 1 to 6 cm wide zone where these prismatic minerals are either parallel or perpendicular to the contact. SØRENSEN (1962, p. 34) has decribed in great detail the lujavrite-naujaite contact from Igdlúnguaq where he notes a dark zone in the black lujavrite, a few centimetres thick, which is enriched in arfvedsonite aligned perpendicular to the border. In some cases the naujaite is also affected by having a bleached appearance due to analcime enrichment. SØRENSEN (1962, p. 59) made a similar observation. Agpaitic pegmatites can also occur along the lujavrite-naujaite contact, having a width of 15 cm. Apophyses and dikes of lujavrite up to a few metres wide commonly occur in the naujaite. Where these pegmatites occur, the naujaite and lujavrites can also show alteration. The black and green lujavrites exhibit bleached zones over a few centimetres, where there is a decrease in arfvedsonite and aegirine respectively and an increase in acmite and analcime. The naujaite is often very altered by zeolites over a zone less than 10 cm wide and is only recognizable by its characteristic poikilitic texture. SØRENSEN (1962, p. 38–39) reports steenstrupine enrichment along the borders of a naujaite block, rich in analcime, and also an intricate network of analcime veins branching out from the naujaite and penetrating the black lujavrite. In some cases the lujavrites increase their felsic content adjacent to naujaite inclusions, developing a coarser grained rock containing sodalite whose habit closely resembles that found in naujaite. In some cases these sodalite-shaped "xenocrysts" are completely replaced

by analcime (GGU 24835). SØRENSEN (1962, p. 36) has reported coarse-grained rocks in a similar environment containing remnants of naujaite minerals as well as fragments of this rock. At sea-level on the west coast of Tuperssuatsiait a green lujavrite dike, less than 50 cm wide, is found in the naujaite, which contains minor inclusions of feldspar of the habit found in the naujaite.

At the west end of Nunasarnaq peninsula, the contact of a naujaite block in the black lujavrite is marked by a 6 cm wide bleached zone, in which arfvedsonite is sparingly present and where there is a corresponding increase in microcline laths and, to a lesser extent, nepheline (GGU 48086).

The naujaite zenoliths in lujavrite are at times strongly boudinaged. This structure is particularly prevalent along the S shore of Tunugdliarfik between Tuperssuatsiait and Agpat. In some cases, the ends of the naujaite boudins are stretched out into thin streaky veins, a metre or two long and a few centimetres wide, which wedge out into the lujavrite. In a number of cases, particularly where the naujaite occurs as small chips, the lujavrite develops a flow pattern around them. These small naujaite fragments in the lujavrite can also be remarkably angular and are frequently unaffected by the strong fissility of the lujavrite. These small fragments are most commonly conformable to the fissility of the lujavrite; however, they sometimes bear a transgressive relationship. At times these naujaite fragments in lujavrite are highly stretched into long stringers.

In two instances, naujaite can be seen intruding lujavrite. In the one case this occurs on a fairly small scale where a few square metres of lujavrite have been brecciated by the intrusive naujaite at 640 m in the Narssaq Elv. The second instance is at a point 2 km NNE of Nordre Siorarssuit, where apophyses of naujaite up to 7 m long and 2 m wide are to be found in lujavrite, almost at right angles to the fissility of the latter rock.

At a distance of 0.9 km to the SSE of Tuperssuatsiait, the contact between a lujavrite dike and naujaite is marked by a 2 to 4 m wide zone in which numerous contorted veins of lujavrite individually measuring 1–5 cm wide, occur over a 2 to 4 m wide zone in the naujaite.

At the mouth of Lakseelv and on the north bank, the contact between green lujavrite and "hybrids" (see kakortokite section) is to be seen. The lujavrite is heavily sheared over a width of 10 m. The fissile plates have a thickness of 0.5 cm and strike N 60° and dip 50° NW. The lujavrite has a very high aegirine content. The "hybrids" have a lower aegirine content and an absence of fissility, but a strong foliation produced by the felsic minerals forming small augen enclosed by aegirine needles. This foliation parallels the fissility in the lujavrite. This contact

is obscured by overgrowth a short distance away from the mouth of the Lakseelv and by alluvium higher upstream.

In continuation of the strike direction of this contact, namely in the area between Lakseelv and Agpat, there is a marked linear depression that extends from the edge of the alluvium-covered area of Lakseelv north-eastwards down to sea-level. The south-western part of this depression occurs in lujavrite(s) and the north-eastern passes through an agpaitic pegmatite and a downfaulted sandstone block. Breccia rocks and fluorite are present along the floor and margins of this depression. It is difficult to establish the amount, if any, of horizontal movement that has taken place along this depression, as there is strong alteration of all these rocks, making identification of possible marker units in the lujavrite(s) impossible. It would appear that the agpaitic pegmatite is unaffected by any horizontal movement. The contact of the linear depression and sandstone block is complicated by a NNW-trending fault. The identity of the sandstone at this intersection was difficult to establish; it is quite possible that there is some horizontal displacement of the sandstone, but if so it cannot be of any great magnitude.

The main contact of the black lujavrite with country rock basalt and diabase was noted at a few localities, particularly at Nunasarnaq peninsula and the E contact on the N shore of Tunugdliarfik, at 150 m. The fissility of the lujavrite is vertical and parallel to the contact and in all cases a gneissic zone is developed, from 1 to 20 m width, comprising small arfvedsonite anhedra and albite together with minor quantities of a very altered mineral that could represent former eudialyte; the feldspar has a distinctly sugary texture in hand specimen (GGU 48067). Apophyses of lujavrite invade the wall rocks for distances up to 30 m. Ussing (1912, pp. 74–75) has reported similar observations on this contact. The sandstone in contact with the lujavrite takes on a dense bleached appearance and the porphyries develop biotite along this contact.

In the case of country rock xenoliths, whether of basalt, diabase, agglomerates or anorthosite, there is a gneissic zone varying from a few centimetres to 1 m wide in which stringers of feldspar and arfvedsonite or aegirine are found; in addition, veins of feldspar penetrate the basalt. At Kvanefjeld, the margins of the anorthosite xenoliths have a strongly gneissic appearance which has been emphasized by the marked colour contrast of the alternating plagioclase feldspar xenocrysts and lujavrite. Shearing has also taken place, with a marked alignment of the stretched plagioclase xenocrysts in lujavrite. Also at Kvanefjeld, the contact between lujavrites and basalts is usually marked by a "murmanite"-[1]

[1]) This mineral probably belongs to the series murmanite-lomonsovite, but may be a new niobium mineral.

or naujakasite-bearing rock. The "murmanite"-bearing rock is stretched and sharply contorted and has a maximum thickness of 50 m. It is fine-grained and dense with the minerals tending to form stringers. The weathered surface is characterized by streaks, knots, swirls and other compositional irregularities. A few stretched inclusions of naujaite and country rock are present in this rock. Aegirine-rich zones measuring a few metres in diameter also occur. The main characteristic of this rock is rhombs of a silver-pink "murmanite" measuring 0.5 cm in length and 1 mm thick. Usually there is a yellow star-shaped metamict mineral associated with the "murmanite"-bearing rock, having an average diameter of 1 cm and a maximum of 3 cm. Semi-quantitative spectrographic analysis of this mineral indicates a high niobium content. The naujakasite lujavrite is also quite common on Kvanefjeld where it forms minor horizons rarely wider than 50 m; the usual width is only 5 to 10 m. It is characterized by 1 mm rhombs of silvery naujakasite occurring in an acmitic lujavrite. Other minerals include microcline, albite laths, nepheline, a high relief metamict mineral and a brown, slightly pleochroic mineral which is usually contained within the margins of the naujakasite. The rock is always highly altered, very schistose, friable and subject to clayey weathering; the naujakasite, however, is always fresh and shiny.

At approximately 200 m to the NNE of Laksefjeld peak, a feldspar porphyry syenite body, 150 m in length, occurs in the green lujavrite. Nearby, also a 1 m thick dike of the same composition is found in the lujavrite. In both cases, the feldspar porphyry syenite develops a chill facies towards the lujavrite over a few centimetres. In addition, 10–15 cm long apophyses of syenite occur in the green lujavrite.

III. PETROLOGY

Petrography

"Hybrids"

The general petrography of the main intrusive rock units of Ilímaussaq has been described in earlier publications (Ussing, 1912 and Ferguson, 1964); this description limits itself therefore to the newly defined "hybrids" and "kakortokitic" rocks. The section following on this does, however, present additional information regarding the optical compositional and crystal lattice parameters of rock-forming minerals taken from the major petrographic units.

General

The "hybrids", as discussed earlier, comprise the controversial non-rhythmically layered rock unit underlying the kakortokite in the area NE of Kringlerne and occurring from sea-level up to 150 m. Ussing (1912, pp. 38 and 46) and Sørensen (1958, pp. 18–19) reported the presence of black lujavrite containing minor kakortokite inclusions underlying the kakortokite in this area. Sørensen (op. cit.) has also reported the occurrence of a 20 m thick layer of kakortokite in the "black lujavite" from this rock unit. Identifying these rocks in the field, the author regarded them to be more in the nature of non-rhythmically layered kakortokite except for the occurrence of an "aegirine dike" which cuts these rocks. Because of the controversial nature of these rocks, the writer decided to form a separate and arbitrary unit, termed "hybrids", to accommodate these rocks. After consideration of the petrochemical aspects of this unit, an attempt will be made to establish the correct identity of these rocks.

Macroscopic features

Generally these rocks are medium-grained, mesocratic and posses a planarism; at times they become fine-grained and more mesocratic than usual having no obvious planarism. In the fine-grained variety the eudialyte grains, less than 1 mm in diameter, tend to aggregate, forming clusters up to 0.5 cm in diameter. Exceptionally, the eudialyte grains can reach 3 mm in diameter.

In the more normal mesocratic medium-grained "hybrid", the feldspars, soda-pyroxenes and amphiboles reach a length of 4 mm.

Abundant, small, generally coarser-grained, leucocratic lenses and veins, rich in feldspar and eudialyte, are to be found in the upper part of this rock unit. The lenses lie parallel to the lamination of the host rock, and in addition possess a planarism coincident with the latter. The veins have a cross-cutting relationship to the lamination in the host rock and lack a preferred mineral fabric.

The "aegirine dike" comprises two components; commonly it is made up of a coarse-grained to pegmatitic rock and locally it develops a medium-grained facies (GGU specimens 21855 and 21856 respectively). There is no regularity to the distribution of the two facies. In the coarser grained rock radiating clusters of aegirine measure up to 5 cm long; it is also rich in fluorite. In the medium-grained rock aegirine prisms bend around the felsic minerals.

Microscopic features

The rock-forming minerals comprise alkali feldspars, acmitic pyroxenes, soda-amphiboles, eudialyte and nepheline. Accessory minerals include sodalite, aenigmatite, brown mica and fluorite. Secondary minerals are analcime, natrolite, fluorite, sodalite and katapleite.

Except in the "aegirine dike", microperthite laths are always developed, ranging in size from 2 to 4 mm long and having a length: breadth ratio of 4. The laths are flattened parallel to (010) with the development of the usual chessboard albite twinned microline. The

Table 2. *Compositions of the two feldspar phases and bulk composition of the homogenized alkali feldspar*

GGU Specimen number	Microcline % $NaAlSi_3O_8$		Plagioclase	Homogenized	
	Method d220 (Si) – d400 (Mi)	Method $2\theta(20_1$ felds – 101 $KBrO_3$) CuK_α	$2\theta(20_1$ felds – 101 $KBrO_3$) CuK_α % Ab	Alkali feldspar % Or	% Ab
21844.....	n.d.	6.0	+100	70	30
21853.....	0.2	6.0	+100	70	30
22636.....	n.d.	5.5	+100	70	30
24770.....	0.2	8.0	±100	69	31
24799.....	0.2	9.0	+100	72	28
48002.....	1.6	7.0	n.d.	n.d.	n.d.
48065.....	*	15.0	+100	70	30

* Value cannot be related to curve
n.d. Not determined

Table 3. *Optic axial angles and structural states of the two feldspar phases*

GGU Specimen number	K-feldspar 2Vx optic plane ~ ⊥ (010)	Δ-values	Na-feldspar 2Vx	2θ (131) – 2θ (131) CuK_α
21844.....	80.0	0.92	79.0	1.03
21853.....	77.0*	n.d.	n.d.	n.d.
21854.....	80.0	n.d.	n.d.	n.d.
21856..... ("aegirine dike" m.g.)	79.0	n.d.	abs.	abs.
21856..... ("aegirine dike" peg.)	80.0	n.d.	abs.	abs.
22635.....	77.0	n.d.	n.d.	n.d.
22636 (leuco)	77.0	n.d.	n.d.	n.d.
24770 (leuco)	77.5	n.d.	81.0*	1.04
24799.....	77.0	0.90	80.0*	1.07
48002.....	79.0	0.88	n.d.	n.d.
48065 (leuco)	77.0*	0.90	n.d.	n.d.

* = less than three direct readings
n.d. = not determined
abs. = absent
m.g. = medium-grained
peg. = pegmatitic
leuco = leucocratic lenses & veins

exsolved Na-phase and twinned microcline are elongated parallel to (010). In a few cases, the microperthite laths are mantled by fairly coarsely twinned albite. In addition to these 2 to 4 mm long microperthite laths, fine laths of albite, measuring less than 1 mm long, are abundantly present. These small albite laths are usually included in all the other minerals present in the rock. In the "aegirine dike" the only feldspar present is microcline in laths. They have the usual chessboard twinning developed. There are no textural differences other than size between the microperthites and small albite laths in the leucocratic lenses and veins when compared to those from the mesocratic host rock.

The optic axial angles and structural states of the K-feldspar indicate that they are near maximum microclines (Table 3).

The bulk chemical composition of the alkali feldspar shows remarkable consistency (Table 2). With the exception of GGU specimen 48065, the microclines show only small compositional variation.

The 2Vs of the exsolved Na-feldspars, combined with their structural states and composition (Tables 2 and 3), indicate that they are low

temperature albites (Fig. 4). The exsolved albite, as well as the small separate albite laths, is twinned on the albite and, less commonly, the Carlsbad laws.

In the mesocratic rocks and "aegirine dike" the microperthite laths do not project into and are not included in the other minerals of the rock. However, in the leucocratic lenses and veins, the feldspar laths usually project into the aegirine and arfvedsonite. The small albite laths are invariably included in all the rock-forming minerals in the "hybrid" unit. Microlites of aegirine and, to a lesser extent, arfvedsonite are always included in the microperthites, tending to parallel the (010) direction. This is in contrast with the small albite laths which only sparingly include similar microlites.

The acmitic pyroxenes within the "hybrids" are aegirine (Table 4) together with barely pleochroic acmite. The refractive index and optic axial angles of the latter are within the range of the aegirines found in this rock unit. The acmitic pyroxenes show either anhedral or euhedral habit; the latter are bounded by the {110} and {100} prism forms and elongated in the direction of the latter.

Table 4. *Optical properties of the acmitic pyroxenes*

GGU Specimen number	2Vx	X:c	Pleochroism X	Y	Z
21844	60°	7°	n.d.	light green	olive green
21856 ("aegirine dike m.g.)	66°	6°	n.d.	light green	olive green
21856 ("aegirine dike peg.)	66°	8°	n.d.	light green	olive green
22636	62°	7°	n.d.	light green	olive green
24770	63°	8°	n.d.	light brownish	brownish
48065	62°	6°	n.d.	light green	olive green

n.d. = not determined
m.g. = medium-grained
peg. = pegmatitic

The refractive index determinations of the soda-amphiboles indicate that they are arfvedsonite (Table 5).

In the mesocratic rocks and "aegirine dike" the aegirine and arfvedsonite, when present, are non-poikilitic except for the frequent occurrence of small albite lath inclusions in the former. In the leucocratic lenses and veins the microperthite laths and nepheline generally project into the aegirine and arfvedsonite grains, producing a semi-poikilitic habit.

Table 5. *Optical properties of the soda-amphiboles*

GGU Specimen number	R.I. Nx.	Pleochroism X	Y	Z
21844	1.685	n.d.	blue-black	olive green
21853	1.687	deep blue-green	blue-black	olive green
22636	1.685	n.d.	blue-black	olive green
24770	1.685	n.d.	blue-black	olive green
24799	1.688	n.d.	blue-black	olive green
48065	1.688	n.d.	blue-black	olive green

n.d. = not determined

The eudialyte tends to form subhedral plates, 1 mm in diameter; however, occasional anhedral poikilitic grains occur, measuring up to 3 mm in diameter. The inclusions comprise abundant small albite laths. The anhedral eudialyte grains tend to have poorly developed birefringence becoming near isotropic, but always give a marked uniaxial positive interference figure. Frequently, the eudialyte shows alteration to a mixture of katapleite, acmite, analcime and fluorite.

Nepheline is always present, occurring as equidimensional anhedra. In the mesocratic rocks and "aegirine dike" the nepheline has interstitial habit to the rock-forming minerals, whereas in the leucocratic bodies it can project into the pyroxene and amphiboles. Small albite laths and minute needles and grains of soda-pyroxene may be present as inclusions. Alteration products include natrolite, analcime and sodalite. The nephelines from these rocks show fairly constant composition (Table 6).

Table 6. *Compositions of nepheline*

GGU Specimen number	% $KAlSiO_4$	Vol. % zeolite in rock	% nepheline altered
21844	21.2	3.5	23.1
21853	19.4	0.0	0.0
21856 ("aegirine dike" m.g.)	25.9	35.6	26.3
22636	16.1	0.0	0.0
24770	19.4	0.9	2.7
24799	16.6	1.6	0.0
48065	23.7	0.8	4.1

m.g. = medium-grained

Sodalite and fluorite occur infrequently as primary minerals having interstitial habit and forming rounded grains, 1 to 2 mm in diameter.

A small amount of a strongly pleochroic, brown-red mica is frequently present, usually occurring in areas marginal to the pyroxenes and amphiboles and in association with aenigmatite.

"Kakortokitic" rocks

General

The "kakortokite" rocks, as previously discussed, are the controversial occurrences of small bodies with conformable and transgressive habit, and having a wide distribution; they occur in the lujavrites and naujaite. Megascopically they are not unlike kakortokite and have been so correlated by SØRENSEN (1958, pp. 15–16). This is borne out by reports made by F. L. JACOBSEN and J. BONDAM. These rocks are generally unlayered, although SØRENSEN (op. cit.) has reported "gravitative accumulation of black crystals of arfvedsonite" in some of the inclusions from a locality to the north of the Lakseelv mouth. Lack of detailed petrochemical work on these rocks made correlation with the kakortokite rather tenuous. For this reason it was decided to treat these small bodies as a separate entity and then, after investigating their petrochemical characteristics, to attempt either a correlation or the establishment of a separate rock group.

The "kakortokitic" rocks are distinguished from the "hybrids" in that the latter are the occurrences of "lujavrite and/or unlayered kakortokite" that underlie the layered kakortokite sequence NW of Laksefjeld. By contrast, the "kakortokitic" rocks are small bodies outside this area, occurring within lujavrites and naujaite.

Macroscopic features

These rocks show highly varied textures and uneven distribution in the proportion of minerals. Texturally they contrast in grain-size, structure and interrelationships of the minerals. They range in grain-size from medium- to coarse-grained and in some cases a planarism of the minerals is absent. By contrast to the other "kakortokitic" rocks where the aegirine is prismatic, in GGU specimen 22526 it is anhedral and has poikilitic habit.

Compositionally they vary markedly in that the rock-forming minerals, feldspar, soda-pyroxene and amphibole, eudialyte and nepheline are present in varying proportions. Eudialyte can, on occasion, be absent.

Microscopic features

The rock-forming minerals usually comprise alkali feldspar, acmitic pyroxenes, arfvedsonite, eudialyte and nepheline.

Accessory minerals include neptunite and mesodialyte. Secondary minerals found are natrolite, analcime, katapleite and fluorite.

The alkali feldspars vary in size from less than 1 mm diameter granules to laths up to 1 cm long. The K- and Na-feldspars have separate development where these bodies are found in lujavrite and occur as intergrowths when enclosed in naujaite. Microcline is always present in either separate laths or in intergrowth with Na-feldspar. The microcline possesses the usual chess board albite twinning and the laths are flattened parallel to (010).

Na-feldspar is usually present; however, in one rock having a high zeolite content, it is absent; this is possibly indicative of replacement.

The optic axial angles and structural states of the K-feldspar (Table 7) in the "kakortokitic" rocks indicate that they are near maximum microcline (Fig. 6).

Table 7. *Optic axial angles and structural states of the two feldspar phases*

GGU Specimen number	K-feldspar 2Vx optic plane ~ ⊥ (010)	K-feldspar Δ-values	Na-feldspar 2Vx	Na-feldspar $2\theta\,(131) - 2\theta\,(131)\ CuK_\alpha$
22526.....	79.0	n.d.	n.d	n.d.
22550.....	77.0	n.d.	n.d.	n.d.
22551.....	n.d.	0.86	n.d.	n.d.
22554.....	76.5	0.92	n.d.	1.02

n.d. = not determined

The bulk compositions of the alkali feldspars show remarkable consistency (Table 8). The compositions of the microcline show a variation from 13.5 to 5.5 per cent $NaAlSi_3O_8$ (Table 8).

Table 8. *Compositions of the two feldspar phases and bulk composition of the homogenized alkali feldspar*

GGU Specimen number	Microcline % $NaAlSi_3O_8$ Method d220 (Si) – d400 (Mi)	Microcline % $NaAlSi_3O_8$ Method 2θ (201 felds-101$KBrO_3$)CuK_α	Albite % Ab Method 2θ (201 felds-101$KBrO_3$)CuK_α	Alkali feldspar % Or	Alkali feldspar % Ab
22526.....	n.d.	5.5	+100	separate laths present	
22541.....	2.1	6.0	n.d.	separate laths present	
22550.....	n.d.	n.d.	n.d.	70.0	30.0
22554.....	n.d.	13.5	+100	73.0	27.0

n.d. = not determined

Unfortunately, the fine multiple-twinned Na-phases did not allow 2V measurements to be made with any accuracy. The one structural state obtained for an Na-phase, taken in conjunction with its composition (Tables 7 and 8), indicates a low albite (Fig. 4, p. 48). The Na-phases usually show normal twinning although complex twinning is present in a few cases.

The feldspar laths are non-poikilitic except for microlitic inclusions of needle-like soda-pyroxene which have a strong tendency to parallel the (010) direction.

The acmitic pyroxenes in the "kakortokitic" rocks are dominantly aegirine (Table 9); however, weakly pleochroic light brown acmite is also present. The optical properties of an anhedra of the latter mineral were found to be similar to those of the aegirines (Table 9).

Table 9. *Optical properties of the acmitic pyroxenes*

GGU Specimen number	2Vx	X:c	X	Y	Z
21851.....	63°	8°	n.d.	light green	olive greeb
21979.....	61°	11°	n.d.	pale-brownish	brownish
22526.....	61°	n.d.	green	light green	olive green
22541.....	67°	12°	n.d.	light green	olive green

n.d. = not determined

The acmitic pyroxenes are frequently bounded by prismatic {110} and {100} forms and elongated parallel to the latter; exceptionally are they entirely anhedral. In only one instance did the acmitic pyroxenes exhibit a poikilitic texture (GGU 22526). In this specimen, inclusions comprise alkali feldspar laths, eudialyte, and zeolite pseudomorphs after nepheline.

The refractive index determinations of the alkali amphiboles indicated that they are arfvedsonite (Table 10).

Table 10.

GGU Specimen number	R.I. Nx	Pleochroism X	Y	Z
22526.....	1.685	n.d.	blue-black	olive green
22541.....	1.685	n.d.	blue-black	olive green
22550.....	1.685	n.d.	blue-black	olive green
22554.....	1.687	deep blue-green	blue-black	olive green
24954.....	1.688	n.d.	blue-black	olive green

n.d. = not determined

In a few of these rocks, arfvedsonite is completely lacking. The arfvedsonite usually occurs as interstitial anhedra, at times showing marked indentations of the borders. Acmite replacement can also be seen and one instance has neptunite included and marginal to it.

In only one instance is eudialyte absent in the rock, otherwise it or its pseudomorphs occur as subhedral grains. Usually the diameter of these hexagonal plates of eudialyte do not exceed 2 mm, the exception being GGU specimen 22554, where there is a marked heterogeneity in the grain size of the eudialyte, ranging in diameter from 2 to 8 mm. In two specimens from Nunasarnaq (GGU 22541 and 22526), mesodialyte makes up most of the crystals, with eudialyte occurring as isolated patches within it. Replacement products of eudialyte include analcime, katapleite and fluorite.

Nepheline is always present, having equidimensional outline, measuring 1 to 2 mm and usually having interstitial habit. The normally interstitial habit of this mineral is reversed in GGU specimen 22526, where it occurs as pseudomorphed inclusions in the acmitic pyroxenes. Inclusions in the nepheline comprise small grains of soda-pyroxene and, in some cases, very small laths of albite and microcline. The alteration products include natrolite and analcime. The composition of the nepheline found in these rocks is given in table 11.

Table 11.

GGU Specimen number	% $KAlSiO_4$	Vol. % zeolite in rock	% nepheline altered
22526	34.4	36.2	*
22541	37.4	37.7	*
22550	24.5	4.2	7.6
22554	19.7	10.3	24.7

* Unable to recognise nepheline pseudomorphs due to high zeolite content of the rock.

Two values (GGU 22526 and 22541) show rather high $KAlSiO_4$ contents as compared to the average value of 20 % Ks for the nephelines from Ilímaussaq. The amount of zeolite alteration does not appear to have any significant affect on the compositions of the nephelines.

Mineral variation

Feldspars

The feldspars of the intrusive rocks of Ilímaussaq are, for the most part perthitic, the exceptions being certain occurrences in pegmatites and veins and in the lujavrites; in these environments, the Na- and K-

phases develop separately. SØRENSEN (1962, p. 178) makes reference to occurrences of non-perthitic alkali feldspars from the lower part of the naujaite body.

The microline-microperthites are flattened parallel to (010) and, as reported by SØRENSEN (1962, p. 224), can be elongated on the a-crystallographic axis. The albite-twinned microcline lamellae and the exsolved albite are elongated parallel to (010). In addition to the twinning of the small microcline lamellae, large simple Carlsbad and Manebach twins can be developed. Hence the microline can display Carlsbad and albite or Manebach and albite twinning.

The angles between the twin axes (T.A.) of the albite-twinned microcline and the optic axes of the latter give the following results:

T. A. : X = 74° (range 70° to 79°)
T. A. : Y = 83° (range 79° to 86°)
T. A. : Z = 18° (range 16° to 20°)

(Average of 10 readings)

These values compare well with values quoted by SØRENSEN (op. cit.) for non-perthitic microclines from Ilímaussaq, namely, 73°, 83° and 19° respectively. As noted by SØRENSEN, these values are in good agreement with those obtained from Lovozero for similar rocks (VLASOV et al., 1959, p. 249).

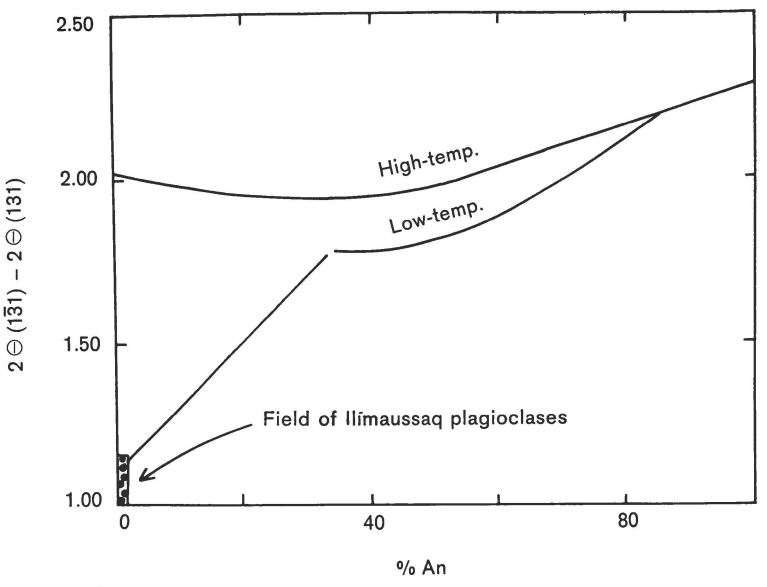


Fig. 4. Field of variation of 2Θ(131)–2Θ(1$\bar{3}$1) with composition for plagioclases from all the major rock units (after SMITH and YODER, 1956).

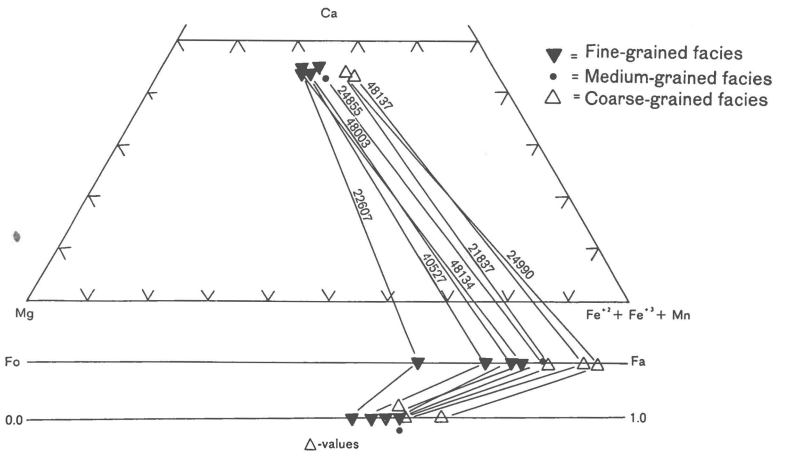


Fig. 5. Plot of the compositions of co-existing augites and olivines and obliquity values (Δ-values) of potash feldspar in the augite syenite GGU specimen numbers are indicated on the tie-lines.

The average optic axial angle of the microcline-microperthites and microclines (2Vx) is 78.5° (150 measurements) and varies from 73° to 83°. SØRENSEN (op. cit.) quotes the range of 2V values for non-perthitic microcline from Ilímaussaq as 76° to 88°, with the majority falling in the interval 76° to 82°. For the non-pegmatitic rocks at Lovozero, the range in corresponding values is from 70° to 84° (VLASOV et al., op. cit.).

The average extinction angle for 10 specimens of perthitic and non-perthitic microcline gave the value X:a = 18° (range 17° to 20°).

The plagioclase occurs in perthitic intergrowth and as separate laths. This feldspar is multiple-twinned, dominantly on the albite law but Carlsbad twinning was recorded in a few instances. The average optic axial angle of the plagioclase in the two types of occurrences is 2Vz = 79°, (70 readings) and varies from 76° to 82°. Ten values of the extinction angle gave X:a = 16° as the average (range 15° to 17°).

X-ray analyses of the structural states and composition of the Na-feldspars in the major rock groups of the intrusion indicate that they are low-temperature albites (Fig. 4, Tables 22 and 23, Appendix). Where the Na-phase showed development coarse enough to allow optic axial angle measurements, the results confirmed those attained by X-ray analysis (Fig. 6). A plot of the optic axial angle of the Na-phases against their composition indicates a very small departure from the pure albite end.

The K-feldspars from the augite syenite are the only group that show any marked structural contrast with those occurring in the other rock types of the Intrusion. The average obliquity value of 0.61 for the K-feldspars from the augite syenite differs from the corresponding average

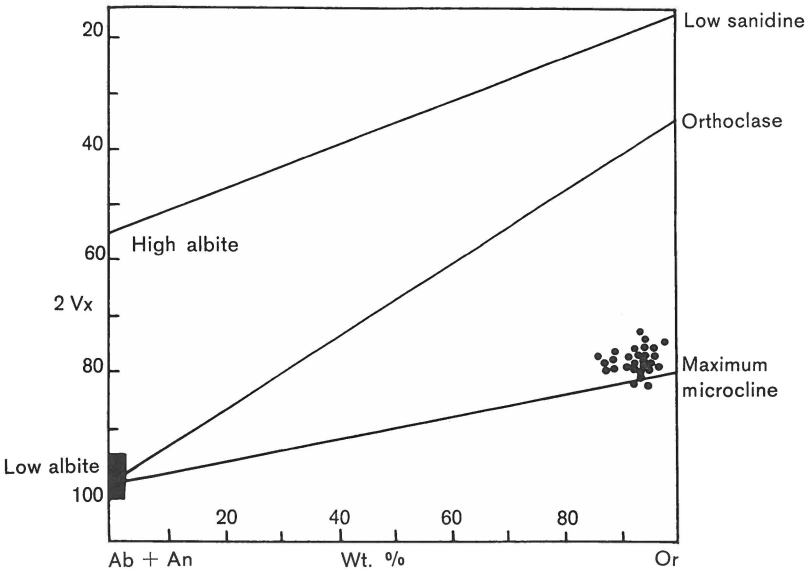


Fig. 6. Plot of 2V against composition of the two feldspar phases.

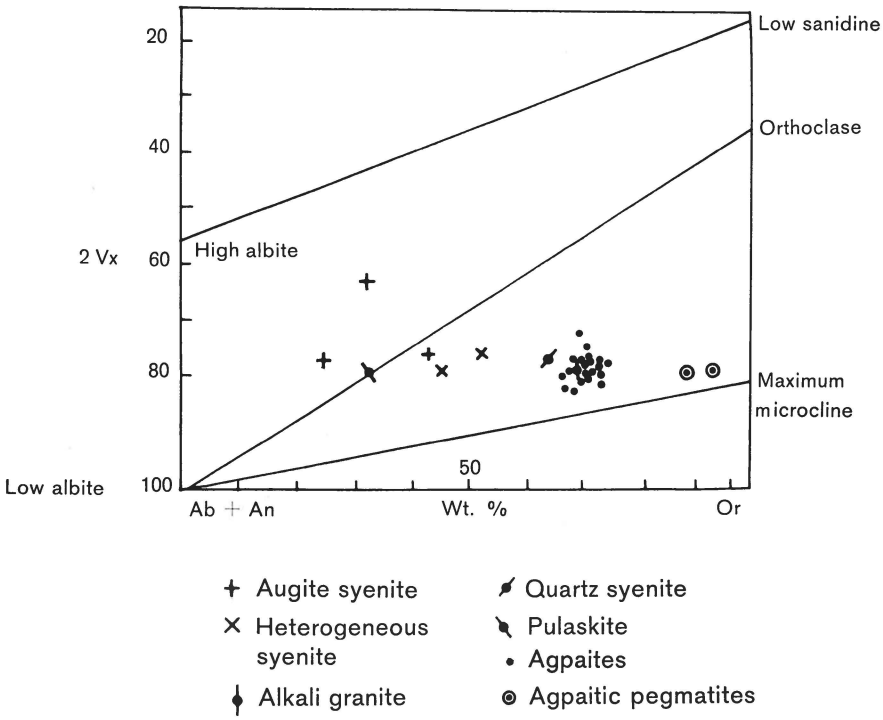


Fig. 7. Bulk composition of feldspars versus 2V of K-feldspars.

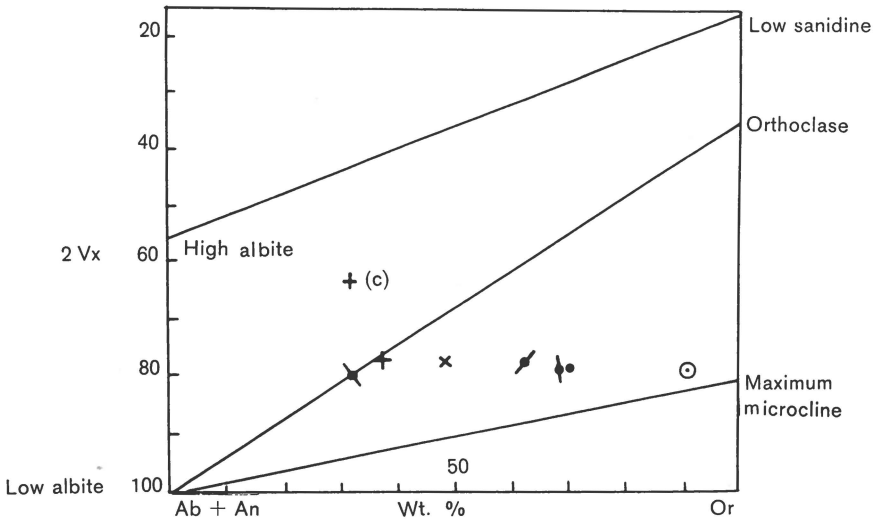


Fig. 8. Plot of average bulk composition of alkali feldspars versus 2V of K-feldspars (symbols as in figure 7; (c) = chill phase).

value of 0.90 for the feldspars of the remaining rock types. In addition, the obliquity values of the K-feldspars within the augite syenite group show a mildly contrasting variation, which is related to the grain size of the rock. A plot of the obliquity (Δ) values of the feldspars from the augite syenite is shown in figure 5. It can be seen that, with the exception of one minor reversal, there is a progressive change accompanying grain-size: feldspars from the fine-grained facies display lower obliquity values than feldspars from the coarser-grained facies. The coexisting augites and olivines vary sympathetically with the obliquity values (Fig. 5). The average obliquity values of the feldspars obtained from the rock types other than augite syenite show almost constant values. The small variations found in the former are probably within the range of experimental error. The two obliquity values obtained for K-feldspars from pegmatites gave values of 0.94 and 0.96. SØRENSEN (1962, p. 224) reports an obliquity value of 0.99 for a non-perthitic microcline from an agpaitic rock in Ilímaussaq.

The bulk chemical composition of heat-treated homogeneous alkali feldspars, plotted against 2V of the K-feldspars or cryptoperthites, displays interesting variations (Figs. 7 and 8). The alkali-feldspars from the augite syenite and pulaskite are noticeably more Na-rich than those occurring in the agpaitic rocks. The alkali feldspars of the heterogeneous syenite occupy an intermediate position between the augite syenite/pulaskite and the agpaitic feldspars. The quartz syenite values are slightly more Na-rich than those from the agpaites, whereas the alkali

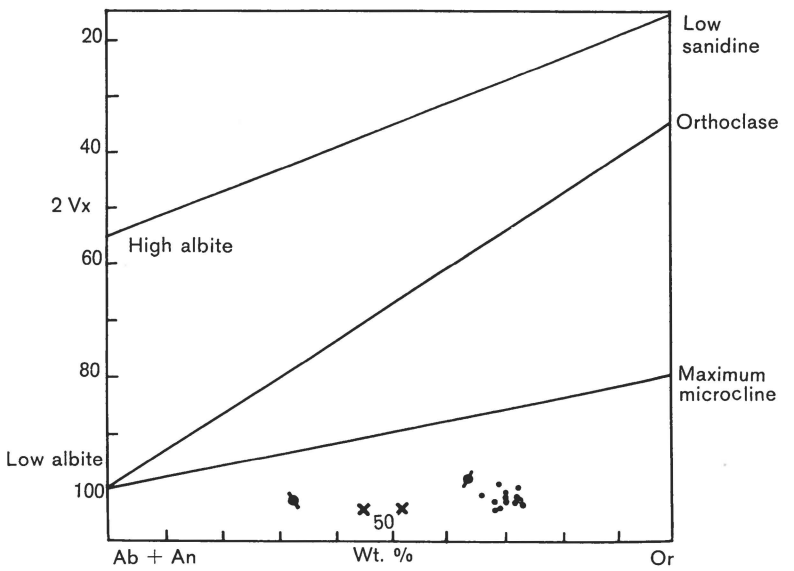


Fig. 9. Plot of average bulk composition of alkali feldspars versus 2V of Na-feldspars (symbols as in figure 7).

granite has an almost identical value to that of the average agpaites. The two bulk chemical compositions of the alkali feldspars taken from pegmatites are in turn further enriched in K than are other agpaitic rocks. The close plotting of the bulk composition values of the alkali feldspars from the variety of agpaites is a marked feature (Fig. 7). In this figure, only two values lie outside of the field of low albite-microcline in orthoclase. These anomalous values belong to the cryptoperthites from the augite syenite, where it wás not possible to obtain optic axial angle measurements for the separate phases.

Correspondingly, the plot of the 2V of the Na-phases versus bulk composition shows a spread similar to that obtained for the K-feldspar (Fig. 9). The cryptoperthitic feldspars from the augite syenite are not shown in this figure.

The obliquity values of the K-feldspars were checked only by powder methods. A number of runs were carried out on different separations of the same hand specimen and in all cases an excellent agreement was obtained. From this it was deduced that any variation in Δ-values within hand specimens or within single grains must be of a small order. It has frequently been reported that Δ-values can vary greatly in single hand specimens as well as within single grains (LAVES, 1952; MACKENZIE, 1952; GOLDSMITH and LAVES, 1954; GUITARD et al., 1960; MARMO et al., 1963 and NILSSEN and SMITHSON, 1965).

There is a general correlation of chemical composition of the rocks and distribution of Δ-values. The augite syenite is characterized by having a higher average concentration of MgO, TiO_2, CaO and a lower average Na_2O content than the remaining rocks. K_2O and total Fe show no clear-cut differences. The lower obliquity of the feldspars from the fine-grained facies of the augite syenite, compared with those of the coarse-grained facies, is marked by a higher concentration of MgO, CaO, TiO_2 and total Fe and a lower concentration of Na_2O and K_2O. It can be seen that there is a tendency for the lower obliquity feldspars to be associated with the more Ca-mafic rich rocks. This feature has also been noted in other rocks by NILSSEN and SMITHSON (1965, p. 385).

It has been noted by LAVES (1952) and SMITH (1961) that the structural state of an exsolved phase can be influenced by its host. In the feldspars under consideration here, it has been noted that there is a broad correlation of the more Na-rich alkali feldspars with lower obliquity values. This represents a reversal of what might be expected if the bulk composition of these feldspars had a marked effect on the obliquity values, particularly as the Na-phases are all low temperature albites. The feldspars from the Loch Ailsh intrusion display a similar "inverted" relationship in that the monoclinic feldspars are associated with higher Na-contents (PARSONS, 1965). NILSSEN and SMITHSON (1965) and WRIGHT (1964) found no correlation between obliquity values and bulk compositions of alkali feldspars.

The effect of the $NaAlSi_3O_8$ content of the microclines on obliquity is difficult to assess. The two determinative X-ray methods gave widely differing $NaAlSi_3O_8$ values. The GOLDSMITH and LAVES (1961) method gave considerably lower Na-contents than the modified BOWEN and TUTTLE method (1950). Analyses of microclines by GOLDSMITH and LAVES (op. cit.) revealed a low content of $NaAlSi_3O_8$ in solid solution. These authors found that the highly ordered microclines contain less than 5 per cent $NaAlSi_3O_8$. Using this method, the microclines other than those from the augite syenite were found to have average $NaAlSi_3O_9$ values of 1.2 per cent (range 0.0 to 3.0), whereas the modified BOWEN and TUTTLE method (op. cit.) gave a corresponding value of 8.2 (range 0 to 15.0). Using the same methods, the respective values for the K-feldspar from the augite syenite were 0.8 to 15.5 per cent. From GOLDSMITH and LAVES findings that the highly ordered microclines have less than 5 per cent $NaAlSi_3O_8$, it would appear that theirs is the more reliable method; however, in four cases negative values were obtained by this method. Unsuccessful attempts were made to separate the perthites in order to chemically analyse the K-feldspar. The microcline from the pegmatite specimens GGU 24935 and GGU 48098 were also

investigated with a view to chemical analysis. Unfortunately GGU specimen 24935 was heavily replaced by zeolites; GGU 48098 appeared to be pure and was analysed flame photometrically, the result being $Na_2O = 2.5\%$ and $K_2O = 12.6\%$ corresponding to 21.2% $NaAlSi_3O_8$ and 74.6% $KAlSi_3O_8$. It is quite obvious from these results that there is an excess of sodium, probably as a result of zeolite contamination. Further attempts at purification of this sample resulted in very little change in the above quoted analysis.

MACKENZIE (1954, p. 364) is of the opinion that the chemical composition might be the determining factor of the structural state of the microclines. RAO (1959, p. 62) has demonstrated that the Na-content can affect the $d_{131} - d_{1\bar{3}1}$ spacings of microclines. MACKENZIE and SMITH (1961, p. 62) show that the amount of Al–Si disorder increases rapidly with a slight increase in the Na-content. GOLDSMITH and LAVES (1961, p. 92) refute MACKENZIE's (1954) claim that the chemical composition may directly affect the structural state, and make the comment that "the triclinicity under equilibrium conditions is influenced by the degree of Al–Si disorder as a function of temperature as well as by the sodium content". The $NaAlSi_3O_3$ values obtained by the GOLDSMITH and LAVES method for the Ilímaussaq rocks show no obvious correlation with the obliquity values; however, the modified BOWEN and TUTTLE method indicates a generally higher Na-content for the lower obliquity microclines from the augite syenite. Moreover, in one instance, a high obliquity microcline (GGU 48065, $\Delta = 0.90$) has a $NaAlSi_3O_8$ content of 15.0 per cent (BOWEN and TUTTLE method). From these results it would appear that there is no obvious correlation of the $NaAlSi_3O_8$ content in the microclines with the obliquity values.

The higher H_2O, F and Cl content of the agpaitic rocks is indisputable evidence of their volatile-enriched crystallization environment in comparison with that of the augite syenite. Judging from chemical analyses the alkali granite would appear to have crystallized under volatile content conditions similar to those of the augite syenite. The chemical analyses of the pulaskite and heterogeneous syenite indicate volatile contents slightly in excess of the augite syenite. The inference drawn by EMELEUS and SMITH (1959, p. 1202) from the structural state of feldspars in ring dikes is that the local volatile content has facilitated the degree of ordering of some of the feldspars. Volatiles are also thought to have played a major role in the ordering process of the K-feldspars from Pilanesberg (RETIEF, 1962). DONNAY et al. (1960) and MCCONNELL and MCKIE (1960) experimentally demonstrated that water aids feldspar inversion. Correlation of the higher obliquity values with increasing volatile content is generally applicable to the Ilímaussaq rocks. How-

ever, this in turn is also a reflection of temperature, as the volatile content lowers the temperature of crystallization.

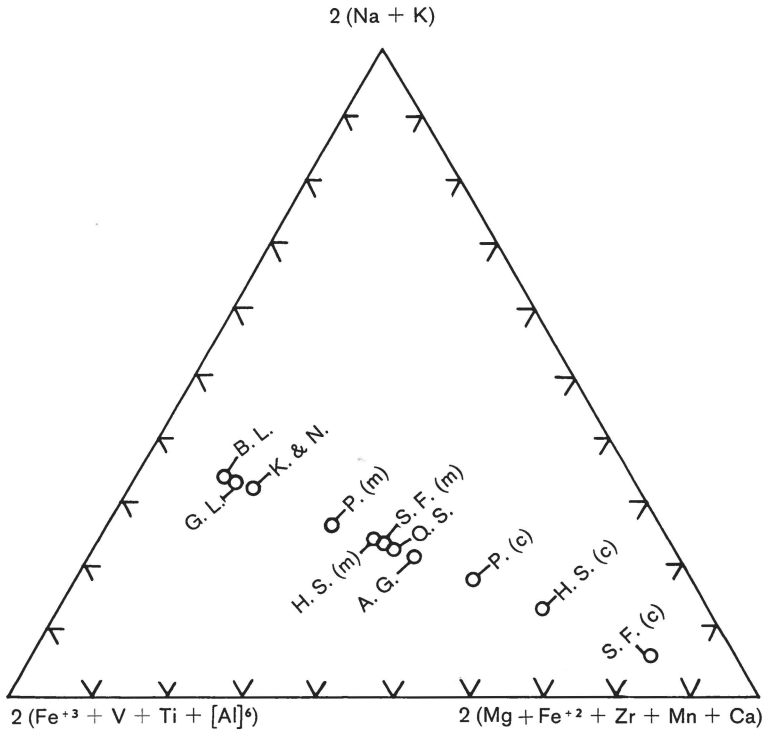
In the inversion of feldspars, the role of stress has been appealed to by ESKOLA (1951) and KARAMATA (1961). NILSSEN and SMITHSON (1965) have attributed to deformation the abnormally higher obliquity values within local areas of the Herefoss granite. PARSONS (1965) also noted the correlation of stress with higher obliquity values in restricted areas. Of the rocks studied from Ilímaussaq, the lujavrites alone display a stressed fabric. The average Δ-value of 0.89 obtained for three feldspars from these rocks lies very close to the average value of the feldspars from the agpaites. It would appear then that in this instance deformation has not faciliated further ordering of the feldspars.

As noted by SØRENSEN (1962, p. 225), the peculiar chessboard albite twinning of the microcline has been observed in other alkaline rock localities, namely Lovozero (VLASOV et al., 1959) and Rockall (SABINE, 1960). Additional occurrences include a low-grade schist (BARTH, 1959) and authigenic microclines (PERRENOUD, 1952 and BASKIN, 1956). LAVES (1950) has taken the presence of normal cross-hatched twinning in microcline to be indicative of inversion of an alkali feldspar of monoclinic habit to triclinic symmetry. Applying this postulation, BARTH (1959) ascribes the chessboard type twinning from the low-grade schists of Støa to crystallization at a low temperature; thus, an alkali feldspar of triclinic habit could form directly without having inverted from monoclinic form. As also noted by SØRENSEN (op. cit.), this is in excellent agreement with the probable conditions at Ilímaussaq, where the high volatile content of the agpaitic rocks must have lowered the crystallization temperature considerably.

Pyroxenes

There are essentially two main groups of clino-pyroxenes occurring in the Ilímaussaq rocks, namely acmitic and non-acmitic. The latter are confined to the augite syenite, whereas the acmitic pyroxenes can be present in all the rock types of the intrusion.

In the fine-grained facies of the augite syenite, the augite anhedra can show an indistinct concentric pattern with the occasional presence of very pale greenish margins; no further optical variation is present between core and margin. By contrast, the pyroxenes from the coarse-grained facies of this rock type can show a strong zoning from augite centres with neutral colour to mildly pleochroic green aegirine-augite margins. In a few instances aegirine-augite constitutes entire grains. The augites show a progressive iron-enrichment from the fine- to coarse-grained facies of the augite syenite (Fig. 5, p. 49), the maximum iron



H. S. = Heterogeneous syenite
P. = Pulaskite
S. F. = Sodalite foyaite
N. = Naujaite
K. = Kakortokite
B. L. = Black lujavrite
G. L. = Green lujavrite
A. G. = Alkali granite
Q. S. = Quartz syenite
(c) = Core
(m) = Margin

Fig. 10. Average compositions of acmitic pyroxenes in the major rock units.

variation being $Ca_{45}\ Mg_{32}\ Fe_{23}$ to $Ca_{43}\ Mg_{24}\ Fe_{33}$. The Ca- and Mg-contents vary by a minimum of 3 and 7.5 per cent respectively (Table 12).

Of the acmitic pyroxenes, aegirine-augite, aegirine and acmite are to be found. As defined here, in accordance with SABINE (1950), the values below and above $2Vx = 70°$ are applicable to aegirine and aegirine-augite respectively, and acmite corresponds to a brown to colourless soda-pyroxene.

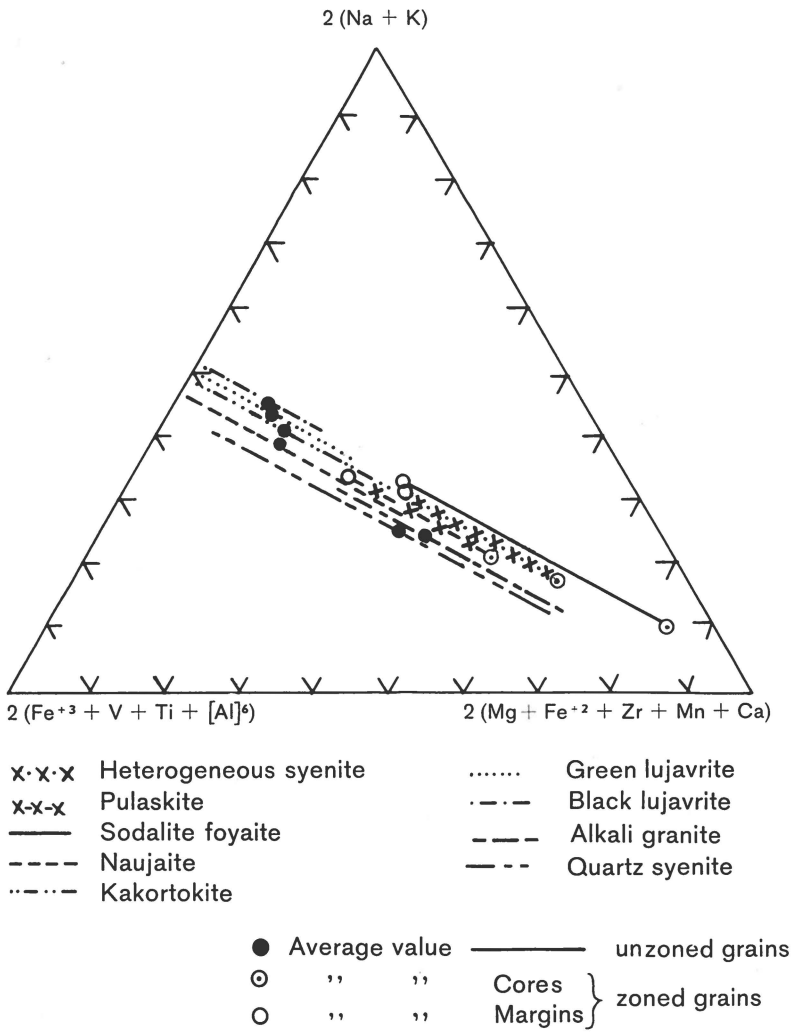


Fig. 11. Compositional range of acmitic pyroxenes in the major rock units.

In the heterogeneous syenite, pulaskite and sodalite foyaite, zoned acmitic pyroxenes generally exhibit cores of a pale-green pleochroic aegirine-augite, whereas the margins comprise strongly pleochroic deep-green to yellow or brownish green ferric-enriched aegirine-augite, or, more commonly, aegirine. At times, as many as four aegirine-augite centres can be enclosed within a single large aegirine anhedron. Acmite can be present as a growth homoaxial to the zoned acmitic anhedra; in all cases, the optical properties of the acmite are identical with those of its host. The occasional unzoned acmitic pyroxene grains that occur

Table 12. *Pyroxenes in augite syenite*

Grain size and GGU Specimen numbers	2 Vz Zoned grains core-margin	2 Vz Unzoned grains	Z ∧ c	Refractive indices Ny	Twinning	Pleochroism x	Pleochroism y	Pleochroism z	Composition of Augite
Fine-grained									
21825	–	55°	43°	1.705	–	———	Neutral	———	$Ca_{45}\,Mg_{29}\,Fe_{26}$
22607	–	55°	40°	1.700	–	———	Neutral	———	$Ca_{45}\,Mg_{32}\,Fe_{23}$
40527	–	54°	48°	1.705	(100)	———	Neutral	———	$Ca_{44}\,Mg_{31}\,Fe_{25}$
48003	–	54°	n.d.	1.700	(100)	———	Neutral	———	$Ca_{44}\,Mg_{32.5}\,Fe_{23.5}$
48134	–	55°	48°	1.700	–	———	Neutral	———	$Ca_{45}\,Mg_{32}\,Fe_{23}$
Medium-grained									
24715	70° – 86°	–	n.d.	1.707	–	(core) n.d.	Neutral	Pale yellow green	
24855						(margin) n.d.	Pale green	green	
	–	53°	50°	1.707	–	———	Neutral	———	$Ca_{43}\,Mg_{29}\,Fe_{28}$
Coarse-grained									
21837	–	55°	n.d.	1.710	–	———	Neutral	———	$Ca_{44}\,Mg_{25}\,Fe_{31}$
24990	–	55°	n.d.	1.710	–	———	Neutral	———	$Ca_{44}\,Mg_{25}\,Fe_{31}$
40110	58° – 65°	62°	n.d.	1.712	–	(core) n.d.	Neutral	Neutral	
						(margin) n.d.	Neutral	Very pale green	
48011 }	60° – 80°		56°	1.710	–	(core) n.d.	Neutral	———	
						(margin) n.d.	Very pale green	Pale green	
48011 }		71°	n.d.	1.710	–	n.d.	Neutral	Very pale yellow	
48137	–	54°	48°	1.713	–	———	Neutral	———	$Ca_{43}\,Mg_{24}\,Fe_{33}$

n.d. = not determined
– = absent

Table 13. *Average optic axial angles of acmitic pyroxenes*

Rock type	Average 2Vx values			Range of 2Vx values		Total Number of Readings
	Unzoned grains	zoned grains		Unzoned grains	zoned grains	
		cores	margins		cores / margins	
Heterogeneous syenite	–	96°	77°	–	120° to 72° / 92° to 60°	20
Pulaskite	60°	88°	71°	only 1 grain	120° to 72° / 90° to 60°	9
Sodalite foyaite	60°	113°	76°	60°	114° to 108° / 106° to 60°	11
Naujaite	66°	–	–	78° to 60°	– / –	12
Kakortokite	66°	–	–	76° to 60°	– / –	12
Green lujavrite	64°	–	–	70° to 60°	– / –	5
Black lujavrite	63°	–	–	68° to 60°	– / –	9
Alkali granite	82°	–	–	98° to 70°	– / –	7
Quartz syenite	79°	–	–	96° to 62°	– / –	7

– = absent

in the pulaskite and sodalite foyaite always have 2V values similar to those of the marginal portions of the zoned anhedra in the rock. The plot of the average 2V values for the zoned acmitic pyroxenes (Fig. 10 and 11) can at best only be approximate. The degree of 2V variation from cores to margins would depend to a large extent on the section cut through the anhedra. This factor probably accounts for the extreme variation of the optic axial angles for the zoned acmitic pyroxenes (Tables 13 and 24 (Appendix)).

With the exception of occasional homoaxial acmite replacement, the acmitic pyroxenes from the alkali granite, quartz syenite, naujaite, kakortokite and lujavrite, do not display compositional zoning. Separate grains of either aegirine-augite or aegirine occur in the alkali granite, quartz syenite, naujaite and karkotokite. In the former two rock types, aegirine-augite predominates over aegirine, whereas the reverse relationship holds for the naujaite and kakortokite. In the lujavrites only aegirine was determined to be present, with the addition of the frequent homoaxial growth of acmite. A plot of the composition of the acmitic pyroxene based on 2V measurements is presented in figures 10 and 11.

As noted by SØRENSEN (1962, p. 216), VLASOV et al. (1959), have distinguished three types of aegirine in the Lovozero massif. Aegirine I is early magmatic, occurring as microlitic inclusions in nepheline, sodalite and K-feldspar in the rocks, and as large prisms, up to 15 cm long, in the pegmatites. Aegirine II is a late-magmatic product which includes the macroscopic aegirine in the non-pegmatitic rocks and constitutes the groundmass of the pegmatites. Aegirine III is of hydrothermal origin, occurring in leached areas as well as in miarolitic cavities and druses. Colour differences and variation of trace element concentrations characterize the three phases of aegirine formation. These three phases of aegirine development have counterparts in the Ilímaussaq Intrusion. As suggested by SØRENSEN (op. cit.), aegirine I probably corresponds to the microlitic inclusions in sodalite and, in the rocks studied by the author, to those similar microlitic inclusions in nepheline and alkali feldspars. Aegirine II would be the equivalent of the interstitial and poikilitic grains found in most of the rock types of Ilímaussaq. "Aegirine III would then correspond to the green felted veins in the naujaite" (SØRENSEN, op. cit.). RETIEF (1962, p. 506), working on Pilanesberg feldspars, speculates on the possibility of aegirine microlites in feldspar being a result of exsolution from an orthoclase during inversion to microcline. The aegirine microlites are only associated with the triclinic, and not with the monoclinic feldspars. There is doubt as to whether the near maximum triclinic microclines from Ilímaussaq ever underwent an inversion; this, however, does not necessarily rule out the

possibility that exsolution was responsible for the formation of the microlites in the Ilímaussaq perthites, and possibly in the sodalites and nephelines.

Nepheline

A table of the Ilímaussaq rocks is presented, showing the average compositional variations of nephelines, in order of increasing % $KAlSiO_4$ (Ks) content (see table 14 and also table 25 (Appendix)).

Table 14. *Composition of nephelines in various rock types*

Rock type	nepheline composition	range
Sodalite foyaite	$Ks_{12.4}$	(10.4 – 16.0)
Black lujavrite	$Ks_{15.4}$	(11.0 – 18.8)
Kakortokite	$Ks_{18.9}$	(12.5 – 24.4)
"Hybrids"	$Ks_{19.4}$	(16.1 – 23.7)
Naujaite	$Ks_{21.2}$	(19.4 – 22.3)
Heterogeneous syenite	$Ks_{24.0}$	(9.5 – 38.7)
"Aegirine" dike	$Ks_{25.9}$	(1 value)
Green lujavrite	$Ks_{27.6}$	(19.2 – 29.9)
"Kakortokitic" rocks	$Ks_{29.0}$	(19.7 – 37.4)

Using the same X-ray technique, SØRENSEN (1962, p. 227) found the composition of three nephelines taken from late-stage rocks to vary from 15 to 21 per cent Ks. Two analyses from naujaite gave 18 and 20 per cent Ks. Partial chemical analyses undertaken by SØRENSEN (op. cit.) for three of these specimens gave a range of 17.6–17.7 % Na_2O, 4.7–5.6 % K_2O and 0.0 % or traces of CaO. The average value of these results corresponds to $Ne_{80.9}$ $Ks_{17.0}$. The silica index (Q) is then presumably about 2.0 %. Two chemical analyses of nepheline from Ilímaussaq (Table 15) gave values corresponding to Ne_{76} Ks_{19} Q_5 and Ne_{69} Ks_{22} Q_9 (analyses 1 and 2 respectively).

Table 15. *Chemical analyses of nephelines*
(BØGGILD, 1953, p. 355)

	1.	2.
SiO_2	43.39	41.87
Al_2O_3	32.28	33.94
Fe_2O_3	0.92	0.70
CaO	0.70	0.47
K_2O	5.62	6.68
Na_2O	16.52	15.03
Cl	tr.	tr.
Loss at ignition	–	0.94
	99.43	99.63

tr. = trace
Analyst J. LORENZEN

With the exception of the heterogeneous syenite and "kakortokitic" rocks, the nephelines show a moderate range of composition within a given rock type (Table 14). D. L. HAMILTON (1961) reports that nepheline can undergo compositional change by reaction with late-magmatic liquids. For this reason the general amount of zeolites associated with

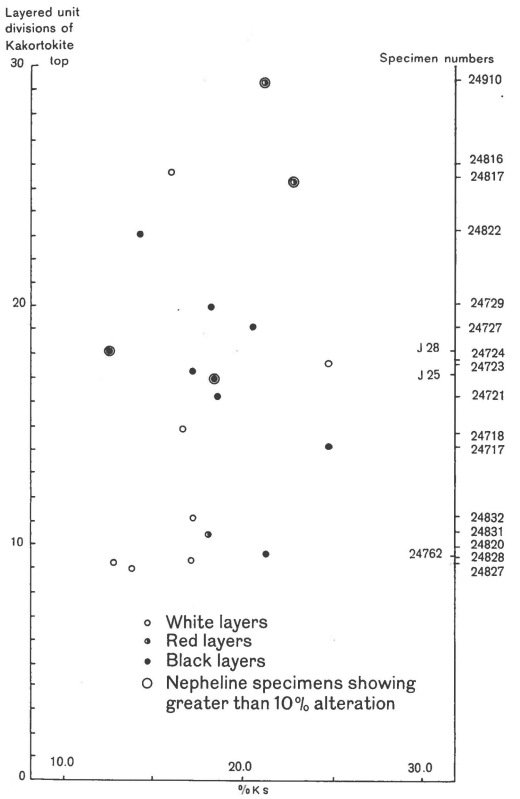


Fig. 12. Plot of nepheline composition against height in the layered kakortokite sequence.

the rocks, as well as the extent of replacement of nepheline, is presented with the analyses given in the appendix section. There does not appear to be any obvious relationship between the zeolite content and the composition of the nepheline.

The marked difference between the average kalsilite value of 27.6 for the green lujavrite and 15.4 for the black lujavrite might possibly be explained by the preferential entry of potassium into the abundant amphibole in the latter rock type (C. H. EMELEUS, personal communication). A plot of nepheline composition against height in the layered kakortokite sequence does not show a progressive trend (Fig. 12).

According to MIYASHIRO (1951), the nephelines of Ilímaussaq would belong to the plutonic rocks of the "P" facies as the associated alkali feldspars are the low temperature members. The variation of the kalsilite values from 9.5 to 38.7 per cent for the Ilímaussaq nephelines is greater than the variation shown by MIYASHIRO of 15.6 to 19.8 per cent Ks for the "P" facies. The overall average value for the Ilímaussaq nephelines is 20% Ks as compared with the similar average value of 17.3% Ks for the "P" facies (MIYASHIRO, 1951, p. 280).

If the Ilímaussaq values presented here do not represent real differences, the only possible factors that might be affecting the values, other than reaction with late-stage magmatic fluids, are variations in the silica or calcium contents. As the undersaturated rocks of Ilímaussaq, and particularly the agpaites, have very low calcium, it would appear unlikely that CaO enters the nepheline in any great quantity. The two chemical analyses presented above support this theory. The chemical analyses also indicate a small silica excess. MIYASHIRO found the silica (Q) content of the nephelines from the "P" facies to vary from 4.1 to 21.5 per cent. As the limited number of chemical analyses indicate low SiO_2 and Ca contents, it would appear unlikely that they are the factors affecting the wide range of values obtained. Similarly the lack of correlation of the degree of alteration with nepheline composition would also lend support to the findings being real rather than just apparent.

The one chemical analysis of a nepheline taken from a pegmatite in the Lovozero massif (VLASOV et al., 1959, p. 243) gives a calculated composition of Ne_{72} Ks_{17}. The Q index appears to be slightly anomalous giving a calculated value of 5 per cent.

Olivine

Olivine only occurs as a rock-forming mineral in the augite syenite and, locally, in the heterogeneous syenite. It is present as an accessory mineral in the pulaskite and sodalite foyaite, and has been reported from the quartz syenite by HAMILTON (1964, p. 51).

Within the augite syenite, the olivine displays a marked compositional variation. The fine-grained rocks contain a more magnesian-rich

Table 16. *Average composition of olivines*

	% Fo
Augite syenite	
Fine-grained	24
Medium-grained	14
Coarse-grained	7
Heterogeneous Syenite	4
Sodalite foyaite	4

olivine than the coarse-grained rocks (Fig. 5, p. 49). The maximum compositional range for these olivines is Fo_{35} to Fo_5.

The olivines occurring in the heterogeneous syenite and sodalite foyaite display a small compositional range from Fo_4 to Fo_0 (Tables 16 and 26 (Appendix)).

Description of layering

Augite syenite

The augite syenite develops layering locally. This layering is confined to the lower 500 m of the exposed part of the outer shell of augite syenite. Layering is well developed in the augite syenite on the north and south shore of Kangerdluarssuk, occurring sporadically from sea-level up to 500 m in the zone adjacent to the kakortokite. The layering is most prominently developed in a medium- to coarse-grained rock over a 100 m wide zone, situated 200 to 300 m in from the margin. The layering, where noted, has a strike roughly parallel to that of the outer margin of the Intrusion. Dips are always inward and rather steep except when they are disturbed by inclusions of country rocks. The dip varies from 50° to 75° inward, averaging 60°.

The layering is essentially due to concentrations of magnetite, augite, kaersutite and olivine. These form dark layers 1 to 3 cm wide which are separated by lighter layers of normal augite syenite, 2 to 3 cm in width. These layers wedge out laterally and also outwardly against the fine- to medium-grained rock and inwardly against the coarse-grained facies of augite syenite. The layers maintain a remarkably constant thickness; anomalously, they can merge up-dip. The minerals comprising these layers do not develop any preferred orientation. The layered structure is entirely due to alternating concentrations of randomly orientated minerals.

Heterogeneous syenite

Rhythmic layering is sporadically produced by alternations of coarse-grained rocks, approximately a metre thick, with lighter-coloured, near-horizontal sheets of pegmatitic rocks, up to a metre thick. Further textural contrast is provided by the 6 cm long feldspars in the pegmatitic rock, which have alignments perpendicular to the layers. By contrast, the 0.5 to 1.0 cm long feldspars from the coarse-grained rock have random orientation. The layering is further emphasized by the relative propensity of the coarse-grained layers for "rust" weathering. This "rust" weathering is thought to be the result of a larger olivine content in the coarse-grained rock although the limited modal analyses offer no confirmation of this (Tables 27 and 28 (Appendix)). Irregularities in the

layering are produced by the inclusion of 20 to 30 cm blocks of the coarse-grained rock in the pegmatitic rocks; this is particularly prevalent where the latter are slightly transgressive.

Pulaskite

To the S side of Tunugdliarfik, where the pulaskite occurs in small plugs and sills, it characteristically develops inch-scale layering. To the north of Tunugdliarfik similar layering was only noted in one locality, 1.7 km E of Taseq. The layering is due to a concentration of arfvedsonite and small amounts of olivine, giving rise to dark layers averaging 1 cm thick. Feldspar enrichment is responsible for the broader, 2 to 3 cm wide, lighter-coloured layers. In the thin sheets, layering may be present throughout the entire thickness and can have a maximum lateral development of 100 m before wedging out into the normal rock. Neither the stumpy feldspar laths or prisms of arfvedsonite show any lamination.

Quartz syenite

The layering that is developed in this rock-type is very similar to that found in the pulaskite. As in the former rock-type, inch-scale layering is present, being found both to the N and S of Tunugdliarfik. It is particularly well developed in the latter locality in narrow sills and small plugs. The layering is produced by concentrations of arfvedsonite, 0.5 to 1.0 cm wide, separated by layers, 2 to 3 cm wide, enriched in feldspar and quartz. In a 2 m thick sill to the S of Tunugdliarfik, layering is present throughout the entire thickness with a discordancy developed between the layers in the central part of the sill. There is no lamination in this layering.

Naujaite

Layered horizons have been observed through the calculated 1000 m of exposed naujaite. SØRENSEN (1958, p. 12) was the first to comment on the presence of these layers. The layering most commonly seen in the naujaite is produced by compositional variations normally associated with textural change. The usual layered sequence is formed of dark layers of aegirine/arfvedsonite concentrations, 60 cm to 1 m wide, alternating with feldspar-rich layers, 1 to 2 m thick. An occasional eudialyte layer, 5 to 10 cm thick, can be interspersed in a repetitive sequence of dark and light layers.

The normal poikilitic texture of the naujaite is retained in these layers; however, the aegirine/arfvedsonite phenocrysts usually have different sizes in the alternating layers. In the dark layers the aegirine/arfvedsonite form the usual 10 cm diameter phenocrysts found in the normal naujaite, but in the light layers the aegirine/arfvedsonite crystals measure 2 to 3 cm long and 1 cm in diameter.

Alternation of aegirine/arfvedsonite concentrations, 20 to 30 cm thick, with normal naujaite, is also a common layered phenomenon. The aegirine and/or arfvedsonite from the dark layers form prisms 2 to 3 cm long and 1 cm in diameter. The remaining minerals have a size development similar to that in the normal rock.

Sodalite-rich and sodalite-poor layers are developed locally in the naujaite. The sodalite-rich layers vary from 0.5 to 5.0 m thick; the sodalite may form up to 70 to 80 per cent by volume of the rock. ROSENBUSCH (1907, p. 240) and USSING (1912, p. 74) have referred to this rock as "sodalitgestein" and "sodalitite" respectively. The remaining minerals in the sodalitites can be any of the usual minerals occurring in the naujaite; due to the excessive amount of sodalite inclusions they usually appear in skeletal form. The sodalite grains in these rocks are usually of the same dimensions as those occurring in the normal naujaite, but can be finer grained. The sodalitite layers can form single individual layers within the naujaite or alternate with 20 to 30 cm thick layers of feldspar and eudialyte-enriched naujaite. The 10 to 20 cm thick sodalite-poor layers occur singly within the normal naujaite and have a poikilitic-free texture. The minerals in these layers are those found in the naujaite and they also have a similar size, with the exception of occasional xenomorphic sodalite crystals which measure up to a few centimeters in diameter.

Narrow, less than 1 m, lenticular pegmatites are sporadically found in the naujaite, having approximately conformable relations to the layering. These pegmatites lack a poikilitic texture and can develop crystals, 20 to 30 cm long. Assymetrical zoning is a common feature of these pegmatites. Eudialyte is concentrated along the lower margin, followed by an intermediate zone of aegirine/arfvedsonite, and finally a feldspar-rich zone at the top. In some pegmatites the upper zone is free of eudialyte. USSING (1912, p. 35), DANØ and SØRENSEN (1959, Fig. 2) and SØRENSEN (1962) have described some of these pegmatites.

Kakortokite

The layering comprises rhythmic compositional alternations developed through an exposed thickness of more than 400 m. Repetitive sequences of black, red and white layers correspond to concentrations of arfvedsonite-aegirine, eudialyte and feldspar respectively. This compositional sequence is never varied, although the red layers may be inconspicuous. The average thickness of the individual black, red and white layers are 1.5 m, less than 1,0 m, and 10 m respectively.

The black layers and, to a lesser extent, the white and red layers possess a marked lamination. The lamination in the kakortokite is pro-

duced by the elongate minerals lying in a common plane. The finer-grained red layers also tend to have a saccharoidal texture.

The transition from a white to black layer is quite abrupt, usually taking place over 5 to 10 cm; in one instance only was a knife sharp contact observed between these two layers. The mineral proportions within the black layers are constant, but there is a sharp increase in the

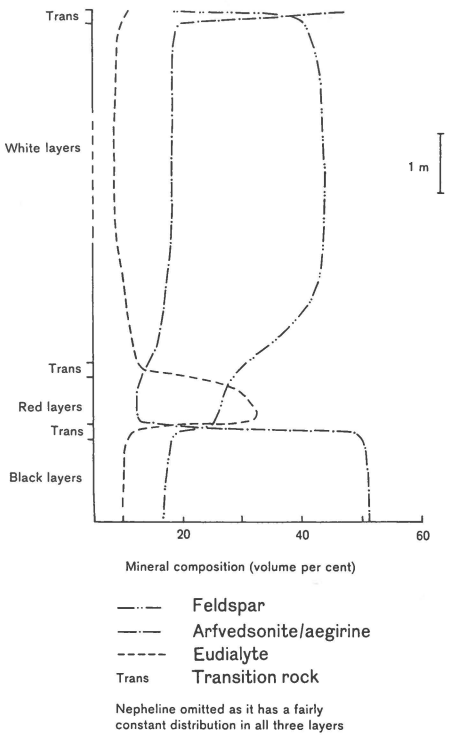


Fig. 13. Mineral variation in layered kakortokite unit.

amounts of eudialyte and feldspar in the 15 to 25 cm wide zone transitional into the red layers (Fig. 13). In the red and white layers the arfvedsonite/aegirine content is fairly constant. Eudialyte concentrates towards the base of the red layers and the amount varies inversely to the feldspar content on transition into the white layers. Nepheline has a relatively constant distribution in all three layers.

The author counted between 25 and 30 units, each of which comprises a black, a red and a white layer. Ussing (1912, p. 41) had a somewhat higher figure of "about 40 black bands". An exact count of these units is a very difficult task as incipient layers can sometimes be developed, which, although observable from a distance, are difficult to identify on close-up inspection. In the kakortokite the prominent layering

is almost ubiquitously present and is gently undulating, very persistent laterally and with a rather constant thickness. A single layer can be traced throughout the whole of the exposed area before wedging out in the marginal kakortokite. Where inclusions of older rocks are found in the kakortokite, the underlying layers are compressed. In one instance the layers were seen to be compressed to a depth of 15 to 20 m and reduced to approximately one third of their original thickness. The overlying layers conformably enclose the inclusions without any thinning on the crests. UPTON (1961, p. 28) claims to have observed "incipient trough banding" and minor disconformities in the kakortokites but these were not observed by the author. Where the kakortokite approches the marginal pegmatitic phase, the layers wedge out to within 50 to 100 m of the contact and a homogeneous rock is found made up entirely of the minerals present in the kakortokite.

Lujavrites

Layering is concentrated at the boundaries of the two lujavrite types in a mixed zone approximately 50 m thick. It is usually due to compositional change, rarely to textural differences. The compositional layering of the lujavrite is produced by arfvedsonite, aegirine or feldspar enrichment. The layers are lens-shaped and may have marked pinch and swell structures.

The following rhythmic layering has been observed:

i. Arfvedsonite lujavrite layers in aegirine lujavrite.
ii. Aegirine lujavrite layers in arfvedsonite lujavrite.
iii. Feldspar-rich layers in either black or green lujavrite.
iv. Feldspar-rich layers in coarser-grained aegirine lujavrite.
v. Nepheline-rich layers in arfvedsonite lujavrite.

Individual layers vary from 1 cm to 15 m in thickness, averaging 10 cm. Layered sequences are normally not developed over thickness exceeding 30 to 40 m; usually they are found within 2 to 5 m thick zones.

Layering due to alternations of aegirine- and arfvedsonite-lujavrite show no textural variation or density stratification. The contacts are sharp and strictly conformable with the fissility of the rock. At Sarfánguaq these layers are truncated by an inhomogeneous 50 cm wide black lujavrite. In addition to the normal 10 cm thick layering, examples of gneissic structures have been observed.

The layering produced by alternations of dark and light minerals in the lujavrites does not show any textural inhomogeneities but does display density stratification. At the base of each dark, 10 cm thick

layer, there is a 3 to 4 mm concentration of pure arfvedsonite; upwards there is a progressive increase in light minerals. The dark layers occasionally grade into an overlying white rock with little or no demarcation line; more often, there is a distinct break. SØRENSEN (1962, p. 57) has also noted the presence of very narrow arfvedsonite-rich layers in the black lujavrite; these layers are in association with white nepheline-rich layers, which measure up to a few centimetres thick.

Only one example of compositional and textural layering was seen in the lujavrite, occurring 1 km SW of Agpat. This occurs in a green lujavrite containing an even distribution of arfvedsonite nodules, 0.5 to 1.0 cm in diameter. Within this nodular lujavrite are light feldspar-rich bands, 50 cm thick, which contain layers of less than 1 cm thickness, composed of arfvedsonite needles, 2 to 3 mm long.

Petrofabrics

General

The lujavrites and karkotokites were selected for petrofabric analysis as these are the only layered rocks to display megascopic lamination in the intrusion. The specimens chosen appear to be fairly representative of the rock types in question, that is to say they show strong lamination in the hand specimens.

Green lujavrite

The lamination of this rock is well displayed by the orientation of the perpendiculars to (010) and a-crystallographic axes of the microcline laths and the c-crystallographic axes of the aegirine prisms (Fig. 14 a, b and e). The a-crystallographic axes of the microcline and the c-crystallographic axes of the aegirine further demonstrate that this rock possesses a lineation (Fig. 14 b and e). It can be seen that there are two well-developed lineation maxima within the plane of lamination for these two minerals and that only a small angular difference separates these maxima. Less well-defined lineation maxima also exist for both the microcline and aegirine and also lie within the plane of lamination. The c-crystallographic axes of the flat hexagonal plates of eudialyte surprisingly do not indicate a marked lamination: one of the maxima lies in the plane of lamination, as defined by the microcline and aegirine, and the other at right angles to it (Fig. 14 c). The c-crystallographic axes of the irregular-shaped nepheline grains display neither lamination nor lineation (Fig. 14 d). Unfortunately the general replacement of the albite laths in the green lujavrite did not allow determination of their orientation.

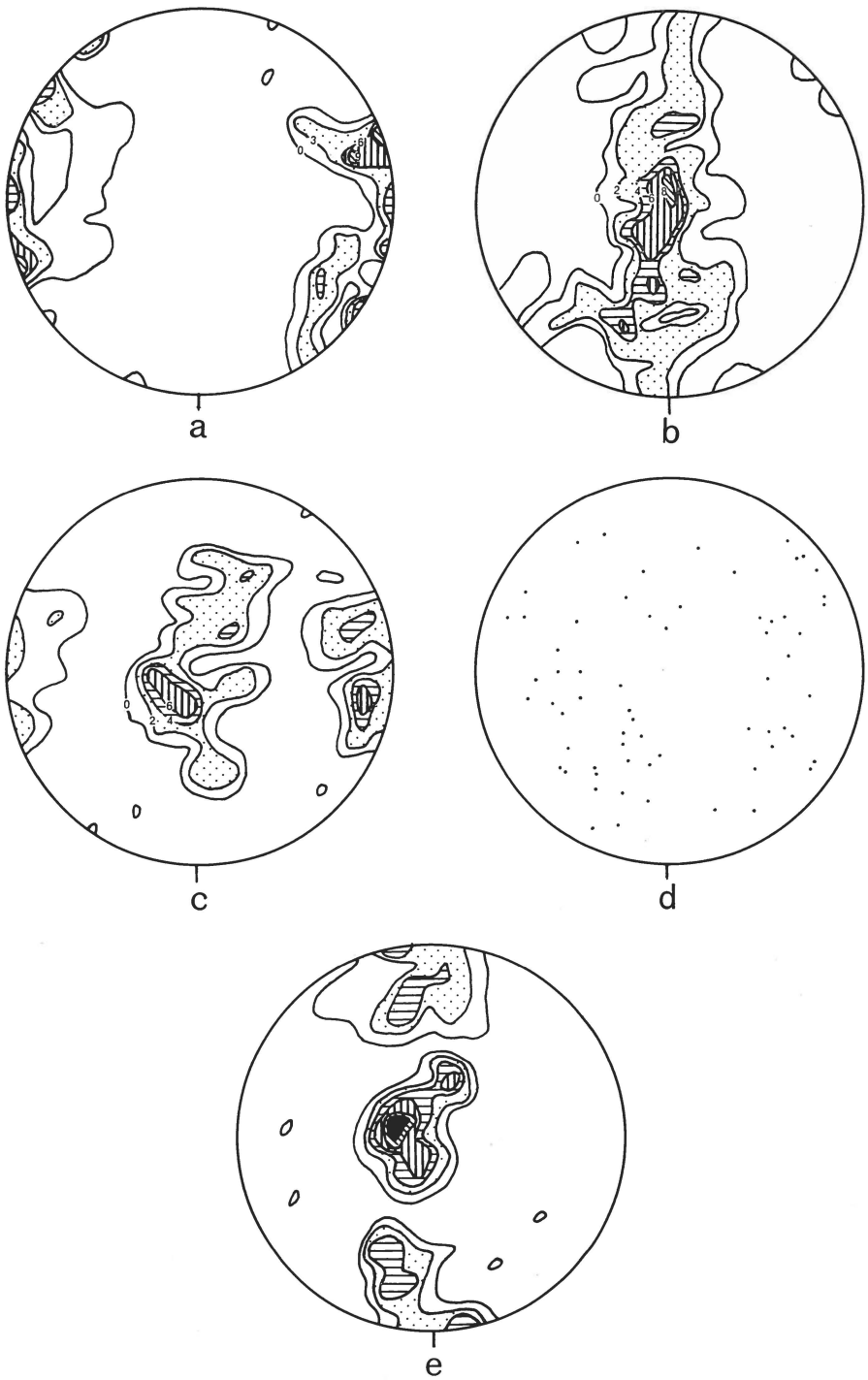


Fig. 14. Green lujavrite.

(a) Stereogram of the poles ⊥ (010) of microcline laths (50 points) in sections cut perpendicular to the layering and oriented N–S (GGU 21915).
(b) Stereogram of the a-crystallographic axes of microcline laths (50 points) in sections cut perpendicular to the layering and oriented N–S (GGU 21915).
(c) Stereogram of the c-crystallographic axes of eudialyte grains (50 points) in sections cut perpendicular to the layering and oriented N–S (GGU 24873).
(d) Stereogram of the c-crystallographic axes of nepheline grains in sections cut perpendicular to the layering and oriented N–S (GGU 21915).
(e) Stereogram of the c-crystallographic axes of aegirine grains (50 points) in sections cut perpendicular to the layering and oriented N–S (GGU 24873).

Black lujavrite

In the black lujavrite the microcline and albite laths both indicate the marked lamination of the rock (Fig. 15 a and c). Within this plane of lamination, the a-crystallographic axes of these two minerals indicate lineation maxima. The microcline has two lineation maxima at right angles to one another and the albite has three maxima lying within 90°. There is a general coincidence of two of the albite lineation maxima with an elongation maxima of the microcline (Fig. 15 b and d). However, a 35° departure exists between the remaining lineation maxima of the two minerals. The c-crystallographic axes of the eudialyte demonstrate a moderate planarism, with a certain amount of diffuseness as a result of a small amount of scattering within the plane of lamination. As in the green lujavrite, the c-crystallographic axes of nepheline show random distribution.

The deep pleochroism of arfvedsonite did not allow accurate determination of the optical axes. In addition, the c-crystallographic axes were impossible to determine entirely from cleavage as in any one section a large proportion of the arfvedsonite was in elongate form. This latter feature indicates that there is, therefore, no one major linear direction of the arfvedsonite prisms. These minerals do, however, possess a marked lamination as can be seen from the hand specimen.

Black layer in kakortokite

The planarism in this layer is demonstrated by the poles perpendicular to (010) of the microperthite and by the c-crystallographic axes of aegirine (Fig. 16 a and e). To a lesser extent, this is also demonstrated by the poles perpendicular to (110) and (110) of arfvedsonite (Fig. 16 f). The a-crystallographic axes of the microperthite show a marked lineation maxima lying in the plane of layering (Fig. 16 b). Lineation of the c-crystallographic axes of aegirine is considerably less well defined, as three maxima occur within the plane of layering (Fig. 16 e). The strong pleochroism of the arfvedsonite prevented determination of any possible linear features. Nepheline and eudialyte demonstrated no preferred orientation of the c-crystallographic axes (Fig. 16 c and d).

Red layer in kakortokite

As in the black layers, the microperthite laths exhibit planarism and lineation (Fig. 17 a and b). Nepheline is the only other mineral in the rock to show preferred orientation; the c-axes are nearly perpendi-

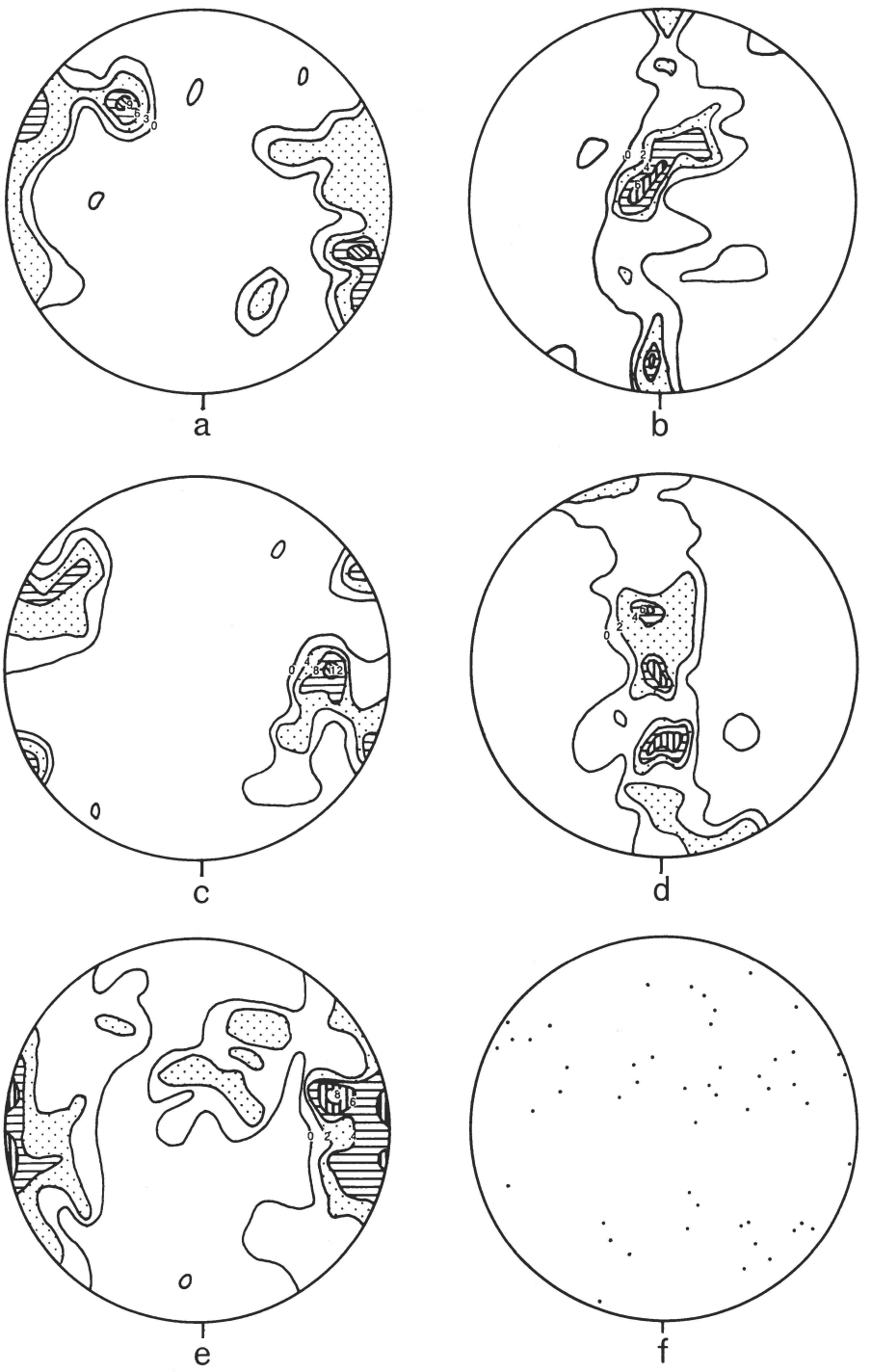


Fig. 15. Black lujavrite.

(a) Stereogram of the poles ⊥ (010) of microcline laths (50 points) in sections cut perpendicular to the layering and oriented N–S (GGU 21874).
(b) Stereogram of the a-crystallographic axes of microcline laths (50 points) in sections cut perpendicular to the layering and oriented N–S (GGU 21874).
(c) Stereogram of the poles ⊥ (010) of albite laths (50 points) in sections cut perpendicular to the layering and oriented N–S (GGU 21874).
(d) Stereogram of the a-crystallographic axes of albite laths (50 points) in sections cut perpendicular to the layering and oriented N–S (GGU 21874).
(e) Stereogram of the c-crystallographic axes of eudialyte grains (100 points) in sections cut perpendicular to the layering and oriented N–S (GGU 21874).
(f) Stereogram of the c-crystallographic axes of nepheline grains in sections cut perpendicular to the layering and oriented N–S (GGU 21874).

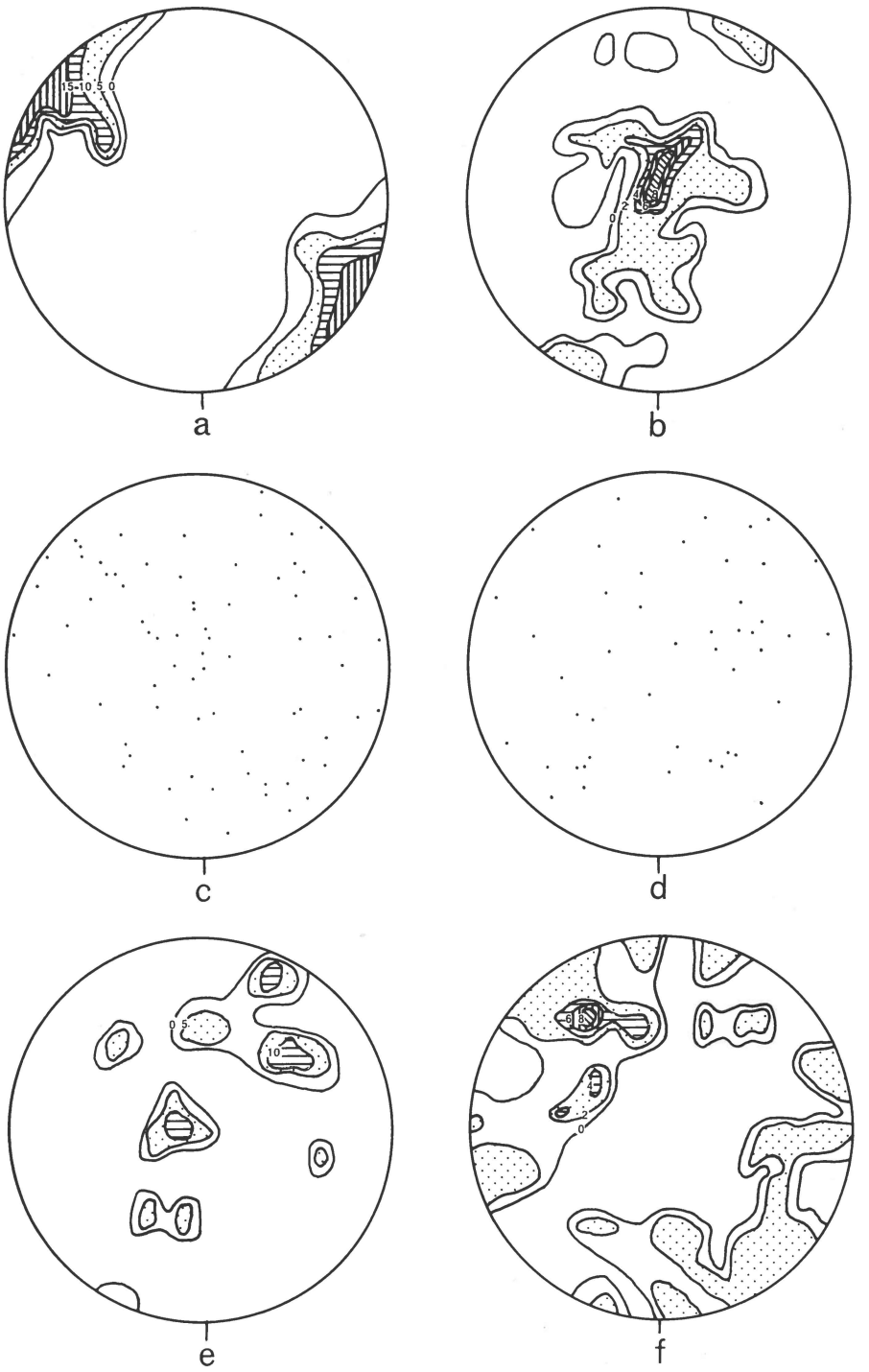


Fig. 16. Black layer in kakortokite.

(a) Stereogram of the poles ⊥ (010) of microperthite laths (50 points) in sections cut perpendicular to the layering and oriented NNE (GGU 24729).
(b) Stereogram of the a-crystallographic axes of microperthite laths (50 points) in sections cut perpendicular to the layering and oriented NNE (GGU 24729).
(c) Stereogram of the c-crystallographic axes of eudialyte grains in sections cut perpendicular to the layering and oriented NNE (GGU 24749).
(d) Stereogram of the c-crystallographic axes of nepheline grains in sections cut perpendicular to the layering and oriented NNE (GGU 24729).
(e) Stereogram of the c-crystallographic axes of aegirine grains (30 points) in sections cut perpendicular to the layering and oriented NNE (GGU 24729).
(f) Stereogram of the poles ⊥ (110) and ($1\bar{1}0$) cleavages of arfvedsonite prisms (60 points) in sections cut perpendicular to the layering and oriented NNE (GGU 24729). (In this plot perfect lamination would be expressed by a conical distribution of the poles as two planes at 60? are involved.)

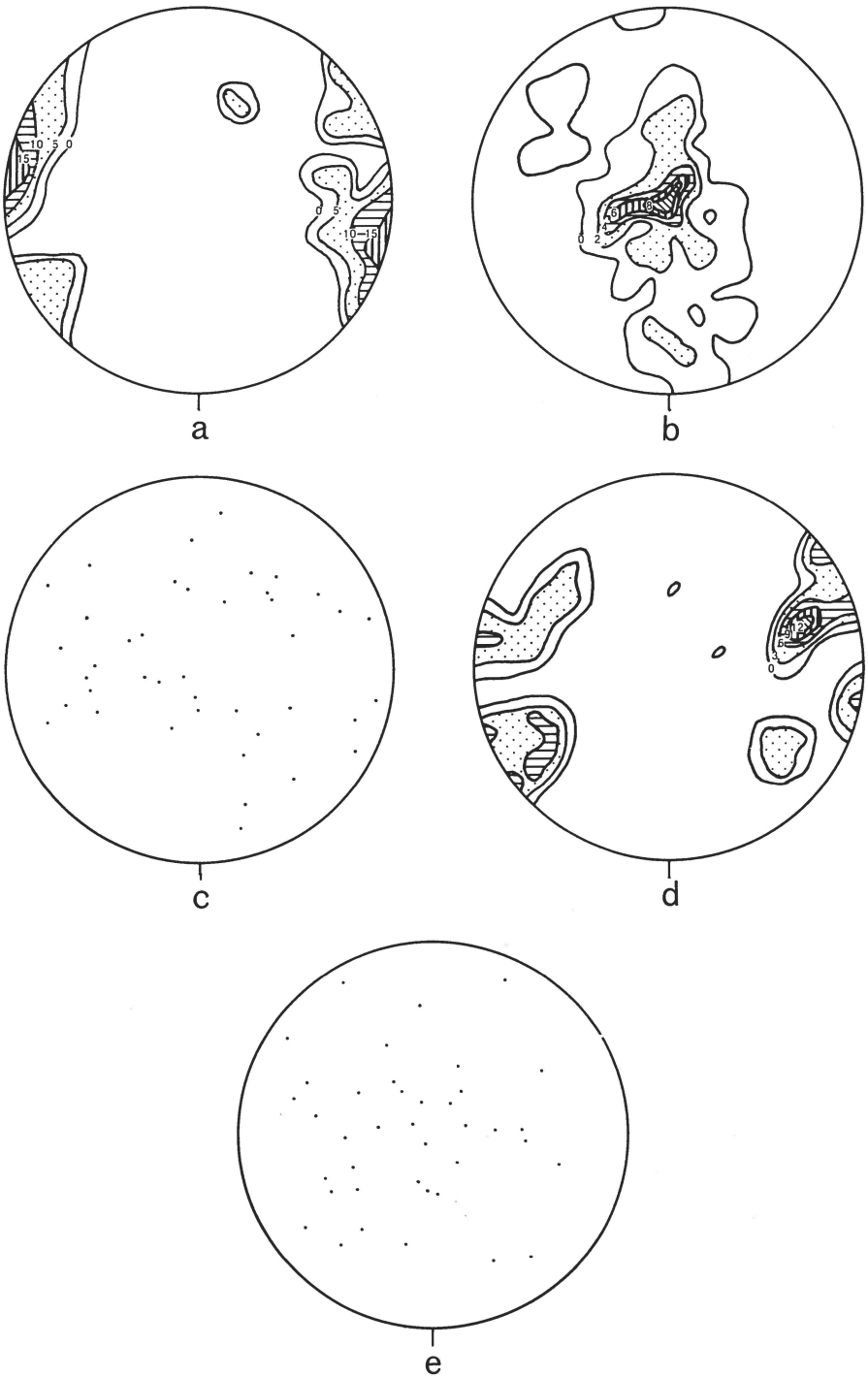


Fig. 17. Red layer in kakortokite.

(a) Stereogram of the poles ⊥ (010) of microperthite laths (50 points) in sections cut perpendicular to the layering and oriented N–S (GGU 24831).
(b) Stereogram of the a-crystallographic axes of microcline laths (50 points) in sections cut perpendicular to the layering and oriented N–S (GGU 24831).
(c) Stereogram of the c-crystallographic axes of eudialyte grains in sections cut perpendicular to the layering and oriented N–S (GGU 24831).
(d) Stereogram of the c-crystallographic axes of nepheline grains (50 points) in sections cut perpendicular to the layering and oriented N–S (GGU 24831).
(e) Stereogram of the c-crystallographic axes of aegirine grains in sections cut perpendicular to the layering and oriented N–S (GGU 24831).

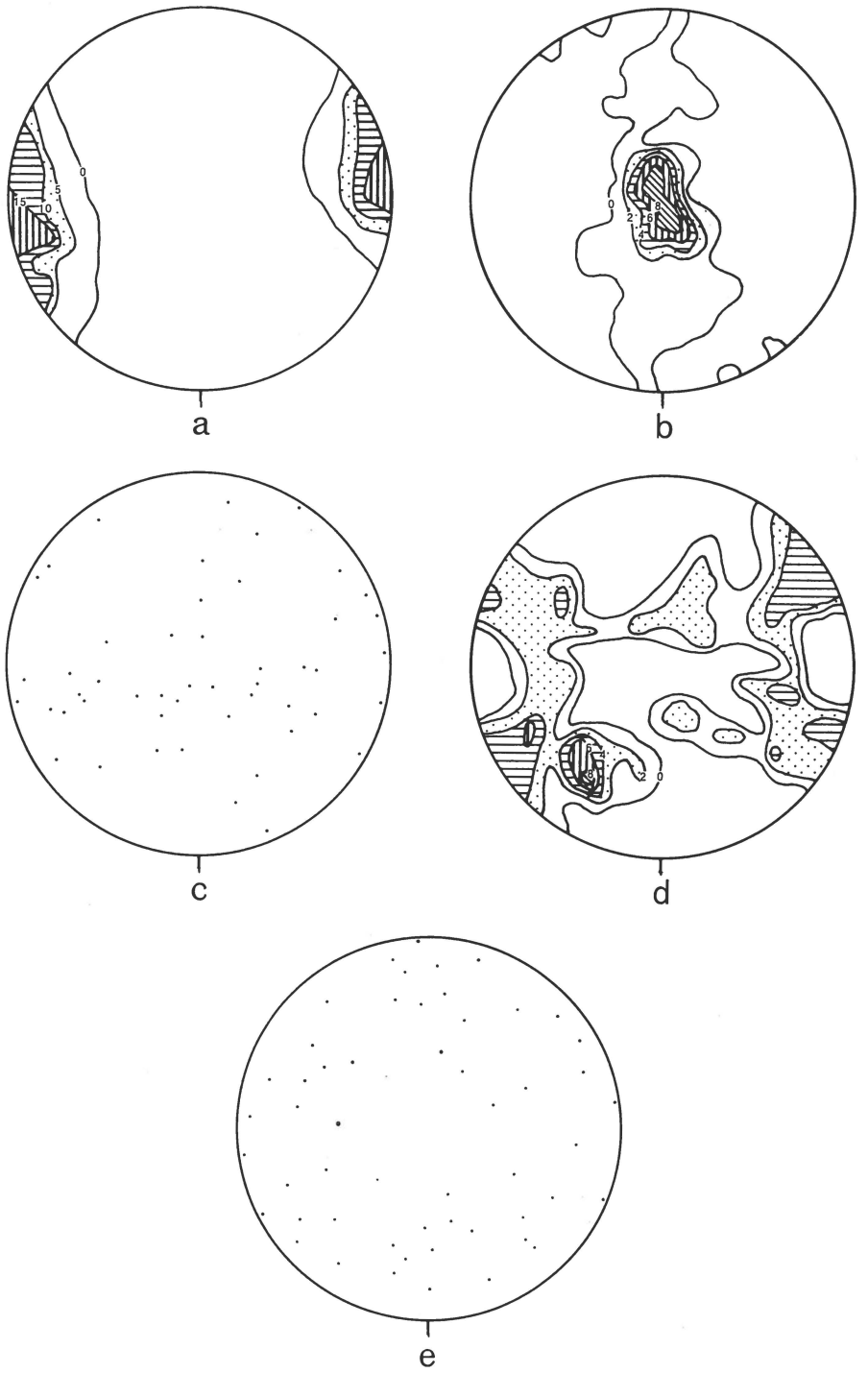


Fig. 18. White layer in kakortokite.

(a) Stereogram of the poles ⊥ (030) of microperthite laths (50 points) in sections cut perpendicular to the layering and oriented N–S (GGU 24827).
(b) Stereogram of the a-crystallographic axes of microperthite laths (50 points) in sections cut perpendicular to the layering and oriented N–S (GGU 24827).
(c) Stereogram of the c-crystallographic axes of eudialyte grains in sections cut perpendicular to the layering and oriented N–S (GGU 24825).
(d) Stereogram of the c-crystallographic axes of nepheline grains (60 points) in sections cut perpendicular to the layering and oriented N–S (GGU 24827).
(e) Stereogram of the poles ⊥ (110) cleavages of arfvedsonite grains in sections cut perpendicular to the layering and oriented N–S (GGU 24827).

cular to the lamination (Fig. 17 d). Neither aegirine nor eudialyte exhibit preferred orientation (Fig. 17 c and e).

White layer in kakortokite

In the white layer the only mineral to display preferred orientation is the microperthite, laths of which exhibit both lamination and lineation (Fig. 18 a and b). The eudialyte, nepheline and arfvedsonite show no preferred orientation (Fig. 18 c, d and e).

IV. GEOCHEMISTRY OF THE KAKORTOKITE WITH COMPARATIVE DATA

General

Of the rock units studied, the layered kakortokite was subjected to the most detailed geochemical analysis, involving 48 specimens. In addition to these quantitative analyses, semi-quantitative analyses were carried out on a further 100 whole rock specimens and 40 minerals. In the presentation of this data the ordinate scale was chosen to represent the layered units and the abscissa to indicate the concentration of the elements. The vertical thickness of the kakortokite is approximately 400 m and comprises approximately 30 layered units, each containing black, red and white layers. These layers can display thickness variations, but the black, red and white layers average 1.5, 1.0 and 10.0 metres thick respectively. These layered units have been represented as having equidimensional thicknesses in the variation diagrams. Analyses for the red layered are limited in number, due to the incipient character of some of these occurrences, which are more in the nature of eudialyte-enriched white layers. Great care was taken in assigning a particular layer to its correct unit; however, due to the considerable lateral extent of these layers, difficulties of correlation did arise. It is felt, however, that, with the exceptions of GGU specimens 24908–09–10, the positioning of these layers has a maximum error of ± 2 units. The position of specimens 24908–09–10 is only approximate as this unit occurs high up on the SW flank of Laksefjeld in a scree-covered area removed from the main layered sequence. In figure 19, the location of the specimens is shown projected on to a vertical plane extending from the peaks of Iviangiussaq kangigdleq to Laksefjeld.

On aerial photographs it is possible to delineate "shadow" layers in the rocks below the main cliff of Kringlerne, that is to say, below specimen J 1. In the field, however, the mineral variations in the rocks below J 1 are so indistinct that these rocks may be regarded as homogeneous kakortokite, which most closely approximates the mineral composition of the white layers. GGU specimens 24775–6 are located

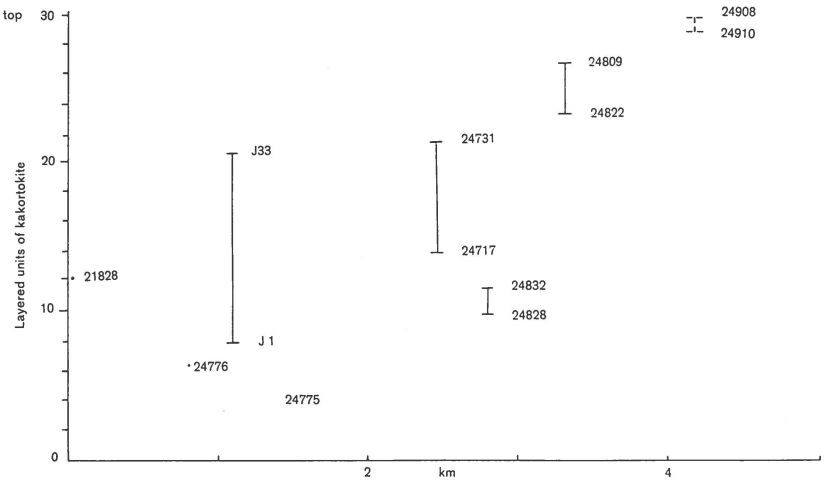


Fig. 19. Position of analysed kakortokite specimens as projected onto a vertical plane extending from the peaks of Iviangiussaq kangigdleq to Laksefjeld.

in this area and have been positioned according to the "shadow" units as shown on aerial photographs.

Variations diagrams of major elements

In the construction of diagrams of the major elements, the author used ternary cation plots similar to those presented by ERICKSON and BLADE (1963) for the alkalic rocks of Magnet Cove, Arkansas.

In addition to the analyses given in table 27 the author has also used recent results, published by GERASIMOVSKII and KUZNETSOVA (1967), in the construction of the ternary diagrams for the major elements (Figs. 20 to 24).

Figure 20 is a plot of the major elements of the intrusive rocks of Ilímaussaq. This ternary diagram illustrates the high percentage of the Na + K + Ca component of these rocks. A cursory view of figures 21 and 22 shows the extreme enrichment of these rocks in the two alkalies, particularly, Na and their relatively low Ca content. In figure 23 a plot, with alkalies, total Fe and Mg as the three components, indicates that the rocks are very low in Mg, with most plots occurring along or near the Na + K and Fe tie-line and being enriched in either of these components. Figure 24 serves to illustrate the low Si content of the rocks, moderate Al content and high total alkalies.

Figures 21 and 22 show that the augite syenite and heterogeneous syenite are conspicuously richer in Ca and K, relative to the other rocks. The "aegirine dike" and the lujavrites with one exception, show extreme Na enrichment, a feature which is further exaggerated by those speci-

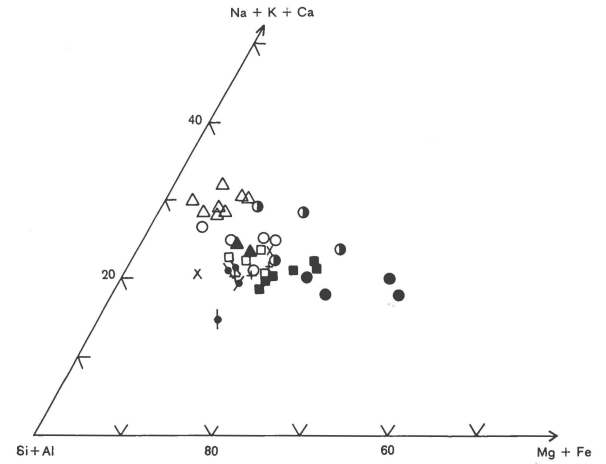


Fig. 20. Ternary diagram showing the atomic proportions of the major elements encountered in the rocks of the Intrusion (only the average value of the alkali granite is given = 12 analyses).

LEGEND to figures 20-24, 26, 29, 31, 34-36.

- ○ White layers
- ◑ Red layers
- ● Black layers
- ⊗ Weighted value

} KAKORTOKITE

- ■ Black
- ◪ Transitional
- □ Green

} LUJAVRITES

- △ Naujaite
- ◭ Transition between naujaite and sodalite foyaite
- ▲ Sodalite foyaite
- ♦ "Kakortokitic" rocks
- ◊ "Hybrid" rocks
- o "Aegirine dike"
- ⸸ Alkali granite
- ⸸ Quartz syenite
- ⸸ Pulaskite
- + Augite syenite
- × Heterogeneous syenite

mens containing a high zeolite content. Green lujavrite GGU specimen 48001 plots anomalously, being relatively richer in K and Ca, this despite its high natrolite content of 13.7 volume per cent. The eudialyte and arfvedsonite content of this rock is not unduly high, so cannot be responsible for the high Ca content of this rock; and by a similar token

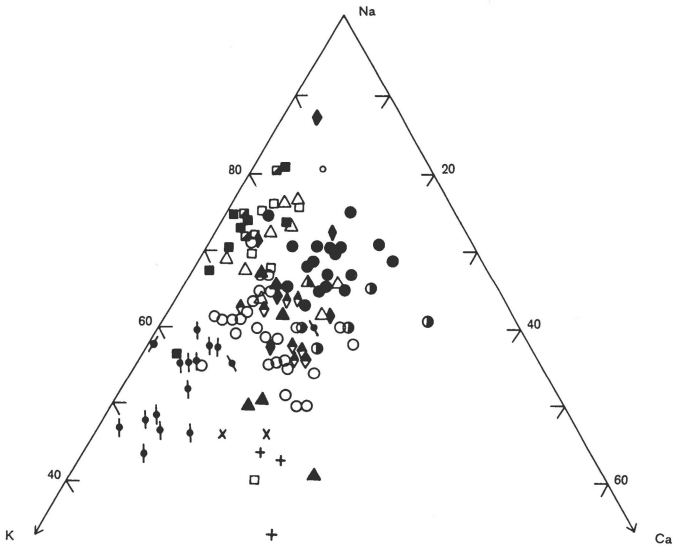


Fig. 21. Ternary diagram showing the atomic proportions of Na – K – Ca encountered in the rocks of the Intrusion.

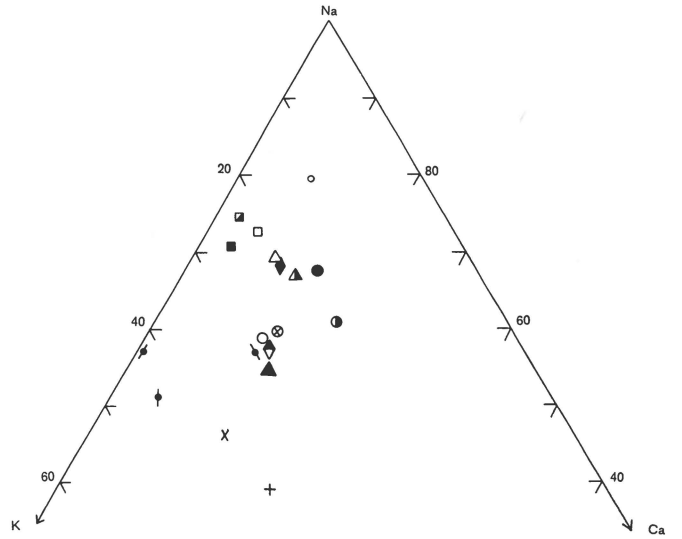


Fig. 22. Ternary diagram showing the average atomic proportions of Na – K – Ca encountered in the rocks of the Intrusion.

the percentage of the remaining minerals is not anomalous. Late-stage fluorite, which was not present in the thin section used in the modal analysis, may in fact account for the high Ca content of this rock, but the K remains an enigma. It would appear likely that this specimen may be anomalous as a result of faulty chemical analysis. In the ternary

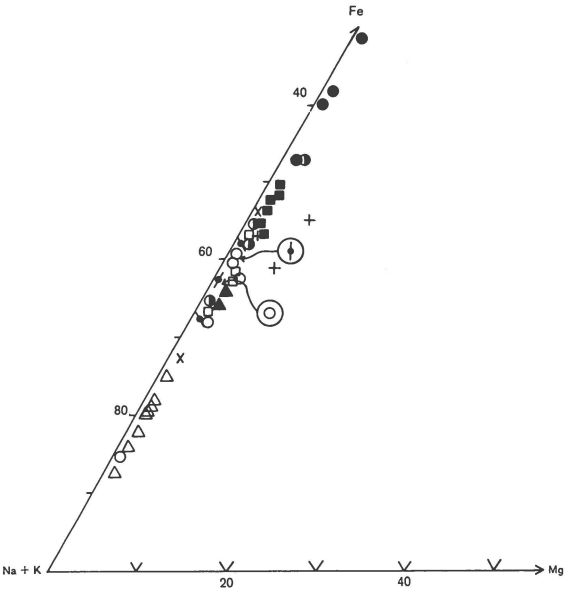


Fig. 23. Ternary diagram showing the atomic proportions of Fe – Mg – Na + K encountered in the rocks of the Intrusion (only the average value of the alkali granite is given = 12 analyses).

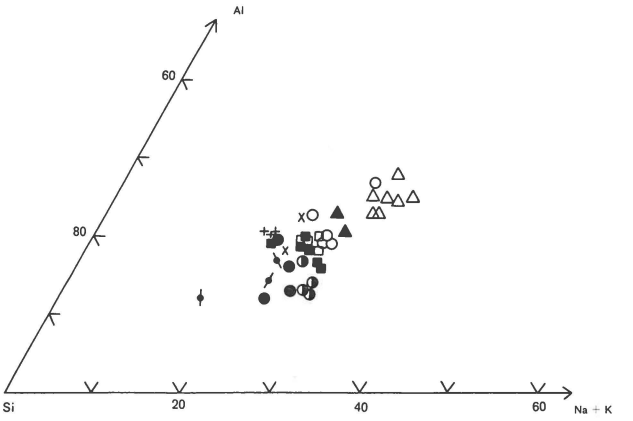


Fig. 24. Ternary diagram showing the atomic proportions of Al – Si – Na + K encountered in the rocks of the Intrusion (only the average value of the alkali granite is given = 12 analyses).

plot using the average values (Fig. 22), GGU specimen 48001 has been omitted.

The higher alkali feldspar content of the white layers of the kakortokite is reflected in their greater K content, compared to the black and, to a lesser degree, the red layers (Fig. 21). The high eudialyte content of the red layers results in Ca enrichment relative to the white and, to

a lesser extent, the black layers. The average Ca value for the latter layers of 15.1% compares with 13.0% Ca in the white layers (on the basis of Na + K + Ca = 100). Some of the white layers do however have higher Ca contents than the black layers. In most cases, the modal analyses of these anomalous white layers indicate eudialyte enrichment, hence accounting for the high Ca contents. Exceptions to the latter are specimens J 13, 24775 and 24776, which have lower eudialyte contents than the average of 9.1 per cent for the white layers as compared to 9.8 per cent for the black layers. Furthermore, these anomalous white layer specimens do not have unusually high arfvedsonite or aenigmatite contents. It would appear unlikely that the degree of eudialyte alteration could be responsible for the anomalous Ca content of some of these rocks, as the white and black layers show similar percentage alterations, 86.6 and 94.4 respectively. It is suggested the fluorite may be responsible for the anomalously high Ca-content of these rocks, although it should be noted that this mineral was only found to occur in GGU specimen 24775. Fluorite has, however, erratic distribution in these rocks, and it is highly conceivable that other thin sections of the investigated hand specimen would in fact show fluorite enrichment.

The high zeolite content present in some of the specimens from the white and black layers of the kakortokite has not markedly affected the close grouping of the average values of the three layers (Fig. 22). The average value of the "hybrid" rocks shows a close affinity with the white layers of the kakortokite and also to the volumetrically-weighted kakortokite average. Conversely, the average value for the "kakortokitic" rocks is far more Na-rich and Ca- and K-poor than the weighted kakortokite value.

The naujaite generally shows considerable Na-enrichment and minor Ca-deficiency compared to the sodalite foyaite. The average values of the alkali quartz syenite and pulaskite form a relatively close grouping, showing K-enrichment and a small Ca-deficiency relative to most of the agpaites.

Figure 23 serves to illustrate the low Mg content of the Ilímaussaq rocks and their high alkali and total iron contents. The kakortokite and lujavrites show the greatest Fe enrichment, which can be attributed to their high acmitic pyroxenes and/or arfvedsonite contents. The augite syenite also shows relatively high iron contents; this is attributed to the relatively high magnetite content of the rock. The relatively low amounts of acmitic pyroxenes and arfvedsonite in the naujaite specimens examined is reflected by their low total iron content.

The close grouping of the oversaturated alkali granite and quartz syenite with the agpaites in figure 20 is a result of their similar Fe and Mg contents and the antipathetic variation of Si and Al producing alike

values for the Si+Al function. Figure 24 distinguishes these groups of rocks, as Si and Al are plotted separately. The augite syenite, heterogeneous syenite and pulaskite are also closely grouped with the agpaites in figure 20, as the alkali deficiency of these rocks relative to the agpaites is compensated for by increased Ca (Fig. 21), thereby keeping the Na + K + Ca function fairly constant.

The alkali metals

Sodium and potassium

As has already been discussed, the Ilímaussaq rocks show enrichment in the alkalies, particularly sodium. The Na : K ratio of the Ilímaussaq rocks varies considerably (Table 30, Appendix) from a near unity ratio for the augite syenite and heterogeneous syenite to a maximum of 8.25 in a zeolite rich "kakortokitic" rock (GGU 24954). The average Na : K values for the rock types containing less than 10 per cent zeolites, range from 0.96 for the augite syenite to 3.91 in the green lujavrite. As can be seen in table 30 this average ratio increases in the order augite syenite, heterogeneous syenite, "hybrids", weighted kakortokite, black lujavrite, "kakortokitic" rocks, sodalite foyaite, naujaite, transition of sodalite foyaite to naujaite, green lujavrite and "aegirine dike".

It may be anticipated that the rocks containing a high zeolite content would show a corresponding increase in the Na : K ratio due to their higher Na content. The sodalite foyaite "hybrids", green lujavrite and the weighted kakortokite averages, however, show reversals of this trend: namely, that the rocks containing more than 10 per cent zeolites show a Na : K ratio decrease compared to their equivalents with less than 10 per cent zeolites. In the case of the sodalite foyaite, the zeolite "poor" specimen used for comparison (GGU 48082) contains 9.7 % analcime. The weighted kakortokite values differ by only a small margin, having a Na : K ratio of 2.49 for the rocks of low zeolite content as opposed to 2.46 for the rocks having a zeolite content in excess of 10 per cent. Similarly the "hybrids" show small differences for this ratio. The large variations in this ratio in the case of the green lujavrite are largely attributed to specimen 48001 which appears to be chemically anomalous, as was discussed in the section of the major oxides. The main variations in the Na : K ratio of these rocks is largely accounted for by the fluctuations in the proportions of the Na- and K-rock-forming minerals present; this applies particularly to the kakortokite where mineral gradations typify this rock unit. A plot of the Na : K ratios for the detailed kakortokite section does not show any particular trend. A possible explanation for the slight discrepancies in the Na : K ratio

for the zeolite-enriched rocks occurs in the finding at Lovozero (VLASOV et al., 1959, p. 517) that there can be small isomorphous replacement of Na by K in the zeolites and other minerals. Further K enrichment may also result by K and Na replacing Ca in the calcic rare-metal minerals (VLASOV et al., 1959, p. 518).

The augite syenite, heterogeneous syenite and alkali granite (HAMILTON, 1964) all show Na : K ratios close to unity. The syenites from Kûngnût (UPTON, 1960, p. 100) also have a near unity value for this ratio. The early miaskitic rocks of Lovozero (GERASIMOVSKII and LEBEDEV, 1959, p. 72), which are more alkaline than the augite syenite and heterogeneous syenite, have a Na : K ratio of approximately 2. There is a further increase of this ratio with the development of the later agpaites. GERASIMOVSKII (1956) noted that the Na content in agpaitic rocks is greater than the K content.

Rubidium

The Rb content of the Ilímaussaq rocks varies within relatively narrow limits as can be seen from tables 17 and 28 (Appendix).

Table 17. *Average Rb contents*

Rock type	Rb (ppm)	
	Less than 10 % zeolites in rock	Greater than 10 % zeolites in rock
	Number of analyses in parentheses	
Heterogeneous syenite	228 (1)	200 (1)
"Hybrids"	209 (6)	235 (2)
"Kakortokitic" rocks	203 (1)	171 (5)
Augite syenite	195 (2)	
Kakortokite*	195 (33)	180 (21)
Sodalite foyaite	192 (1)	218 (4)
Black lujavrite	192 (2)	137 $(3)_8$
Naujaite	189 (5)	
Transition sodalite foyaite to naujaite	189 (1)	
Green lujavrite	148 (2)	219 (2)
Transition black to green lujavrite		158 (3)
"Aegirine dike"		94 (1)

* weighted average

VOLKOV and SAVINOVA (1959, p. 636) found that in the rocks from Lovozero the Rb content decreases with zeolitization. A perusal of table 17 shows that in the Ilímaussaq rocks there is a general decrease in Rb in those specimens with the higher zeolite content. The zeolite-rich specimens of black lujavrite show a Rb loss of 29 %; however, the re-

maining rocks show losses of less than 16%. The "hybrids", sodalite foyaite and green lujavrite show reversals of this trend. However, it is to be noted that these are the only rocks that also show a reversal of the potassium content; that is, the zeolite-rich rocks have a higher K content than their zeolite-poor equivalents. It would appear then that there is an inter-dependency of the Rb and K contents.

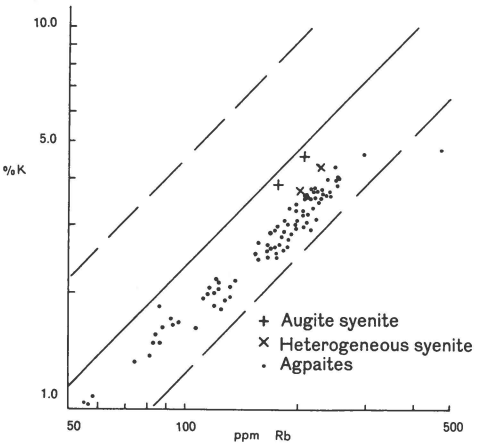


Fig. 25. K:Rb ratios of the Ilímaussaq rocks superposed on the average K:Rb curve given by AHRENS et al. (1952). Broken lines indicate the normal limits of scatter.

Potassium: Rubidium ratio

AHRENS et al., (1952) and other workers (TAYLOR et al., 1956) have shown that the ratio of K : Rb varies within restricted limits for a wide variety of rock types. In figures 25 and 26 it can be seen that the Ilímaussaq rocks are no exception; they display a consistent Rb enrichment relative to K. The two augite syenite values approach the average K : Rb curve of AHRENS et al., (op. cit.) and the two heterogeneous syenite values occupy a position intermediate between the former values and the average values of the agpaites. With one exception the K : Rb values of the Ilímaussaq rocks fall within the limits of scattering (Fig. 25). The one anomalous result (GGU 24720) is from a white layer in the kakortokite particularly enriched in alkali feldspar (61.8 volume %). The zeolite content of this rock is only moderate so that its anomalous nature is a little perplexing.

AHRENS et al., (1952, p. 239–40) and GOLDSCHMIDT (1954, p. 164) discuss the relative enrichment of Rb to K in pegmatitic and residual material. TAYLOR et al., (1956) have demonstrated the enrichment of Rb to K from strongly differentiated magmas. As noted by various

authors a feature of the K : Rb ratio is a decrease in this value with progressive differentiation (DEMIN and KHITAROV, 1958; GERASIMOVSKII and LEBEDEV, 1959, VOLKOV and SAVINOVA 1959; BUTLER et al., 1962 and SIEDNER, 1965). In the Ilímaussaq rocks the K : Rb ratio decreases from 217 in the augite syenite to 146 in the lujavrites that are transitional between the black and green varieties. For the Ilímaussaq rocks containing less than 10 per cent zeolites the K : Rb ratio decreases in

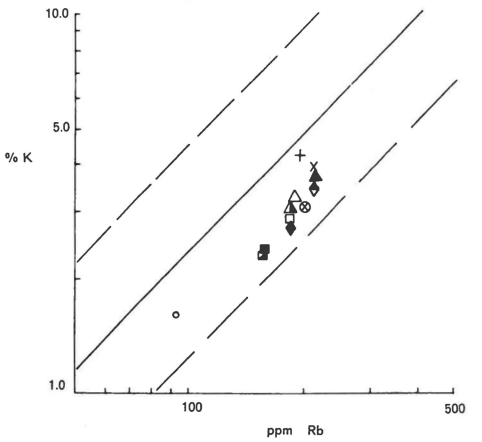


Fig. 26. Average K:Rb ratios of the Ilímaussaq rocks (superposed curves as in figure 25).

the following order: augite syenite, heterogeneous syenite, sodalite foyaite, naujaite, "hybrids", transition sodalite-foyaite to naujaite, weighted kakortokite, "kakortokitic" rocks, black and green lujavrite (Fig. 26).

The detailed kakortokite sequence (Figs. 27 and 28) shows that in the white layers there is in general a decrease of the K : Rb ratio with height. As can be seen in these figures the rocks high in zeolites do tend to have a higher value for this ratio resulting from their lower Rb content. GGU specimen 24909 shows the extreme of this development. GGU specimen 24728 is, however, anomalous in this respect in that although it has a high zeolite content it shows Rb enrichment. With the exception of GGU specimen 24817 the red layers show similar value to those in the white (Fig. 28). The anomalous specimen has a low Rb content. In the black layers (Fig. 27) the K : Rb ratios are much higher than in the other two layers and furthermore show an indefinite trend; in fact, the specimens low in zeolites show a slight positive trend. These values taken collectively with the ratios for the rocks high in zeolites do, however, present a negative trend. In his respect specimen 24908 is anomalous (Fig. 27) due to its low Rb content.

The consistency of the K : Rb ratio of the Ilímaussaq rocks is a surprising feature in view of the frequent large scale zeolite alterations present which can reach a maximum of 44.9 volume per cent in the lujavrites. It can be seen from table 30 (Appendix) that there is very little difference between the K : Rb ratio for the rocks containing less

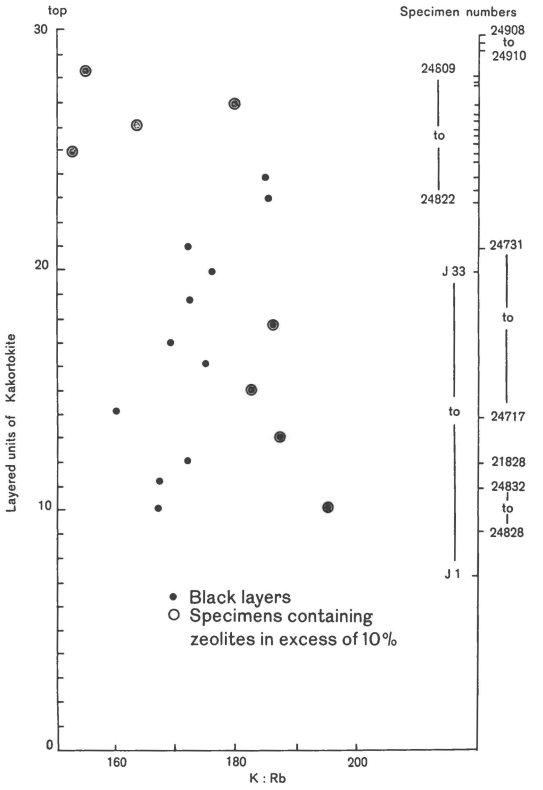


Fig. 27. K:Rb ratios of the black layers of the kakortokite plotted against height of the layered units.

than 10 per cent zeolites and for their equivalents containing zeolites in excess of 10 per cent. The black and green lujavrites show a maximum K : Rb difference between 146 for the rock low in zeolite and 159 for the rocks with zeolites in excess of 10 per cent. The average K : Rb ratios of the agpaitic rocks vary between the relatively narrow limits of 172 for the sodalite foyaite and 146 for the black and green lujavrites in the rocks with less than 10 per cent zeolites. The limits of this ratio for the rocks containing zeolites in excess of 10 per cent is 174 for the sodalite and 146 for the lujavrite that is transitional between the black and green varieties.

The variation within relatively narrow limits of the K : Rb ratio in the agpaitic rocks of Ilímaussaq compares with the findings of VOLKOV and SAVINOVA (1959, p. 74) for the agpaitic rocks of Lovozero where the K : Rb ratio varied from 200 to 170. GERASIMOVSKII and LEBEDEV's (1959) earlier preliminary findings for the agpaitic rocks of Lovozero

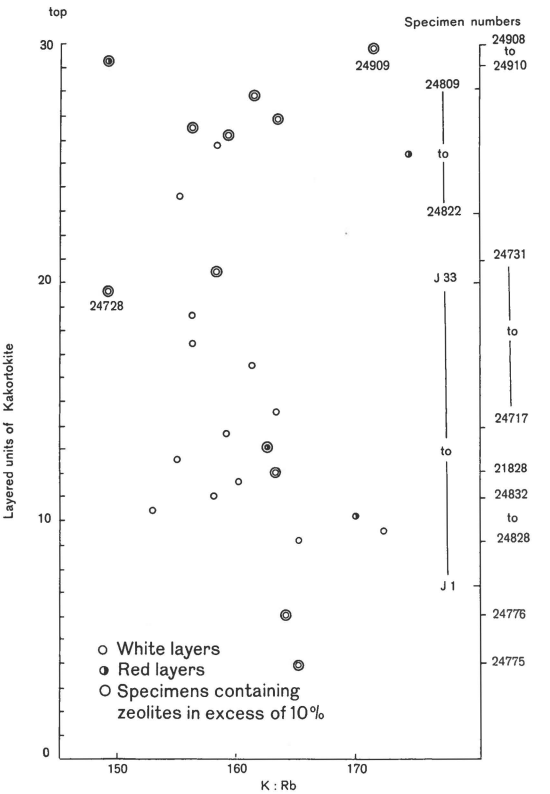


Fig. 28. K:Rb ratios of the red and white layers of the kakortokite plotted against height of the layered units.

contrast markedly with those of VOLKOV and SAVINOVA (op. cit.); however, as these latter authors suggest, this earlier work requires "amplification and refinement (p. 635)".

HAMILTON's (1964, fig. 31A) K : Rb values for the Ilímaussaq rocks show a high proportion of anomalous Rb enrichment relative to K, with a number of plots falling outside the normal limits of scattering. It is a little difficult to reconcile this finding with those of the author, namely that, with only one exception, the K : Rb values all fall within the limits of normal scatter. Both sets of results show a general increase in Rb in the later differentiates and a near normal K : Rb ratio for the augite syenite.

Lithium

By far the highest concentration of lithium occurs in the black lujavrite (Table 28, Appendix), whereas the augite syenite contains the lowest concentration. In the rocks containing less then 10 per cent zeolites the order of decreasing lithium content is black lujavrite, sodalite foyaite, naujaite, weighted kakortokite, heterogeneous syenite, transition sodalite foyaite to naujaite, "kakortokitic" rocks, "hybrids", green lujavrite and augite syenite. The affect of zeolites on the Li content is difficult to assess as specimens containing an excess of 10 per cent zeolites can show either greater or lesser amounts of Li than their equivalents which are low in zeolites. In turn the Li content does not appear to bear any obvious relationship to the mineral content. FERSMAN (1941) suggested that Li + Al may substitute for Mg in ferro-magnesian minerals. AHRENS (1965, p. 66) is of the opinion that hornblende is the most favourable location for Li in the ferro-magnesian minerals as it substitutes for Fe^{2+} and Mg^{2+}. However, the most favourable location for Li is in the mica structure where it is accepted into the octahedral structure sites occupied by the cations Mg^{2+}, Fe^{2+} and also Al^{3+} (AHRENS, op. cit., p. 66). In the Ilímaussaq rocks lepidolite mica has wide distribution in the agpaitic rocks. This may account for the "erratic" distribution of Li in the rocks studied; in the analysis of a limited number of thin sections of any one rock specimen, lepidolite may not necessarily be present and so not appear in the modal analysis.

Limited trace element analyses of minerals from Ilímaussaq rocks undertaken by HAMILTON (1964, p. 48) show that eudialyte contains a greater amount of Li than sodalite, aegirine, steenstrupine, feldspar and mafics. Individual analyses of arfvedsonite were not carried out.

The black lujavrite has by far the greatest Li content, suggesting that the major host for this element is the amphibole; however, the black arfvedsonite-rich layers in the kakortokite contain less Li than do the white layers. It would seem then that the distribution of Li is possibly connected with the irregular distribution of lepidolite.

Cesium

Cs was sought for in the spectra but found to be below detection limit; however, semiquantative spectrographic analyses carried out by I. SØRENSEN (HAMILTON, 1964, table 20) show the augite syenite to be almost devoid of cesium and the concentration in the agpaites ranges from 0 to 9 ppm, averaging less than 3 ppm.

The alkaline earth metals

The highest concentration of strontium occurs in the eudialyte-rich red layers of the kakortokite where a maximum of 298 ppm is reached as compared to a minimum of 59 ppm in the naujaite (Table 28, Appendix). Averages of the strontium contents in the Ilímaussaq rocks vary from 203 ppm in the augite syenite to 74 ppm in the naujaite. The red layers of the kakortokite and the "aegirine dike" give averages of 246 ppm and 257 respectively.

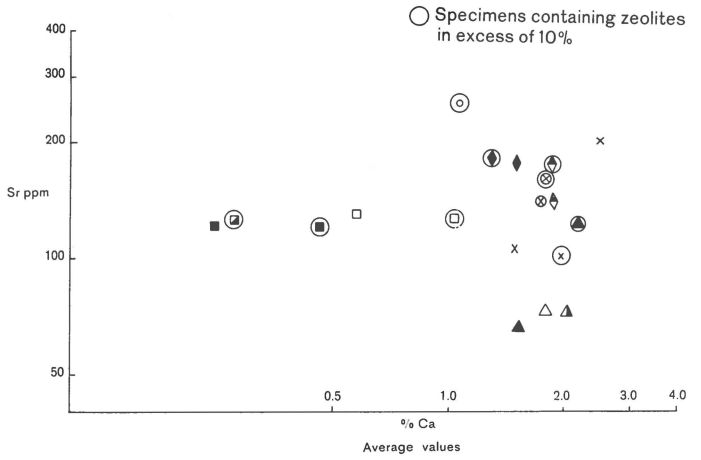


Fig. 29. Plot of the average Ca contents versus Sr for the rocks of the Intrusion.

The presence of a high zeolite content in the rocks has no consistent affect on the Sr and Ca contents. Only minor variations exist between the Sr and Ca contents of the rock specimens low in zeolites and those of their zeolite-rich equivalents.

As can be seen from figure 29 the covariance of Sr and Ca is by no means clearly marked. There is, however, a general tendency for the rocks having the highest Ca contents to have a correspondingly high Sr content and vice versa. The sodalite foyaite and naujaite behave anomalously in this respect in that they show Sr deficiency relative to calcium. A similar relationship was found to hold in the Lovozero massif (GERASIMOVSKII and LEBEDEV, 1958, p. 703) where the sodalite-rich rocks also display a Sr deficiency relative to Ca. The lujavrites of Ilímaussaq show a marked Ca decrease accompanied by only moderate Sr deficiency. The increase of the Sr : Ca ratio with fractionation is a noted feature of differentiated complexes (NOCKOLDS and MITCHELL, 1948; WAGER and MITCHELL, 1951; GERASIMOVSKII and LEBEDEV, 1958). As in Lovozero (GERASIMOVSKII and LEBEDEV, 1958, p. 703), the Sr and Ca contents in the Ilímaussaq rocks do not have a directly sym-

pathetic relationship to one another. The Ca-rich rocks in Lovozero did, however, contain the highest percentage of Sr and similarly those rocks low in Ca were correspondingly low in Sr.

The plot of the Sr : Ca ratios for the kakortokite sequence (Fig. 30) indicates that the zeolite-rich and -poor rocks show little discrepancy. In addition the three layers of the kakortokite show similar values and

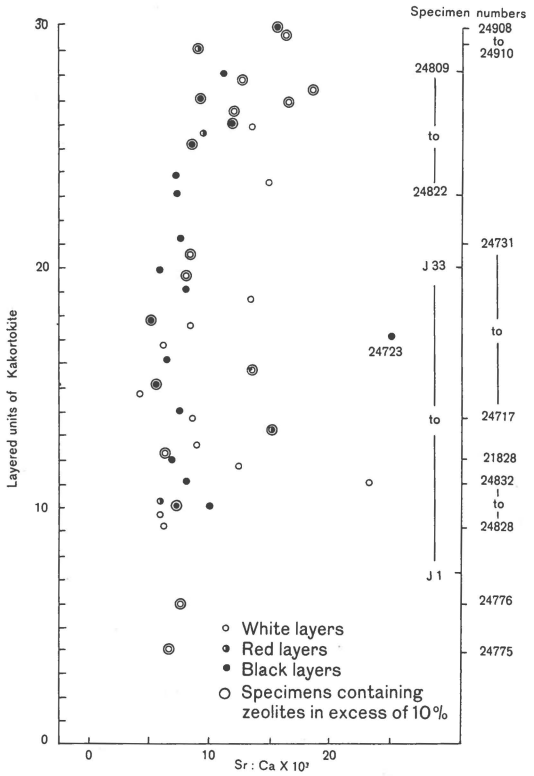


Fig. 30. Sr:Ca ratios of the individual layers of the kakortokite plotted against height of the layered units.

in general the Sr : Ca ratio displays an increase with height. The two anomalous specimens, GGU 24723 and 24832, result from their exceptionally low Ca content; the latter specimen has a very high nepheline content (70 volume %) but 24723 is not mineralogically anomalous. Gerasimovskii and Lebedev account for the absence of a direct interdependence of these two elements by postulating isomorphous replacement by strontium of not only calcium, but also potassium. No covariance was shown by either a plot of Sr vs K for the Ilímaussaq rocks or a plot of Ca + K vs Sr. As pointed out by Siedner (1965, p. 124 and 125), the concept of Sr – K diadochy results from the frequently substantial presence of Sr in alkali feldspars in which Ba can also be present in large

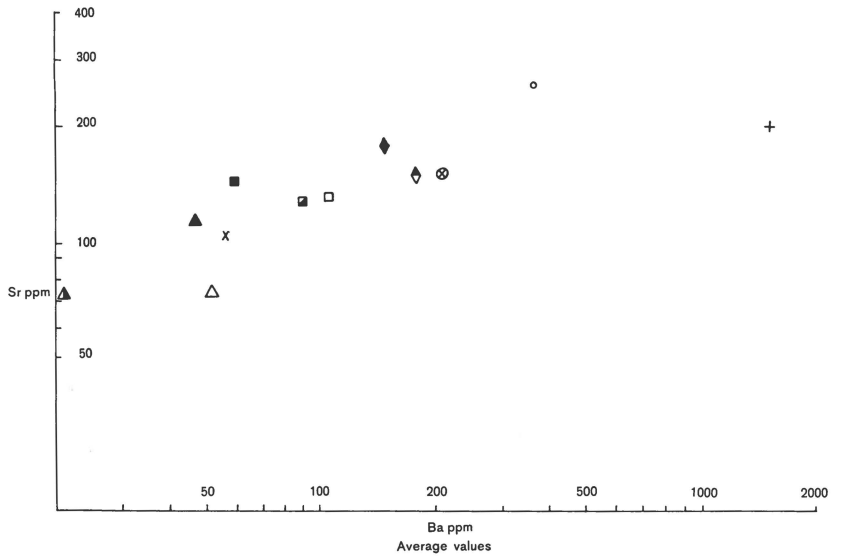


Fig. 31. Plot of the average values of Sr versus Ba for the rocks of the Intrusion.

amounts. SIEDNER suggests that Sr could substitute for either Ba or K with equal facility. As is the case for the Paresis complex (SIEDNER, op. cit.), there is a fairly marked covariance between Ba and Sr for the Ilímaussaq suite (Fig. 31), with the sodalite-rich naujaite and sodalite foyaite being once again slightly enomalous by showing Ba enrichment relative to Sr. The Sr : Ca ratio of the Ilímaussaq rocks varies from 0.003 in a naujaite (GGU 48004) to 0.061 in the black lujavrite (GGU 24693, see Table 30). The comparative values for the Lovozero rocks vary from 0.033 to 0.541 (GERASIMOVSKI and LEBEDEV, op. cit.), a ratio approximately ten times in excess of the corresponding ratios for the Ilímaussaq rocks. These higher ratios are produced by the much increased Sr contents of the Lovozero rocks which range from 0.008 to 1.75% SrO. The calcium also displays a bigger range, *viz.* 0.03 to 11.0% Ca. The differences in the Sr concentration of these two intrusions is very surprising. HAMILTON (1964, table 20) shows Sr values for the Ilímaussaq rocks to be of a similar order to those presented here, namely, a range from 400 ppm in the augite syenite to 0 ppm in the naujaite.

In view of the preference of Ca^{2+} for the 6-fold coordination with O and Sr^{2+} for the 8-fold co-ordination, TAYLOR (1965, p. 154) anticipates that Sr may be expected to increase relative to Ca during fractionation.

Trace elements analyses on a few minerals from the Ilímaussaq rocks (HAMILTON, 1964, table 5) show that Sr and Ba are concentrated in eudialyte where a maximum of 3000 ppm Sr and 2000 ppm Ba is found. By comparison the maximum amounts of these two elements

in feldspar are 100 and 5 ppm respectively. Of the rock-forming minerals common to the Ilímaussaq and lovozero complexes it was found that at Lovozero the eudialyte contained the most strontium, occurring in amounts up to 1.42% SrO (Gerasimovskii and Lebedev, op. cit.). At Lovozero barium also displays a high concentration in eudialyte which contains 0.65% BaO (Vlasov et al., 1959, p. 537).

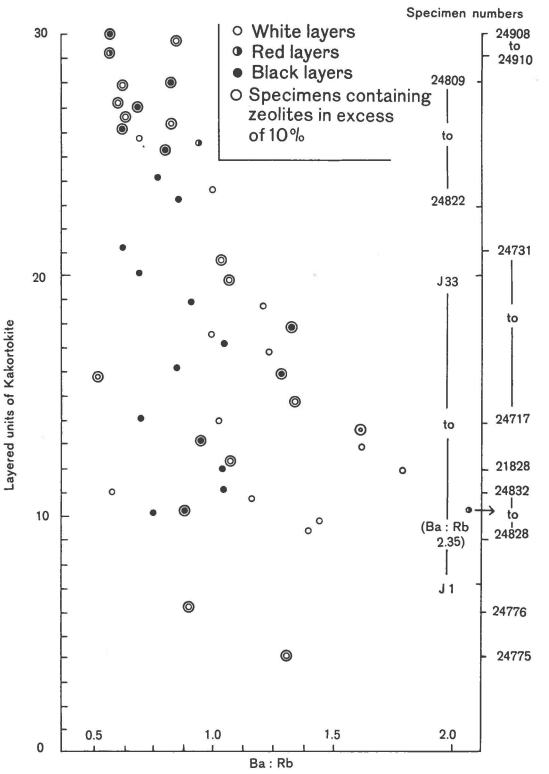


Fig. 32. Ba:Rb ratios of the individual layers of the kakortokite plotted against height of the layered units.

The Ilímaussaq rocks display a wide range of the Ba : Rb ratio; the average values of 7.64 for the augite syenite and 0.22 for the sodalite foyaite mark the extremes of this variation (Table 30, Appendix). Attempts were made to correlate, in a given rock unit, the Ba : Rb variation with the degree of zeolite alteration. It was found that there was no consistency between the variations displayed in the rock unit and the degree of zeolite alteration.

There is a fall-off in this ratio from the augite syenite to the agpaites; the sodalite-rich rocks, naujaite and sodalite foyaite, have particularly low values. The heterogeneous syenite also has a surprisingly low value for the Ba : Rb ratio, namely 0.27. In the kakortokite suite

it can be seen that there is a general decrease in this ratio from bottom to top. For a particular layered unit the black layers of the kakortokite tend to have slightly lower values than the corresponding white and red layers (Fig. 32). Three kakortokite specimens show strongly anomalous Ba : Rb values; GGU 24720 contains an anomalously high feldspar

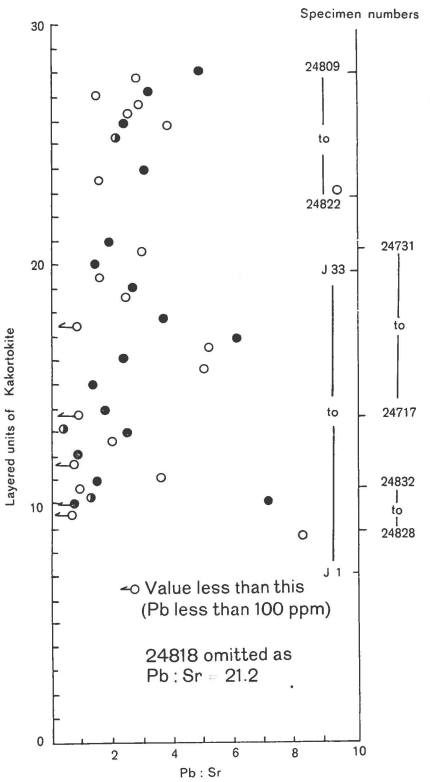


Fig. 33. Pb:Sr ratios for the individual layers of the kakortokite plotted against height of the layered units (symbols as in figure 32).

content and is enriched in Rb; GGU 24831 is excessively rich in eudialyte and shows Rb deficiency; GGU 24832 contains 70 % nepheline and is deficient in Ba. It is felt that these anomalous mineral contents can account for the irregular behaviour of these three rocks.

Pb^{2+} and Sr^{2+}, being of similar size, substitute for both Ca^{2+} and K^{+}; however, the more covalent character of the Pb-O bond leads to an increase with fractionation in the Pb/Sr ratio (AHRENS, 1953).

The Pb:Sr ratio of the kakortokite suite (Fig. 33) shows an ill-defined trend of progressive increase towards the top of this series. It must be remembered that the Pb analyses are only semi-quantitative but on a comparative basis, the trend indications are probably valid.

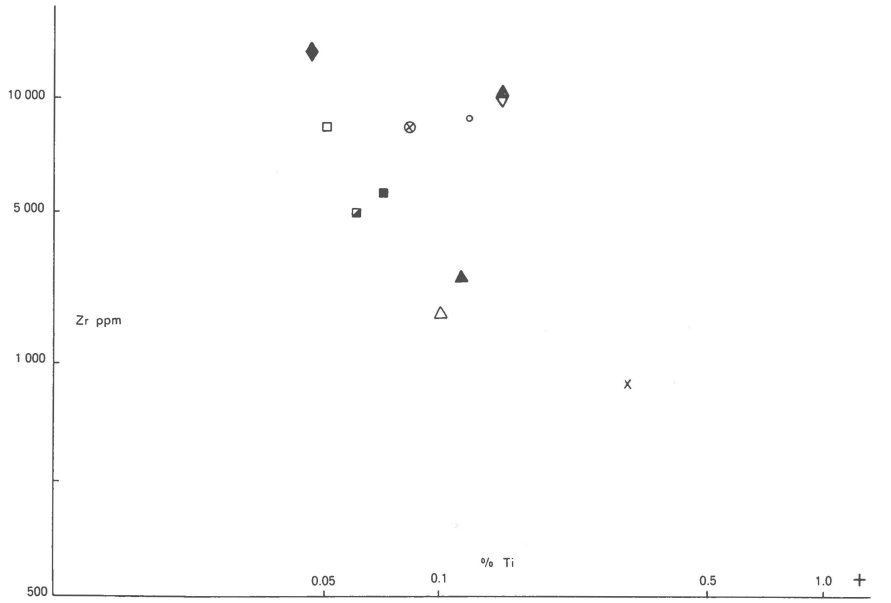


Fig. 34. Plot of the average values of Ti versus Zr for the rocks of the Intrusion.

Analyses of the rock-forming minerals in the kakortokite show that eudialyte and aegirine contain the most Pb, averaging approximately 250–300 ppm (Table 31, Appendix). Arfvedsonite, nepheline and feldspar average less than 100 ppm. The aegirine in specimen J 17 has a Pb content of 1300 ppm; this exceedingly high value suggests that small inclusion(s) of a lead mineral may be present in the aegirine. A kakortokite specimen submitted to Dr Oen Ing Soen revealed the presence of galena. The exceptionally high Pb:Sr ratios for GGU specimen 24818 (Table 31) (omitted from figure 33), and specimens 24822 and 24828 are probably the result of a lead mineral, like galena, being present in the rock.

Titanium, zirconium and niobium

Titanium and zirconium show antipathetic variation, with the augite syenite and heterogeneous syenite being richer in Ti and the agpaites richer in Zr (Table 29 (Appendix), fig. 34). The augite syenite contains an average Ti content of 1.383 % as contrasted with a Ti minimum of 0.047 % in the "kakortokitic" rocks. The minimum average Zr content is 532 ppm, occurring in the augite syenite, and a maximum is found in the "kakortokitic" rocks where 1.37 % Zr is present. The eudialyte-rich red layers in the kakortokite contain a higher average of 1.99 % Zr although the weighted Zr content of the kakortokite is only 8276 ppm. Niobium is concentrated in the agpaites, where a maximum average

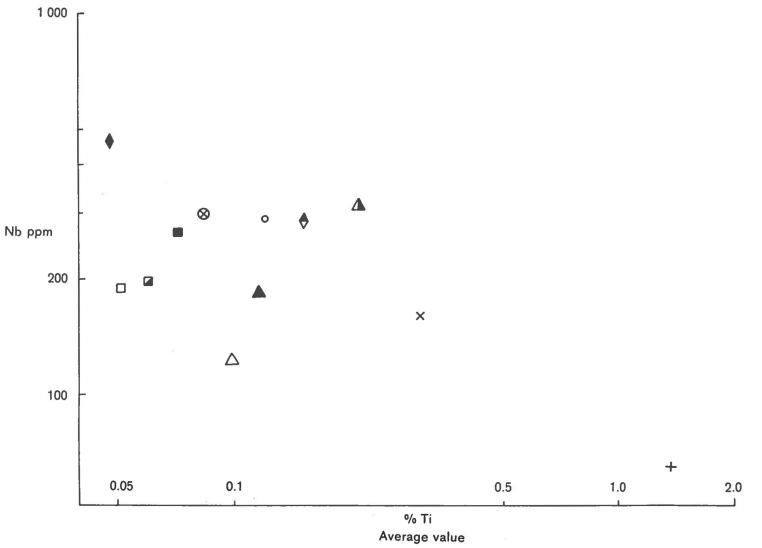


Fig. 35. Plot of the average values of Ti versus Nb for the rocks of the Intrusion.

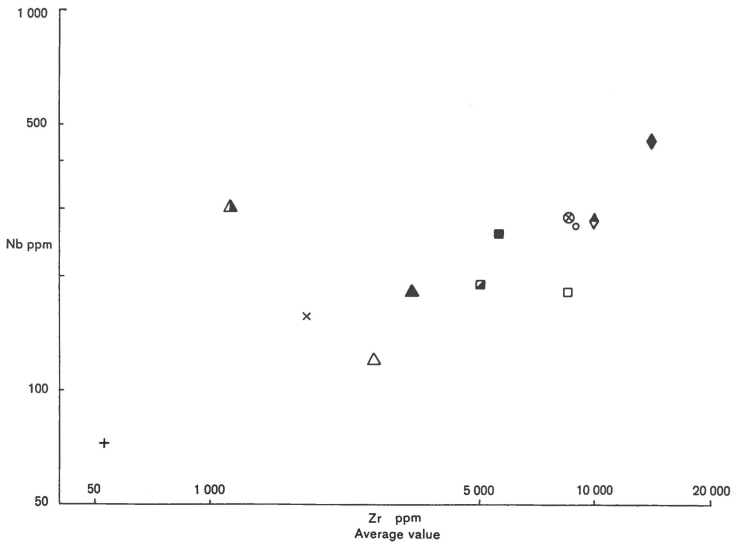


Fig. 36. Plot of the average values of Zr versus Nb for the rocks of the Intrusion.

amount of 463 ppm occurs in the "kakortokitic" rocks. The augite syenite, with an average of 73 ppm, is poorest in this element.

In the agpaitic rocks of Ilímaussaq Ti is concentrated in the complex Ti-silicates, the most important of which are neptunite, rinkite, aenigmatite, astrophyllite, "murmanite", epistolite and lovozerite. Trace element analyses of major minerals in the main agpaitic rock

units (HAMILTON, 1964, table 5) show that aegirine and, to a lesser extent, eudialyte contain considerable amounts of Ti in solid solution. In the augite syenite and heterogeneous syenite the Ti is bound to ilmenite/magnetite, biotite, augite and aegirine-augite.

In the agpaites, Zr concentrates mainly in eudialyte-eucolite, katapleite, astrophyllite, and lovozerite. In addition Zr also occurs in moder-

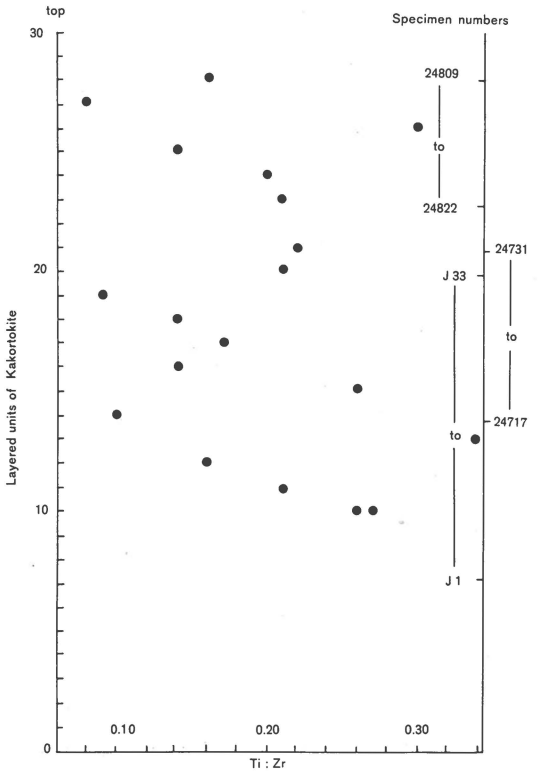


Fig. 37. Ti:Zr ratios of the black layers of the kakortokite plotted against height of the layered units (specimen 24908 omitted, Ti:Zr = 0.57).

ate amounts in aegirine, steenstrupine (HAMILTON, 1964, table 5), and, as is the case at Lovozero, probably occurs in significant amounts in the titanium and niobium minerals. Elpidite occurs as a frequent accessory mineral in the alkali granite and BØGGILD (1953, p. 245) has reported its presence from Kangerdluarssuk. Zircon from the augite syenite has been reported by USSING (1912, p. 186).

Microlite and pyrochlore are the two niobium minerals found in Ilímaussaq but due to similar chemical properties Nb substitutes for Ti^{4+} and Zr^{4+} in the Ti- and Zr-silicates. Of the analysed rock-forming minerals of the kakortokite (Table 31, Appendix), eudialyte and, to a lesser degree, aegirine contain moderate amounts of Nb.

It can be seen that a plot of the average values of Nb vs Ti (Fig. 35) produces a negative slope with the augite syenite containing the lowest Nb and highest Ti while the "kakortokitic" rocks show the reverse (Table 30, Appendix) By contrast the Nb vs Zr plot (Fig. 36) shows a positive slope with the aforementioned rocks once again showing the extremes of this variation. It can be seen from table 30 that the

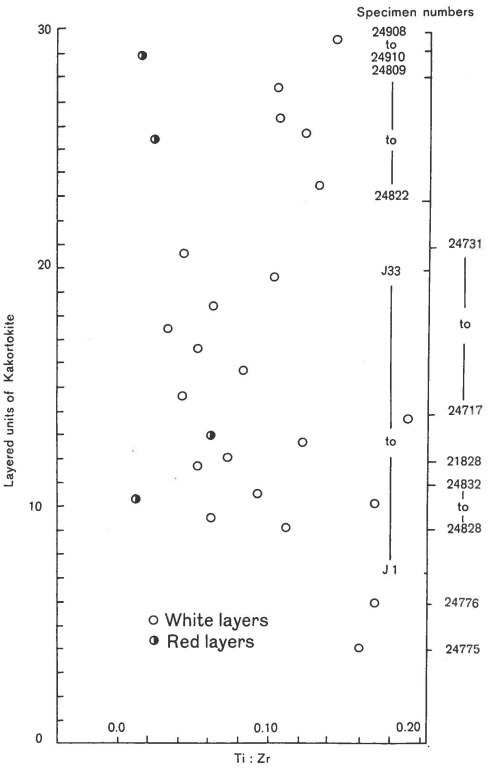


Fig. 38. Ti:Zr ratios of the red and white layers of the kakortokite plotted against height of the layered units.

Ti:Zr and Ti:Nb ratios decrease from the augite syenite to the agpaitic rocks with the "kakortokitic" rocks in each case exhibiting the lowest values for these ratios. The decrease in these ratios is brought about by a decrease in the Ti content in passing from the augite syenite to agpaitic rocks and a corresponding increase in the Nb content. The Zr:Nb ratio offers an inverse relationship to the latter ratios in that the agpaites have the highest values and the augite syenite has the lowest. There is considerable range of the ratio within the agpaites, varying from Zr:Nb = 18.1 in the sodalite foyaite to 43.6 in the green lujavrite.

The rock transitional between a sodalite foyaite and naujaite (GGU 24943) has the very low value of 3.5 for the Zr:Nn ratio. Sample GGU

48082 in the sodalite foyaite gives a similar value, considerably lower than the average for this rock of 18.1. As there is a wide range of these values within one rock type it is felt that the single ratio obtained for this transitional rock should be viewed with extreme caution.

The Ti:Zr ratio plotted against height for the layered kakortokite sequence shows an ill-defined decrease with height (Figs. 37 and 38).

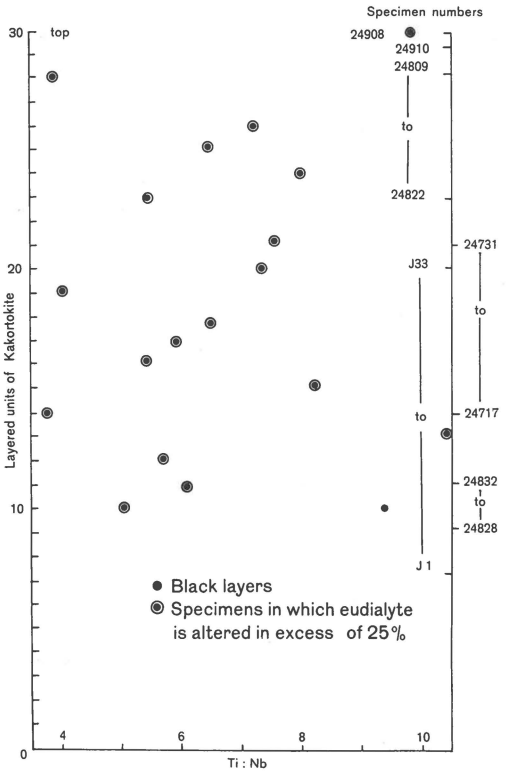


Fig. 39. Ti:Nb ratios of the black layers of the kakortokite plotted against height of the layered units.

Similar plots of Ti:Nb and Zr:Nb vs height show no trends (Figs. 39, 40 and 41).

At Lovozero (Gerasimovskii et al., 1959, p. 811) it was found that the Ti:Nb + Ta and the Zr + Hf:Nb + Ta ratios decrease with differentiation. There is an increase of Ti, Zr + Hf and Nb + Ta with differentiation, with relative enrichment of Nb + Ta.

A similar pattern of behaviour occurs between Ti and Nb + Ta in the nepheline syenites of the Vishnevyie Mountains (Es'kova 1959, p. 170). The low zirconium content in these rocks does not, however, noticeably affect the behaviour of niobium and tantalum. Unfortunately the Ilímaussaq rocks were not analysed for Hf or Ta. However,

the Nb:Ta and Zr:Hf ratios vary very little at Lovozero where they average approximately 12 and 37 respectively (GERASIMOVSKII et al., 1959). It has been subsequently reported that the Nb:Ta ratio does vary for certain altered Zr and Ti minerals at Lovozero (GERASIMOVSKII and VENKINA, 1960, p. 743). The Nb:Ta ratio from the nepheline syenites of Vishnevyic Mountains (ES'KOVA, 1959) also gives an ap-

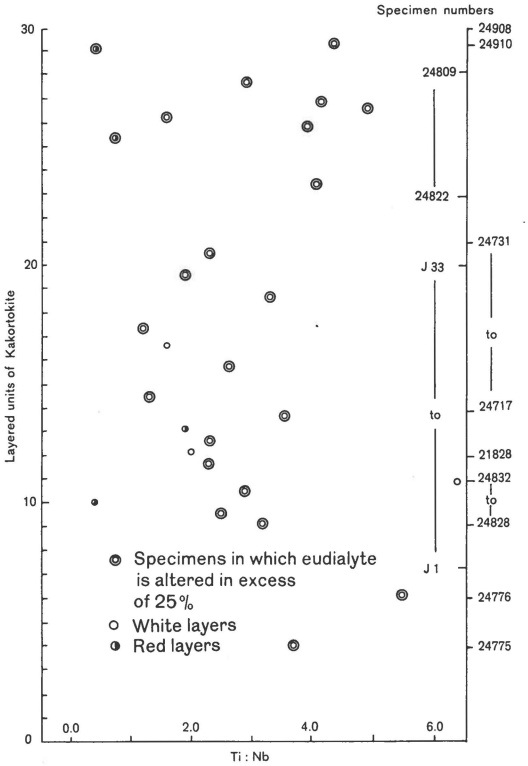


Fig. 40. Ti:Nb ratios of the red and white layers of the kakortokite plotted against height of the layered units.

proximate value of 12. As the Nb:Ta and Zr:Hf ratios are approximately fixed for the agpaitic rocks, it has been taken for purposes of comparison that the Ti:Nb and Zr:Nb ratios should also serve as indices of fractionation.

Using the Beckmann spectrophotometer, HAMILTON (1964, table 23 A) carried out Nb analyses on the Ilímaussaq rocks. There are significant differences between these values and those presented here. The augite syenite values presented by HAMILTON have approximate Nb averages of 12 ppm compared to 73 ppm obtained in the author's investigation. By contrast, HAMILTON obtains higher Nb values for the agpaitic rocks than are presented here. The author is at a loss to explain

the differences in the Nb contents obtained by the two respective methods although the trends shown in each case do correspond. The semi-quantitative spectrographic analyses of Zr presented by HAMILTON (1964, table 20) do, however, show a good correlation.

In nepheline syenites there is a far greater percentage of Zr and Ti than niobium; therefore in the majority of cases Nb is not found as an

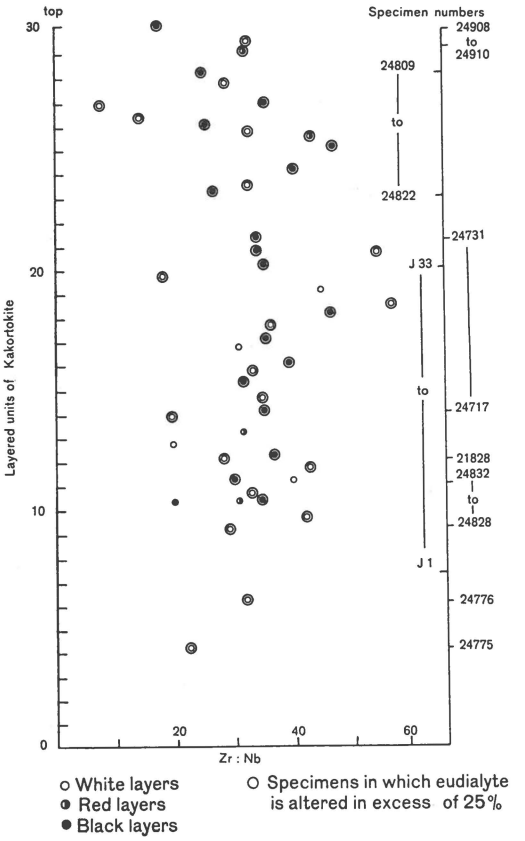


Fig. 41. Zr:Nb ratios for individual layers of the kakortokite plotted against height of the layered units.

individual mineral but is in solid solution with the zirconium and titanium minerals (BORODIN, 1935). It would follow therefore that for the formation of Nb minerals it is necessary to have a large concentration of Nb in the melt. If Nb concentration is lacking in the original melt, it may occur in the late-stage phases, having been achieved by magmatic differentiation or by the capture of a highly mobile complex fraction.

It would seem that either of these processes could account for the development of pyrochlore/microlite in the late-stage lujavrite and analcime- and natrolite-rich rocks of Ilímaussaq. The non-entry of Nb

into the early-formed minerals of the Nemegos Complex, Ontario (HODDER, 1961, p. 58) is accounted for by the high charge of niobium, its low concentration in the parent magma and its capacity to form a volatile fluoride (SAETHER, 1948, p. 128); hence the niobium was concentrated in the residual volatile fraction. VLASOV et al. (1959, p. 565) draw a different conclusion for the behaviour of Nb at Lovozero, pointing out that as the Nb content of the three units of the differentiated complex is similar and of the same order as that occurring in the massif as a whole, the mobility of niobium in the volatile state must be slight. The presence of pyrochlore in the latest differentiates of the miaskitic rocks of the Vishnevyie Mountains (Es'KOVA, 1959, p. 169) has attributed to the relatively low concentration of titanium in the alkalic magma and to the limited diadochy between Nb + Ta and Ti in the early stages of crystallization.

Other elements

Tin

Semi-quantative tin analyses of the kakortokite (Table 31, Appendix) indicate that the black and red layers contain the most tin, averaging 90 and 87 ppm respectively as compared with the corresponding value of 69 ppm in the white layers. Analyses of the rock-forming minerals in the kakortokite indicate that aegirine, arfvedsonite and eudialyte contain the most Sn, averaging 339 ppm, 295 ppm and 178 ppm respectively. Feldspar and nepheline contain less than 40 ppm Sn.

Sn^{4+} is closest in size to Fe^{3+} and Ti^{4+}; in the absence of detailed ferric iron analyses the Sn:Ti ratio was calculated for the kakortokite but gave no consistent pattern when plotted against height. TAYLOR (1965, p. 184) predicts that the Sn:Ti ratio should increase with fractionation.

Due to the similar size of Sn^{4+} and Zr^{4+}, and the Zr – O bond being more ionic than the Sn – O bond, the Sn:Zr ratio will increase with fractionation (TAYLOR, 1965, p. 185). A plot of the Sn:Sr ratio against height for the kakortokite shows this ratio to be fairly constant for all three layers (Fig. 42). The anomalously high values of GGU specimens 24812–13 and 24830 are due to Zr deficiency and specimen J 14 shows Sn enrichment.

Beryllium

The Be averages for the rocks of Ilímaussaq range from 5 ppm in the augite syenite to 85 ppm in the "aegirine dike" (Table 29). The latter single value is far in excess of the averages of the other agpaites; the "kakortokitic" rocks have the next highest Be content, with 34 ppm.

Be is found in a number of beryllium minerals, namely, leucophane (Bøggild, 1953), chkalovite, tugtupite (Sørensen, 1960), epididymite (Hamilton, 1964; Semenov and Sørensen, 1966), eudidymite (Semenov and Sørensen, 1966) and sorensenite (Semenov et al., 1965). Normally these minerals are found in late-stage pegmatite and veins; however, epididymite occurs as an accessory mineral in the alkali gra-

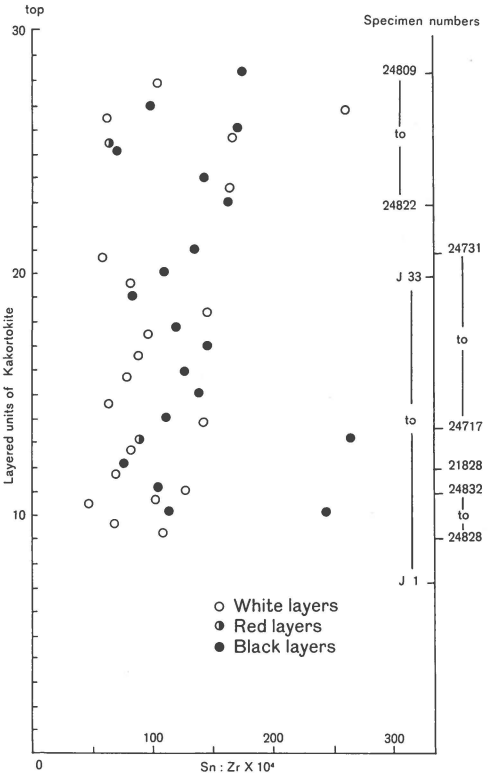


Fig. 42. Sn:Zr ratios for individual layers of the kakortokite plotted against height of the layered units.

nite and eudidymite has been identified by the author in an augite syenite xenolith in the kakortokite.

Limited chemical analyses of minerals presented by Hamilton (1964, table 5) show Be to occur in minor amounts in sodalite. Analyses of the rock-forming minerals in the kakortokite (Table 31, Appendix) show that, with only one exception, Be occurs in amounts in excess of 10 ppm. In nepheline of sample J 18,16 ppm Be is present and in sample J 27 nepheline and feldspar both contain 10 ppm Be. As mentioned by Hamilton (1964), Goldschmidt (1954) gave a value of 24 ppm Be for an arfvedsonite from Kangerdluarssuk.

Presentation of Be analyses on Ilímaussaq rocks by HAMILTON (1964, table 22) indicates similar values to those given here. Sixteen Be analyses of augite syenite give an average of 2.5 ppm as compared to an average of 30.0 ppm for the agpaites (HAMILTON, op. cit.).

In the agpaitic syenites of Kola Peninsula, Be^{2+} mainly occurs in solid solution replacing Al^{3+} in ussingite, natrolite and sodalite. However, beryllium minerals do occur in the pegmatites (GERASIMOVSKII, 1956).

Because of the small size of Be^{2+} it can be expected to exist in magmas partly as $(BeO_4)^{6-}$ (TAYLOR, 1965, p. 151). This Be complex should substitute for $(SiO_4)^{4-}$ (RINGWOOD, 1955); however, as pointed out by GANEEV (1961) this substitution leads to difficulties in charge balance unless cations of high charge, like Ti^{4+} Zr^{4+}, or anions of low valency, such as F^- or OH^-, are present in quantity. In the absence of high concentration of these cations and anions, Be will tend to concentrate in residual liquids. In the agpaitic rocks of Ilímaussaq there is a high concentration of these cations and anions leading to Be concentration in these rocks with late-stage fractions being further enriched. SOBOLEV (1959, p. 21) suggests that during the endogenetic process of mineral formation, beryllium may be transported in the form of complex chlorine and fluorine compounds of the double fluorine type. It is assumed that these compounds are transported both in the gaseous phase (early stage of the process) and in the later solutions. In Ilímaussaq villiaumite and fluorite are found in late-stage rocks as are most of the beryllium minerals, so that SOBOLEV's thesis may well be applicable to this area.

Lanthanum

Lanthanum shows its greatest concentration in the red layers of the kakortokite where it reaches a maximum of 860 ppm. The augite syenite shows the lowest concentration of this element averaging 143 ppm and the black lujavrite contains the highest averaging 729 ppm (Table 28, Appendix).

The Ilímaussaq rocks show the following progressive increase in their La content; augite syenite, naujaite, heterogeneous syenite, sodalite foyaite, "hybrids", kakortokite (weighted value), green lujavrite, "kakortokitic" rocks, lujavrite transitional between black and green varieties, and black lujavrite. It can be seen from La analyses of the rock-forming minerals in the kakortokite (Table 31, Appendix) that eudialyte contains up to 3500 ppm. This would then account for the high La content of the red eudialyte-rich layers of the kakortokite. Aegirine contains a maximum of 350 ppm La as compared to arfvedsonite with a maximum of 160 ppm. Feldspar and nepheline contain

less than 100 ppm. HAMILTON (1964, p. 48) shows that La is also concentrated in steenstrupine.

Gallium

The Ga content of the Ilímaussaq rocks ranges from a minimum of 37 ppm in the augite syenite to 133 ppm in a lujavrite transitional between the black and green varieties. The average values of these rocks show a range of 42 ppm in the augite syenite to 118 ppm in the transitional variety of lujavrite (Table 29, Appendix). Ga shows progressive increase in the rock types in the following order; augite syenite, heterogeneous syenite, "kakortokitic" rocks, green lujavrite, kakortokite (weighted value), "hybrids", sodalite foyaite, naujaite, black lujavrite, transitional lujavrite and "aegirine dike".

The geochemistry of Ga is complex (MORRIS and BREWER, 1954) as it can enter the Al^{3+} and Fe^{3+} positions and also substitute for Zn^{2+} in sphalerite (TAYLOR, 1965, p. 181). In the absence of detailed analyses of the latter elements it is impossible to explain its particular affinity in these rocks. The general increase of Ga from the augite syenite to the agpaites is also coupled with a general increase in Fe^{3+}, although in this respect the heterogeneous syenite is anomalous in that it contains a high percentage of ferric oxide.

Zinc

Semi-quantative analyses of Zn (Table 31, Appendix) in the kakortokite and its associated minerals show that this element is preferentially concentrated in the arfvedsonite where it can occur in amounts not exceeding 1200 ppm and averaging approximately 820 ppm. Aegirine also contains Zn in moderate amounts averaging 540 ± ppm. The Zn content of the feldspar and nepheline is less than 100 ppm. The preferential entry of Zn into arfvedsonite and aegirine is indicated by the black layers in the kakortokite containing more Zn than the other two layers (Table 31).

V. CORRELATION OF THE "HYBRID" AND "KAKORTOKITIC" ROCKS

General

As noted previously, the "hybrid" rocks are the controversial rock suite underlying the layered kakortokite in the area to the NE of Kringlerne. These rocks have been identified as black lujavrite by Ussing (1912, p. 38 and 46) and Sørensen (1958, pp. 18–19), while on field identification the author regarded them to be more in the nature of unlayered kakortokite. The discovery of a green "aegirine-dike" cutting the hybrids and megascopically not unlike green lujavrite, has further complicated the age relationship of this suite of rocks.

The "kakortokitic" rocks are the problematical small bodies with both conformable and transgressive habit, having a wide distribution in lujavrites and naujaite. These bodies have been correlated with kakortokite by Sørensen (1958, pp. 15–16). Lack of previous petrochemical work, together with their generally unlayered character, made this a highly tenuous correlation.

Mineralogical evidence

The feldspars in the "hybrids" compare well with those in the kakortokite; microcline-microperthites and small albite laths are developed in both rock types in contrast with the black lujavrite in which the K- and Na-feldspar phases form separate laths. In the "aegirine-dike", microcline laths are the only feldspar present; zeolite replacement in this rock may account for the absence of albite laths. The alkali feldspars in the "kakortokitic" rocks offer an interesting variation; where this rock occurs in lujavrite, there is separate development of the feldspar phases; when they appear in the naujaite, microcline-microperthites are developed. In other words, the "inclusions" adopt the feldspar habit of the host rock. Other than these differences, the optics, compositions and structural states of the alkali feldspars occurring in these controversial rocks display no unique characteristics differing from those in the other agpaitic rocks.

The optical properties of the soda-pyroxenes and amphiboles in the "hybrids" and "kakortokitic" rocks and the soda-pyroxenes in the "aegirine-dike" differ in no respect from those of either the kakortokite or lujavrites.

The compositions of the nephelines do, however, present some interesting comparisons. The average value of the nephelines in the "hybrid" and "kakortokitic" rocks is $Ks_{19.4}$ and $Ks_{29.0}$ compared with values of $K_{18.9}s$ and $Ks_{15.4}$ in the kakortokite and black lujavrite respectively. The one value of the nepheline composition from the "aegirine-dike" is $Ks_{25.9}$, compared to $Ks_{27.6}$ in the green lujavrite.

Geochemical evidence

The ternary plot of the average values for Na-K-Ca (Fig. 22, p. 80) shows that the values of the "hybrids" and the weighted kakortokite have a close affiliation; the "hybrids" are far removed from the black lujavrite average. The "kakortokitic" rocks show considerable Na-enrichment and minor Ca-impoverishment relative to the weighted kakortokite value. In this respect, however, the "kakortokitic" rocks generally have a higher zeolite content, possibly accounting for their Na-enrichment. The zeolitized "aegirine-dike" also shows considerable Na-enrichment, compared with the green lujavrite.

A plot of K vs Rb (Fig. 26, p. 86) shows the weighted kakortokite value to lie equidistant from the "hybrids" and "kakortokitic" rocks, with the "hybrids" having a closer affinity with the kakortokite than with the black lujavrite. The "aegirine-dike" has very low K and Rb contents, the plot of which is far removed from that of the green lujavrite.

A plot of Ca vs Sr (Fig. 29, p. 90) shows the "hybrids" to be closely allied to the weighted kakortokite value and far removed from the relatively Ca-deficient black lujavrite. The "kakortokitic" value indicates Sr enrichment, plotting some distance away from the weighted kakortokite value. Regarding Sr enrichment the "aegirine-dike" displays no affinity with any of the remaining rocks.

Although the plot of Sr vs K showed no covariance for the rocks in general, the distribution characteristics of the "hybrids" and the weighted kakortokite averages are closer than those of the "hybrids" and the black lujavrite. The "kakortokitic" value is farther removed from the weighted kakortokite value than are the "hybrids". The "aegirine-dike" once again occupies an isolated position, showing Sr enrichment relative to the kakortokite.

The plot of the average values of Ba vs Sr (Fig. 31, p. 92) shows the "hybrids" and "kakortokitic" rocks to be equally closely disposed towards the weighted kakortokite value and far removed from the black

lujavrite plot. The "aegirine-dike" once again displays an anomalous position relative to the agpaites by showing a marked compositional departure due to Sr and Ba enrichment.

The Ba:Rb ratios for the rocks considered are:

	Ba:Rb
"Hybrids"	0.83
"Kakortokitic" rocks	0.84
"Aegirine-dike"	3.81
Black lujavrite	0.36
Kakortokite*	1.06

* Weighted value

This shows the "hybrid" rocks to have a Ba:Rb value distinct from that of the black lujavrite. The "aegirine-dike" has a uniquely high value for this ratio.

In the plots of Zr vs Ti and Nb vs Zr (Figs. 34, p. 95, and 36, p. 96), the "hybrids" show a relatively strong affiliation with the weighted kakortokite value, when compared with the black lujavrite; this is particularly so in the latter graph. The values for the "aegirine-dike" plot close to the weighted kakortokite values in these two graphs but are relatively far removed from the green lujavrite values. In the Ti vs Nb plot (Fig. 35, p. 96), the distribution of these three controversial rock types is not as clearly marked as in the previous two cases. The "hybrid" and "kakortokitic" rock values have approximately equidistant positions relative to kakortokite and black lujavrite, being fairly distinct from these latter plots. The "aegirine-dike" is Ti and Nb enriched and thus has little affiliation with the green lujavrite.

Conclusion

The development of microcline-microperthites in the "hybrids" contrasts with the separate lath development of the alkali feldspars in the lujavrites, and compares with the similar texture developed in the kakortokite. Compositionally, the nephelines from the "hybrids" relate more closely to the kakortokite than they do to the black lujavrite. The geochemical results show the "hybrid" rocks to have a remarkably close affinity with the kakortokite, particularly when compared with the black lujavrite. For the above reasons it is concluded that the "hybrid" rocks are more closely related to the kakortokite than to the black lujavrite. It may be argued that as these rocks are not rhythmically layered they should be given a separate name. It is to be noted in this respect that neither USSING (1912, p. 47) nor SØRENSEN (1958, p. 18)

objected to the non-rhythmically layered marginal or lowermost rocks of the kakortokite being included in this definition.

The mineralogy and variable texture of the "kakortokitic" rocks is most interesting, particularly the development of the alkali feldspars. The finding that the feldspars in the small "kakortokitic" bodies adopt the habit of the feldspar in the enclosing host rocks, points to the possible genetic relation of the inclusions to the host rocks. The geochemistry of the "kakortokitic" rocks reveals the erratic composition of these rocks relative to the agpaites and their seldom close affinity with the kakortokite values. Unless the "kakortokitic" rocks have undergone extreme metasomatism, they would appear to bear little relation to the kakortokite, and furthermore they do not appear to be direct correlatives of any of the other agpaitic rocks.

The "aegirine-dike" occupies a similar position to the "kakortokitic" rocks in that it appears to have no consistant geochemical relation to any of the agpaitic rocks. Furthermore, most of the geochemical plots of this rock bear little relationship to the grouping of the agpaitic rocks.

Further consideration of the "kakortokitic" rocks and the "aegirine-dike" is included in a discussion on fractionation trends in the following chapter.

VI. CHRONOLOGICAL SEQUENCE OF CRYSTALLIZATION

Field evidence

The oldest intrusive rock of the Ilímaussaq Intrusion would appear to be the augite syenite. Apart from the alkali granite, which also can show a marginal decrease in grain size, this is the only major rock unit that has chilled contacts with the country rocks of both margin and roof. Apophyses of augite syenite penetrate the country rocks; however, back-veining is also developed. That the augite syenite is older than the agpaitic rocks would seem to be borne out by the fact that where these rocks are in contact there is either no change in texture or else there is a coarsening in grain-size of the augite syenite. Additional evidence of the age of the augite syenite relative to the agpaites is the presence of augite syenite blocks in the kakortokite and in the adjacent agpaitic pegmatite. The intrusive lujavrites and naujaites within the marginal development of the augite syenite indicate the earlier age of the latter. In the only exposure of a contact, the alkali granite is chilled against the augite syenite (HAMILTON, 1964, p. 23). In one instance the quartz syenite shows an intrusive relationship towards the augite syenite.

Taken collectively, the field evidence strongly indicates that the augite syenite pre-dates the agpaitic and acid rocks of the intrusion.

The age relationship between the heterogeneous syenite and pulaskite is not at all clear. The augite syenite makes contact with the heterogeneous syenite and pulaskite in only one area where actual contacts are obscured by scree. The distribution of the heterogeneous syenite and pulaskite is always confined to the inner side of the augite syenite shell.

To the north of Tunugdliarfik, the age relationships are indistinct, both for the individual rocks of the transition series and between these and the alkali granite and agpaitic rocks. The perfect compositional and textural gradation from alkali granite through quartz syenite, pulaskite, heterogeneous syenite to sodalite foyaite indicates no noteworthy time gap between the consolidation of these rocks. The presence of a finer grained variety of naujaite underlying the sodalite foyaite and

heterogeneous syenite does not necessarily indicate a "chilling" effect, as the rock is still relatively coarse-grained and similar occurrences appear elsewhere in the intrusion away from any contacts.

To the S of Tunugdliarfik, the plug- and sill-like bodies of the alkali granite, quartz syenite and pulaskite, contained within the remnant cappings of heterogeneous syenite, allow for some speculation as to the sequence of intrusion.

Interpretation of the nature of the alkali granite occurrences to the S of Tunugdliarfik is strongly contested. The author (1964, p. 23) has interpreted these alkali granite occurrences as being separate plug intrusions into the heterogeneous syenite sheet, since in one case the latter rock type appears to be overlying the alkali granite. Ussing (1912, p. 70) has suggested that these occurrences of alkali granite are erosion remnants left by an overlying alkali granite sheet. The attitude of one of the alkali granite plugs to the apparently overlying heterogeneous syenite, however, does not support this idea.

The quartz syenite and pulaskite occur within the heterogeneous syenite in two different forms, namely, as narrow "envelopes" surrounding granite bodies and as separate plugs and sills. One expects to find disorientation in xenolithic bodies; but the quartz syenite and pulaskite display near horizontal layering. Ussing's view (1912, p. 69) that the foyaite (heterogeneous syenite) cappings are overlain by pulaskite sheets is not supported by the author's observations.

Considering the evidence to the S of Tunugdliarfik, the author is forced to conclude that the heterogeneous syenite predates the alkali granite, quartz syenite and pulaskite. The latter three rock-types would appear to be approximately synchronous.

The relative ages of the acid intrusives and the agpaites are not incontrovertibly fixed. Except for a naujaite block in the alkali granite, these rocks are not found in contact. The intrusive lujavrites are not found cutting the acid rocks of the Intrusion; however, the former occur dominantly in the lowermost exposed part of the naujaite "sheet" and rapidly decrease upwards, so that the overlying sodalite foyaite sheet is only cut by lujavrite dikes in two localities. As the lujavrites are rare in the sodalite foyaite, their absence in higher rock sequences may be attributed to level rather than relative age differences of the rocks. The presence of a large naujaite xenolith in the alkali granite poses some problem. Hamilton (1964, p. 58) is of the opinion that xenoliths of sodalite foyaite and pulaskite are also present at this locality. As mentioned earlier, the latter were not identified by the author in this area of faulting and high degree of rock alteration. The naujaite block could either have been caught up by acid magma invading the naujaite, or alternatively it could have been faulted into its present position. The

work of HAMILTON (1964, pl. 1) and the author shows this to be a faulted area, thus rendering the latter assumption possible.

The author interprets the plug- and sill-like masses of alkali granite, quartz syenite and pulaskite within the small remnant cappings of heterogeneous syenite as intrusions from below. If this interpretation is correct, it would seem reasonable to conclude that, as these numerous small bodies are confined to the limited occurrences of heterogeneous syenite and do not occur elsewhere, they probably preceded the consolidation of the agpaitic rocks. In addition, if the agpaitic rocks were to pre-date the acid rocks, it would be remarkable that no feeder(s) to the large masses of acid rocks between Nákâlâq and Tunugdliarfik are to be found cutting the extensively-developed agpaitic rocks.

The transitional and, in some cases, sharp contacts of the sodalite foyaite with the heterogeneous syenite, without textural change in either rock, indicate no noteworthy time interval to have elapsed between the consolidation of these two rock types. Chemical and petrological evidence indicates that the heterogeneous syenite has a strong affiliation with the augite syenite, whereas the per-alkaline sodalite foyaite shows marked contrasts with these two rock-types. HAMILTON (1964, p. 38) views the texture at the foyaite (heterogeneous syenite)-sodalite foyaite contact as being indicative of the latter replacing the foyaite. This evidence suggests the heterogeneous syenite to have been emplaced prior to the sodalite foyaite.

The transitional to sharp contacts of the sheets of sodalite foyaite and naujaite once again make conclusive age relationships difficult to assess. The author has not interpreted as a chilling effect the one occurrence of naujaite showing a decrease in grain size towards the sodalite foyaite since other occurrences of a similar naujaite were found, far removed from any contacts. HAMILTON's evidence (1964, p. 45, fig. 21) of sodalite foyaite xenoliths in naujaite indicates that during at least some stage in the development of naujaite, the sodalite foyaite was already in a consolidated state.

The presence of naujaite xenoliths in the kakortokite need not indicate that the crystallization of the naujaite *in toto* preceded that of the kakortokite; the two processes may have been concomitant, at least in part. Rheomorphic veining emanating from a naujaite block into kakortokite is indicative that these blocks were semi-consolidated or at elevated temperatures.

The frequently exposed intrusive nature of lujavrites into sodalite foyaite and brecciated naujaite clearly demonstrates their later age, although two exceptional cases were noted of naujaite intruding lujavrite. The latter feature is interpreted as backveining produced by remobilization of the naujaite. That the black and green lujavrites are

closely related in time is demonstrated by their normal transitional mutual contacts and by rarer cases of minor bodies of both the rock varieties truncating one another. The presence of diopside in the black "lujavrite" inclusions from the W end of Nunasarnaq peninsula, suggests that these xenoliths are more in the nature of lujavritized country rock than black lujavrite. By a similar token the interdependence of "murmanite lujavrite" and basalts may indicate a hybrid origin for these rocks.

Geochemical evidence

From field evidence, the order of consolidation of the Ilímaussaq rocks, excluding the acid members, has been deduced as follows:

Augite syenite
Heterogeneous syenite
Sodalite foyaite
Naujaite } possibly concomitant
Kakortokite ("hybrids") } possibly concomitant
Lujavrites

The geochemistry will now be examined in order to ascertain to what extent established trace-element fractionation trends substantiate the field evidence, and also as an aid to classification of the "aegirine-dike" and "kakortokitic" rocks.

A decrease of the K:Rb ratio with progressive differentiation has been noted by a number of workers (Ahrens et al., 1952; Demin and Khitarov, 1958; Gerasimovskii and Lebedev, 1959; Volkov and Savinova, 1959; Butler et al., 1962 and Siedner, 1965). The decreasing order of the K:Rb ratio for the Ilímaussaq rocks shows a remarkably strong correlation with the chronology as determined from field evidence.

Table 18.

	K:Rb*
Augite syenite	217
Heterogeneous syenite	187
Sodalite foyaite	174
Naujaite	171
"Hybrids"	166
Kakortokite**	162
"Kakortokitic" rocks	147
Green lujavrite	146
Black lujavrite	146

* Values for rocks containing less than 10 per cent zeolites
** Weighted value.

The value for the "kakortokitic" rocks is significant in that it indicates a close affiliation with the late-stage lujavrites. The K:Rb value of 171 for the "aegirine-dike" is not included in table 18 as this rock contains considerably more than 10 per cent zeolites; this excess may be responsible for the relatively high K:Rb ratio of the "aegirine-dike".

The K:Rb values for the detailed kakortokite sequence (Figs. 27 and 28, p. 87–8) display a general decrease with height for this ratio suggesting that these rocks have crystallized from the floor upwards.

Table 19

	Sr:Ca × 10^3
Sodalite foyaite	5.4
Naujaite	5.3
Heterogeneous syenite	6.2
Augite syenite	8.2
"Hybrids"	8.7
Kakortokite*	10.2
"Kakortokitic" rocks	18.0
Green lujavrite	19.4
"Aegirine-dike"	24.7
Black lujavrite	42.8
Lujavrite transitional between black and green varieties	47.2

* Weighted value

The Sr:Ca ratios of the Ilímaussaq rocks show some interesting trends (Table 19); except for a small reversal of the values of the heterogeneous syenite and augite syenite and the anomalous position of the sodalite-rich naujaite and sodalite foyaite, the remaining rocks occur in the previously deduced chronological order. The anomalous values of the sodalite-rich rocks are produced by Sr deficiency, a feature that is also to be found in the sodalite-rich rocks of the Lovozero Complex (GERASIMOVSKII and LEBEDEV, 1958, p. 703). The "kakortokitic" rocks once again give an average value similar to that of the green lujavrite, and the "aegirine-dike" shows an even further increase in this ratio.

The increase with height of Sr:Ca ratios for the kakortokite suite (Fig. 30, p. 91) suggests that these rocks have crystallized from the floor upwards.

In keeping with the alkaline rocks of Lovozero (GERASIMOVSKII and LEBEDEV, op. cit.) Kûngnât (UPTON, 1960) and Oslo province (GOLDSCHMIDT, 1954), the Ilímaussaq rocks also show a decrease in the absolute amounts of Ca and Sr with progressive differentiation (Fig. 29, p. 90). The sodalite-rich naujaite and sodalite foyaite are anomalous

in that they show marked Sr deficiency relative to Ca. The Sr trend in these alkaline rocks is a reversal of the conditions found at Skærgaard (WAGNER and MITCHELL, 1951) and Stillwater (TUREKIAN and KULP, 1956) where progressive fractionation is accompanied by an increase in Sr.

As pointed out by UPTON (1960, p. 102), TUREKIAN and KULP (1956) remark that while Sr is found in Ca-rich minerals, to an equal or lesser extent it can occur also in high-temperature potassium-rich minerals. This may account for the antipathetic relationship of Sr and Ca in mafic intrusions: where plagioclase is crystallizing out Sr increases, but where alkali feldspar is crystallizing the preferential entry of Sr into the feldspar produces Sr deficiency with differentiation. NOCKOLDS and MITCHELL (1948) and HEIER and TAYLOR (1959) show that in co-existing feldspars Sr shows preferential replacement of K relative to Ca.

TAYLOR et al., (1960) found that the Ba:Rb ratio provided an excellent index of fractionation in K-bearing minerals. Because of the size difference between these two elements, Ba has a tendency to enter the earlier K-minerals resulting in Rb enrichment in the later fractions.

The Ba:Rb ratio for the Ilímaussaq rocks did not provide a very good index of fractionation although there is a general decrease of values for this ratio from the augite syenite to the agpaites (Table 30, Appendix). Once again the sodalite-rich naujaite and sodalite foyaite show anomalously low values for this ratio. The "aegirine-dike" is also anomalous, having a surprisingly high value for this ratio. The layered kakortokite sequence shows a general decrease with height for this ratio (Fig. 32, p. 93), again suggesting that these rocks crystallised from the floor upwards.

Table 20

	Ti:Zr	Ti:Nb	Zr:Nb
Augite syenite	26.00	189.5	7.3
Heterogeneous syenite	1.71	19.1	11.2
Naujaite	0.90	8.6	22.0
Sodalite foyaite	0.34	6.2	18.1
"Hybrids"	0.14	5.1	35.5
"Aegirine-dike"	0.14	4.3	30.9
Black lujavrite	0.13	2.7	20.9
Lujavrite transitional between black and green varieties	0.12	3.1	25.2
Kakortokite*	0.11	2.8	27.3
Green lujavrite	0.06	2.7	43.6
"Kakortokitic" rocks	0.03	1.0	29.6

* Weighted value

From a study of bond strengths, AHRENS (1953) predicted that the Ti:Nb + Ta and the Zr + Hf:Nb + Ta ratios should fall with increasing fractionation, as is the case af Lovozero (GERASIMOVSKII et al., 1959). It is interesting in this respect that the Ti:Nb and Zr:Nb ratios of the Ilímaussaq rocks vary antipathetically. In contrast to Lovozero where the Ti and Nb + Ta contents both increase with differentiation with progressive enrichment of the latter, at Ilímaussaq Ti decreases with differentiation, while it is Zr that becomes progressively enriched. A further exaggeration of the Zr:Nb ratios at Ilímaussaq may be the result of the alteration of eudialyte, decreasing the Nb:Ta ratio by the loss of Nb (GERASIMOVSKII and VENKINA, 1960, p. 843). In the calculation of the Zr:Nb ratios of the Ilímaussaq rocks (Table 20, p. 115), an attempt was made to correlate the effects on this ratio of zeolite alteration and alteration of the Zr-bearing minerals, in particular eudialyte.

Although rocks of one rock unit displayed a fairly marked ratio variation this could not be correlated with the degree of zeolite or eudialyte alteration as determined by volumetric modal analyses (Table 28, Appendix). A possible reason for this lack of correlation between degree of alteration of minerals with variation of the Zr:Nb ratio may be the fact that the modal analyses in this respect can at best be only approximate. This anomaly stems from the fact that the degree of eudialyte alteration varies considerably within a given hand specimen, so that one or two thin sections may give a fictitious result in this respect. It is worth noting, however, that in the "kakortokitic" rocks which display a very high value for the Zr:Nb ratio, the modal analyses and hand specimen identification indicate, with one exception (GGU 22550), that the eudialytes in these rocks have undergone very little alteration. This suggests that the "inverse" relationship of the Zr:Nb ratio is a valid one.

In addition, the "kakortokitic" specimen containing the high eudialyte alteration has a Zr:Nb ratio of 31.6, which is close to the average of 29.6 for the "kakortokitic" rocks. The intimate behaviour of Zr and Nb can be seen from the average values of the three layers that constitute the kakortokite. Although the average Zr contents vary widely from 7139 ppm in the white layers to 1.99 % in the red layers, the Zr:Nb ratios vary little being 26.1 for the white, 33.6 for the red and 28.0 for the black layers. The Ti:Nb ratios have values of 2.8, 0.7 and 2.8 respectively for the three layers.

It can be seen from the foregoing discussion that the geochemical fractionation trends lend relatively good support to the chronology based on field relations. The geochemical characteristics of the "kakortokitic" rocks and "aegirine-dike" generally indicate that these rocks are of late-stage habit. It is suggested by the author that the "kakor-

tokitic" rocks represent local variations of volatile-enriched crystallization of the naujaite and lujavritic magmas. The classification of the "aegirine-dike" is by no means clear-cut other than that it has strong mineralogical and geochemical affinity with the late-stage rocks. However, in this respect it shows striking divergences from the geochemical characteristics of the green lujavrite. The high zeolite content of this rock no doubt complicates its geochemical characteristics. It is suggested that this rock is of a late-stage nature and may be related to the aegirine veins which are found in all the agpaitic rocks, although this "dike" has greater dimensions than is usual for these veins.

VII. EVOLUTION OF THE INTRUSION

The Ilímaussaq Intrusion has penetrated basement granite and gneisses in the lower levels and supracrustal rocks of the Eriksfjord Formation in the higher levels. Two large outliers of roof rocks comprising porphyries are to be found resting on the intrusive Ilímaussaq rocks. The original thickness of the roof of the Intrusion is difficult to asses. Ussing's view (1912, p. 306) that the "Ilímaussaq porphyry" of the Eriksfjord Formation was consaguineous with the "batholitic" rocks would appear to be unlikely as the former rocks are now regarded as being of early- and mid-Gardar age (Berthelsen and Noe-Nygaard, 1965, p. 143). From the presence of porphyry outliers resting on the intrusive rocks it would appear that large-scale areal de-roofing has not taken place. A possible reason for this may be that the magma near the roof became viscous due to heat and volatile loss through fractures in the roof.

The annular form of the Ilímaussaq Intrusion and the presence of a remnant augite syenite shell with steeply dipping sides together suggest emplacement by ring-diking and cauldron subsidence (Daly, 1933; Anderson, 1936; Korn and Martin, 1953).

The intersection of ESE and ENE faults appears to have played an important rôle in the location of the alkaline centres. The dominant ENE trend of Gardar diking is evidence that this fault direction was the major control for the emplacement of these magmas. Ring-fractures at shallow levels could have been produced by the magma pressure in the main reservoir (Richey, 1932, pp. 135–137). "A general pressure in a local reservoir tending to raise the roof, which was already in a state of tension, would be expected to induce fracturing where roof meets wall". Large crustal blocks are loosened, so that they founder into the underlying magma and the space vacated by the sinking blocks is filled by magma (see figure 24, p. 57*). Ussing (1912, p. 300) and Hamilton (1964, p. 100) are also of the opinion that the emplacement of the Ilímaussaq magma was controlled by faulting and achieved by

*) British Regional Geology; Scotland: The Tertiary volcanic districts. Third Edition 1961. Department of Scientific Industrial Research Geological Survey and Museum.

overhead stoping. Evidence of block stoping is quite clear. It is particularly well shown in the Kvanefjeld region, where blocks of country rocks in lujavrites measure 0.5 km in diameter. Near the base of Iviangiussaq kangigdleq, the occurrence of sandstone blocks in the marginal augite syenite testifies that these blocks have sunk a distance of at least a few hundred metres. It would seem, then, that ring-dike intrusion, followed by cauldron subsidence, could account for the form of the Ilímaussaq Intrusion.

The general location of the various nepheline syenites within a discontinuous augite syenite shell has been interpreted by Ussing (1912, p. 327) and Hamilton (1964, p. 99) as the replacement of an earlier syenite "batholith" by nepheline syenite magma. This replacement was envisaged by Ussing as probably having taken place whilst the "syenite" was in a somewhat viscous state; however, as he himself pointed out, the presence of xenoliths of augite syenite within nepheline syenite indicates that some portions of the augite syenite were removed in the solid state.

Sørensen (1958, p. 29) considered the Intrusion to have been derived from a primary magma of syenitic composition (pulaskitic) that crystallized to form the marginal augite syenite shell and, by subsequent volatile enrichment of the inner portion of magma, succeeded in developing a magma of agpaitic composition. The author (1962, 1964) shares this view with Sørensen but regards the original magma as having been of augite syenitic composition rather than pulaskitic.

Wegmann (1938, pp. 74–80), having briefly viewed the Ilímaussaq Intrusion, advanced a transformation hypothesis to account for most of the "intrusive" rocks. Troubled by the fissile nature of the lujavrites and the "boudins" of naujaite within them, he suggested that the separation of naujaite into fragments "has accordingly not taken place at the magmatic stage, but at a stage at which the lujavrite behaved like a crystalline schist" (p. 76). Using this argument, he postulated the lujavrite to be a metamorphic correlate of the porphyry formation. Continuing this transformation hypothesis, the naujaite becomes the equivalent of essexite-gabbros and the foyaite and pulaskite represent transformed nordmarkite. Other transformations include the alkali granite of Ilímaussaq which is produced by contamination of the essexite series with sandstone and granite; the alkali granite hence differs from the other transformations in that it is not entirely an autochthonous transformation but has an allochonous origin. These transformations are thought to have been brought about by pneumatolytic solutions containing Cl, CO_2, P_2O_5, F and Zr.

Wegmann found the "bedding" of the kakortokites, which is in juxtaposition with the massive basement granite, a difficult feature to

explain and, not being able "to form a sufficiently reliable basis of another explanation" (p. 79), did not comment further.

During the following discussion on the style of emplacement, each rock type will be discussed in terms of WEGMANN's "migmatitic hypothesis" and the reasons given why this theory is not tenable. It may be stated now that the author has fundamental objections to this theory of WEGMANN, in that the allegedly transformed autochthonous rocks of the Intrusion are not usually in continuity with the primary rocks from which they are suggested to have been derived. In addition, chilled and fine-grained contacts are present as well as apophyses, features which strongly suggest a magmatic origin for these rocks. Finally, the agpaitic rocks contain xenoliths of porphyries and anorthositic gabbro which in some cases do not even display a reaction rim.

The initial magma intrusion of Ilímaussaq is now represented by the chilled augite syenite, a rock of just saturated composition. As crystallization proceeded, this magma developed a more undersaturated nature, as indicated by the presence of nepheline in the coarse-grained inner facies of this rock type. The anomalous presence of quartz in the latter is directly related to its juxtaposition with quartz-bearing rocks, suggesting contamination. It can be seen, then, that the differentiation trend of the augite syenite is firmly established as being undersaturated.

The 50° to 75° dips exhibited in the Ilímaussaq Intrusion by the layering in the augite syenite are steeper than the maximum angle of rest of the cumulate floor in the comparable South Greenland augite syenites of Kûngnât and Nunarssuit (UPTON, 1960; HARRY and PULVERTAFT, 1963); this tends to disprove that the layering was formed by gravity-assisted magmatic currents. Rather it seems that mafic nuclei were repeatedly precipitated and grew on the cooling marginal contact wall of the magma chamber. WELLS (1962, p. 41) attributes steep layering in the Freetown Basic Complex to flow movements whereby successive layers became "welded" to the floor or margin.

To the north of Tunugdliarfik, the augite syenite is separated from the heterogeneous syenite by the alkali granite and the transition series, whereas to the south of this fiord the heterogeneous syenite occurs only as remnant cappings, making contact with the augite syenite at one locality. The heterogeneous syenite and pulaskite are the only two rock types that bear a resemblance to the augite syenite, in as much as they are undersaturated but not per-alkaline and contain iron-rich olivine. The geochemical evidence generally supports the thesis that the augite syenite and heterogeneous syenite are related. The author is of the opinion that the heterogeneous syenite represents the roof-development of the innermost differentiate of the augite syenite. HAMILTON (1964, p. 38) has lent his support to this idea. USSING (1912, p. 341) is, how-

ever, of the opinion that the foyaite (heterogeneous syenite) is of hybrid origin resulting from an interaction of granitic and agpaitic magmas. This sheeted body certainly has no continuity or relationship whatsoever with nordmarkite from which, according to WEGMANN (1938, p. 78) it is supposed to have been derived by transformation.

The heterogeneous syenite is regarded as having crystallized from the roof downwards. The layering may best be accounted for by repetitive volatile accumulations at the base of the downward crystallizing rock, resulting in the formation of the pegmatitic bands. The interdigitating habit of the pegmatitic rock towards the coarse-grained pockets of this rock, suggests that we are dealing with arrested syngenetic roof-stoping. No detached blocks of the coarse-grained rock were located in the underlying rocks.

To the north of Tunugdliarfik, the acid rocks both over- and underlie the augite syenite sheet. To the south of Tunugdliarfik, erosion has removed the roof zones overlying the heterogeneous syenite; these may or may not have contained acid rocks. The juxtaposition of the augite syenite and heterogeneous syenite to the NE of Nunasarnaussaq, coupled with the 70° outward dip of the former, seems to indicate that the augite syenite extended over the remaining area as a roof capping, as it does in the northern part of the Intrusion. USSING suggested (1912, p. 341) that the pulaskite represents "a remnant of the original syenite that at one time filled the reservoir". He gives as his reasons, the chemical similarity, and the presence of the pulaskite in juxtaposition with the augite syenite to the NE of Nunasarnaussaq. Detracting from this theory are the author's findings that the pulaskite does not have sheet-like form to the S of Tunugdliarfik.

The age relationship between the acid and per-alkaline rocks has not been incontrovertibly fixed. To the N of Tunugdliarfik, the alkali granite sheets are normally separated from the augite syenite by thin sheets of quartz syenite. In the case of the upper alkali granite sheet, a continuous quartz syenite sheet separates it from the augite syenite. The lower alkali granite sheet has only a partially developed quartz syenite zone in contact with the overlying augite syenite sheet; the lower contact is, however, characterized by the development of a continuous quartz syenite sheet which grades into a pulaskite sheet which in turn normally grades into the underlying heterogeneous syenite. The latter may be absent locally.

To the S of Tunugdliarfik, the relationships between these rock types is a little different. Here, the quartz syenite and pulaskite occur in two contrasting situations within the heterogeneous syenite. In the one setting they bear a relationship similar to that found to the N of Tunugdliarfik, *viz.* they are marginal to the alkali granite. However, in this

southern area they occur as narrow "envelopes" to plug-like occurrences of alkali granite. The second setting for the quartz syenite and pulaskite is as separate sill and plug-like masses, independent of alkali granite, contained within the heterogeneous syenite. The intrusive nature of the quartz syenite is demonstrated in only one occurrence to the N of Tunugdliarfik, where this rock sends a network of veins into the augite syenite. The normally perfect transitional contact of alkali granite with augite syenite and heterogeneous syenite, would appear to indicate that the quartz syenite and pulaskite are a result of *in situ* reaction between the over- and under-saturated rocks. The fact that the pulaskite is found only when the alkali granite is in contact with the heterogeneous syenite, and not against the augite syenite, may possibly be accounted for by the requirement for this reaction of a more undersaturated rock.

USSING (1912, p. 341) is of the opinion that the foyaite (heterogeneneous syenite), together with the other members of the transition series, namely quartz syenite and pulaskite, could have been produced by an *in situ* interaction of the granitic and agpaitic magmas. As USSING (op. cit.) viewed the pulaskite as being sheet-like form in the southern half of the Intrusion, he suggests alternatively that this rock may in fact represent "a remnant of the original syenite which at one time filled the reservoir". For reasons given in the chronological section, the author is of the opinion that the heterogeneous syenite (foyaite) predates the granitic magma, but fully subscribes to the idea that, at least in the northern half of the Intrusion, the quartz syenite and pulaskite are products of *in situ* reaction, not as a result of the reaction between the agpaitic magma and the acid magma but rather between the latter and heterogeneous syenite. To the S of Tunugdliarfik, there is evidence that some of the quartz syenite and pulaskite is a product of *in situ* reaction between alkali granite and the heterogeneous syenite; however, as mentioned previously, where there is separate development of these two rock types and if they are of hybrid origin, mixing of magmas must have taken place either before emplacement or reaction was complete. Commenting on the author's work, HAMILTON (1964, p. 38) suggests that the hybrid origin "may explain why the pulaskite is always present as a well defined layer".

A few problems are posed by the presence of closely spaced unlaminated bands throughout the entire thickness of narrow sills of quartz syenite and pulaskite. The fact that only one instance of a discordancy was noted and that in the central part of a sill, suggests that crystal growth took place simultaneously from both sides of the sill towards the centre.

Ussing (1912, p. 339) suggested that, because of the extreme contrast of the alkali granite with the agpaites, the former may have originated from the augite syenite magma but not from the agpaitic magma. Owing to the lower specific gravity of the alkali granite compared to the augite syenite, it may have accumulated at the top of the chamber. On the evidence of the alkali granite occurrences to the S of Tunugdliarfik, the author feels that the intrusive nature of these rocks has been clearly demonstrated. Hamilton (1964, p. 61), without having seen these small alkali granite occurrences, has put forward the additional suggestion that, by reaction between the augite syenite magma and the sandstone of the former roof of the Intrusion soda granite was produced, followed by rheomorphic intrusion downwards. Although there is evidence in the Intrusion that an alkali granite can be produced in this manner, it should be pointed out that in the two cases of rheomorphic intrusion observed, lateral rather than downward injection was involved. It is possible that these two small bodies of alkali granite do not have the same origin as the large sheets occurring to the N of Tunugdliarfik. Hamilton's observation of the alkali granite being chilled against the augite syenite (1964, p. 23) is at variance with Ussing's idea that this rock type developed as a result of differentiation and accumulation at the top of the augite syenitic magma chamber.

Ussing (1912, p. 366) also discussed the possibility that the alkali granite formed through assimilation of roof rocks by augite syenitic magma, and found the idea not unattractive. Backlund (1932) advanced the idea that the alkali granite may be a product of fenitization of the sandstone and country granite, a theory also supported by Sørensen (1958). It would seem on the basis of Hamilton's observation, together with the intrusive nature of the related quartz syenite, that the acid rocks have an extraneous origin and did not result from *in situ* development. This of course does not preclude the possibility that these acid rocks have been formed by assimilation.

Whether the alkali granite pre- or post-dates the agpaitic rocks, it is still difficult to understand how a magma that is differentiating towards an undersaturated end-product is capable of reversing this trend so rapidly. This may be a little easier to understand if we banish the process to depth where an oversaturated differentiation trend may be able to develop from the saturated augite syenitic magma. In this case, the oversaturated magma would have to be intruded into the higher levels to occupy its present position. An alternative to this suggestion is that large-scale assimilation of country rocks may have assisted in changing the overall composition of the magma or else have produced enough silica to displace the differentiation trend, so that for a limited

period the magma differentiated towards an acid end-product. During this investigation, no new criteria have been established to assign categorically a particular genesis to the alkali granite. The author and USSING (1912), for different reasons, consider the alkali granite to predate the agpaites, whereas HAMILTON (1964, p. 63) considers the reverse to be the case (see section on chronology).

The sodalite foyaite sheet, which overlies the naujaite "sheet", probably represents the earliest of the exposed rocks of the agpaitic suite. USSING (1912, pp. 353–54) did not share this view. He pointed out that the sodalite foyaite shows structural and mineralogical resemblances to certain of the horizontal pegmatite veins in the naujaite; since these represent the latest product of the consolidation process, by analogy the volatile-rich sodalite foyaite should also represent a late crystallization product. He argued that, if sodalite represents the first mineral to crystallize and if, due to its low specific gravity, it concentrates in the upper part of the agpaitic magma chamber, then the only rock type to be produced in this region would have been naujaite. However, due to contraction on consolidation of the naujaite, volatiles accumulated above the naujaite to form a moderate quantity of volatile-rich magma eventually crystallizing as sodalite foyaite. The author sees no reason why the development of sodalite should not have been initially relatively inhibited, thus allowing the crystallization of a roof rock with only a moderate sodalite content, in comparison with the naujaite, and also having a fairly high volatile content thereby producing the sodalite foyaite. The presence of sodalite foyaite xenoliths in naujaite (HAMILTON, 1964, p. 45) would also support the view that at least some, if not all, of the sodalite foyaite was in a consolidated state before the crystallization of the naujaite.

WEGMANN's thesis (1938, pp. 77–78) that the naujaite is a transformation product of essexite-gabbros finds little support. The author feels that the "complicated intergrowths and the strongly poikilitic minerals" (p. 78) are more easily explained by the postulation of a flotation of sodalite crystals acting as growing nuclei.

If the postulation of a fault separating the lujavrites and kakortokite (for discussion see section on contact relations of lujavrite) is acceptable on the evidence provided: that is to say, that there is a relative vertical upthrow of the order of 400–600 m to the S of the postulated ENE fault extending from Lakseelv mouth to Agpat, then this would place the kakortokite in the lowermost exposed agpaitic rock sequence. If this is the case, one must now account for the abundance of sodalite in the naujaite and its almost complete absence in the kakortokite. Sodalite has a specific gravity of 2.320 and the specific gravity of the average agpaitic rock is 2.689 (Table 32, Appendix). These figures

are in fair agreement with those quoted by Ussing (1912, p. 346). Even allowing for the specific gravity of the agpaitic magma being slightly less than the figure for the solid rock quoted above, it would appear that under gravity sodalite would tend to float in this environment. Acceleration or retardation of the process may also be brought about by current action. Thus, the pegmatoid naujaite could be the product of floating sodalite crystals trapped in a downward crystallizing rock, resulting in the poikilitic texture which characterizes the rock. It would seem unlikely that sodalite would be the only mineral crystallizing from the agpaitic magma at this stage. In all probability, crystallizing more or less concomitantly with the sodalite would be the remaining major minerals of the agpaites namely, arfvedsonite, aegirine, aenigmatite, feldspar, nepheline and eudialyte. With the possible exception of nepheline, the specific gravities of these latter minerals are all in excess of the specific gravity of the agpaitic magma, so that under gravity in a fluid magma they would sink. By cyclic precipitations of these latter rock-forming minerals the remarkable series of layered kakortokite could have been formed by gravity accumulation, aided or retarded by current action. Deposition of these crystals possibly started during the formation of the sodalite foyaite, although there is no direct evidence of this; the process probably continued during the crystallization of the naujaite. The one determination of the specific gravity of nepheline gave a value of 2.667 (Table 32, Appendix), a figure close to that of the calculated specific gravity of the agpaitic magma. As the nepheline has fairly constant modal distribution throughout the kakortokite and is also present as a cumulus mineral in the naujaite, it would appear unlikely that its distribution was gravity controlled. Current action may well have been responsible for circulating these light crystals which were plastered onto the crystallizing surfaces (T. C. R. Pulvertaft, personal communication). The possibility then exists that the naujaite and kakortokite were forming concomitantly. The author arrived at this viewpoint quite independently of Ussing (1912, pp. 349–352) who also postulated that differentiation due to fractional crystallization could have produced the naujaite by the flotation of sodalite. However, Ussing differs from the author in having vizualized that the lujavrites are the product of the residual magma after the sodalite has been removed to form the naujaite. Conversely, the author is of the opinion that the kakortokite underlies the lujavrite and that the former represents the product of sinking of the heavier minerals; thus the lujavrites would be the residual product trapped between the kakortokite and naujaite. Ussing (1912, p. 355) was a little puzzled by the position of "lujavrite" underlying the kakortokite; his statement that the kakortokite may have consolidated before the lujavrite is actually in support of the au-

thor's views. USSING observed "that as a result of the movements connected with the subsidence of the roof of the batholite a portion of the lujavrite in a fluid condition was forced into its present position below the other rock" (p. 355). As already discussed, the geochemical and petrographic evidence indicates that these "lujavrites" underlying the kakortokite are more in the nature of unlayered kakortokite (see discussion on "hybrids").

The fact that the microperthite laths in the kakortokite display a lamination as well as a lineation (Figs. 16 to 18, pp. 73 to 75), supports the interpretation that these minerals are of cumulus origin. Significantly, the cumulus aegirine in the black layer shows lamination as well as weak lineation directions, whereas in the red layer the poikilitic intercumulus aegirine has random orientation. The arfvedsonite in the black layer also shows a lamination, whereas in the white layer its intercumulus habit is reflected by its unpreferred orientation (Fig. 18). Unfortunately, the scarcity of arfvedsonite in the red layer did not allow sufficient measurements to be made. With the exception of nepheline displaying lamination in the red layer, neither this mineral nor eudialyte exhibit preferred orientation elsewhere in the kakortokite. These two cumulus minerals display practically no preferred orientation, presumably as a result of their only ill-defined platiness.

Some idea of the maximum size of the original cumulus minerals in the red and white layers can be gained from the poikilitic texture. The nepheline and, less commonly, the eudialyte crystals included in the arfvedsonite and aegirine are approximately half the size of their interstitial equivalents. As the perthites are only partially included in the arfvedsonite and aegirine, the interstitial variety does not show any obvious size difference. In the black kakortokite the lack of zoning and poikilitic texture makes it impossible to determine the amount of post-depositional growth undergone by the cumulus minerals.

If the lack of compositional zoning of the kakortokite minerals is taken as an indication of accumulate growth, the diffusion of magma material and intercumulus liquid must have taken place, at least locally, through a depth of 15 to 20 m. This is the depth of unconsolidated mush as indicated by the compression of the layers by the weight of a foreign inclusion.

A cyclic precipitation whereby either arfvedsonite or aegirine crystallized out first, would account for the excellent black-red-white layered sequence of the kakortokite. UPTON (1961, p. 12) considers that the black layers formed during periods of flow that were sufficiently strong to retain much of the cumulus feldspar in suspension. The sinking rate of the minerals could have been retarded by a density increase in the magma brought about by increased pressure, rather than by magma

flow; as the feldspar is the lightest of the gravity cumulate minerals, its sinking rate would have been impeded the most.

Outwash channels or other evidence of strong convection currents or turbulence, which are thought to be responsible for gravity layering in some layered igneous rocks, have not been seen in the kakortokite by the author, although UPTON (1961, p. 25) claims to have observed small-scale "incipient through banding" and minor disconformities in the kakortokite. Conditions allowing relatively undisturbed accumulative settling appear to have been operative on the floor of the magma chamber.

USSING (1912) advanced the following hypothesis for the formation of the kakortokite of the Ilímaussaq Intrusion: "that simplest supposition is perhaps that the recurred layers have originated in consequence of repeated variation of pressure" (p. 361). As pointed out by SØRENSEN (1958, p. 33), experimental work by YODER (1954) on the system diopside-anorthite-water has demonstrated that such a mechanism can produce layering. By varying the water vapour pressure the eutectic point of the melt could be lowered and displaced, thereby accounting for alternations in the order in which different phases crystallize out.

USSING (op. cit.), SØRENSEN (1958, p. 33) and the author (FERGUSON and PULVERTAFT, 1963, p. 17) propose that the layering in the kakortokite of the Ilímaussaq Intrusion was produced by fluctuation of water vapour pressure, release taking place by access to the surface through fractures and volcanic conduits. The periodicity of the water vapour pressure variation caused displacements of the eutectic of the system with the early formation of arfvedsonite and aegirine at the beginning of each crystallization sequence.

It is considered that the naujaite and kakortokite crystallized simultaneously but at different levels in the same magma chamber and so both rock units must have been subjected to similar physico-chemical conditions. The main difference between the kakortokite and naujaite is that the former is thought to have crystallized by bottom accumulation on the floor of the Intrusion whereas the naujaite crystallized from the roof downwards. From the textural relations of the naujaite, it would appear that the sodalite and, in some instances, nepheline are the only cumulus minerals. The poikilitic habit of aegirine, arfvedsonite, aenigmatite, perthite and eudialyte suggests that these are all intercumulus minerals.

The commonest layered sequence, in the naujaite, comprises dark and light units with minor associated red layers. The sodalite-rich layers could be formed by efficient flotation processes produced either by strong current action or pressure increase, which would increase the

density of the volatile-rich magma, particularly if bubbles existed. This would allow the sodalite to rise more rapidly. Conversely the sodalite-poor layers may correspond to periods of low pressure or lack of current action in the magma chamber. There are few features that can be ascribed to current action; the irregular habit of some of the agpaitic pegmatites in the naujaite suggests that the roof was locally uneven, perhaps as a result of a gentle scouring action. Otherwise the layered units maintain a uniform thickness and regular strike suggesting quiet periods of crystallization. The layered agpaitic pegmatites in the naujaite have been interpreted by SØRENSEN å1962) as having been formed by the accumulation of volatiles in irregularities at the base of the downward-crystallizing rock.

The crystal differentiation process envisaged by VLASOV et al. (1959, p. 593) seems likely to have caused the development of rhythmic layering in these downward crystallizing rocks; SØRENSEN is of the same opinion (1962, p. 132). In the downward crystallizing rocks of the differentiated complex of the Lovozero massif, this process involved the initial crystallization of nepheline due to the favourable composition of the magma and by adcumulate growth a nepheline-rich rock developed. In this diffusion process the surrounding magma suffered depletion of the nepheline components and thereby changed in composition so that different mineral(s) accompanied further crystallization. With further adcumulate growth this process was repeated; at Lovozero a repetitive sequence of urtite, lujavrite and foyaite was developed. This type of fractionation may well account for some of the layering seen in the naujaite, in particular the assymetrical zoned pegmatites.

The structure of the lujavrites is rather puzzling; the Ilímaussaq occurrences of these rocks have been regarded as "a kind of gneiss" (GIESECKE, 1910), a metasomatic product (WEGMANN, 1938, p. 76), the product of a combination of metasomatic and magmatic processes (SØRENSEN, 1958), and a magmatic product (USSING, 1912, pp. 328–334; FERGUSON, 1962 and 1964; SØRENSEN, 1962, p. 155 and HAMILTON, 1964, p. 46).

USSING (1912, p. 330) saw a relationship between "the magmatic movements and the structure of the lujavrite" in that he also postulates that the overlying rocks may have sunk. However, as USSING regarded the lujavrites as the visible base of the "batholith", he was hard put to understand why the schistose structure of these rocks should be developed everywhere "for it would appear that a structure produced in this way must be limited to the border zone, whereas as a matter of fact the schistose structure affects the whole mass" (p. 331). To explain this parodox he visualized a magma underlying the lujavrite that "had probably a higher consolidation temperature than lujavrite" (p. 332), and

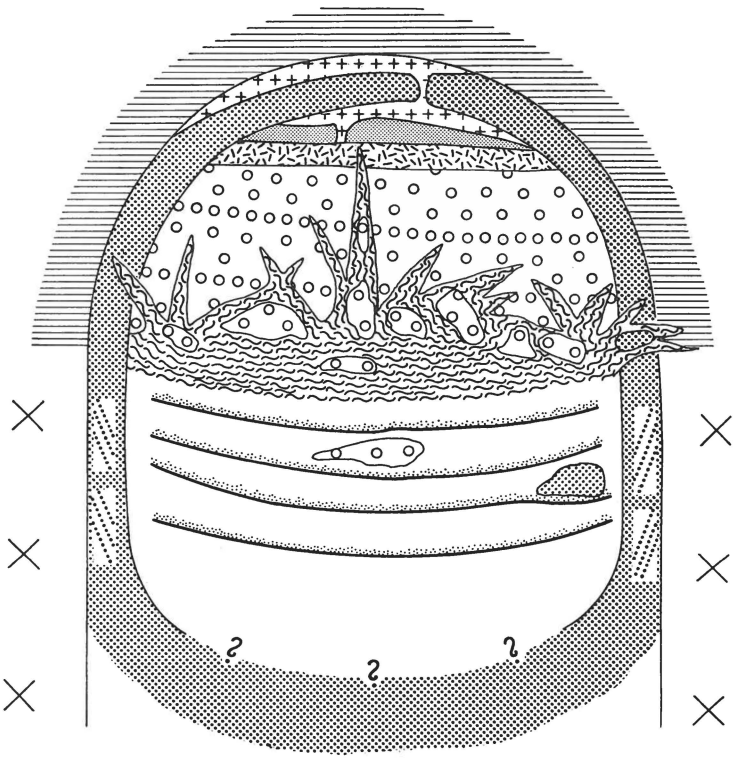
was hence a development of the necessary solid substratum. From the author's viewpoint the problem does not exist, since he regards the kakortokite as the solid substratum.

Sørensen (1958) discussed the possibilities of magmatic and metasomatic origins for the lujavrites. With regard to the former theory, he also visualizes the lujavrite as developing from a level below that of the kakortokite, and suggested the development of a ring system (pp. 35–36). This idea is not attractive to the author as, according to his ideas, the lujavrite was probably injected along the entire base of the naujaite; hence the appearance of breccia zones would depend on the level of erosion rather than on ring-fracturing. If marginal lujavrite breccia zones are to be attributed to ring-fractures, then, according to the author's idea, these would be confined to a level above that of the kakortokite.

Wegmann (1938) regarded the lujavrite as "a metamorphic correlate of the porphyry formation" (p. 77) and the naujaite blocks as "boudins". The author cannot seriously entertain this suggestion, since numbers of porphyry blocks were seen in the lujavrite at Nunasarnaq which in some cases totally lack even a reaction rim. In addition, apophyses of lujavrite can be seen in the porphyries and sandstone.

Sørensen (1958), when discussing the metasomatic hypothesis, rightly points out the similarity between the lujavrite and kakortokite and suggests that "the naujaite and kakortokite during a period of deformation have recrystallized into green rocks and that the latter may be replaced by the black lujavrites" (p. 38). However, after further work on the black lujavrite, Sørensen (1962, p. 155) feels that some features may suggest a metasomatic origin, "but the combined observations are in better agreement with the magmatic interpretation". As pointed out by Sørensen (1962, p. 213) there has been an interplay of magmatic and hydrothermal processes (at the probable low temperature of formation of the lujavrite).

It is generally accepted, then, that the lujavrite represents a rest magma rich in volatiles that was injected during the slumping and faulting accompanying the closing stages of the evolution of the intrusion (Ussing, 1912; Ferguson, 1962 and 1964; Sørensen, 1962 and Hamilton, 1964). Due to the compression of this magma, the volatiles were squeezed out into the overlying rocks. The author and Hamilton (1964, p. 100) regard the lujavrite magma as a residual trapped between the naujaite and kakortokite, whereas Ussing (1912) and Sørensen (1962) are of the opinion that the lujavrite originated from a level below that of the kakortokite. Figures 43 and 44 are a diagrammatic presentation of the structure and evolution of the Ilímaussaq Intrusion as interpreted by the author.



COUNTRY ROCK

Gardar continental series

Julianehåb Granite

BORDERGROUP

Heterogeneous Syenite

Augite Syenite

INTRUSIVE

Alkali Granite

AGPAITES

Lujavrites

Naujaite

Sodalite Foyalite

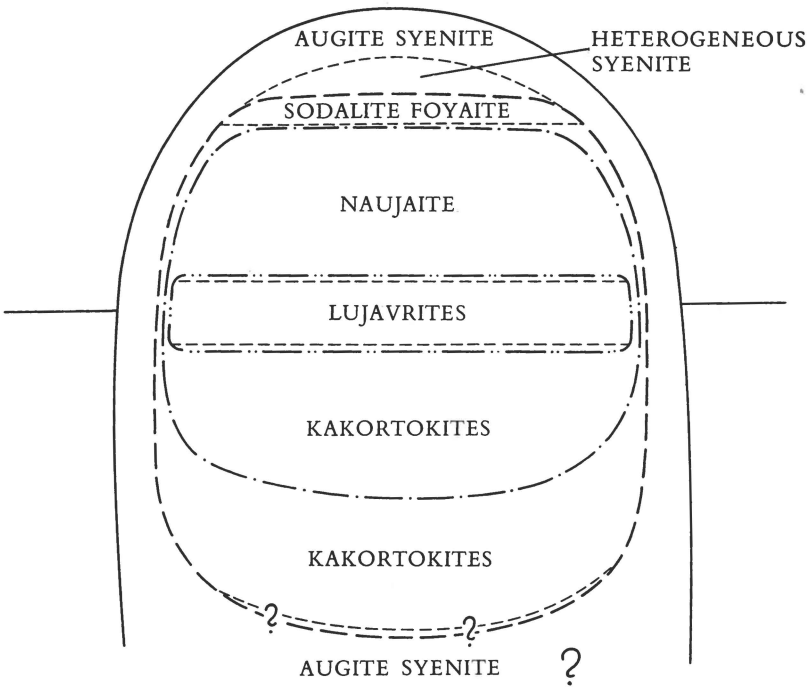
Kakortokite

SCALE

Vertical 0 1 km

Horizontal 0 1 km

Fig. 43. Diagrammatic cross section of the Ilímaussaq Intrusion.



OUTER BORDERS OF SUCCESSIVE AGPAITE DIFFERENTIATES

Third phase

Second phase

First phase

Boundaries of rock units

Alkali Granite omitted as it is not part of in situ differentiation

SCALE

Vertical 0 1 km

Horizontal 0 1 km

Fig. 44. Diagrammatic representation of the proposed sequence of development of the members of the Ilímaussaq Intrusion.

It is postulated that aegirine, feldspar, eudialyte and nepheline formed cumulus minerals in the residual volatile-enriched magma. The intercumulus areas are thought to have had a high volatile content which kept the floor accumulates in a fluid state. Lack of poikilitic texture and zoning in the crystals give no indication of the amount of post-depositional growth by these minerals. Subsequent to the gravity-accumulation of about half the volatile-enriched magma, there was replacement of aegirine by arfvedsonite as the dominant cumulus mineral. Alternations in the formation of these two minerals produced arfvedsonite- and aegirine-enriched bands. Finally, arfvedsonite completely replaced aegirine as the dominant cumulus mineral.

The alternating layers of aegirine- and arfvedsonite-rich lujavrite are probably due to the increased stability of arfvedsonite at high water pressure (FYFE et al., 1958, pp. 162–63). YAGI (1953) found this condition to hold in the Sakhalin Peninsula, where he inferred that, in the presence of volatiles, especially water, arfvedsonite rather than aegirine-augite, crystallized out. These hypotheses are in excellent agreement with conditions in the lujavritic magma of the Ilímaussaq Intrusion, where an increase in volatiles and pressure presumably took place in the late residual magma. The density layering could have been produced by variation in water vapour pressure combined with winnowing effects due to magmatic currents.

The lamination and lineation features displayed by some of the minerals in the lujavrites (Figs. 14 and 15, p. 70 and 72) could be interpreted as having been produced by crystal settling, although stress may equally account for the preferred orientation of minerals in these rocks.

In his treatise on the structural behaviour of igneous rocks, BALK (1937) draws attention to the formation of flow layers in intrusive as well as extrusive rocks. These layers he regards as being formed by solid bodies in the magma, whether crystals or foreign inclusions that maintain their identity as inhomogeneities. Differential movement between solid and fluid is particularly evident in some of the lujavrites of the Ilímaussaq Intrusion where recognizable foreign inclusions have been stretched into slender lenticular bodies giving the rock a gneissic appearance. Elsewhere flow-layering is due to inhomogeneous distribution of mineral phases of the lujavrite which forms strongly fissile sheets. Flow-layering is subscribed to by THAYER (1960 and 1963) to explain certain layered structures in alpine-type peridotite-gabbro complexes. Part of the layered structures of the Bay of Islands Complex (SMITH, 1958, p. 45) are also thought to have resulted from laminar flow. Both of these authors postulate partial differentiation at depth with intrusion of crystal mushes. Flow in the emplaced rocks would accentuate the layering by a mecha-

nical process of separation. Basing his conclusions on analogous flow structures in diatremes, WILSHIRE (1961, p. 484) postulates an *in situ* process for flow-layering rather than pre-emplacement differentiation; provided that ... "high viscosity (rapid cooling) or slow movement is postulated there will be consequent deformation resulting in size-sorting of crystals". ALPER and POLDERVAART (1957, p. 962) ascribe similar flow-layering in the high-level Animas monzonite stock to differential movement of crystal mush and magma. Some of the layering seen in the lujavrites of the Ilímaussaq Intrusion could well fit in with a mechanical separation of solid and liquid phases during laminar flow; however, pre-emplacement differentiation appears to be unlikely.

As a result of faulting and/or sagging, this accumulated crystal mush was compressed and injected into the overlying brecciated rocks, the final crystallization producing the fissile lujavrites. At least two periods of movement occurred, as indicated by auto-intrusion in the lujavrites. The volatile phase was squeezed out during crystallization to form the late-stage natrolite-analcime veins in the overlying rocks. The fractured and bent minerals in the lujavrites are probably a result of this deformation. BROUWER (1912) had a similar theory for the general development of lujavrites. He regarded the schistose and fine-grained structure as the result of the escape of a large volume of pneumatolytic gases from a fluid magma, which thereby "suddenly becomes viscous". All this, coupled with "one-sided pressure" during crystallization, could produce the lujavritic structure.

At first sight it appears unusual that the rocks of Ilímaussaq lack evidence of marked current action during the development of rhytmic layering. The shape of the Intrusion is well-suited to the development of convection cell(s). The lineation of some minerals in the kakortokite and lujavrites and the local irregularities at the base of the downward crystallized naujaite are probably indicative that some current action has taken place. SØRENSEN (personal communication) argues that the temperature distribution in the agpaitic magma was very even and that with a concentration of volatiles in the upper and central parts of the magma chamber the density here was decreased, thereby prohibiting convection. The author would like to endorse this theory to account for the lack of strong current features in the Intrusion.

A possible indication of the fluidity of magmas is the angle of repose of rhythmic layering. Within the agpaitic sequence of Ilímaussaq the major undulations in the layering are thought to be the result of later bending (see also USSING, 1912, pp. 321–24) and not indicative of deposition on an undulating floor. The absence of slump features in the gravity-accumulated and dipping rhythmic layering would tend to

support this thesis. If the theory of crystal settling is applicable to Ilímaussaq, then a prime requisite of the magma would be a low viscosity to allow the crystals to settle out under gravity without the aid of strong currents. From a theoretical standpoint, BUERGER (1948, pp. 744–47) considers that volatiles would appreciably lower the viscosity of magmas due to the oxygen in the silicon-oxygen bond being replaced by (OH) and F. Despite the lack of direct evidence, it is therefore suggested that the volatile-rich agpaitic magma of Ilímaussaq had a very low viscosity. USSING (1912, p. 361) was also of the opinion that the magma was in a "very fluid condition".

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APPENDIX

Table 21. *Augite Syenite Optic axial angles of cryptoperthites and structural states of the two feldspar phases.*

Grain size and GGU specimen number	K-feldspar Cryptoperthite 2 Vx* Optic plane ~ ⊥ (010)	K-feldspar Δ-value	Na-feldspar Method 2θ (131 − 2θ (131) CuK_α
Fine-grained			
22607	n.d.	0.54	n.d.
40527	63.5	0.58	1.035
40528	63.5	n.d.	n.d.
48003	n.d.	0.62	n.d.
48134	n.d.	0.60	n.d.
Medium-grained			
24855	n.d.	0.62	n.d.
Coarse-grained			
21837	77.5	0.62	n.d.
24990	76.0	0.69	n.d.
48137	n.d.	0.63	n.d.

* These values are an average of three or more direct readings.
n.d. = not determined.

Table 22. *Compositions of the two feldspar phases and bulk composition of the homogenized alkali feldspar*

Rock type and GGU specimen number	Microcline % $NaAlSi_3O_8$		Plagioclase % Ab	Homogenized alkali feldspar	
	Method d 220 (Si) – d 400 (Mi)	Method 2θ ($20\bar{1}$ felds-$101 KBrO_3$) CuK_α	Method 2θ ($20\bar{1}$ felds-$101 KBrO_3$) CuK_α	% Or	% Ab
Augite syenite					
40527 (f.g.)	1.5	n.d.	n.d.	32.0	68.0
48134 (f.g.)	n.d.	17.0	100	44.0	56.0
21837 (c.g.)	n.d.	n.d.	100	24.0	76.0
24990 (c.g.)	0.0	14.0	100	42.0	58.0
Heterogeneous syenite					
24991 (c.g.)	2.7	6.0	100	51.0	49.0
24992 (peg.)	2.8	9.0	100	44.0	56.0
Alkali granite					
24999	1.0	3.0	100	69.0	31.0
40103	0.1	6.0	100	n.d.	n.d.
Quartz syenite					
24995	n.d.	n.d.	100	69.0	31.0
40101	0.5	9.5	100	n.d.	n.d.
Pulaskite					
40102	n.d.	8.0	n.d.	32.0	68.0
40105	0.5	n.d.	n.d.	n.d.	n.d.
40121	n.d.	8.0	100	n.d.	n.d.
Sodalite foyaite					
24935 (peg.)	1.8	7.0	n.d.	93.0	7.0
24971	n.d.	8.0	100	66.0	34.0
24974	*	9.0	n.d.	69.0	31.0
48082	n.d.	8.0	100	72.0	28.0
Naujaite					
21953 (f.g.)	n.d.	8.0	100	68.0	32.0
22581	*	6.9	100	68.0	32.0
40108	*	9.0	98	66.0	34.0
48098 (peg.)	2.8	7.0	100	88.0	12.0
Kakortokite – Black layers					
24717	n.d.	n.d.	100	72.0	28.0
24721	n.d.	13.5	n.d.	72.0	28.0
24723	n.d.	7.0	100	69.0	31.0
24727	n.d.	n.d.	n.d.	70.0	30.0
24729	1.5	11.0	100	72.0	28.0
24731	n.d.	13.5	100	70.0	30.0
24829	0.6	9.5	100	69.0	31.0
24830	1.4	6.0	100	n.d.	n.d.
24908	n.d.	7.0	100	n.d.	n.d.

(continued)

Table 22 (cont.)

Rock type and GGU specimen number	Microcline % $NaAlSi_3O_8$		Plagioclase % Ab	Homogenized alkali feldspar	
	Method d 220(Si) – d 400(Mi)	Method 2 θ ($20\bar{1}$ felds-101 $KBrO_3$) CuK_α	Method 2 θ ($20\bar{1}$ felds-101 $KBrO_3$) CuK_α	% Or	% Ab
White layers					
24718	n.d.	13.5	n.d.	72.0	28.0
24720	9.0	n.d.	n.d.	n.d.	n.d.
24724	n.d.	8.0	100	68.5	31.5
24776	0.0	6.0	100	n.d.	n.d.
24828	0.3	8.0	100	72.0	28.0
24832	n.d.	n.d.	100	69.0	31.0
24909	1.0	9.0	100	n.d.	n.d.
Red layers					
24817	1.6	9.0	100	69.0	31.0
24831	0.2	7.0	100	68.0	32.0
24910	3,0	n.d.	100	72.0	28.0
Black lujavrite					
21897	1.6	9.0	100	separate laths present	
Green lujavrite					
24790	0.3	6.0	n.d.	do.	
24873	n.d.	0.0	100	do.	
48146	n.d.	14.0	n.d.	do.	
"Hybrids"					
21844	n.d.	6.0	+ 100	70.0	30.0
21853	0.2	6.0	+ 100	70.0	30.0
22636	n.d.	5.5	+ 100	70.0	30.0
24770	0.2	8.0	+ 100	69.0	31.0
24799	0.2	9.0	+ 100	72.0	28.0
48002	1.6	7.0	n.d.	n.d.	n.d.
48065	*	15.0	+ 100	70.0	30.0
"Kakortokitic" rocks					
22526	n.d.	5.5	+ 100	separate laths present	
22541	2.1	6.0	n.d.	do.	
22550	n.d.	n.d.	n.d.	70.0	30.0
22554	n.d.	13.5	+ 100	73.0	27.0

* = value cannot be related to curve
\+ = in excess of
n.d. = not determined
f.g. = fine-grained
c.g. = coarse-grained
peg. = pegmatitic

Table 23. *Optic axial angles and structural states of the two feldspar phases*

Rock type and GGU specimen number	K-feldspar 2Vx optic plane ~⊥(010)	K-feldspar Δ-value	Na-feldspar $2V_z$	Na-feldspar Method $2\theta(1\bar{3}1) - 2\theta(131)$ CuK_α
Heterogeneous syenite				
24991 (c.g.)	75.5*	0.92	77.0*	1.06
24992 (peg.)	78.5	0.88	77.0*	1.06
Alkali granite				
24999.....	78.5	0.95	n.d.	0.97
40103.....	75.5	0.90	n.d.	1.14
Quartz syenite.				
24995.....	77.0	0.88	82.0	1.04
40101.....	80.0	n.d.	78.5	1.06
Pulaskite				
40102.....	80.0	0.93	78.0	1.03
40115.....	79.0	0.88	n.d.	n.d.
40121.....	n.d.	n.d.	n.d.	1.07
Sodalite foyaite				
24935 (peg.)	78.5	0.96	n.d.	1.00
24971.....	82.0	0.93	79.0	0.98
24974.....	79.0	0.94	n.d.	0.97
48082.....	79.5	0.93	77.5	0.98
Naujaite				
21953 (f.g.).....	73.0°	n.d.	78.0°	n.d.
21980.....	n.d.	n.d.	80.0*	n.d.
22581.....	83.0	0.90	n.d.	1.02
40108.....	80.0	0.88	n.d.	1.01
48098 (peg.)	n.d.	0.94	n.d.	1.00
Kakortokite – Black layers				
24717.....	77.0°	0.86	78.0°	n.d.
24721.....	79.5°	n.d.	n.d.	1.07
24723.....	79.5°	n.d.	n.d.	n.d.
24727.....	79.5°*	n.d.	78.0°*	n.d.
24729.....	n.d.	0.94	n.d.	n.d.
24731.....	78.5°	n.d.	78.0°	1.07
24829.....	79.0°	0.88	77.0°	n.d.
24830.....	78.5°	0.87	78.5°	n.d.
24908.....	79.0°	0.94	76.5°*	n.d.
White layers				
J 4.....	82.0°*	n.d.	80.0°*	n.d.
J 13.....	81.5°	n.d.	n.d.	n.d.
J 24.....	79.9°	n.d.	n.d.	n.d.
J 29.....	80.0°*	n.d.	n.d.	n.d.
24718.....	78.0°	n.d.	n.d.	n.d.
24720.....	79.0°	n.d.	78.0°*	n.d.
24722.....	79.0°	n.d.	n.d.	n.d.

Table 23 (cont.)

Rock type and GGU specimen number	K-feldspar 2Vx optic plane ~⊥(010)	K-feldspar Δ-value	Na-feldspar $2V_z$	Na-feldspar Method $2\theta(1\bar{3}1) - 2\theta(131)$ CuK_α
24724	78.0°	0.90	n.d.	n.d.
24730	n.d.	n.d.	n.d.	n.d.
24776	76.0°	0.90	n.d.	1.00
24828	78.0°	0.90	77.5°	1.01
24909	78.0°	0.90	81.0°	n.d.
Red layers				
J 3	80.0°*	n.d.	80.0°*	n.d.
24817	77.0°	0.86	78.0°	1.04
24831	78.5°	n.d.	78.0°	0.98
24910	n.d.	n.d.	n.d.	n.d.
Black lujavrite				
21897	82.0°*	0.88	n.d.	1.03
24962	77.0°*	n.d.	n.d.	n.d.
Green lujavrite				
24790	78.5°	0.92	79.5°	n.d.
24873	79.5°	0.88	n.d.	0.98
48146	78.5°	n.d.	79.0°	1.05
"Hybrids"				
21844	80.0	0.92	79.0	1.03
21853	77.0*	n.d.	n.d.	n.d.
21854	80.0	n.d.	n.d.	n.d.
21856 ("aegirine dike" m.g.)	79.0	n.d.	abs.	abs.
21856 ("aegirine dike" peg.)	80.0	n.d.	abs.	abs.
22635	77.0	n.d.	n.d.	n.d.
22636 (leuco.)	77.0	n.d.	n.d.	n.d.
24770 (leuco.)	77.5	n.d.	81.0*	1.04
24799	77.0	0.80	80.0*	1.07
48002	79.0	0.88	n.d.	n.d.
48065 (leuco.)	77.0*	0.90	n.d.	n.d.
"Kakortokitic" rocks				
22526	79.0	n.d.	n.d.	n.d.
22550	77.0	n.d.	n.d.	n.d.
22551	n.d.	0.86	n.d.	n.d.
22554	76.5	0.92	n.d.	1.02

* = less than three direct readings
n.d. = not determined
abs. = absent
c.g. = coarse-grained
f.g. = fine-grained
m.g. = medium-grained
peg. = pegmatitic
leuco. = leucocratic lenses and veins

Table 24. *Optical data of the acmitic pyroxenes*

	Cores		Margins and unzoned grains		Pleochroism					
					Cores			Margins and unzoned grains		
	2Vx	X:c	2Vx	X:c	X	Y	Z	X	Y	Z
Heterogeneous syenite										
Coarse-grained										
21995	110°	n.d.	88°	n.d.	n.d.	green	olive green	n.d.	dark green	green
21995	120°	n.d.	92°	n.d.	n.d.	green	olive green	n.d.	dark green	green
21995	84°	n.d.	70°	n.d.	n.d.	green	olive green	n.d.[3]	dark green	green
24987	72°	n.d.	64°	n.d.	n.d.	green	olive green	n.d.	dark green	green
24991	92°	n.d.	64°	n.d.	green	dark green	pale green	dark green	very dark gr.	green
40117	86°	n.d.	80°	n.d.	neutral brown	pale green	pale grey-gr.	pale yellow green	green	pale green
Pegmatitic										
24977	110°	n.d.	76°	n.d.	n.d.	pale green	pale grey gr.	n.d.	dark green	green
24977	100°	n.d.	60°	n.d.	n.d.	pale green	pale grey gr.	n.d.	dark green	green
24992	94°	n.d.	92°	n.d.	green	dark green	pale green	dark green	dark green	green
24992	92°	22°	82°	10°	green	n.d.	olive green	dark green	n.d.	green
Alkali granite										
48006	–	–	68°	n.d.	–	–	–	green	pale green	n.d.
48024	–	–	70°	2°	–	–	–	n.d.	pale olive green to brown	pale brown
48024	–	–	70°	4°	–	–	–	n.d.	pale olive green to brown	pale brown
48060	–	–	98°	32°	–	–	–	n.d.	pale olive green to brown	pale brown
48060	–	–	96°	26°	–	–	–	n.d.	pale olive green to brown	pale brown
48144	–	–	80°	n.d.	–	–	–	n.d.	olive green	pale brown
48144	–	–	90°	n.d.	–	–	–	n.d.	olive green	pale brown

Quartz syenite										
22507	–	–	88°	n.d.	–	–	–	n.d.	light green	green
22507	–	–	78°	n.d.	–	–	–	dark green	green	n.d.
24995	–	–	78°	n.d.	–	–	–	apple green	pale yellow green	n.d.
48008	–	–	64°	n.d.	–	–	–	pale green	very pale green	n.d.
48030	–	–	96°	26°	–	–	–	n.d.	green	olive green
48039	–	–	90°	25°	–	–	–	n.d.	pale olive brown to green	pale brown
48029	–	–	62°	6°	–	–	–	n.d.	pale olive brown to green	pale brown
Pulaskite										
22507	82°	n.d.	72°	n.d.	n.d.	light apple gr.	murky green	n.d.	pale apple gr.	murky green
22507	–	–	60°	10°	–	–	–	n.d.	pale apple gr.	green
25000	72°	n.d.	60°	n.d.	green	pale green	n.d.	apple green	green	n.d.
48035	110°	n.d.	90°	n.d.	pale green	pale grey gr.	neutral brown	apple green	pale green	brownish gr.
48035	120°	n.d.	90°	n.d.	pale green	pale grey gr.	neutral brown	apple green	pale green	brownish green
Sodalite foyaite										
21940	–	–	60°	8°	–	–	–	n.d.	pale green	olive green
21940	–	–	60°	n.d.	–	–	–	n.d.	pale green	olive green
21947	114°	n.d.	92°	n.d.	pale green	pale grey gr.	pale green	apple green	pale green	olive green
22512	–	–	60°	10°	–	–	–	apple green	pale green	olive green
24974	113°	n.d.	106°	n.d.	pale green	pale grey gr.	pale green	green	pale green	olive green
24974	116°	32°	74°	4°	n.d.	pale grey gr.	pale green	n.d.	pale green	olive green
40109	108°	n.d.	80°	n.d.	pale green	pale grey gr.	pale green	n.d.	pale green	olive green
Naujaite										
21882	–	–	64°	n.d.	–	–	–	n.d.	pale green	olive green
21890	–	–	68°	4°	–	–	–	n.d.	pale green	olive green
21901	–	–	64°	4°	–	–	–	n.d.	pale green	olive green
21903	–	–	74°	4°	–	–	–	n.d.	pale green	olive green
21903	–	–	78°	5°	–	–	–	n.d.	pale green	olive green
21935	–	–	60°	10°	–	–	–	n.d.	pale green	olive green
22617	–	–	62°	n.d.	–	–	–	apple green	pale green	n.d.

(continued)

Table 24 (cont.)

	Cores		Margins and unzoned grains		Pleochroism: Cores			Pleochroism: Margins and unzoned grains		
	2Vx	X:c	2Vx	X:c	X	Y	Z	X	Y	Z
22617	–	–	60°	9°	–	–	–	n.d.	yellow green	olive green
24943	–	–	76°	n.d.	–	–	–	apple green	pale green	n.d.
24946	–	–	68°	n.d.	–	–	–	apple green	pale green	n.d.
40108	–	–	60°	9°	–	–	–	n.d.	pale green	olive green
40108	–	–	60°	9°	–	–	–	n.d.	pale green	olive green
Kakortokite										
White layers										
J 1	–	–	65°	4°	–	–	–	n.d.	light green	olive green
J 1	–	–	60°	7°	–	–	–	n.d.	light green	olive green
J 11	–	–	62°	6°	–	–	–	n.d.	light green	olive green
J 29	–	–	66°	5°	–	–	–	n.d.	light green	olive green
24750	–	–	60°	10°	–	–	–	n.d.	light green	olive green
24812	–	–	68°	3°	–	–	–	n.d.	light green	olive green
Red layers										
J 15	–	–	64°	n.d.	–	–	–	green	light green	n.d.
J 26	–	–	76°	n.d.	–	–	–	green	light green	n.d.
Black layers										
J 7(2)	–	–	66°	4°	–	–	–	n.d.	light green	olive green
J 28	–	–	76°	n.d.	–	–	–	green	light green	n.d.
24745	–	–	60°	8°	–	–	–	n.d.	light green	olive green
24749	–	–	66°	n.d.	–	–	–	n.d.	light green	n.d.
Green lujavrite										
21902	–	–	70°	4°	–	–	–	n.d.	pale green	olive green
21902	–	–	66°	4°	–	–	–	n.d.	pale green	olive green
21988	–	–	64°	8°	–	–	-	n.d.	pale green	olive green
21988	–	–	61°	6°	–	–	–	n.d.	pale green	olive green
48001	–	–	60°	9°	–	–	–	n.d.	pale green	olive green

Black lujavrite										
21930	–	–	68°	n.d.	–	–	–	green	pale yellow green	n.d.
21953	–	–	66°	n.d.	–	–	–	green	pale yellow green	n.d.
21985	–	–	60°	n.d.	–	–	–	n.d.	pale green	n.d.
21985	–	–	63°	3°	–	–	–	n.d.	pale green	olive green
24959	–	–	66°	9°	–	–	–	n.d.	pale green	olive green
24959	–	–	62°	5°	–	–	–	n.d.	pale green	olive green
48086	–	–	62°	5°	–	–	–	n.d.	pale green	olive green
48086	–	–	61°	8°	–	–	–	n.d.	pale green	olive green
48093	–	–	62°	5°	–	–	–	n.d.	pale green	olive green
"Hybrids"										
21844	–	–	60°	7°	–	–	–	n.d.	light green	olive green
21856 ("aegirine dike" m.g.)	–	–	66°	6°	–	–	–	n.d.	light green	olive green
21856 ("aegirine dike" peg.)	–	–	66°	8°	–	–	–	n.d.	light green	olive green
22636	–	–	62°	7°	–	–	–	n.d.	light green	olive green
224770	–	–	63°	8°	–	–	–	n.d.	light brownish	brownish
48065	–	–	62°	6°	–	–	–	n.d.	light green	olive green
"Kakortokitic" rocks										
21851	–	–	63°	8°	–	–	–	n.d.	light green	olive green
21979	–	–	61°	11°	–	–	–	n.d.	pale brownish	brownish
22526	–	–	61°	n.d.	–	–	–	green	light green	olive green
22541	–	–	67°	12°	–	–	–	n.d.	light green	olive green

– = absent
n.d. = not determined
m.g. = medium grained
peg. = pegmatitic
gr. = green

Table 25. *Composition of the nephelines*

Rock type and GGU specimen number	% KS	Vol. % zeolites in rock	% nepheline altered
Heterogeneous syenite			
24991 (c.g.)	38.7	0.7	14.0
24992 (peg.)	23.8	12.4	30.3
40116 + (peg.)	9.5	34.6	50.0
Sodalite foyaite			
22558 +	11.4	23.5	13.1
22566 +	16.0	6.1	7.5
24971 +	13.9	26.6	*
24972	12.9	19.3	14.5
24974 +	11.2	21.0	*
24976 +	10.4	35.5	*
Naujaite			
21935 +	22.3	64.8	24.4
21937	19.4	14.7	30.7
40108	22.1	3.6	0.0
48004	20.8	0.0	0.0
Kakortokite			
Black layers			
J 25	18.5	17.8	15.4
J 28	12.5	14.7	17.0
24717	24.9	4.7	0.0
24721	18.6	0.2	1.0
24723	17.0	5.8	2.4
24727	20.5	6.1	0.0
24729	18.3	7.5	5.8
24822	14.3	7.2	0.0
24829	21.2	0.7	0.0
White layers			
24718	16.6	4.2	0.0
24724	24.4	4.6	0.0
24762	17.1	0.0	0.0
24816	14.3	5.2	5.8
24827 +	13.6	0.0	0.0
24828	12.9	6.4	0.0
24832	17.1	0.9	0.0
Red layers			
24817	22.9	5.4	10.4
24831	18.2	3.7	0.0
24910	20.9	11.9	23.7

(continued)

Table 25 (cont.)

Rock type and GGU specimen number	% Ks	Vol. % zeolites in rock	% nepheline altered
Lujavrites			
Green			
21849	29.9	30.1	0.0
24790	34.2	3.2	0.0
48146	19.2	2.8	0.0
Transitional var.			
24959 +	35.1	44.9	*
Black			
21897	18.8	3.3	0.0
21898 +	11.0	8.6	3.7
21956 +	16.4	37.7	28.1
"Hybrids"			
21844	21.2.	3.5	23.1
21853	19.4	0.0	0.0
21856	25.9	35.6	26.3
(m.g. "Aegirine dike")			
22636	16.1	0.0	0.0
24770	19.4	0.9	2.7
24799	16.6	1.6	0.0
48065	23.7	0.8	4.1
"Kakortokitic" rocks			
22526	34.4	36.2	*
22541	37.4	37.7	*
22550	24.5	4.2	7.6
22554	19.7	10.3	24.7

\+ = Determinations by M. Danø
* = Unable to recognise nepheline pseudomorphs due to high zeolite content of the rock
transitional var. = Variety transitional between black and green lujavrite
m.g. = medium-grained
c.g. = coarse-grained
peg. = pegmatitic

Table 26. *Composition of olivines*

Rock type and GGU specimen number	% Fo Method d_{130}	% Fo Method d_{174}	% Fo Method 2 Vx
Augite syenite			
22607 (f.g.)	34	30	36
40527 (f.g.)	28	22	20
48003 (f.g.)	19	22	20
48134 (f.g.)	19	n.d.	17
24853 (m.g.)	14	n.d.	n.d.
21837 (c.g.)	14	3	13
24764 (c.g.)	4	*	n.d.
24781 (c.g.)	9	0	8
24990 (c.g.)	4	*	6
48049 (c.g.)	9	n.d.	0
48137 (c.g.)	9	14	6
Heterogeneous syenite			
21995 (c.g.)	9	0	0
24978 (c.g.)	4	*	n.d.
24987 (c.g.)	*	*	1
24977 (peg.)	4	*	n.d.
24992 (peg.)	0	*	n.d.
40124 (peg.)	4	n.d.	3
Sodalite foyaite			
21940	4	n.d.	n.d.
22510	4	*	n.d.
24934	4	*	n.d.
24943	4	n.d.	n.d.
24973	n.d.	n.d.	0
24985	4	*	n.d.
48019	4	*	n.d.

n.d. = not determined
* = value too high to be related to curve
f.g. = fine-grained
m.g. = medium-grained
c.g. = coarse-grained

Table 27. *Chemical Analyses of Major Oxides and Modal Analyses of Rocks*

	1	2	3	4	5	6	7	8	9
	*	*	40124	–	*	33249	40102	–	–
SiO_2	53.91	57.58	55.07	56.31	72.32	63.0	59.91	57.88	49.38
TiO_2	1.65	1.20	0.56	2.82	0.33	0.1	0.38	1.23	0.63
ZrO_2	–	–	0.27		–	0.1	0.37	–	0.61
Al_2O_3	15.96	16.65	14.05	20.11	10.27	12.4	16,14	14.80	17.31
Fe_2O_3	3.43	2.75	6.20	3.93	2.71	8.9	3.24	5.86	4.20
FeO	6.83	5.80	5.80	1.45	3.50	0.4	3.99	3.71	5.25
MnO	0.21	0.20	0.26	0.70	0.23	–	0.15	0.15	0.08
MgO	2.00	0.63	tr.	0.36	0.16	–	0.06	–	0.53
CaO	4.60	2.48	3.07	0.62	0.67	–	1,64	2.71	2.23
Na_2O	5.56	6.25	8.44	8.76	5.17	8.4	8.46	9.12	13.87
K_2O	4.73	5.10	4.76	4.65	3.92	5.5	4.88	3.06	2.55
P_2O_5	0.55	0.45	0.10	0.13	0.18	–	0.06	tr.	–
H_2O^+	0.60	0.53	1.39	1.13	0.54	–	0.48	1.13	1.30
H_2O^-			0.13			–	0.10		0.16
Cl	–	–	0.04	0.15	–	–	0.03	–	1.68
CO_2	–	–	–	–	0.67	–	–	–	–
Rare earths	–	–	–	–	–	–	tr.	–	–
	100.03	99.62	100.17	101.02	100.00	98.8	99.89	99.65	99.78
Cl = O				0.03					0.38
				100.99					99.40

(continued)

Table 27 (cont.)

	1	2	3	4	5	6	7	8	9
	*	*	40124	+	*	33249	40102	+	–
Perthite									
Microcline	69.0	76.0	45.0		54		42.8		15.2
Albite			20.5				35.9		3.0
Nepheline	1.8	2.7	–		–		6.9		14.0
Altered	–	–	5.3		–		2.9		1.3
Augite	11.5	5.7	–		–		–		–
Acmitic pyroxenes	–	–	10.6		15		7.6		4.9
Altered	–	–	2.7				0.6		–
Arfvedsonite	–	–	6.2				1.1		3.0
Kaersutite	4.3	10.0	–		–		–		–
Aenigmatite	–	–	3.3		–		1.3		2.1
Olivine	6.7	1.2	2.4		–		–		–
Eudialyte	–	–	–		–		–		17.0
Sodalite	–	–	–		–		–		31.5
Analcime	–	–	–		–		–		7.9
Zeolites	–	–	4.0		–		0.9		–
Quartz	–	–	–		30		–		–
Fluorite	tr.	0.7	–		–		–		–
Apatite	1.3	1.4	–		–		–		–
Opaques	5.3	2.4	–		–		–		–
Accessories	–	–	–		1		–		–

1. * Chilled augite syenite
2. * Coarse-grained augite syenite
3. 40124 Coarse-grained heterogeneous syenite
4. – Heterogeneous syenite
5. * Alkali granite
6. 33249 Quartz syenite
7. 40102 Pulaskite
8. – Pulaskite
9. – Sodalite foyaite

tr. = trace
* = average analysis
+ = thin section not available for modal analysis

(continued)

Table 27 (cont.)

	10	11	12	13	14	15	16	17	18
	48004	–	–	–	24816	24817	24818	24832	24831
SiO_2	45.43	49.46	43.39	43.82	51.49	52.54	49.01	49.25	50.90
TiO_2	0.36	0.16	0.20	0.20	0.14	0.11	0.44	0.20	0.18
ZrO_2	0.15	0.38	0.27	1.05	0.68	2.85	0.75	n.d.	n.d.
Al_2O_3	22.48	23.53	23.13	25.62	19.81	14.05	14.37	26.00	9.75
Fr_2O_3	3.41	3.04	3.62	2.66	7.92	6.18	6.85	1.81	2.67
FeO	2.69	1.02	3.24	0.40	2.40	4.20	10.40	1.90	4.81
MnO	0.12	0.17	tr.	0.25	0.17	0.29	0.31	0.08	0.66
MgO	0.06	tr.	–	0.06	0.03	0.03	0.04	–	0.17
CaO	2.56	0.80	0.56	0.70	1.02	2.79	1.90	0.92	6.18
Na_2O	16.20	14.71	19.68	18.45	10.66	9.57	8.90	14.00	11.60
K_2O	3.52	4.34	1.51	1.00	3.53	3.36	2.20	4.50	2.37
P_2O_5	0.03	–	–	–	0.03	0.02	0.02	0.05	0.07
H_2O^+	0.66	1.38	1.57	2.40	2.32	2.70	3.88	0.70	2.75
H_2O^-	0.09								
Cl	2.79	2.25	3.63	4.60	n.d.	n.d.	n.d.		
	100.55	101.24	100.80	101.21	100.20	98.69	99.07		
Cl = O	0.63	0.51	0.82	1.01					
	99.92	100.73	99.98	100.20					

	10	11	12	13	14	15	16	17	18
	48004	–	–	+	24816	24817	24818	24832	24831
Perthite	23	30	6		14.6	23.8	11.7	13.6	32.0
Small albite laths	–	–	–		7.8	4.9	0.6	1.2	0.2
Nepheline	14	18	5		44.2	23.4	–	70.0	14.2
Altered	–	–	–		2.7	2.7	–	–	–
Acmitic pyroxenes	7	10	12		6.3	1.9	4.9	2.6	2.1
Arfvedsonite	7	1	5		5.4	13.4	34.4	4.3	4.8
Aenigmatite	6	–	2		–	–	–	3.1	0.2
Eudialyte	4	3	2		–	21.4	–	4.3	42.8
Altered	–	–	–		16.5	6.1	10.1	–	–
Sodalite	39	31	54		–	–	–	–	–
Analcime	–	7	14		2.5	0.9	0.8	–	–
Natrolite	–	–	–		–	1.5	37.5	0.9	3.7

10. 48004 Naujaite
11. – Naujaite
12. – Naujaite
13. – Naujaite
14. 24816 Kakortokite – white layer
15. 24817 Kakortokite – red layer
16. 24818 Kakortokite – black layer
17. 24832 Kakortokite – white layer
18. 24831 Kakortokite – red layer

n.d. = not determined
\+ = thin section not available for modal analysis

(continued)

Tabel 27 (cont.)

	19	20	21	22	23	24	25	26	27
	24830	–	–	–	–	–	–	–	–
SiO_2	53.17	51.62	49.39	48.90	53.74	53.44	50.72	53.01	56.64
TiO_2	0.29	0.44	0.49	n.d.	0.50	0.30	2.84	0.33	0.30
ZrO_2	n.d.	1.70	4.89	1.96	1.63	1.00		0.65	–
Al_2O_3	12.70	15.63	10.39	7.85	14.02	18.64	15.45	15.33	16.10
Fe_2O_3	7.84	6.06	4.31	11.46	10.63	9.38	11.82	9.14	4.90
FeO	6.97	4.98	7.72	13.32	1.71	0.86	0.80	4.44	6.86
MnO	0.32	0.33	0.97	1.11	0.36	0.10	0.31	0.13	0.57
MgO	0.37	tr.	–	0.38	tr.	–	0.13	0.10	–
CaO	1.98	3.13	5.11	1.95	1.18	0.79	0.14	0.67	0.39
Na_2O	8.52	10.09	11.45	7.40	9.02	12.10	10.83	11.86	11.50
K_2O	3.89	4.19	2.62	3.23	4.77	2.43	2.94	2.60	1.00
P_2O_5	0.12	–	–	–	–	–	–	tr.	–
H_2O^+	3.31	2.12	1.46	1.80	3.40	1.12	4.66	1.88	1.54
H_2O^-						0.34		0.20	0.04
Cl	n.d.	0.17	0.51	0.03	–	0.12	–	0.23	tr.
F	n.d.	n.d.	0.75	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
		100.46	100.36	99.39	100.96	100.62	100.64	100.57	100.29
Cl = O		0.04	0.12	0.01		0.03		0.05	
F = O		–	0.32	–		–		–	
		100.42	99.92	99.38		100.59		100.52	

	19	20	21	22	23	24	25	26	27
	24830	–	+	–	+	+	+	+	+
Perthite	21.8	39.9		17.7					
Small albite laths	–	9.4		3.9					
Nepheline	8.3	16.5		14.7					
Altered	–	6.7		8.5					
Acmitic pyroxenes	–	4.6		4.0					
Arfvedsonite	6.3	13.3		39.9					
Altered	–	–		1.0					
Aenigmatite	–	tr.		–					
Eudialyte	2.2	8.0		0.5					
Altered	0.2	1.4		9.9					
Sodalite	0.6	–		–					
Analcime	1.7	–		–					
Natrolite	1.7	–		–					
Fluorite	0.5	–		–					

19. 24830 Kakortokite – black layer
20. – Kakortokite – white layer
21. – Kakortokite – red layer
22. – Kakortokite – black layer
23. – Green lujavrite
24. 24830 Green lujavrite
25. – Green lujavrite
26. – Black lujavrite
27. – Black lujavrite

\+ = thin sections not available for modal analysis
tr. = trace
n.d. = not determined

(continued)

Tabel 27 (cont.)

1. 33452, 33390, 33391, 33662 — Chilled augite syenite

Analysts: E. I. HAMILTON (33452, 33390-1)
H. B. WIIK (33662)
Publ: HAMILTON (1964) analyses 1, 2, 3 and 4, p. 27.
Remarks: Trace element analyses also include Ga, Li, Zr, Y, La, Sr and Rb. It is a little difficult to understand the absence of mica in the modal analyses given by HAMILTON as this mineral is invariably present in the rock.

2. 33320, 33321, 33326, 33327 — Coarse-grained augite syenite

Analyst: E. I. HAMILTON
Publ: HAMILTON (1964) analyses 5, 6, 8 and 8, p. 27.
Remarks: Trace element analyses also include Ga, Li, Zr, Y, La, Sr and Rb. It is a little difficult to understand the absence of mica in the modal analyses given by HAMILTON as this mineral is invariably present in the rock.

3. 40124 — Coarse-grained heterogeneous syenite

Analyst: M. MOURITZEN
Publ: FERGUSON (1964) p. 36.

4. – — Heterogeneous syenite

Analyst: C. DETLEFSEN
Publ: USSING (1912) analysis 4, p. 132.

5. (average of 10 analyses) — Alkali granite

Analysts: E. I. HAMILTON (7)
M. MOURITZEN (1)
H. B. WIIK (1)
C. WINTER (1)
Figure in parenthesis indicates number of analyses.
Publ: HAMILTON (1964) table 8, analysis 11, p. 69.
Remarks: Trace element analyses also include Ga, Mo, Li, Zr, Y, La, Sr, Ba and Rb.

6. 33249 — Quartz syenite

Analyst: E. I. HAMILTON
Publ: HAMILTON (1964) table 6, analysis 5, p. 52.
Remarks: Trace element analyses also include Ga, Li, Y, La, Sr, Ba and Rb.

7. 40102 — Pulaskite

Analyst: M. MOURITZEN
Publ: FERGUSON (1964) p. 44.

(continued)

Table 27 (cont.)

8.	40102	Pulaskite	
		Analyst:	C. WINTHER
		Publ:	USSING (1912) analysis 3, p. 124.
9.	–	Sodalite foyaite	
		Analyst:	C. WINTHER
		Publ:	USSING (1912) analysis 5, p. 141.
10.	48004	Naujaite	
		Analyst:	M. MOURITZEN
		Publ:	FERGUSON (1964) p. 56.
11.	–	Naujaite	
		Analyst:	N. V. USSING
		Publ:	USSING (1912) analysis 6, p. 154.
12.	–	Naujaite	
		Analyst:	C. WINTHER
		Publ:	USSING (1912) analysis 7, p. 154.
13.	–	Naujaite	
		Analyst:	E. I. HAMILTON
		Publ:	HAMILTON (1964) analysis 3, p. 47.
14.	24816	Kakortokite – white layer	
		Analyst:	R. DANCHIN
		Publ:	–
15.	24817	Kakortokite – red layer	
		Analyst:	R. DANCHIN
		Publ:	–
16.	24818	Kakortokite – black layer	
		Analyst:	R. DANCHIN
		Publ:	–
17.	24832	Kakortokite – white layer	
		Analyst:	I. SØRENSEN
		Publ:	–
18.	24831	Kakortokite – red layer	
		Analyst:	I. SØRENSEN
		Publ:	–
19.	24830	Kakortokite – black layer	
		Analyst:	I. SØRENSEN
		Publ:	–
20.	–	Kakortokite – white layer	
		Analyst:	N. V. USSING
		Publ:	USSING (1912) analysis 13, p. 182.

(continued)

Table 27 (cont.)

21. 24830 Kakortokite – red layer
Analyst: C. Christensen
Publ: Ussing (1912) analysis 14, p. 182.

22. – Kakortokite – black layer
Analyst: C. Detlefsen
Publ: Ussing (1912) analysis 15, p. 182.

23. – Green lujavrite
Analyst: N. V. Ussing
Publ: Ussing (1912) analysis 8, p. 168.

24. – Green lujavrite
Analyst: C. Winther
Publ: Ussing (1912) analysis 9, p. 168.

25. – Green lujavrite
Analyst: C. Detlefsen
Publ: Ussing (1912) analysis 10, p. 168.

26. – Black lujavrite
Analyst: C. Winther
Publ: Ussing (1912) analysis 11, p. 175.

27. – Black lujavrite
Analyst: C. Christensen
Publ: Ussing (1912) analysis 12, p. 175.

Table 28. *Partial chemical analyses and modes*

Elements as ppm unless stated.	Augite syenite		Heterogeneous syenite		Sodalite foyaite				
Oxides as percentages	24990 (C.G.)	48134 (F.G.)	24991 (C.G.)	24992 (PEG.)	24971	24974	24976	40109	48082
CaO	2.72	4.24	2.09	2.78	2.34	2.07	3.13	4.67	2.10
Na_2O	5.90	5.00	6.60	6.55	7.67	11.97	8.53	6.67	13.47
K_2O	5.60	4.58	5.14	4.46	4.30	3.99	5.20	4.78	3.99
Rb	204	185	228	200	203	187	248	235	192
Li	26	62	118	80	133	121	110	145	149
Be	5	4	12	9	21	12	15	11	32
Zr	655	408	1810	1760	6850	4050	3730	1400	805
Ba	1240	1740	60	49	64	37	39	42	47
TiO_2	1.36	3.25	0.29	0.73	0.13	0.17	0.22	0.14	0.31
Nb	66	79	170	150	224	160	175	145	228
Sr	163	242	108	102	112	63	137	190	66
La	138	147	232	240	312	221	223	230	272
Ga	47	37	67	58	73	94	93	89	101
Perthite	72.9	71.8	64.5	51.8	32.1	23.2	45.5	38.9	36.9
Nepheline	–	–	4.3	4.6	8.4	18.2	1.5	7.0	12.2
Altered	–	–	0.7	2.0	–	–	–	–	–
Pyroxenes	6.8	7.1	6.4	19.4	16.3	9.8	12.9	6.4	5.8
Amphiboles	5.5	1.9	22.3	11.5	16.3	15.7	1.5	11.5	5.5
Olivine	6.9	2.0	0.8	–	–	–	–	–	–
Altered	–	3.8	–	–	–	–	–	–	–
Eudialyte	–	–	–	0.3	–	1.4	–	–	–
Altered	–	–	–	–	0.3	–	–	–	0.4
Sodalite	–	–	–	–	repl.	10.7	3.1	repl.	29.5
Analcime	–	–	1.0	5.1	4.0	8.3	9.3	6.2	9.7
Natrolite	–	–	–	5.3	22.6	12.7	26 2	30.0	–
Biotite	5.6	5.5	–	–	–	–	–	–	–
Chlorite	1.2	–	–	–	–	–	–	–	–
Apatite	0.6	1.3	–	–	–	–	–	–	–
Opaque	0.5	6.6	–	–	–	–	–	–	–

(continued)

Table 28 (cont.)

	Naujaite					Green lujavrite			
	21953	22581	40108	48004	48027	24790	24873	48001	48146
CaO	4.34	1.08	1.49	3.80	1.57	0.97	1.43	3.17	0.64
Na_2O	14.93	14.43	16.53	15.73	14.23	10.65	10.70	6.35	11.67
K_2O	4.52	3.00	3.48	3.50	3.92	2.17	3.42	5.00	3.02
Rb	216	195	168	170	195	124	186	251	172
Li	176	97	110	162	104	148	133	23	54
Be	7	12	18	27	12	24	15	10	16
Zr	8150	550	445	755	3400	8150	1.09%	7450	6470
Ba	76	53	54	29	42	113	113	403	86
TiO_2	0.07	0.15	0.04	0.21	0.35	0.07	0.09	0.08	0.10
Nb	175	75	92	140	122	220	228	157	150
Sr	96	66	59	81	67	127	128	348	140
La	238	176	182	243	209	428	440	333	505
Ga	81	93	95	113	88	68	72	63	116
Perthite	24.5	36.3	24.9	23.0	35.3	–	–	–	–
Microcline	–	–	–	–	–	31.9	30.5	28.5	15.5
Albite	–	–	–	–	–	12.6	–	2.7	23.3
Nepheline	3.7	8.6	15.1	14.0	5.1	13.8	3.8	repl.	19.0
Acmitic pyroxenes	3.1	1.8	9.7	6.5	2.9	24.7	36.5	38.2	29.4
Arfvedsonite	15.5	4.4	2.8	7.3	3.2	–	2.7	6.0	1.3
Aenigmatite	1.6	–	–	6.2	2.1	–	–	–	–
Eudialyte	12.6	5.9	0.1	4.0	6.8	–	9.4	–	3.1
Altered	–	–	–	–	–	11.3	4.3	10.9	3.0
Sodalite	38.8	34.4	43.8	39.0	40.0	2.5	–	–	2.6
Analcime	–	–	1.0	–	3.2	2.1	–	–	2.7
Natrolite	–	8.4	2.6	–	1.0	1.1	12.8	13.7	0.1
Fluorite	0.2	0.2	–	–	0.4	–	–	–	–

(continued)

Table 28 (cont.)

	Transitional black to green lujavrite			Black lujavrite					"Aegirine-dike"
	24959	24960	24961	21861	21897	24860	24963	48145	21856
CaO	0.40	0.37	0.38	1.33	0.34	n.d.	0.31	0.30	1.46
Na_2O	10.13	10.43	11.50	11.33	9.71	9.87	10.80	9.73	13.60
K_2O	3.16	2.96	2.22	2.60	3.50	3.20	2.02	3.08	1.94
Rb	183	172	120	134	212	172	97	180	94
Li	159	160	65	173	311	218	252	175	56
Be	26	27	24	23	27	15	43	19	85
Zr	5450	4980	4300	1.18%	1980	8400	2400	3050	8650
Ba	91	95	82	88	46	63	38	54	358
TiO_2	0.09	0.09	0.12	0.09	0.20	0.10	0.08	0.13	0.20
Nb	228	197	159	390	290	268	218	154	280
Sr	145	123	120	140	123	234	133	94	257
La	635	500	565	472	1180	455	1250	288	580
Ga	114	133	108	81	109	96	111	114	126
Microcline	23.9	29.0	16.0	19.7	9.8	23.4	7.7	24.0	17.0
Albite	–	12.2	–	2.8	9.5	–	30.3	–	–
Nepheline	0.5	0.4	repl.	repl.	10.8	12.8	0.2	0.9	11.0
Altered	–	–	–	–	–	2.1	–	–	–
Acmitic pyroxenes	14.6	13.0	40.5	16.4	1.5	5.2	2.4	1.3	24.9
Arfvedsonite	7.5	9.8	5.3	24.5	56.6	44.4	27.5	31.0	–
Eudialyte	3.3	2.1	1.8	9.5	1.6	–	–	–	–
Altered	1.1	0.5	0.2	–	4.6	5.3	6.9	4.8	9.8
Sodalite	4.2	–	0.5	–	2.3	0.5	6.6	8.2	1.7
Analcime	41.6	33.0	36.7	–	–	6.3	18.4	29.1	31.2
Natrolite	3.3	–	–	27.1	3.3	–	–	0.7	4.4

(continued

Table 28 (cont.)

	"Hybrids"								
	21844	21853	21854	22635	22636	24770	24799	48002	48065
CaO	2.50	3.19	1.78	2.78	3.14	3.17	1.10	2.38	3.52
Na_2O	10.78	10.39	9.85	10.40	10.42	10.25	9.07	8.42	10.17
K_2O	3.52	4.46	4.01	3.20	4.48	4.32	3.96	5.60	4.52
Rb	180	216	215	174	218	208	201	295	228
Li	117	64	124	107	118	109	178	148	88
Be	23	7	16	15	14	18	15	13	13
Zr	1.62%	5950	7770	1.73%	8150	1.09%	6650	6850	1.00%
Ba	118	113	179	134	310	325	134	105	158
TiO_2	0.11	0.31	0.11	0.10	0.48	0.54	0.10	0.03	0.37
Nb	395	224	228	383	275	352	175	152	346
Sr	159	112	130	154	163	200	104	205	140
La	454	240	305	520	269	352	254	322	347
Ga	85	75	126	65	71	71	85	86	777
Perthite	24.7	38.7	37.5	19.8	45.6	38.1	30.1	28.7	35.8
Albite laths	4.4	4.8	6.2	4.8	3.2	4.1	8.5	9.2	5.0
Nepheline	11.7	18.8	–	4.4	19.8	17.7	25.3	–	18.9
Altered	3.5	–	–	12.4	–	0.5	–	22.9	0.8
Acmitic pyroxenes	12.0	–	6.2	14.7	9.4	8.4	3.2	24.3	–
Arfvedsonite	14.5	14.7	32.6	14.0	5.6	6.4	14.7	–	13.9
Aenigmatite	–	2.8	–	–	2.6	4.8	–	–	5.7
Eudialyte	2.6	12.8	1.0	3.0	6.2	10.1	0.2	–	4.2
Altered	21.3	–	4.6	24.2	1.2	5.3	10.1	9.7	–
Sodalite	5.3	7.4	11.9	2.7	6.4	2.5	6.3	–	15.4
Analcime	–	–	–	–	–	0.4	1.6	3.8	–
Natrolite	–	–	–	–	–	–	–	1.4	–
Li-mica	–	–	–	–	–	1.3	–	–	–
Brown mica	–	–	–	–	–	0.4	–	–	0.3

(continued)

Table 28 (cont.)

	"Kakortokitic" rocks					
	21851	22526	22541	22550	22554	24954
CaO	2.10	2.80	1.06	2.08	2.41	0.44
Na_2O	8.12	9.53	12.67	10.88	12.47	12.02
K_2O	3.66	3.00	3.76	3.60	2.34	1.22
Rb	207	249	220	203	130	50
Li	99	76	189	115	155	192
Be	23	51	70	25	29	7
Zr	1.58 %	1.73 %	1.03 %	1.58 %	1.88 %	4300
Ba	194	218	130	152	102	60
TiO_2	0.08	0.05	0.08	0.08	0.10	0.08
Nb	580	580	290	500	535	290
Sr	216	238	165	180	186	114
La	800	590	478	538	555	405
Ga	68	69	104	97	71	67
Perthite/microcline	20.1	23.9	34.9	36.5	16.6	0.1
Albite laths	–	–	–	1.8	3.6	–
Nepheline	–	–	0.3	25.5	18.6	–
Altered	–	–	–	2.1	6.1	–
Acmitic pyroxenes	19.3	14.4	18.1	1.0	1.7	–
Arfvedsonite	–	–	–	18.8	21.7	27.1
Aenigmatite	–	–	–	–	–	0.6
Eudialyte	19.2	25.5	7.4	–	24.0	4.2
Altered	–	–	1.6	12.2	–	0.2
Sodalite	–	--	–	–	3.5	–
Analcime	–	5.8	3.5	1.5	2.0	49.3
Natrolite	41.4	30.4	34.2	0.6	2.2	18.5

Table 28 (cont.)

	Kakortokite – white layers							
	J 9	J 11	J 13	J 16	21828	24718	24720	24722
CaO	1.13	1.47	2.64	1.98	3.93	4.62	1.33	4.17
Na_2O	10.00	9.14	8.66	9.68	11.45	10.60	9.24	9.14
K_2O	4.60	4.40	4.24	3.16	3.32	3.27	5.77	4.87
Rb	250	228	227	165	169	166	484	251
Li	153	157	123	123	121	119	671	143
Be	21	14	103	23	29	36	32	124
Zr	5450	6650	5100	7940	1.50%	1.09%	6850	8150
Ba	290	410	365	170	183	222	253	314
TiO_2	0.08	0.06	0.10	0.25	0.18	0.07	0.09	0.07
Nb	167	157	260	415	535	320	210	268
Sr	135	129	151	128	168	163	130	184
La	285	226	420	394	440	355	315	435
Ga	96	96	84	64	81	77	90	91
Perthite	45.3	50.8	47.9	32.1	43.8	29.9	59.7	47.5
Small albite laths	5.3	8.2	6.2	3.6	1.8	3.4	2.1	5.6
Nepheline	19.7	11.5	12.5	10.8	22.6	27.4	1.0	11.1
Altered	–	–	–	–	2.3	–	12.2	–
Acmitic pyroxenes	2.6	2.3	17.1	4.0	4.0	5.9	1.0	15.0
Arfvedsonite	17.5	13.1	–	30.2	8.7	11.1	12.8	–
Eudialyte	3.4	1.2	–	1.5	11.1	1.2	–	–
Altered	4.7	3.5	7.3	12.0	2.2	9.8	6.0	11.4
Sodalite	–	2.4	1.4	2.4	–	7.1	–	0.3
Analcime	1.5	6.2	7.6	3.4	–	4.2	5.2	9.1
Natrolite	–	0.8	–	–	3.5	–	–	–

(continued)

Table 28 (cont.)

	Kakortokite – white layers							
	24724	24726	24728	24730	24775	24776	24810	24812
CaO	2.47	1.51	2.80	2.43	3.35	3.28	2.25	1.33
Na_2O	10.74	10.80	9.32	9.46	8.25	7.32	8.66	11.40
K_2O	4.48	4.88	4.48	3.80	4.30	3.92	3.24	4.26
Rb	238	259	249	199	217	198	167	217
Li	138	126	99	167	176	184	110	226
Be	38	20	20	22	20	24	19	23
Zr	5450	8150	8650	1.25%	4450	1.00%	6450	2950
Ba	240	314	270	208	282	178	107	134
TiO_2	0.03	0.08	0.15	0.09	0.12	0.28	0.11	0.24
Nb	152	144	485	232	194	305	228	343
Sr	138	142	160	152	154	172	198	167
La	246	268	550	307	248	370	300	328
Ga	97	104	79	81	81	69	74	112
Perthite	46.6	33.1	34.1	29.2	32.4	38.9	14.4	30.9
Small albite laths	9.6	3.0	4.2	2.0	1.6	2.3	10.2	6.8
Nepheline	21.9	32.6	16.0	7.2	3.3	–	0.9	–
Altered	–	–	–	–	22.6	24.3	44.8	21.4
Acmitic pyroxenes	8.7	11.9	15.6	21.1	8.7	5.1	10.3	19.1
Arfvedsonite	–	–	1.8	6.2	10.4	8.0	11.7	7.7
Aegnigmatite	–	–	–	–	–	0.7	–	–
Eudialyte	–	–	–	0.3	–	1.3	–	–
Altered	6.3	10.4	15.3	17.8	9.2	8.4	4.4	10.7
Sodalite	2.3	1.8	–	2.4	–	–	–	–
Analcime	3.8	7.2	11.4	13.8	9.9	9.9	1.5	3.4
Natrolite	0.8	–	1.6	–	1.1	1.1	–	–
Fluorite	–	–	–	–	0.8	–	–	–

(continued)

Table 28 (cont.)

	Kakortokite – white layers							
	24813	24814	24816	24821	24828	24829	24832	24909
CaO	1.09	2.58	1.17	1.20	3.26	3.58	0.70	1.06
Na_2O	9.54	9.00	10.44	9.66	9.34	8.24	12.70	8.22
K_2O	3.38	4.04	3.52	4.20	4.32	3.64	3.92	3.80
Rb	180	211	185	225	217	176	206	184
Li	156	178	162	143	109	130	90	132
Be	19	58	19	22	17	13	14	8
Zr	520	1.22%	4550	5250	7000	9150	3600	4420
Ba	118	178	130	228	303	257	118	158
TiO_2	0.22	0.23	0.09	0.11	0.13	0.09	0.10	0.10
Nb	272	890	140	162	243	220	92	138
Sr	122	216	117	127	144	150	99	116
La	295	785	230	260	312	270	165	232
Ga	90	77	111	91	83	62	114	67
Perthites	26.6	28.7	14.6	30.9	54.1	47.3	13.6	32.9
Small albite laths	9.3	–	7.8	13.2	5.7	1.7	1.2	11.0
Nepheline	5.6	–	44.2	26.0	19.4	17.5	70.0	–
Altered	24.8	0.9	2.7	–	–	–	–	22.5
Acmitic pyrozenes	7.1	22.2	6.3	4.2	2.1	1.4	2.6	11.7
Arfvedsonite	18.9	3.9	5.4	17.8	4.2	22.7	4.3	15.3
Aenigmatite	–	–	–	–	–	0.1	3.1	–
Eudialyte	–	–	–	4.5	6.3	3.8	4.3	–
Altered	4.6	13.8	16.5	–	1.8	2.7	–	3.6
Analcime	3.0	3.2	2.5	2.5	6.4	0.7	–	3.0
Natrolite	0.1	27.3	–	0.9	–	–	0.9	–
Fluorite	–	–	–	–	–	2.1	–	–

(continued)

Table 28 (cont.)

	Kakortokite – red layers				Kakortokite – black layers			
	J 15	24817	24831	24910	J 8	J 10	J 12	J 14
CaO	2.75	2.67	5.32	4.03	2.57	2.00	2.69	n.d.
Na_2O	8.06	10.20	11.08	12.25	9.00	8.74	9.46	5.40
K_2O	3.00	3.28	1.68	2.34	1.74	2.40	2.30	1.24
Rb	154	156	82	130	74	119	111	55
Li	117	103	49	n.d.	164	160	134	83
Be	17	13	19	21	13	17	21	14
Zr	1.15%	1.88%	3.03%	1.88%	7450	6830	1.06%	6100
Ba	255	147	193	76	66	122	115	53
TiO_2	0.12	0.05	0.07	0.02	0.34	0.24	0.28	0.35
Nb	370	440	980	580	220	235	295	197
Sr	298	182	233	270	132	115	133	145
La	410	535	860	645	258	243	400	324
Ga	51	64	26	80	66	62	54	41
Perthites	34.0	23.8	32.0	1.9	7.9	20.8	14.3	4.2
Small albite laths	4.9	4.9	0.2	2.5	0.8	5.9	3.4	1.0
Nepheline	0.8	23.4	14.2	38.3	2.1	27.4	15.3	–
Altered	18.4	2.7	–	11.9	13.2	1.9	1.1	–
Acmitic pyroxenes	4.8	1.9	2.1	3.8	–	4.0	2.0	3.7
Arfvedsonite	13.0	13.4	4.8	3.3	59.6	29.6	43.9	49.5
Aenigmatite	0.6	–	0.2	–	–	–	–	–
Eudialyte	16.9	21.4	42.8	13.2	–	–	–	–
Altered	3.8	6.1	–	25.1	11.9	10.0	18.6	11.4
Sodalite	–	–	–	–	0.2	–	–	–
Analcime	2.8	0.9	–	–	3.0	0.9	1.1	–
Natrolite	–	1.5	3.7	–	–	–	–	30.2
Fluorite	–	–	–	–	1.3	0.5	0.3	–

(continued)

Table 28 (cont.)

	Kakortokite – black layers							
	24717	24719	24721	24723	24725	24727	24729	24731
CaO	2.22	2.85	2.37	0.68	3.30	2.41	2.48	1.94
Na_2O	11.72	9.3	11.40	9.98	9.74	9.34	10.00	9.58
K_2O	2.35	1.23	1.58	2.50	1.30	2.40	2.46	2.56
Rb	131	56	75	123	58	116	116	123
Li	150	143	107	146	112	152	98	129
Be	29	11	15	32	12	20	12	12
Zr	1.03%	7050	8650	7450	1.18%	1.37%	8150	7250
Ba	91	74	64	130	76	105	82	76
TiO_2	0.18	0.31	0.20	0.21	0.28	0.20	0.29	0.27
Nb	295	228	224	213	260	310	240	217
Sr	120	113	112	124	122	137	116	107
La	340	314	295	280	324	405	300	283
Ga	66	33	51	59	36	54	54	63
Perthites	6.6	0.7	4.5	19.9	0.7	19.9	17.2	14.7
Small albite laths	2.2	0.9	7.9	2.8	1.4	4.3	2.9	3.6
Nepheline	27.0	2.8	19.0	16.3	12.7	24.4	16.2	21.7
Altered	–	13.6	0.2	0.4	2.1	–	1.0	–
Acmitic pyroxenes	15.5	4.7	22.0	13.6	8.4	1.3	6.1	5.6
Arfvedsonite	31.4	60.5	38.9	32.3	52.0	29.4	40.1	40.1
Eudialyte	0.1	–	–	–	–	2.9	–	–
Altered	12.5	7.6	7.5	9.3	12.4	11.7	10.0	7.3
Analcime	2.4	9.2	–	5.4	6.7	4.6	5.8	7.0
Natrolite	2.3	–	–	–	3.6	1.5	0.7	–

(continued)

Table 28 (cont.)

	Kakortokite – black layers							
	24809	24811	24815	24818	24820	24822	24830	24908
CaO	2.81	3.01	1.48	1.94	2.23	2.39	1.67	1.27
Na_2O	8.33	8.68	8.78	9.18	9.80	9.00	9.23	8.32
K_2O	3.66	2.62	3.60	1.94	1.88	1.96	3.10	2.20
Rb	198	121	183	108	85	88	154	86
Li	106	95	97	108	140	121	98	62
Be	25	22	16	8	13	13	18	9
Zr	5000	1.06%	3600	1.18%	8650	9700	3950	3500
Ba	166	84	118	88	66	76	115	51
TiO_2	0.13	0.13	0.18	0.27	0.29	0.34	0.17	0.33
Nb	307	305	150	255	217	375	204	203
Sr	228	200	125	118	116	127	120	143
La	348	425	283	285	290	460	298	232
Ga	81	70	86	50	56	55	75	58
Perthites	28.1	9.9	36.3	11.7	8.1	6.8	21.8	2.1
Small albite laths	10.1	6.7	5.0	0.6	4.5	4.6	–	9.9
Nepheline	–	–	0.1	–	6.3	9.8	8.3	–
Altered	24.2	20.3	10.8	–	–	–	–	–
Acmitic pyroxenes	8.6	4.7	3.9	4.9	9.5	0.6	–	3.7
Arfvedsonite	18.5	37.2	26.3	34.4	40.9	57.8	63.0	72.1
Eudialyte	–	–	–	–	–	5.8	2.2	–
Altered	5.3	11.2	6.8	10.1	9.0	7.5	0.2	4.5
Sodalite	–	–	–	–	12.8	0.1	0.6	–
Analcime	2.9	8.9	5.2	0.8	8.2	5.8	1.7	3.8
Natrolite	2.3	1.1	5.6	37.5	0.7	1.4	1.7	3.9
Fluorite	–	–	–	–	–	–	0.5	–

Analysts: J. FERGUSON CaO, Na_2O and K_2O
I. H. WRIGHT Rb, Li, Be, Zr, Ba, TiO_2, Nb, Sr, La and Ga

PEG. = pegmatitic
n.d. = not determined
C.G. = coarse-grained
F.G. = fine-grained
repl. = replaced

Table 29 (cont.)

Rock Type and Specimen No	%CaO	%Na_2O	%K_2O	Rb	Li	Be	Zr	Ba	%TiO_2	Nb	Sr	La	Ga
"Hybrids"													
GGU 21844	2.50	10.78	3.52	180	117	23	1.62%	118	0.11	395	159	454	85
GGU 21853	3.19	10.39	4.46	216	64	7	5950	113	0.31	224	112	240	75
GGU 21854	1.78	9.85	4.01	215	124	16	7700	179	0.11	228	130	305	126
GGU 22635*	2.78	10.40	3.20	174	107	15	1.73%	134	0.10	383	154	520	65
GGU 22636	3.14	10.42	4.48	218	118	14	8150	310	0.48	275	163	269	71
GGU 24770	3.17	10.25	4.32	208	109	18	1.09%	325	0.54	352	200	352	71
GGU 24799	1.10	9.07	3.96	201	178	15	6650	134	0.10	175	104	254	85
GGU 48002*	2.38	8.42	5.60	295	148	13	6850	105	0.03	152	205	322	86
GGU 48065	3.52	10.17	4.52	228	88	13	1.00%	158	0.37	346	140	347	77
Average values	2.62	9.97	4.23	215	117	15	9967	175	0.24	281	152	340	82
"Aegirine dike"													
GGU 21856*	1.46	13.60	1.94	94	56	85	8650	358	0.20	280	257	580	126
"Kakortokitic" rocks													
GGU 21851*	2.10	8.12	3.66	207	99	23	1.58%	194	0.08	580	216	800	68
GGU 22526*	2.80	9.53	3.00	249	76	51	1.73%	218	0.05	580	238	590	69
GGU 22541*	1.06	12.67	3.76	220	189	70	1.03%	130	0.08	290	165	478	104
GGU 22550	2.08	10.88	3.60	203	115	25	1.58%	152	0.08	500	500	538	97
GGU 22554*	2.41	12.47	2.34	130	155	29	1.88%	102	0.10	535	186	555	71
GGU 24954*	0.44	12.02	1.22	50	192	7	4300	60	0.08	290	114	405	67
Average values	1.82	10.95	2.93	177	138	34	1.37%	143	0.78	463	183	561	79
Black lujavrite													
GGU 21861*	1.33	11.33	2.60	134	173	23	1.18%	88	0.90	390	140	472	81
GGU 21897	0.34	9.71	3.50	212	311	27	1980	46	0.20	290	123	1180	109
GGU 24860	n.d.	9.87	3.20	172	218	15	8400	63	0.10	268	234	455	96
GGU 24963*	0.31	10.80	2.02	97	252	43	2400	38	0.08	218	133	1250	111
GGU 48145*	0.30	9.73	3.08	180	175	19	3050	54	0.13	154	94	288	114
Average values	0.56	10.29	2.88	159	226	26	5526	58	0.12	264	145	729	102
Transition black-green lujavrite													
GGU 24959*	0.40	10.13	3.16	183	159	26	5450	91	0.09	228	145	635	114
GGU 24960*	0.37	10.43	2.96	172	160	27	4980	95	0.09	197	123	500	133
GGU 24961*	0.38	11.50	2.22	120	65	24	4300	82	0.12	159	120	565	108
Average values	0.38	10.69	2.78	158	128	26	4910	89	0.10	195	130	567	118

Green lujavrite													
GGU 24790	0.97	10.65	2.17	124	148	24	8150	113	0.07	220	127	428	68
GGU 24873*	1.43	10.70	3.42	186	133	15	1.09%	113	0.09	228	128	440	72
GGU 48001*	3.17	6.35	5.00	251	23	10	7450	403	0.08	157	348	333	63
GGU 48146	0.64	11.67	3.02	172	54	16	6470	86	0.10	150	140	505	116
Average values	1.55	9.84	3.40	167	90	16	8243	176	0.09	189	186	427	80
Kakortokite – White layers													
J 9	1.13	10.00	4.60	250	153	21	5540	290	0.08	167	135	285	96
J 11	1.47	9.14	4.40	228	157	14	6650	410	0.06	157	129	226	96
J 13	2.64	8.66	4.24	227	123	103	5100	365	0.10	260	151	420	84
J 16	1.98	9.68	3.16	165	123	23	7940	170	0.25	415	128	394	64
GGU 21828*	3.93	11.45	3.32	169	121	29	1.50%	183	0.18	535	168	440	81
GGU 24718	4.62	10.60	3.27	166	119	36	1.09%	222	0.07	320	163	355	77
GGU 24720*	1.33	9.24	5.77	484	671	32	6850	253	0.09	210	130	315	90
GGU 24722	4.17	9.14	4.87	251	143	124	8150	314	0.07	268	184	435	91
GGU 24724	2.47	10.74	4.48	238	138	38	5450	240	0.03	152	138	246	97
GGU 24726	1.51	10.80	4.88	259	126	20	8150	314	0.08	144	142	268	104
GGU 24728*	2.80	9.32	4.48	249	99	20	8650	270	0.15	485	160	550	79
GGU 24730*	2.43	9.46	3.80	199	167	22	1.25%	208	0.09	232	152	307	81
GGU 24775*	3.35	8.25	4.30	217	176	20	4450	282	0.12	194	154	248	81
GGU 24776*	3.28	7.32	3.92	198	184	24	1.00%	178	0.28	305	172	370	69
GGU 24810*	2.25	8.66	3.24	167	110	19	6450	107	0.11	228	198	300	74
GGU 24812*	1.33	11.40	4.26	217	226	23	2950	134	0.24	343	167	328	112
GGU 24813*	1.09	9.54	3.38	180	156	19	520	118	0.22	272	122	295	90
GGU 24814*	2.58	9.00	4.04	211	178	58	1.22%	178	0.23	890	216	785	77
GGU 24816	1.17	10.44	3.52	185	162	19	4550	130	0.09	140	117	230	111
GGU 24821	1.20	9.66	4.20	225	143	22	5250	228	0.11	162	127	260	91
GGU 24828	3.26	9.34	4.32	217	109	17	7000	303	0.13	243	144	312	83
GGU 24829	3.58	8.24	3.64	176	130	13	9150	257	0.09	220	150	270	62
GGU 24832	0.60	12.70	3.92	206	90	14	3600	118	0.10	92	99	165	114
GGU 24990*	1.06	8.22	3.80	184	132	8	4420	158	0.10	138	116	232	67
Average values	2.30	9.63	4.08	220	164	31	7139	226	0.13	274	148	335	86
Red layers													
J 15*	2.75	8.06	3.00	154	117	17	1.15%	255	0.12	370	298	410	51
GGU 24817	2.67	10.20	3.28	156	103	13	1.88%	147	0.05	440	182	535	64
GGU 24831	5.32	11.08	1.68	82	49	19	3.03%	193	0.07	980	233	860	26
GGU 24910*	4.03	12.25	2.34	130	n.d.	21	1.88%	76	0.02	580	270	645	80
Average values	3.69	10.40	2.58	131	90	18	1.74%	168	0.07	593	246	613	55

(continued)

GGU 24790	0.97	10.65	2.17	124	148	24	8150	113	0.07	220	127	428	68
GGU 24873*	1.43	10.70	3.42	186	133	15	1.09%	113	0.09	228	128	440	72
GGU 48001*	3.17	6.35	5.00	251	23	10	7450	403	0.08	157	348	333	63
GGU 48146	0.64	11.67	3.02	172	54	16	6470	86	0.10	150	140	505	116
Average values	1.55	9.84	3.40	167	90	16	8243	176	0.09	189	186	427	80
Kakortokite – White layers													
J 9	1.13	10.00	4.60	250	153	21	5540	290	0.08	167	135	285	96
J 11	1.47	9.14	4.40	228	157	14	6650	410	0.06	157	129	226	96
J 13	2.64	8.66	4.24	227	123	103	5100	365	0.10	260	151	420	84
J 16	1.98	9.68	3.16	165	123	23	7940	170	0.25	415	128	394	64
GGU 21828*	3.93	11.45	3.32	169	121	29	1.50%	183	0.18	535	168	440	81
GGU 24718	4.62	10.60	3.27	166	119	36	1.09%	222	0.07	320	163	355	77
GGU 24720*	1.33	9.24	5.77	484	671	32	6850	253	0.09	210	130	315	90
GGU 24722	4.17	9.14	4.87	251	143	124	8150	314	0.07	268	184	435	91
GGU 24724	2.47	10.74	4.48	238	138	38	5450	240	0.03	152	138	246	97
GGU 24726	1.51	10.80	4.88	259	126	20	8150	314	0.08	144	142	268	104
GGU 24728*	2.80	9.32	4.48	249	99	20	8650	270	0.15	485	160	550	79
GGU 24730*	2.43	9.46	3.80	199	167	22	1.25%	208	0.09	232	152	307	81
GGU 24775*	3.35	8.25	4.30	217	176	20	4450	282	0.12	194	154	248	81
GGU 24776*	3.28	7.32	3.92	198	184	24	1.00%	178	0.28	305	172	370	69
GGU 24810*	2.25	8.66	3.24	167	110	19	6450	107	0.11	228	198	300	74
GGU 24812*	1.33	11.40	4.26	217	226	23	2950	134	0.24	343	167	328	112
GGU 24813*	1.09	9.54	3.38	180	156	19	520	118	0.22	272	122	295	90
GGU 24814*	2.58	9.00	4.04	211	178	58	1.22%	178	0.23	890	216	785	77
GGU 24816	1.17	10.44	3.52	185	162	19	4550	130	0.09	140	117	230	111
GGU 24821	1.20	9.66	4.20	225	143	22	5250	228	0.11	162	127	260	91
GGU 24828	3.26	9.34	4.32	217	109	17	7000	303	0.13	243	144	312	83
GGU 24829	3.58	8.24	3.64	176	130	13	9150	257	0.09	220	150	270	62
GGU 24832	0.60	12.70	3.92	206	90	14	3600	118	0.10	92	99	165	114
GGU 24990*	1.06	8.22	3.80	184	132	8	4420	158	0.10	138	116	232	67
Average values	2.30	9.63	4.08	220	164	31	7139	226	0.13	274	148	335	86
Red layers													
J 15*	2.75	8.06	3.00	154	117	17	1.15%	255	0.12	370	298	410	51
GGU 24817	2.67	10.20	3.28	156	103	13	1.88%	147	0.05	440	182	535	64
GGU 24831	5.32	11.08	1.68	82	49	19	3.03%	193	0.07	980	233	860	26
GGU 24910*	4.03	12.25	2.34	130	n.d.	21	1.88%	76	0.02	580	270	645	80
Average values	3.69	10.40	2.58	131	90	18	1.74%	168	0.07	593	246	613	55

(continued)

Table 29 (cont.)

Rock Type and Specimen No	%CaO	%Na_2O	%K_2O	Rb	Li	Be	Zr	Ba	%TiO_2	Nb	Sr	La	Ga
Kakortokite – Black layers													
J 8*	2.57	9.00	1.74	74	164	13	7450	66	0.34	220	132	258	66
J 10	2.00	8.74	2.40	119	160	17	6830	122	0.24	235	115	243	62
J 12	2.69	9.46	2.30	111	134	21	1.06%	115	0.28	295	133	400	54
J 14	n.d.	5.40	1.24	55	83	14	6100	53	0.35	197	145	324	41
GGU 24717	2.22	11.72	2.53	131	150	29	1.03%	91	0.18	295	120	340	66
GGU 24719*	2.85	9.30	1.23	56	143	11	7050	74	0.31	228	113	314	33
GGU 24721	2.37	11.40	1.58	75	107	15	8650	64	0.20	224	112	295	51
GGU 24723	0.68	9.98	2.50	123	146	32	7450	130	0.21	213	124	280	59
GGU 24725*	3.30	9.74	1.30	58	112	12	1.18%	76	0.28	260	122	324	36
GGU 24727	2.41	9.34	2.40	116	152	20	1.37%	105	0.20	310	137	405	54
GGU 24729	2.48	10.00	2.46	116	98	12	8150	82	0.29	240	116	300	54
GGU 24731	1.94	9.58	2.56	123	129	12	7250	76	0.27	217	107	283	63
GGU 24809*	2.81	8.33	3.66	198	106	25	5000	166	0.13	207	228	348	81
GGU 24811*	3.01	8.68	2.62	121	95	22	1.06%	84	0.13	305	200	425	70
GGU 24815*	1.48	8.78	3.60	183	97	16	3600	118	0.18	150	125	283	86
GGU 24818*	1.94	9.18	1.94	108	108	8	1.18%	88	0.27	255	118	285	50
GGU 24820	2.23	9.80	1.88	85	140	13	8650	66	0.29	217	116	290	56
GGU 24822	2.39	9.00	1.96	88	121	13	9700	76	0.34	375	127	460	55
GGU 24830	1.67	9.23	3.10	154	98	18	4950	115	0.17	204	120	298	75
GGU 24908*	1.27	8.32	2.20	86	62	9	3500	51	0.33	203	143	232	58
Average values	2.23	9.25	2.26	109	120	17	8107	91	0.25	243	133	320	59
Weighted kakortokite averages on the basis White:red:black = 10:1:1.5	2.40	9.65	3.74	200	153	28	8076	205	0.14	296	154	355	80

n.d. = not determined
* = greater than 10% zeolites

Table 30. *Ratios of quantitative analyses presented in table 28*

Rock type and GGU Specimen Number	Na:K	K:Rb	Ba:K $\times 10^3$	Sr:Ca $\times 10^3$	Ba:Rb	Ti:Zr	Ti:Nb	Zr:Nb
Augite syenite								
24990.....	0.98	228	32.63	8.4	6.08	12.46	123.6	9.9
48134.....	0.94	205	37.42	8.0	9.41	47.79	246.8	5.2
Average values ..	0.96	217	35.03	8.2	7.64	26.00	189.5	7.3
Heterogeneous syenite								
24991.....	1.15	187	1.41	7.2	0.26	0.96	10.2	10.6
24992*.....	1.32	185	1.33	5.2	0.25	2.49	29.2	11.7
			1.38	6.2	0.26	1.71	19.1	11.2
Sodalite foyaite								
24971*+.....	1.60	176	1.78	6.7	0.32	0.11	3.5	30.6
24974*.....	2.66	177	1.12	4.3	0.20	0.25	6.4	25.3
24976*.....	1.47	174	0.91	6.1	0.16	0.40	7.5	21.3
40109*.....	1.10	169	1.06	5.7	0.18	0.60	5.8	9.7
48082 +.....	3.03	172	1.42	4.4	0.24	2.31	8.2	3.5
Average values ..	3.03	172	1.22	5.4	0.22	0.34	6.2	18.1
Average values* .	1.71	174						
Transition sodalite foyaite-naujaite								
24943.....	3.13	164	0.63	3.6	0.10	1.94	6.9	3.5
Naujaite								
21953.....	2.60	174	2.03	3.1	0.35	0.05	2.4	46.6
22581.....	2.84	170	1.60	8.6	0.27	1.64	12.0	7.3
40108.....	3.74	172	1.87	5.6	0.32	0.54	2.6	4.8
48004.....	3.54	171	1.00	3.0	0.17	1.67	9.0	5.4
48027.....	2.86	167	1.29	6.0	0.22	0.62	17.2	27.9
Average values ..	3.12	171	1.56	5.3	0.27	0.82	8.6	22.0
"Kakortokitic" rocks								
21851*.....	1.99	147	6.05	14.4	0.94	0.03	0.8	27.2
22526*.....	2.85	153	8.76	11.9	0.88	0.02	0.5	29.9
22541*.....	3.02	142	4.17	21.7	0.59	0.05	1.7	35.5
22550 +.....	2.71	147	5.08	12.1	0.75	0.03	1.0	31.6
22554*.....	4.78	149	5.26	10.8	0.78	0.03	1.1	35.1
24954*.....	8.85	202	5.94	36.8	1.20	0.11	1.7	14.8
Average values ..	2.71	147	5.08	18.0	0.84	0.03	1.0	29.6
Average values* .	4.30	159						

(continued)

Table 30 (cont.)

Rock type and GGU Specimen Number	Na:K	K:Rb	Ba:K $\times 10^3$	Sr:Ca $\times 10^3$	Ba:Rb	Ti:Zr	Ti:Nb	Zr:Nb
"Hybrids"								
21844 +	2.71	162	3.05	4.9	0.52	0.31	8.3	26.6
21853	2.09	171	5.38	10.0	0.83	0.86	2.9	33.8
21854 +	2.20	155	4.04	8.9	0.66	0.04	1.7	41.0
22635*	2.91	153	5.04	7.8	0.77	0.03	1.6	45.2
22636	2.08	171	8.33	7.3	1.42	0.35	10.5	29.6
24770	2.13	173	9.05	8.8	1.56	0.30	9.2	31.0
24799 +	2.05	164	4.07	13.2	0.67	0.90	3.4	38.0
48002* +	1.18	158	2.26	12.0	0.36	0.03	1.2	45.1
48065	2.02	164	4.21	5.6	0.69	0.22	6.4	28.9
Average values	2.18	166	3.65	8.7	0.83	0.14	5.1	35.5
Average values*	2.05	156						
"Aegirine dike"								
21856* +	6.29	171	22.24	24.7	3.81	0.14	4.3	30.9
Black lujavrite								
21861*	3.90	161	4.07	14.7	0.66	0.05	1.4	30.3
21897 +	2.45	137	1.58	51.3	0.22	0.61	4.1	6.8
24860 +	2.76	155	2.37	n.d.	0.37	0.07	2.2	31.3
24963* +	4.79	173	2.26	60.5	0.39	0.20	2.2	11.0
48145* +	2.83	142	2.11	44.8	0.30	0.26	5.1	19.8
Average values	2.61	146	2.48	42.8	0.39	0.13	2.7	20.9
Average values*	3.84	159						
Transition black-green lujavrite								
24959* +	2.84	143	3.47	50.0	0.50	0.09	2.4	23.9
24960* +	3.15	143	3.86	47.3	0.55	0.11	2.7	25.3
24961*	4.65	153	4.46	44.4	0.68	0.17	4.5	27.0
Average values	3.55	146	3.93	47.2	0.58	0.12	3.1	25.2
Green lujavrite								
24790 +	4.35	145	6.28	18.4	0.91	0.05	1.9	37.0
24873* +	2.80	153	3.98	12.5	0.61	0.05	2.4	47.8
48001* +	1.14	165	9.71	15.4	1.61	0.06	3.1	47.5
48146 +	3.46	146	3.43	31.1	0.50	0.09	4.0	43.1
Average values	3.91	146	5.85	19.4	0.91	0.06	2.7	43.6
Average values*	1.97	159						

(continued)

Table 30 (cont.)

Rock type and GGU Specimen Number	Na:K	K:Rb	Ba:K ×10³	Sr:Ca ×10³	Ba:Rb	Ti:Zr	Ti:Nb	Zr:Nb
Kakortokite								
White layers								
J 9 +	1.95	153	7.59	16.7	1.16	0.09	2.9	32.6
J 11 +	1.86	160	11.23	12.3	1.80	0.05	2.3	42.4
J 13 +	1.83	155	10.37	8.0	1.61	0.12	2.3	19.6
J 16 +	2.75	159	6.49	9.1	1.03	0.19	3.6	19.1
21828*	3.09	163	6.63	6.0	1.08	0.07	2.0	28.0
24718 +	2.91	163	8.19	4.9	1.34	0.04	1.3	34.1
24720* +	1.43	99	5.28	13.7	0.52	0.08	2.6	32.6
24722 +	1.68	161	7.77	6.2	1.35	0.05	1.6	30.4
24724 +	2.15	156	6.45	7.8	1.01	0.03	1.2	35.9
24726 +	1.99	156	7.75	13.1	1.21	0.06	3.3	56.6
24728* +	1.86	149	7.26	8.0	1.08	0.10	1.9	17.8
24730* +	2.23	158	6.60	8.7	1.05	0.04	2.3	53.9
24775* +	1.72	165	7.90	6.4	1.30	0.16	3.7	22.9
24776* +	1.68	164	5.48	7.4	0.90	0.17	5.5	32.8
24810* +	2.23	161	3.98	12.3	0.64	0.10	2.9	28.3
24812* +	2.40	163	3.79	17.6	0.62	0.49	4.2	8.6
24813* +	2.53	156	4.20	15.6	0.66	0.25	4.9	1.9
24814* +	2.00	159	5.31	11.7	0.84	0.11	1.6	13.7
24816 +	2.66	158	4.45	13.9	0.70	0.12	3.9	32.5
24821	2.06	155	6.53	14.8	1.01	0.13	4.1	32.4
24828	1.94	165	8.44	6.2	1.40	0.11	3.2	28.8
24829 +	2.03	172	8.51	5.9	1.46	0.06	2.5	41.6
24832	2.91	158	3.63	23.0	0.57	0.17	6.5	39.1
24909* +	1.94	171	5.02	15.3	0.86	0.14	4.3	32.0
Average values	2.21	159	6.62	10.3	1.05	0.11	2.8	26.1
Average values*	2.10	155						
Red layers								
J 3	2.06	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
J 6	2.43	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
J 15*	2.12	162	10.24	15.2	1.66	0.06	1.9	31.1
J 18	2.21	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
J 21	2.39	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
J 26	2.88	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
24761	4.59	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
24817 +	2.79	174	5.40	9.5	0.94	0.02	0.7	42.7
24831	5.93	170	13.88	6.1	2.35	0.01	0.4	30.9
24910* +	4.70	149	3.92	9.4	0.58	0.01	0.2	32.4
Average values	3.16	172	7.08	10.1	1.38	0.02	0.7	44.6
Average values*	3.41	156						

(continued)

Table 30 (cont.)

Rock type and GGU Specimen Number	Na:K	K:Rb	Ba:K ×10³	Sr:Ca ×10³	Ba:Rb	Ti:Zr	Ti:Nb	Zr:Nb
Black layers								
J 8*+.....	4.65	195	4.58	7.2	0.89	0.27	9.3	33.9
J 10 +.....	3.23	167	6.13	8.0	1.03	0.21	6.1	29.1
J 12 +.....	3.69	172	6.02	6.9	1.04	0.16	5.7	35.9
J 14*+.....	3.90	187	5.15	n.d.	0.96	0.34	10.7	31.0
24717 +.....	4.15	160	4.33	7.5	0.69	0.10	3.7	34.9
24719*+.....	6.78	182	7.25	5.5	1.32	0.26	8.2	30.9
24721 +.....	6.47	175	4.89	6.6	0.85	0.14	5.4	38.6
24723 +.....	3.57	169	6.25	25.3	1.06	0.17	5.9	35.0
24725*+.....	6.71	186	7.04	5.2	1.31	0.14	6.5	45.4
24727 +.....	3.49	172	5.28	8.0	0.91	0.09	3.9	44.2
24729 +.....	3.65	176	4.02	6.6	0.71	0.21	7.3	34.0
24731 +.....	3.36	172	3.58	7.7	0.62	0.22	7.5	33.4
24809*+.....	2.04	154	5.46	11.3	0.84	0.16	3.8	24.2
24811*+.....	2.98	179	3.87	9.3	0.69	0.07	2.6	34.8
24815*+.....	2.18	163	3.95	11.8	0.64	0.30	7.2	24.0
24818*+.....	4.24	149	5.47	8.5	0.81	0.14	6.4	46.3
24820 +.....	4.67	184	4.23	7.3	0.78	0.20	8.0	39.9
24822 +.....	4.11	185	4.66	7.4	0.86	0.21	5.4	25.9
24830.....	2.67	167	4.47	10.1	0.75	0.26	5.0	19.4
24908 +.....	3.38	213	2.79	15.7	0.59	0.57	9.8	17.2
Average values...	3.87	176	4.99	9.3	0.87	0.19	6.2	33.4
Average values*..	4.19	174						
Weighted kakortokite averages on the basis White:red:black = 10:1:1.5	2.49	162	6.46	10.2	1.06	0.11	2.81	27.3
*	2.46	157						

* Rocks containing more than 10 % zeolites
\+ Eudialyte more than 25 % altered
n.d. = not determined

Table 31. *Semi-quantitative analyses of kakortokite rocks and minerals*

Sample No.	Bi	Pb	Zn	Sb	Sn	Y	Be	Mo	Nb	Cu	Ni	La	Ag	Co	V
						Rocks									
						Parts per Million									
J 1 (W)	<100	110	350	<100	45	130	<10	<40	<100	<40	<40	<100	<10	<40	<100
J 2 (B)	<100	<100	650	<100	55	150	<10	<40	200	<40	<40	<100	<10	<40	<100
J 3 (R)	<100	200	200	<100	70	700	<10	<40	300	<40	<40	800	<10	<40	<100
J 4 (W) .	<100	<100	300	<100	50	130	<10	<40	<100	<40	<40	<100	<10	<40	<100
J 5 (B)	<100	140	650	<100	85	200	<10	<40	200	50	<40	190	<10	<40	<100
J 6 (R)	<100	450	300	<100	90	750	20	<40	250	<40	<40	850	<10	<40	<100
J 7 (W)	<100	<100	250	<100	40	80	<10	<40	<100	<40	<40	<100	<10	<40	<100
J 7(2) (W)	<100	200	250	<100	<40	160	<10	<40	<100	<40	<40	250	<10	<40	<100
J 8 (B)	<100	<100	700	<100	85	200	<10	<40	300	60	<40	180	<10	<40	<100
J 9 (W)	<100	110	250	<100	55	160	<10	<40	<100	<40	<40	190	<10	<40	<100
J 10 (B)	<100	170	750	<100	70	140	<10	<40	<100	<40	<40	<100	<10	<40	<100
J 11 (W)	<100	<100	190	<100	45	150	<10	<40	<100	<40	<40	150	<10	<40	<100
J 12 (B)	<100	110	550	<100	80	250	<10	<40	<100	50	<40	250	<10	<40	<100
J 13 (W)	<100	300	250	<100	40	190	20	<40	<100	<40	<40	350	<10	<40	<100
J 14 (B)	110	350	1000	<100	160	200	<10	90	500	<40	<40	250	<10	<40	<100
J 15 (R)	<100	110	200	<100	95	650	<10	<40	250	45	<40	750	<10	<40	<100
J 16 (W)	<100	<100	1200	<100	110	300	<10	<40	170	45	<40	400	<10	<40	<100
J 17 (B)	<100	130	850	<100	100	200	<40	<40	<100	<40	<40	160	<10	<40	<100
J 18 (R)	<100	<100	350	<100	75	350	<10	<40	250	45	<40	500	<10	<40	<100
J 19 (W)	<100	300	250	<100	95	450	<10	<40	200	<40	<40	750	<10	<40	<100
J 20 (B)	<100	120	1100	<100	160	250	<10	<40	450	<40	<40	300	<10	<40	<100
J 21 (R)	<100	<100	250	<100	65	300	<10	<40	<100	140	<40	350	<10	<40	<100
J 22 (W)	<100	<100	350	<100	45	180	<10	<40	140	<40	<40	300	<10	<40	<100
J 23 (B)	<100	300	650	<100	100	300	<10	<40	<100	50	<40	300	<10	<40	<100
J 24 (W)	<100	2500	650	<100	85	200	<10	<40	<100	60	<40	250	<40	<40	<100
J 25 (B)	<100	150	850	<100	85	170	<10	<40	<100	90	<40	<100	<10	<40	<100
J 26 (R)	<100	160	600	<100	100	650	<10	<40	200	<40	<40	950	<10	<40	<100
J 27 (W)	<100	400	1600	<100	90	170	<10	<40	<100	<40	<40	170	<10	<40	<100
J 28 (B)	<100	550	650	<100	120	200	<10	<40	<100	40	<40	190	<10	<40	<100
J 29 (W)	<100	<100	600	<100	50	200	<10	<40	<100	<40	<40	140	<10	<40	<100
J 30 (B)	<100	350	550	<100	95	500	<10	<40	<100	<40	<40	600	<10	<40	<100

(continued)

Table 31 (cont.)

Sample	No.	Bi	Pb	Zn	Sb	Sn	Y	Be	Mo	Nb	Cu	Ni	La	Ag	Co	V
J 31	(W)	<100	600	400	<100	90	350	<10	<40	140	<40	<40	400	<10	<40	<100
J 32	(W)	<100	600	400	<100	55	180	<10	<40	<100	<40	150	<10	<10	<40	<100
J 33	(B).....	<100	850	500	<100	100	130	<10	<40	<100	45	<40	130	<10	<40	<100
24717	(B).....	<100	200	600	<100	110	200	<10	<40	<100	60	<40	250	<10	<40	<100
18	(W)	<100	150	500	<100	70	300	<10	<40	200	<40	<40	350	<10	<40	<100
19	(B).....	<100	140	850	<100	100	190	<10	<40	100	70	<40	120	<10	<40	<100
20	(W)	<100	650	450	<100	55	180	<10	40	<100	45	<40	200	<10	<40	<100
21	(B).....	<100	250	550	<100	110	200	<10	<40	<100	<40	<40	130	<10	<40	<100
24722	(W)	<100	950	900	<100	70	350	20	<40	170	45	<40	550	<10	<40	<100
23	(B).....	<100	750	650	<100	110	250	<10	<40	<100	40	<40	170	<10	<40	<100
24	(W)	<100	<100	400	<100	50	130	12	<40	<100	45	<40	170	<10	<40	<100
25	(B).....	<100	450	700	<100	140	300	<10	<40	1200	55	<40	300	<10	<40	<100
26	(W)	<100	350	700	<100	120	250	<10	<40	<100	<40	<40	190	<10	<40	<100
24727	(B).....	<100	350	650	<100	110	350	<10	<40	<100	<40	<40	350	<10	<40	<100
28	(W)	<100	250	500	<100	70	400	<10	<40	150	40	<40	700	<10	<40	<100
29	(B).....	<100	160	450	<100	90	200	<10	<40	180	45	<40	200	<10	<40	<100
30	(W)	<100	450	500	<100	75	250	<10	<40	<100	45	<40	190	<10	<40	<100
31	(B).....	<100	200	550	<100	95	160	<10	<40	<100	40	<40	130	<10	<40	<100
24741	(B).....	<100	350	650	<100	120	350	<10	<40	250	<40	<40	350	<10	<40	<100
42	(W)	<100	250	400	<100	90	750	<10	<40	200	150	<40	650	<10	<40	<100
43	(B).....	<100	200	650	<100	95	300	<10	<40	<100	<40	<40	250	<10	<40	<100
44	(W)	<100	600	600	<100	70	200	<10	<40	<100	<40	<40	200	<10	<40	<100
45	(B).....	<100	400	600	<100	100	250	<10	<40	110	<40	<40	250	<10	<40	<100
24747	(W)	<100	450	400	<100	100	400	<10	<40	140	<40	<40	550	<10	<40	<100
47	(B).....	<100	250	650	<100	140	350	<10	<40	250	<40	<40	350	<10	<40	<100
48	(W)	<100	250	300	<100	55	140	<10	<40	<100	<40	<40	140	<10	<40	<100
49	(B).....	<100	300	500	<100	130	250	<10	<40	<100	<40	<40	250	<10	<40	<100
50	(W–R)..	<100	<100	350	<100	90	450	<10	<40	300	<40	<40	450	<10	<40	<100
24809	(B).....	<100	1100	600	<100	85	140	<10	<40	<100	60	<40	130	<10	<40	<100
10	(W)	<100	550	650	<100	65	180	<10	<40	<100	50	<40	150	<10	<40	<100
11	(B).....	<100	650	1600	<100	100	300	<10	<40	200	90	<40	450	<10	<40	<100
12	(W)	<100	250	300	<100	75	100	<10	<40	<100	45	<40	<100	<10	<40	<100
13	(W)	<100	350	850	<100	85	80	<10	<40	<100	120	<40	<100	<10	<40	<100
24814	(W)	<100	550	700	<100	70	550	<10	<40	300	140	<40	750	<10	<40	<100
15	(B).....	<100	300	850	<100	60	130	<10	<40	<100	95	<40	130	<10	<40	<100
16	(W)	<100	450	400	<100	75	140	<10	<40	<100	140	<40	190	<10	<40	<100

17	(R)	<100	400	400	<100	90	550	<10	<40	170	65	<40	500	<10	<40	<100
18	(B)	<100	2500	400	<100	80	250	<10	<40	110	60	<40	190	<10	<40	<100
24820	(B)	<100	350	850	<100	120	170	<10	<40	140	45	<40	130	<10	<40	<100
21	(W)	<100	200	550	<100	85	150	<10	<40	<100	<40	<40	140	<10	<40	<100
22	(B)	<100	1200	750	<100	130	250	<10	<40	400	45	<40	350	<10	<40	<100
23	(W)	<100	850	700	<100	75	110	<10	<40	<100	75	<40	<100	<10	<40	<100
24	(B)	<100	250	700	<100	140	120	<10	<40	200	65	<40	120	<10	<40	<100
24825	(W)	<100	400	450	<100	70	300	<10	<40	<100	50	<40	250	<10	<40	<100
26	(B)	<100	190	800	<100	100	160	<10	<40	190	55	<40	250	<10	<40	<100
27	(W)	<100	300	700	<100	80	250	<10	<40	<100	85	<40	350	<10	<40	<100
28	(W)	<100	1200	550	<100	75	150	<10	<40	130	100	<40	190	<10	<40	<100
29	(W–B)	<100	<100	350	<100	60	200	<10	<40	<100	85	<40	200	<10	<40	<100
24830	(B)	<100	850	950	<100	95	80	<10	<40	160	75	<40	160	<10	<40	<100
31	(R)	<100	300	300	<100	140	1800	<10	85	350	60	<40	1600	<10	<40	<100
32	(W)	<100	350	200	<100	45	50	<10	<40	<100	85	<40	<100	<10	<40	<100

Minerals

24830																
1		<100	170	1000	<100	190	50	<10	<40	<100	<40	<40	<100	<10	<40	<100
2		<100	300	250	<100	<40	<40	<10	<40	<100	<40	<40	<100	<10	<40	<100
3		<100	180	130	<100	<40	<40	<10	<40	<100	<40	<40	<100	<10	<40	<100
4		<100	160	550	<100	550	55	<10	<40	<100	<40	<40	<100	<10	<40	<100
24831																
1		<100	<100	650	<100	700	200	<10	<40	190	<40	<40	150	<10	<40	<100
2		<100	<100	<100	<100	<40	55	<10	<40	<100	<40	<40	<100	<10	<40	<100
3		<100	<100	<100	<100	<40	<40	<10	<40	<100	<40	<40	<100	<10	<40	<100
4		<100	<100	500	<100	200	400	<10	<40	500	<40	<40	350	<10	<40	<100
5		200	500	<100	<100	200	1500	<10	250	800	<40	60	3500	<10	40	<100
24832																
1		<100	<100	600	<100	1000	<40	<10	<40	<100	<40	<40	<100	<10	<40	300
2		<100	<100	<100	<100	<40	<40	<10	<40	<100	<40	<40	<100	<10	<40	<100
3		<100	<100	<100	<100	<40	<40	<10	<40	<100	<40	<40	<100	<10	<40	<100
4		<100	200	400	<100	600	<40	<10	<40	<100	<40	<40	<100	<10	<40	<100
5		140	140	<100	<100	150	1500	<10	130	650	<40	80	3500	<10	<40	<100
J 17																
1		<100	<100	1200	<100	140	80	<10	<40	250	<40	<40	<100	<10	<40	<100
2		<100	<100	200	<100	<40	55	<10	<40	<100	<40	<40	<100	<10	<40	<100
3		<100	<100	<100	<100	<40	<40	<10	<40	<100	<40	<100	<10	<10	<40	<100
4		<100	1300	800	<100	250	110	<10	<40	100	<40	<40	<100	<10	<40	<100

(continued)

Table 31 (cont.)

Sample No.	Bi	Pb	Zn	Sb	Sn	Y	Be	Mo	Nb	Cu	Ni	La	Ag	Co	V
J 18															
1	<100	<100	600	<100	120	130	<10	<40	350	<40	<40	130	<10	<40	<100
2	<100	<100	<100	<100	<40	<40	16	<40	<100	<40	<40	<100	<10	<40	<100
3	<100	<100	<100	<100	<40	<40	<10	<40	<100	<40	<40	<100	<10	<40	<100
4	<100	<100	550	<100	300	110	<10	<40	190	<40	<40	<100	<10	<40	<100
J 19															
1	<100	100	750	<100	150	120	<10	<40	150	<40	<40	160	<10	<40	<100
2	<100	140	<100	<100	<40	95	<10	<40	<100	<40	<40	130	<10	<40	<100
3	<100	<100	<100	<100	<40	<40	<10	<40	<100	<40	<40	<100	<10	<40	<100
4	<100	350	550	<100	350	200	<10	<40	300	<40	<40	250	<10	<40	250
5	140	350	<100	<100	180	<2000	<10	140	550	<40	65	3000	<10	<40	<100
J 25															
1	<100	<100	1100	<100	140	180	<10	<40	<100	<40	<40	<100	<10	<40	<100
2	<100	<100	100	<100	<40	<40	<10	<40	<100	<40	<40	<100	<10	<40	<100
3	<100	<100	<100	<100	<40	<40	<10	<40	<100	<40	<40	<100	<10	<40	<100
4	<100	<100	600	<100	250	100	<10	<40	250	<40	<40	<100	<10	<40	<100
J 26															
1	<100	140	900	<100	120	110	<10	<40	400	150	<40	<100	<10	<40	<100
2	<100	<100	110	<100	<40	60	<10	<40	<100	<40	<40	<100	<10	<40	<100
3	<100	<100	<100	<100	<40	<40	<10	<40	<100	<40	<40	<100	<10	<40	<100
4	<100	120	500	<100	250	350	<10	<40	450	<40	<40	300	<10	<40	<100
5	150	190	100	<100	200	1500	<10	180	170	<40	55	3000	<10	45	<100
J 27															
1	<100	400	600	<100	95	50	<10	<40	200	<40	<40	<100	<10	<40	<100
2	<100	110	250	<100	<40	<40	10	<40	<100	<40	<40	<100	<10	<40	<100
3	<100	<100	<100	<100	<40	<40	10	<40	<100	<40	<40	<100	<10	<40	<100
4	<100	300	400	<100	300	90	<10	<40	<100	<40	<40	<100	<10	<40	<100
5	140	<100	<100	<100	160	>2000	<10	150	850	<40	120	3000	<10	<40	<100

1 = Arfvedsonite 2 = Nepheline 3 = Feldspar 4 = Aegirine 5 = Eudialyte
W = White layers B = Black layers R = Red layers
Analyst V. SCHULLER

Table 32. *Specific gravities of agpaitic rocks*

Sodalite foyaite			
	GGU 24939	2.625	
	GGU 48025	2.668	
	GGU 48019	2.650	
	Average		2.648
Naujaite			
	GGU 48004	2.518	
	GGU 48020	2.625	
	GGU 48051	2.704	
	Average		2.620
Kakortokite			
Red layers			
	GGU 24761	2.793	
	GGU 24796	2.788	
	GGU 24736	2.793	
	Average		2.791
White layers			
	GGU 24709	2.717	
	GGU 24742	2.722	
	GGU 24730	2.782	
	Average		2.774
Black layers			
	GGU 24735	2.988	
	GGU 24719	3.130	
	GGU 24712	3.100	
	Average		3.073

Weighted on the basis of volume we have white:black:red = 10:1.5:1 giving an average sp.gr. = 2.810

Black lujavrite			
	GGU 24965	2.677	
	GGU 24957	2.673	
	GGU 48059	2.662	
	Average		2.671
Green lujavrite			
	GGU 24967	2.689	
	GGU 24844	2.779	
	GGU 48052	2.844	
	Average		2.771

(continued)

Table 32 (cont.)

Average specific gravity of agpaitic rocks

	sp.gr.	Approximate thickness (metres)	sp.gr. × thickness
Sodalite foyaite	2.648	60	158.9
Naujaite	2.620	800	2096.0
Kakortokite	2.810	400	1124.0
Black lujavrite	2.671	200	534.2
Green lujavrite	2.771	150	415.7
		1610	4328.8

$$\text{Average sp.gr. of agpaites } \frac{4328.8}{1610} = 2.689$$

Specific gravities of nepheline and sodalite

Nepheline		
	GGU 40108	2.667
Sodalite		
	GGU 40108	2.325
	GGU 48004	2.314

Methods used

Nepheline

The determination of the nephelines were carried out using the X-ray method described by SMITH and SAHAMA (1954). The specimens were mounted in a holder and scanned from $2\theta_{Cu}$ 26.5 to 30° using the scale of 1 inch per degree of 2θ using a 1° slit and filtered CuK_α radiation. In the analyses carried out by M. DANØ use was made of Si as the interval standard using the Si line at 28.465°. The author used KCl as the internal standard, the nepheline lines being corrected by measuring the 28.344 KCl line. Two records of each sample were taken and the result arithmetically averaged.

Alkali feldspars

Obliquity values of K-feldspars

The obliquity of the alkali feldspars were determined by measurement of the separation of the $1\bar{3}1$ and 131 peaks as described by GOLDSMITH and LAVES (1954). The powdered specimen was mounted in a holder and scanned from $2\theta_{Cu}$ 29° to 31° on the scale of 1 inch per $^1/_4$° of 2θ.

Determination of $NaAlSi_3O_8$ content of microcline

The method of BOWEN and TUTTLE (1950) and GOLDSMITH and LAVES (1961) were used for the determination of $NaAlSi_3O_8$ in microcline, microcline microperthites and crypto-perthites. The modified BOWEN and TUTTLE method (op. cit.) gave much higher values of $NaAlSi_3O_8$; it was concluded that the GOLDSMITH and LAVES method is the more reliable for the Ilímaussaq feldspars (see discussion in feldspar section).

Using the GOLDSMITH and LAVES method silicon was used as an internal standard together with filtered CoK_α, radiation. Taking an average obliquity value of 0.92 for the microclines an appropriate curve between the two curves of Fig. 2 (op. cit., p. 83) was taken as an obliquity correction. This means that a Δd value of -0.0075 corresponds to a microcline free of $NaAlSi_3O_8$. In four cases this latter value was exceeded, otherwise the remaining values can be related to the given curves. The obliquity correction used may, as suggested by the authors, be subjected to an error of ± 2 % $NaAlSi_3O_8$.

Bulk composition of homogenized alkali feldspars

The perthites, anti-perthites, microperthites and cryptoperthites were heated for several hours at 1050° C to effect homogenization. Thereafter using ORVILLE's (1960 and 1963) modified method of BOWEN and TUTTLE (1950) the following parameter was measured $\Delta 2\theta$ ($20\bar{1}$ feldspar $-$ 101 $KBrO_3$)CuK_α and related to the given curves for bulk composition.

Determination of the $NaAlSi_3O_8$ content of albite

ORVILLE's (1960 and 1963) modified method of BOWEN and TUTTLE (1950) was also used to determine the $NaAlSi_3O_8$ content of the albite.

Structural state of albite

The structural state of albite was determined by measuring the 2θ ($1\bar{3}1$) $- 2\theta$ (131) CuK_α parameter and relating it to the curves of SMITH and YODER (1956).

Olivine and pyroxene

Where possible the compositions of olivine were determined by both optical and X-ray means.

The optic axial angles of olivines and pyroxenes were measured by direct orthoscopic reading. Following the suggestion of MUNRO (1963) hemispheres of low refractive index were used and a correction made for refraction errors using Fedorow's diagram.

The X-ray diffraction patterns of olivine were taken on a small diameter camera and where possible both the d_{130} front reflection method of YODER and SAHAMA (1957) and the d_{174} back reflection method of JAMBOR and SMITH (1964) were utilized. In most cases the d_{130}-spacing lines were sharper and more distinct than the d_{174}-spacing lines and, in addition, a number of d_{174} values exceeded the measured d value = 1.0419 of synthetic fayalite. After having sent the X-ray film results of three specimens to JAMBOR and SMITH for re-interpretation of the d_{174} spacings they were in agreement that they gave anomalous results. These authors suggested that it was most likely that they are chemically anomalous, possibly in terms of Mn. As a fairly good check was arrived at between the compositions as determined by the d_{130} and optic axial angle methods these latter two values were used in preference to the values obtained from the d_{174} spacings.

Modal analyses

With one exception a Swift point counter was used in the determination of the modal analyses. A minimum of 2000 counts was carried out on each rock. In the case of the coarse-grained rocks a minimum of three rock slices were used in determining the volume percentage of minerals present. In the fine- and medium-grained rocks a maximum of two thin sections were used, more frequently, however, modal analyses were carried out on one thin section.

As naujaite GGU specimen 48004 was a bulk sample weighing approximately 80 kilograms, the modal analysis was completed in the field. Using a flexible tape point, counts were taken every 1 cm and in all six runs were made giving a total length of 5 m. The individual dark minerals were, however, determined using the Swift point counter as field identification of the intergrowths between these minerals was difficult to determine megascopically.

Attempts were made to distinguish the percentage alteration of individual minerals. This was relatively easy with eudialyte because of its widely developed euhedral habit so that its pseudomorphs were easily identifiable. However, in the case of the felsic minerals identification of their pseudomorphs was only possible with any certainty where minor zeolites and sodalite were present in the rock.

Preparation of specimens for analysis

The crushing equipment used was a core splitter, a 6×8 inch jaw crusher with hardened manganese flat steel jaws and a modified "Red Devil" paint mixer. The modification adopted for the latter apparatus was based on that used in the Geochemistry Department, Cape Town. The specimen is placed in a precision engineered steel cylinder containing ball bearings, the hardness of the container and bearings being 60 Rockwell. The cylindrical container was then transferred to the "Red Devil" paint mixer, clamped between two plates and subjected to the eccentric shaking motion of the mixer. All the specimens were subjected to a constant period of crushing.

The usual sample weight taken for crushing was of the order of 500 to 1000 gm. In the case of the very coarse-grained rocks like naujaite and heterogeneous syenite larger samples were taken, usually of the order of 2000 gm.

After thorough scrubbing and cleansing of the rock specimen it was dried at 110° C and then using a core splitter specimens were broken into pieces large enough to fit into the jaw crusher. The specimen was then reduced to −12 mesh by the jaw crusher, and split taking off a 250 to 300 gm sample. This latter representative sample was transferred to the steel cylinder and crushed in the "Red Devil" paint mixer for 14 minutes which reduced the specimen to −80 mesh. The latter −80 mesh sample was further split and a 50 gm ± sample taken and transferred to a smaller cylindrical steel vessel and subjected to an additional 14 minutes crushing, this reduced the sample to −120 mesh. The specimen was now ready for analysis.

Sodium and potassium analyses

The preparation of specimens for flame photometer analyses were carried out using the method suggested by the National Institute of Metallurgy, Johannesburg. 0.25 gm of −120 mesh of the sample was taken into solution by transferring to a platinum basin, adding 10 ml hydrofluoric acid and 2 ml perchloric acid and evaporated to dryness on a sandbath. The residue was then allowed to cool and an additional 5 ml of hydrofluoric acid added together with 0.5 ml nitric acid and 1 ml

Table 33. *Reliability of* Na_2O *and* K_2O *analyses. A comparison with international standards*

Specimen	International Standards Values		Measured Values	% Error	
	Median	Arithmetic		Median	Arithmetic
			Na_2O		
T-1[1]	4.40	4.39	4.46	1.36	1.59
SY-1[2]	3.36	3.24	3.40	1.19	4.94
G-1[3]		3.29	3.37		2.43
USBS-91[4]		8.48	8.48		0.00
STD-GH[5]		3.75	3.82		1.87
STD-GR[5]		3.80	3.90		2.63
			K_2O		
T-1[1]	1.23	1.23	1.28	4.07	4.07
SY-1[2]		2.65	2.64		0.38
G-1[3]		5.52	5.60		1.45
USBS-91[4]		3.25	3.22		0.92
STD-GH[5]		4.70	4.62		1.70
STD-GR[5]		4.50	4.48		.44

[1] Tanganyika Geological Survey Division, Standard geochemical sample. T-1 Supplement No. 1 (1961)
[2] Webber (1965)
[3] Ingamells and Suhr (1963)
[4] Certificate issued by United States Bureau of Standards
[5] Roubault and Govindaraju (1964).

perchloric acid. Once again the sample was evaporated to dryness. Using about 25 ml of water the residue was boiled to effect a solution which in turn was filtered into a standard flask. Adding 10 ml of 8 normal sulphuric acid and 2 ml of 50000 ppm Al (using aluminium nitrate) the solution was then diluted with water to 100 ml. To calibrate the results solutions were prepared containing 0 to 70 ppm in multiples of 10 of sodium and potassium oxides.

The samples were done in batches of seven and in each case a blank was carried throughout the procedure using the same quantities of reagents as were used for the samples. Frequent checks were made by repeated analysis and in all cases good confirmation was obtained.

The instrument used was a Zeiss PMQ II spectrophotometer with flame attachment.

Calcium analyses

Calcium was estimated using the technique of X-ray fluorescence spectrography. The following conditions were used:–

Philips vacuum spectrograph – PW 1540
Chromium target tube set at 20 kV, 10 mA.
480 collimator
LiF analysing crystal
Vacuum lath
Flow (proportional) counter set at 1500 V
Counter 32
Peak measured at 113.12° 2θ
Background measured at 110.00° 2θ
Count recorded for a period of 10 seconds.

For measurement purposes, the −200 mesh powdered sample was loaded into a sample holder containing a mylol window.

One sample containing (0.60) % CaO was used as a reference standard to compensate for any differences in vacuum changes or circuit characteristics for each batch of three samples.

For the establishment of a working curve, the following international standards were used:–

	% CaO	References
GA	2.50	ROUBAULT and GOVINDARAJU (1964)
GH	0.79	ROUBAULT and GOVINDARAJU (1964)
G-1	1.36	STEVENS (1960)
T-1	5.19	*

These four standards provided an excellent straight line working curve passing through the origin.

* Geological survey Division, Tanganyika (1963). Standard Msusule tonalite Supplement No. 1. Mineral Resources Division, Dodoma.

Spectrographic analyses

Mr. I. H. WRIGHT, who undertook the quantitative spectrographic analyses, kindly supplied the author with the following report on conditions used during this investigation.

Estimation of Li and Rb

The Na and K contents of these rocks were estimated flame-photometrically by the author using a Zeiss PMQ II spectrophotometer with flame attachment. This procedure was necessary not only because the flame photometric results for Na and K are considered the most reliable but because the spectrographic procedure developed during this investigation required a knowledge of the K concentration for the final evaluation of the Li, Rb and Cs contents. In other words, K was used as a variable internal standard for the estimation of Rb and Li.

Up to now, the more generally accepted spectrographic procedure for the estimation of the alkali elements Li, Na, K, Rb and Cs (AHRENS and TAYLOR 1960) consisted in packing a graphite electrode of suitable dimensions with the powdered silicate sample and arcing this sample as anode with a counter carbon cathode at a low direct current amperage (3–4 amps) for a period of time commonly referred to as "to the end of the alkali phase".

Recent investigation (personal communication to Mr. A. J. ERLANK, Geochemistry Department, University of Cape Town) has shown, however, that under these conditions, the alkali elements volatilise off at apparently different rates. It is an established fact that the temperature of the D.C. arc is to a large extent governed by the ionisation potential (I.P.) of the dominant constituent present in the arc. In the initial stages, therefore, the temperature of the arc would be determined by the more abundant K and Na present in all alkali syenite or alkali granite rocks.

The following table, Table 34, lists the ionisation potentials (I.P.) of the various alkali elements.

Table 34

Element	I.P. (ev.)
Li	5.40
Na	5.14
K	4.34
Rb	4.17
Cs	3.89

Under these conditions, Rb and Cs, with their lower ionisation potentials, volatilise off at an early stage. However, only when a considerable portion of the Na and K vapour has volatilised, would the temperature of the arc be raised sufficiently to allow the complete volatilisation of Li which has the highest ionisation potential.

To counteract this obviously disadvantageous mutual alkali effect, the answer might lie in the replacing of the dominant Na and K content with another element of such ionisation potential that during its period of volatilisation, the temperature of the D.C. arc would be raised to such a temperature that all the alkali elements, Li, Na, K, Rb and Cs would volatilise off at the same rate.

Such compounds as Li, Ca or Mg as their respective fluorides, are considered to fulfil this requirement very satisfactorily.

In order to discuss the method so developed, the final conditions used will first be given followed by discussion of the more important factors involved.

Final conditions developed:–

Hilger E 478 large quartz and glass prism spectrograph
Glass optics
Range 4500–8000 Å
Electrodes: C 2 undercut graphite anode ($^1/_8$" – I.D.; 2.5 mm deep)

shaped from National L 4306 12″ × 3/16″ graphite rods. Tapered 5 mm Morganite SG 305 H carbon cathode.

Sample preparation: Sample buffered with 20 % by weight of CaF_2 (B.D.H. "extra pure" grade) and packed by method of inversion packing (AHRENS and TAYLOR 1960) into C 2 anodes. These were sintered for one hour at 450° C before arcing.

Excitation: 6 amp d.c. short circuit
Analytical gap: 4 mm
Exposure: 2 seconds pre-burn; 1 minute 15 seconds burn (or until just before end of CaF_2 phase)
Plate colibration: Hilger 2:1 rotating step sector in order to record 2 7-step-sectored exposure for each burn.
Optics: 3-lens system with image of electrodes focussed on the collimator but masked off by a diaphram, 6 mm in aperture (see optics diagram Section 3e).
Slit width: 15 micron
Slit height: 11 mm.
Rack 12 mm between exposures
Emulsion: Ilford long range spectrum plates were used.

Line density readings: A Jarrell-Ash console model comparator-densitometer was used to take the transmission readings and an A.R.L. "Respectra" calculating board was used for the construction of the working curves and the reading off of the quantitative results. Background correction readings in all instances were found to be unnecessary.

Analysis lines used:–

Li.....	6707.844
Rb.....	7800.227
Cs.....	4555.355
K.....	7698.978 (variable internal standard).

Instead of the glass optics of the Hilger spectrograph, grating optics could be used to advantage provided that second order interference was filtered out by use for example of a Spex Industries red filter to filter out the second order Fe interference on Cs 8521.

Carbon cathodes have been found in general to give a hotter more concentrated arc as compared to that when using a graphite upper cathode. This is complementary to the theory behind using CaF_2 as a "buffer" (to use the term in the loosest possible sense) in producing a hotter arc more conducive to the uniform volatilisation of the alkali elements.

Research in the Geochemistry Department, University of Cape Town has shown that for the alkali elements in particular, and for many elements in general, maximum line intensity can be obtained if the sample is "buffered" with 15 to 20 % of CaF_2 by weight. Through its presence, the arc is considerably stabilised and the dominant Ca^{2+} ions with a relatively high ionisation potential, maintain the arc at a sufficiently high temperature to allow the volatilisation of the alkali elements to take place smoothly and uniformly.

Similar observations have been made for LiF and MgF_2. However, as far as the alkali elements are concerned, LiF cannot be used as a "buffer" and MgF_2 has the disadvantage that certain regions of the spectrum are concealed behind dominant molecular MgF and MgF_2 band spectra.

Estimation of Be, Zr, Ti, Nb, La, Sr, Ba and Ga

For the estimation of the above elements, the main problem facing the spectrographer is the development of one set of experimental conditions which will satisfy the requirements for the estimation of the volatile elements such as Ga, medium volatile elements such as Sr, Ba, La etc. and highly involatile elements such as Zr. Ideally, one should develop optimum conditions for the estimation of elements falling into each of these 3 major groups. However, an attempt has been made in this investigation to combine the analytical requirements of all 3 groups of elements into one compromise procedure.

Final condition developed:–

Jarrall-Ash 3.4 metre, Mark IV grating spectrograph with a 30,000 line/inch grating giving a dispersion of 2.5 angstroms in the first order.

Range 2950 to 4820 Å (30 inch camera with 3885 Å in centre of camera *i. e.* a grating angle of 13.27°).

Electrodes: C 2 undercut graphite anode ($^1/_8$″ I.D.; 2.5 mm deep) shaped from National L 4306 12″ × $^3/_{16}$″ graphite rod. Tapered 5 mm Morganite S.G. 305 H. carbon cathode.

Sample preparation: Sample buffered 4:1 with National S.P. 2 grade graphite powder containing 0.01 % Sc_2O_3 and P.02 % $(NH_4)_2$ Pd Cl_4 as internal standards and packed by method of inversion packing into C 2 anodes. These were sintered for 1 hour at 450° C before arcing.

Inert atmosphere conditions. The buffered samples were arced in a National Institute of Metallurgy designed "jet" surmounted by a cylindrical quartz sleeve and upper disc to exclude any air. Gas consisting of 70 % argon and 30 % oxygen was led into the base of the jet to provide a nitrogen free atmosphere during arcing.

Excitation: 8 amps d.c. short circuit.

Analytical gap: 5 mm.

Exposure: 2 seconds pre-burn followed by a $2^1/_2$ minute burn (which under these circumstances was to completion).

Plate colibrator: Hilger 2:1 rotating step-sector in order to record a full 7-step-sectored exposure for each burn.

Optics: Jarrell-Ash standard 2-lens, crossed cylindrical lens system.
Slit width: 15 micron
Slit height: 12 mm.
Rock 13 mm between exposures.

A four parts graphite to one part sample provided the buffered mixture.

After examination of all possible line interference, both first and second order, the following lines were chosen:–

Left hand plate A.

Be	3131.07	
Zr.....	3438.23	
Sc.....	3353.73	(Internal standard line)

For the estimation of the elements in this investigation, it was decided to use:–

(i) K as a variable internal standard for the estimation of Ga.
(ii) Pd or Sc as a fixed internal standard for the estimation of Be.
(iii) Sc as a fixed internal standard for the estimation of Zr, La, Nb, Sr, Ba and Ti.

Standards used in the construction of the working curves for this investigation included the international standards:–

G – 1, W – 1, Sy – 1 and T – 1.

The values used together with their references are given below:–

Table 35. *Concentrations in ppm unless otherwise stated*

	G – 1	W – 1	Sy – 1	T – 1
Li	24 (1)	12 (1)	126 (3)	8 (6)
	(2)	(2)	68 (5)	8 (5)
Rb	330 (1)	22 (1)	142 (4)	32 (4)
	(2)	(2)	118 (5)	28 (5)
Zr	210 (1)	100 (1)	3.048 (3)	120 (4)
	(2)	(2)		133 (5)
Be	3.3 (1)	0.8 (1) (2)	25 (3)	1.1 (4)
	(2)	1.0 (5)		1.8 (5)
Ba	1,220 (1)	130 (4)	273 (3)	490 (4)
	(2)	110 (5)		500 (5)
TiO_2	0.25 % (1)	1.07 % (1)	0.48 % (3)	0.56 % (4)
	(2)			0.57 % (5)
Nb	20 (1)	10 (1)	150 (3)	6 (6)
	(2)	(2)		11.5 (5)
Sr	250 (1)	175 (1)	262 (3)	280 (4)
	(2)	(2)		270 (5)
La	150 (1)	30 (1)	230 (3)	50 (6)
	(2)	(2)		52 (5)
Ga	18 (1)	16 (1)	20 (3)	21 (6)
	(2)	(2)		30 (5)
K	4.59 % (1)	0.524 % (1)	2.24 % (3)	1.02 % (6)
	(2)	(2)		
$\frac{\text{Ga (ppm)}}{\text{K \%}}$	3.92	30.50	8.93	20.60

1. STEVENS (1960).
2. FLEISCHER and STEVENS (1962).
3. WEBBER (1965).
4. INGAMELLS and SUHR (1963).
5. WRIGHT (1966).
6. Geological survey division, Tanganyika (1963) Standard geochemical sample T – 1: Msusule tonalite Supplement No. 1. Government printer, Dar es Salaam 6 pp. (available from Mineral Resources Division, Dodoma).

Due to the fact that 4 internationally known silicate standards were used for the drawing up of the element working curves, the accuracy of the results is considered to be high. The analyst is, however, not unaware of the dangers encountered in optical spectrographic work classified under such headings as matrix effect, sample inhomogeneity, particle size etc. Nevertheless the accuracy achieved is considered to be superior to that obtained had artificial standards been made up containing varying amounts of the particular elements.

No calculations of precision have at the time of writing been made but the precision in the case of the alkali elements is expected to be less than 10 % and generally not greater than 20 % relative standard deviation for the rest of the elements investigated.

Specific gravity

Hand specimens were selected which ranged in weight from 500 to 1500 gm. The weight of the specimen used was determined by the grain-size of the rock, in that for the coarser grained rocks heavier specimens were chosen than in the case of the finer grained rocks. In addition specimens were especially selected to ensure that they were free of cavities and fractures. Using the hand specimens the specific gravities were then calculated using a chemical scale balance.

A number of attempts were made to determine the specific gravity of powdered samples of the hand specimens using specific gravity bottles. No consistent values could be attained by this method despite vigorous control. The inconsistent results were attributed to wetting problems related to the −120 mesh grain-size.

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GRØNLANDS GEOLOGISKE UNDERSØGELSE
THE GEOLOGICAL SURVEY OF GREENLAND

THE ILÍMAUSSAQ INTRUSION

SPECIMEN LOCALITY OVERLAY

Geological map of the intrusion published as Plate 1 accompanying Bull. Grønlands Geol. Unders. Nr. 39 (also Meddr Grønland Bd. 172 Nr. 4)

Scale 1:20 000

1 0 1 2

- Geological boundaries
- Inferred geological boundaries
- Truncated geological boundaries
- Faults
- Rivers