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THE GEOCHEMISTRY OF THE NORTHERN PART OF THE ILÍMAUSSAQ INTRUSION, S. W. GREENLAND

BY

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WITH 31 FIGURES, 23 TABLES IN THE TEXT
AND 1 MAP

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CONTENTS

Abstract.

The Ilímaussaq intrusion (S. W. Greenland) was emplaced into granitic Precambrian basement rocks. The intrusion is of a highly alkaline nature and in terms of rocks types, its major-, minor- and trace elements, may be compared to the Khibina-Lovozero intrusion of the Kola Peninsula, U.S.S.R. The present paper describes the geochemistry of the northern part of the intrusion and the marginal rocks. New total rock analyses are given together with the detailed geochemistry of U, Th, Radioactivity, Nb, Rb, Li and Be.

The Ilímaussaq intrusion consists of an early augite syenite chilled against the country rocks. The augite syenite forms a more or less continuous ring around and above the intrusion. The main central mass of the intrusion consists of poorly layered, very coarse-grained, Na-rich "foyaite" containing relatively large amounts of sodalite and eudialyte. Differentiation of the "foyaite magma" gave rise to a volatile rich residual liquid from which lujavrites were formed. Differentiation of the lujavrites in the central area of the intrusion resulted in a lower banded sequence, the kakortokites, and an upper lujavrite liquid. When the confining pressure was exceeded, explosive brecciation occurred and lujavrite was intruded into the surrounding rocks.

At a high level in the intrusion a sheet-like body of soda granite was emplaced together with various quart-bearing syenites. The relative time of intrusion of the quartz-bearing syenite is uncertain through lack of field evidence. Emplacement of the early augite syenite may be related to ring faulting followed by cauldron subsidence. The later Na-rich rocks may have replaced the earlier layered augite syenite, or have been emplaced into a "magma chamber" developed by cauldron subsidence. The Na-Zr-Cl-rich rocks show evidence of cooling inwards with the development of a central volatile-rich pocket. The Ilímaussaq rocks probably represent a final highly fractionated stage of the more normal augite syenite magma common to the S. W. Greenland alkaline province.

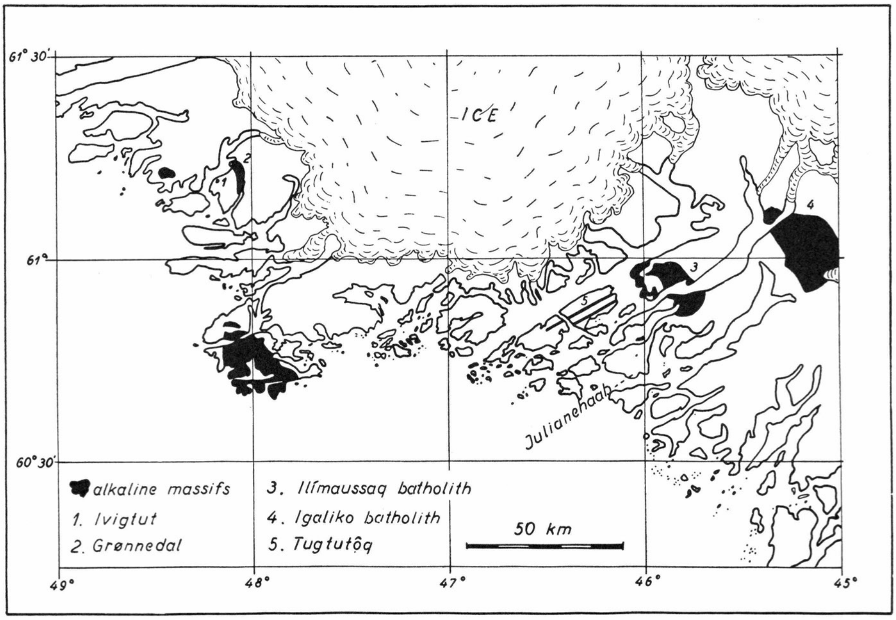

Fig. 1. Sketch map showing the position of the Ilímaussaq Intrusion in relation to south-west Greenland.

INTRODUCTION

The igneous rocks of the Ilímaussaq Intrusion have become classical through the careful and detailed work of N. V. Ussing (1912). In the present study the northern half of the intrusion has been mapped on a scale of 1:10,000. In the first season, 1957, the approximate distribution of the rocks was mapped and a detailed collection made. In the second field season, 1959, the northern part of the intrusion was mapped in conjunction with geochemical field studies at a base geochemical laboratory.

Ussing described the intrusion in terms of a sequence of magmatic events. Wegmann (1938) viewed the intrusion as having been formed through the metasomatic transformation of essexite, nordmarkite and volcanics into nepheline syenites. Recently Sørensen (1958) expressed the opinion that a combination of magmatic and metasomatic processes are in best agreement with the field observations.

This paper forms the first of a series of papers dealing with the petrochemistry of the northern part of the intrusion bounded on the

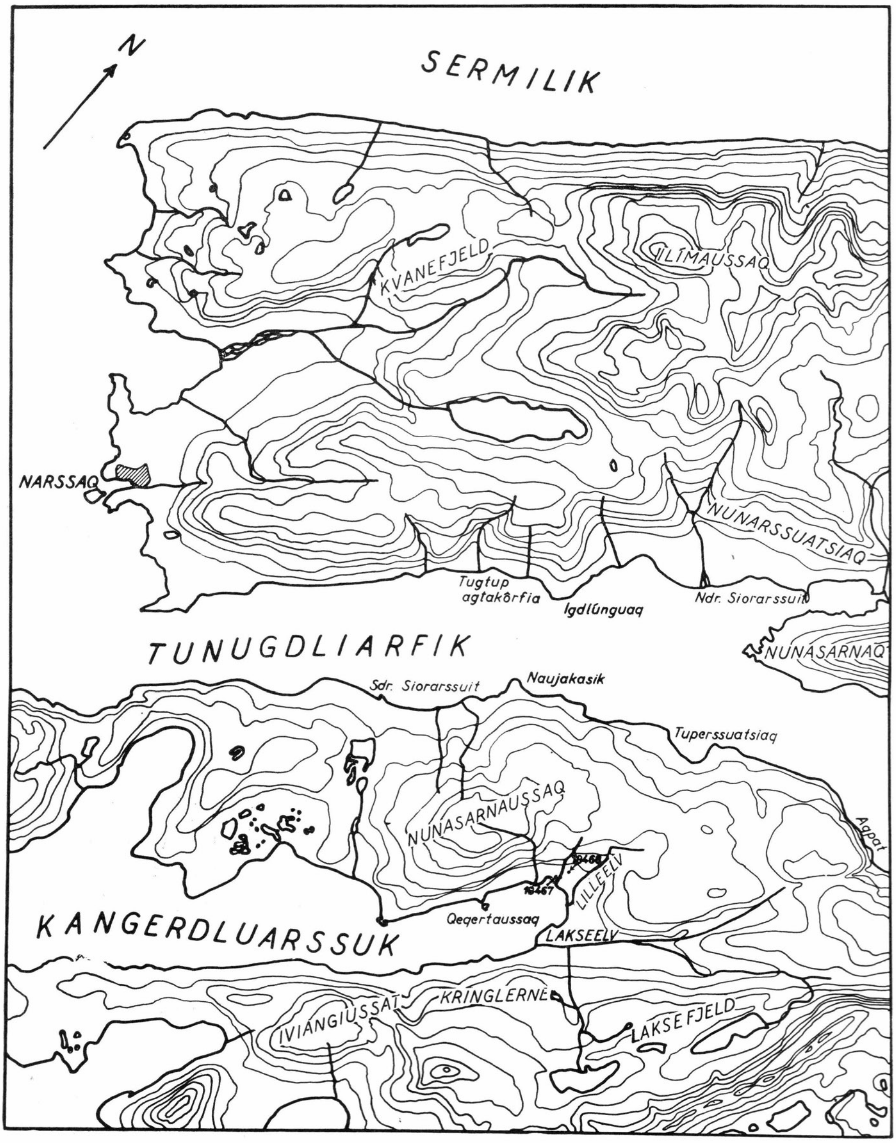

Fig. 2. Outline map of the Ilímaussaq area with local place names. Scale 1:143.000. (From SØRENSEN, M. o. G. Bd. 167, Nr. 1, fig. 1).

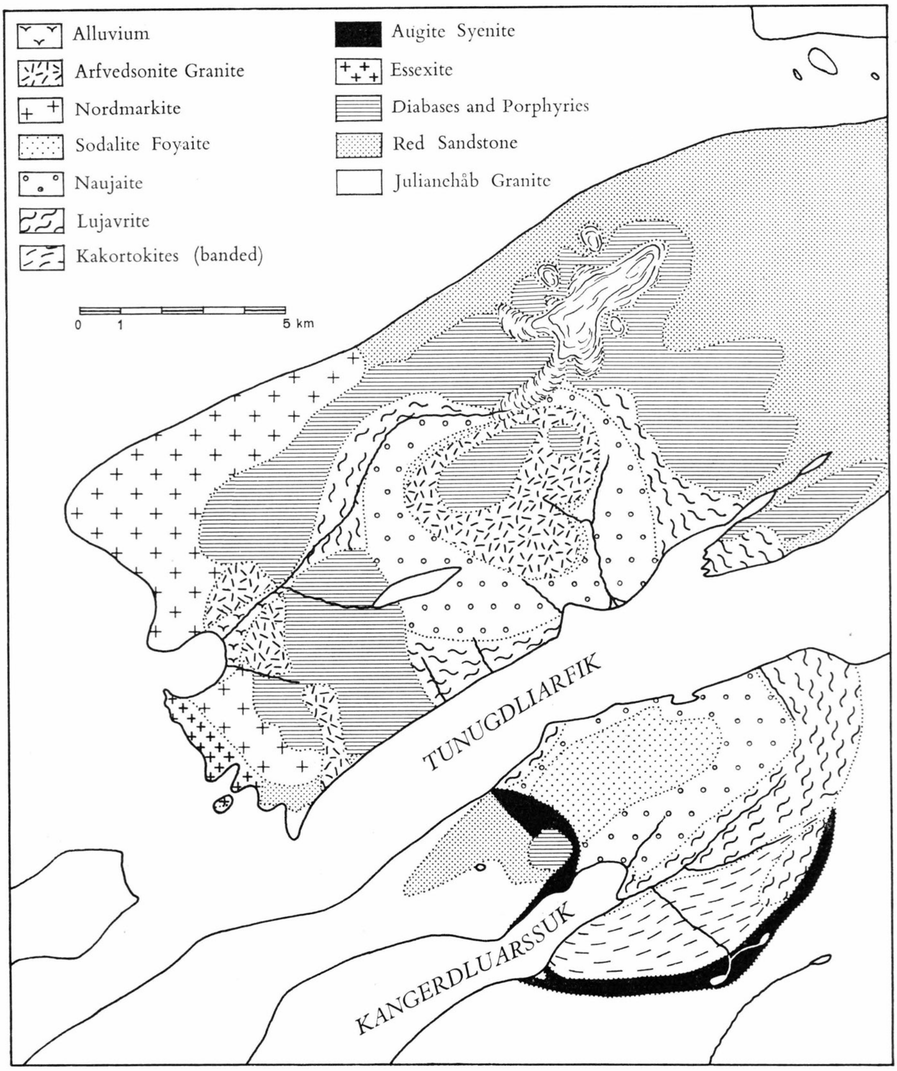

Fig. 3. Ussing's original geological map of the Ilímaussaq Intrusion.

south by Tunugdliarfik fjord. It is in this area that down-faulting has preserved the roof rocks and the total sequence of marginal syenite, agpaites and granite can be observed.

USSING (1912) described the intrusion under two main rock groups, the "unstratified" (augite syenite, essexite, nordmarkite) and the stratified, peralkaline, agpaitic nepheline syenites (foyaite, sodalite foyaite, naujaite, kakortokites, lujavrite).

Although the intrusion is free from vegetation the outcrops are commonly obscured by thick and extensive scree slopes. In some areas exceptionally good and continuous exposures from the naujaite to the overlying volcanics may be studied. It is, however, difficult to correlate the various exposures due to almost vertical rock faces or exceptionally steep slopes. The field relations will be described under the headings of the main rock types together with the result of preliminary optical examination of thin sections. A sketch map showing the position of the Ilímaussaq Intrusion in relation to southwest Greenland is given in Fig. 1. An outline map of the intrusion and local place names is given in Fig. 2., while Fig. 3. is USSING's original geological map of the Ilímaussaq region.

Acknowledgement.

The author would like to express his gratitude to: K. ELLITSGAARD-RASMUSSEN, mag. scient., Director of the Geological Survey of Greenland, for his ready assistance; the Staff of the Mineralogical Museum, Copenhagen, for laboratory facilities; Dr. H. SØRENSEN, for valuable discussions concerning the Ilímaussaq intrusion and particularly for the identification of rare minerals; J. BONDAM, mag. scient., field-leader during the 1957 and 1959 field seasons; IB SØRENSEN, engineer, for his willingness in carrying out spectrochemical analyses; Dr. C. JACOBSEN, of the Atomic Energy Commission's Research Establishment at Risø, for irradiation facilities and for the construction of a fluorimeter; Dr. B. UPTON, for discussions on alkaline rocks.

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THE OUTER CONTACT, AND ROCKS OF THE MARGINAL AUGITE SYENITE

The Ilímaussaq Intrusion, and related rocks, form a crude rectangle measuring 19 km. by 13 km. and trending N. W.—S. E. The intrusion is cut into two parts by Tunugdliarfik fjord trending roughly N. E.—S. W. In the south-eastern part the marginal syenite (Ussing's augite syenite) forms a more or less complete border around the intrusion, and has been described by Ussing (1912).

In the north-western half of the intrusion, recent mapping has shown that at one time the marginal syenite was probably continuous around the intrusion, as has also recently been mentioned by Bondam (1960). In this north-eastern sector it is presumed from the mapping that the marginal syenite is overlain by a continental series of volcanics and sandstones called the Gardar Formation (Wegmann, 1938). The intrusion was originally roofed by syenite identical in mineral and chemical composition to that of the marginal augite syenite. These rocks are overlain by, and chilled against, a few erosion relics of the Gardar Formation.

The type area for the marginal augite syenite is in the south-eastern half of the intrusion along the shores of Kangerdluarssuk fjord. The rocks are exceptionally well exposed along the shores of the fjord, and in river sections draining the Iviangiussat and Kringlerne areas. A fault passing through Kangerdluarssuk fjord has resulted in rocks of a lower level being exposed along the south-eastern shore. Although the author has not mapped the rocks in the south-eastern half of the intrusion, the marginal syenite has been carefully examined and specimens have been collected for a detailed study. The distribution of the marginal syenite in this area as mapped by Ussing (1912) is accurate and only minor differences were noted.

I) Type Area – Kangerdluarssuk Fjord.

a) South-east side of the fjord.

In this area the marginal syenite is distinctly chilled against the country rock of Julianehåb granite. The granite is leucocratic, phanerocrystalline, non-porphyritic, and rather poor in macrocrystalline quartz.

Fig. 4. Typical pegmatite of the augite syenite, developed just within the chilled border. Kangerdluarssuk fjord, south side.

The granite appears to be slightly altered up to a distance of seven metres from the contact with the marginal syenite. At the actual contact the granite is of a chalky altered nature with occasional clusters of brown mica and brown zircons.

The chilled syenite is fine-grained at the contact and shows local flow patterns. The chilled zone changes inwards into a rock of slightly coarser grain size with the development of small patches of pegmatite, as shown in Fig. 4. The development of these pegmatitic patches adjacent to a chill zone is a common feature of the area. Similar pegmatitic patches are developed in the chilled Narssaq gabbro (Ussing's essexite). The pegmatitic variety passes gradually into a medium- to fairly coarse-grained syenite, with well developed mafic and leucocratic bands, Fig. 5. Where the rock is not banded the mafic minerals are grouped together in

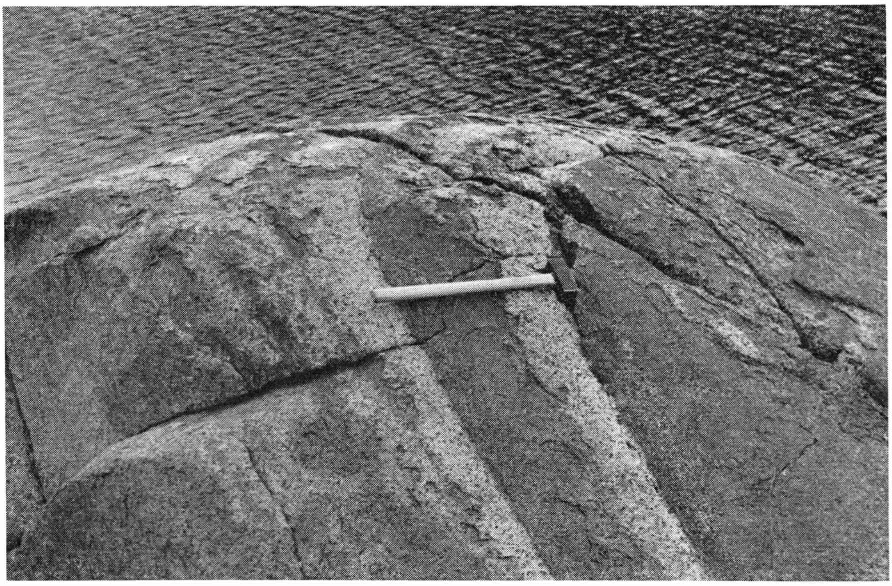

Fig. 5. Leucocratic and mafic bands of a rhythmic type developed in the augite syenite. Kangerdluarssuk Fjord, south side.

clusters measuring between 1—2 cm. in width. The undisturbed banding dips steeply inwards. The banding or layering is of a rhythmic type, several units being developed in a normal non-layered augite syenite. In the differentiated layers the mafics are concentrated at the bottom; passing upwards they become less abundant and the rock passes into a leucocratic syenite with local poor lamination of the feldspars. It appears to be significant that the traces of interprecipitate nepheline normally found in the augite syenite, are missing in the banded parts.

Inwards from the banded zone of the marginal augite syenite there is an area of unbanded rock adjacent to the kakortokites. The syenite shows no decrease in grain size at the contact with the kakortokites which in contrast are extremely pegmatitic and very variable in grain size, Fig. 6. Within the kakortokites the marginal syenite is present as large and small generally flat lying inclusions. The banding of the kakortokites passes around these inclusions. It is believed that these xenoliths of the marginal type syenite are not derived from the actual marginal areas, but from originally overlying augite syenite.

At the foot of Iviangiussat the augite syenite contains abundant inclusions of very pure white sandstone. Some of the fragments measure at least 100×50 m. while others range down to small angular inclusions a few cms. in diameter. The banding in the augite syenite is locally disturbed about the sandstone blocks which are generally surrounded by a

Fig. 6. Banded pegmatite developed between the inner facies of the augite syenite and the kakortokites. Kangerdluarssuk fjord, south side.

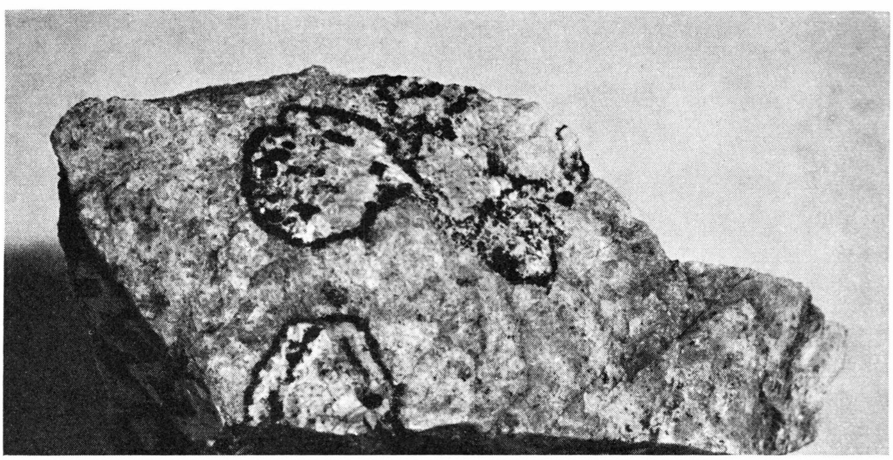

Fig. 7-A. Globular areas of soda granite developed in pure white sandstone. Iviangiussat, Kangerdluarssuk fjord. Half natural size.

zone of soda granite. Ussing regarded the granite as having been formed by reaction between the xenoliths of sandstone and the enclosing augite syenite magma. Although this view seems reasonable there remain certain features which are difficult to explain, the main one being that the sandstone does not normally grade out into soda granite and then into

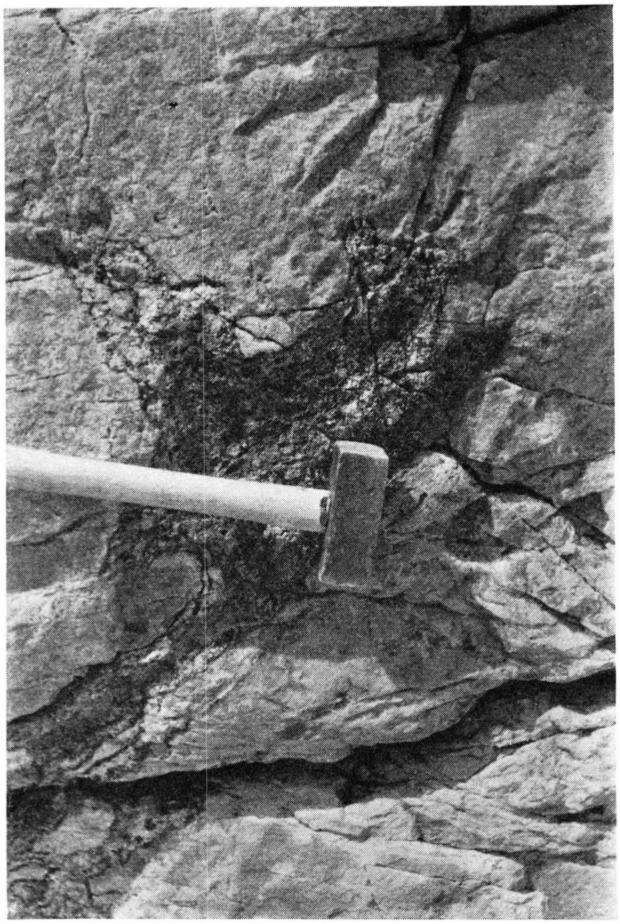

Fig. 7-B. Pockets of soda granite cutting and replacing sandstone. Iviangiussat, Kangerdluarssuk fjord, south side.

syenite. The contacts are quite sharp; the only visual effect on the sandstone is recrystallisation, and an increase in the grain size. The granite cuts both the syenite and the sandstone. Another remarkable feature is the development of almost spherical lobes of granite completely enclosed within the sandstone, Figs. 7A, 7B. The outer rim of mafic minerals which is a feature of the granite appears to be an example of a local basic front. Optical examination of some of the rocks collected has shown that the first "foreign minerals" to develop in the sandstone are aegirine, aegirine-augite and some sodic amphibole. Within the surrounding augite syenite nepheline is absent, whereas a little quartz both enclosed by and enclosing the major minerals is a common feature. Elsewhere in this southern area the marginal augite syenite does not show any tendency to become quartz bearing. In fact, passing inwards away from the margins the amount of nepheline increases. For these reasons it appears that the small amount of quartz seen in the augite syenite is a feature of contamination with the enclosed sandstone, as was described by Ussing (1912).

b) Border-zone between Kangerdluarssuk and Tunugdliarfik.

As described before, these exposures are regarded as representing a higher level in the intrusion. The country rock is still the Julianehåb granite. At the contact the granite is altered, and iron-stained for a distance of at least 20 m. The rock exposures in this area are rather narrow due to the steep scree-covered slopes of Nunasarnaussaq. This mountain is composed of granite overlain by sandstone associated with several flows of diabase.

At the contact zone of marginal augite syenite with the granite, the syenite is fine-grained and shows chill features against the granite. The chill zone is composed of rounded blocks of syenite, measuring at the maximum about two metres, enclosed within a matrix of mixed augite syenite and granite. It forms a good example of backveining by the partly remobilised granite. The granite became partly liquid at the contact and enclosed masses of the almost solid augite syenite which solidified before the remobilised granite. A typical exposure is given in Fig. 8. The biotite in the country rock contains radioactive inclusions surrounded by well-developed pleochroic haloes. In the zone of back-veining microscopic examination shows that the haloes become bleached, and after the breakdown of the biotite small zircons are released which occur locally in the augite syenite.

Inward from the zone of back-veining the syenite develops typical patches of pegmatite, and then with an increase in grain size passes into the typical augite syenite. There are indications that some of the syenite is banded, but the exposures are covered with scree. On the slopes of Nunasarnaussaq the syenite intrudes the sandstone, leading to the development of local quartz-bearing apophyses.

At the contact of augite syenite with naujaite neither rock shows any decrease in grain size. The actual contact is obscured by scree but the covered zone is only about 1 metre wide. Up to 30 metres from the naujaite contact the augite syenite shows the development of eudialyte and eucolite in pegmatites, along cracks, and in intercrystal areas. The zirconium silicates are associated with feldspar, nepheline, aegerine, and small amounts of sodalite. From the field relationships it would appear that these minerals have been introduced from the naujaite, but it is also possible that some of them represent extreme differentiates of the augite syenite.

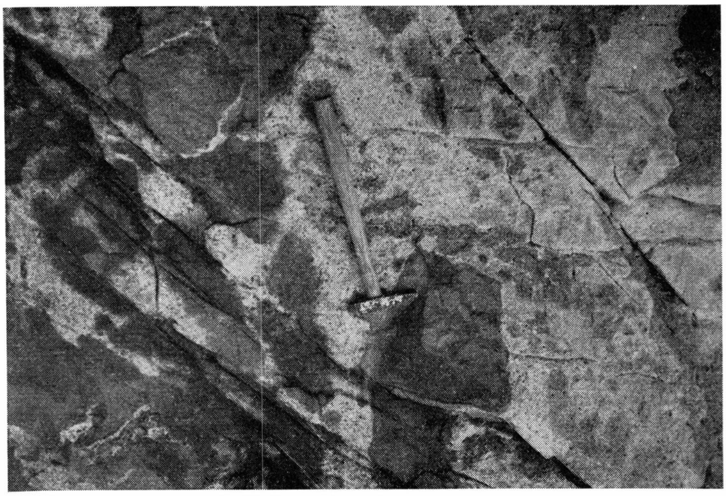

Fig. 8. Augite syenite (dark colour) back-veined by the remobilised Julianehåb granite. Kangerdluarssuk fjord, north side.

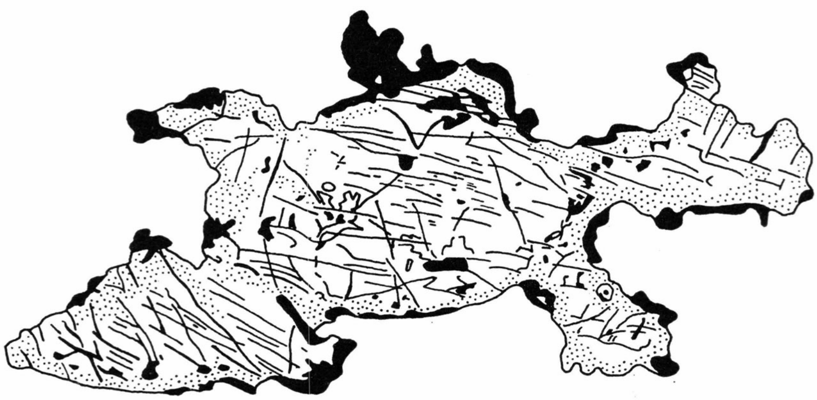

Fig. 9. Aegirine, rims surrounding titaniferous augite. Augite syenite, inner facies Kangerdluarssuk fjord.
Key: Stippled — Aegirine
Black — Iron ore.
Mag. ×28.

An examination of thin sections of the marginal augite syenite from this type area shows a distinct trend. In the contact zones the main minerals are cryptoperthite, purple-brown augite, fayalite, brown hornblende, biotite, iron ore with rims of lepidomelane, intercrystal nepheline and fluorite, and accessory apatite. Passing inwards the grain size increases and the conspicuous mafic spots develop. The feldspars show signs of exsolution and twinning, the hornblende develops in ophitic patches, the olivines often show rims of myrmekite-like symplectities of green amphibole, there is marginal replacement of the augite by aegirine (Fig. 9.), and an increase in amount of intercrystal nepheline. Still nearer the contact with the naujaite the previously ophitic brown hornblende becomes poikilitic in texture. The amount of aegirine-augite increases and the olivines become filled with orientated inclusions of iron ore. Occasional intercrystal wedges of analcite have also been observed.

The fluorite in these inner rocks appears to have crystallised over a wide temperature range. It occurs as inclusions within the primary precipitate minerals, in addition to crystallising from the interprecipitate liquid. In some rocks the fluorite forms an almost continuous reticulate pattern around the other minerals. In the eudialyte-eucolite-bearing varieties apatite is rare.

II) Marginal syenite in the north-western area.

The following part of this paper is based on mapping carried out on the scale of 1:10,000. The geological sketch map is given in Plate 1.

The syenite exposed on the northern slopes above Tunugdliarfik is difficult to examine in detail due to the very steep gradient and unstable scree. The author is indebted to Dr. B. G. J. Upton for help in mapping this slope. From sea-level to the 600 m. contour the syenite is associated with lujavrite. The luvjavrite has brecciated the syenite into angular fragments, and the mafic minerals and feldspar of the lujavrite form flow patterns around the inclusions of syenite. The syenite is chilled against the country rock volcanics, but the intrusion of lujavrite has led to much alteration. In addition to brecciating the marginal syenite the lujavrites also intrude the volcanics. The rocks from the 600 m. contour to Taseq are badly exposed. The chill zone tends to be more resistant to erosion and outcrops in a few places.

Three inclusions of an almost pure feldspar rock occur along the syenite-naujaite contact. They are very altered and are probably xenoliths derived from the volcanic series. The outcrop of the marginal augite syenite is displaced along the small stream draining the south-west end of Taseq. The rocks in this valley are heavily faulted with the development of much shearing and iron staining. Passing up the north-west slopes from Taseq to the 600 m. contour the exposures of marginal syenite are good. The chilled type is in contact with a porphyritic basalt which is locally metamorphosed along the contact, and intruded by the chilled syenite. The syenite does not appear to be banded. Heavy shearing and iron staining obscures the exposures down to the Gletscher Elv. Fluorite is developed along the shear planes and joint surfaces. Numerous large inclusions of a gabbro-like rock occur locally in the syenite. The inclusions can be divided into two types; an almost pure feldspar rock and a

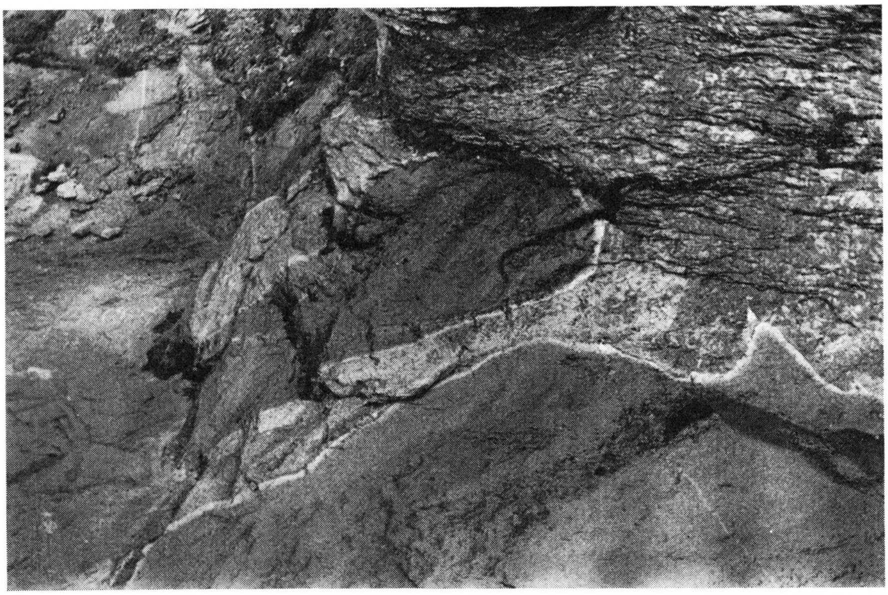

Fig. 10. Contact of marginal augite syenite and naujaite (top right). At the contact the white zone is formed by feldspathisation of the augite syenite. Narssaq Elv. 200 m.

laminated gabbro. Both types are very altered with the development of epidote. The contact of marginal syenite with the naujaite is generally obscured by scree. Several veins of lujavrite cut the syenite, and it is noticeable that in the actual contact zone green aegirine-analcite-lujavrite predominates.

At the intersection of the marginal syenite contact with Gletscher Elv a new variety of the augite syenite is encountered. In texture and appearance it is very similar to some of Ussing's nordmarkites exposed between Dyrnæs and Kusanga, but differs from them in that quartz is very rare. In the hand-specimen the type rock is characterised by clove-brown feldspars, generally measuring 1×0.5 cm., rimmed by a narrow zone of white feldspar. The feldspars are unlaminated, and the mafic minerals occur between them. The other constituent minerals are slightly exsolved cryptoperthite, clove-brown augite with narrow aegirine rims, relicts of fayalitic olivine, ore, green amphibole, biotite, apatite, and fluorite.

The syenite is chilled at the contact with the Gardar volcanics. This medium- to fine-grained chilled rock contains cryptoperthite, relict olivines, acicular masses of aegirine, nepheline, aenigmatite, sphene, abundant apatite, ore and fluorite.

The adjacent basaltic rocks have been locally altered at the contact, the most outstanding feature being the development of poikilitic aegirine

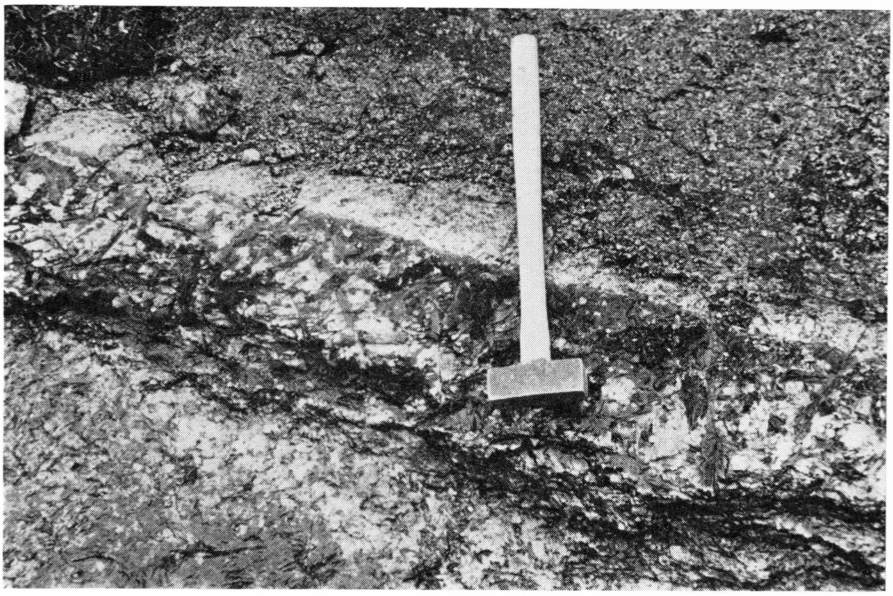

Fig. 11. Contact of the marginal syenite, upper right in photograph, with naujaite. Coarse aegirine pegmatite is developed at the contact. Narssaq Elv. 200 m.

accompanied by the development of albite. In the syenite one metre in from the contact, nepheline appears to be absent and the major minerals are cryptoperthite, fayalitic olivine, clove-brown augite, biotite, iron ore and apatite. Fluorite, which was concentrated along the actual contact and is visible in hand-specimens is still present in small amounts. The main textural feature is the development of laminated feldspars which dip inwards at 45°, but the lamination cannot be traced for any distance because of the poor exposure. The chilled facies passes into a rock of slightly coarser grain size containing the typical patches of pegmatite as seen in the type areas at Kangerdluarssuk. The zone of pegmatitic syenite, which is about 20 m broad, passes into typically banded augite syenite. The mafic bands dip inwards at an angle of 45°. The banded syenite then passes into the main mass of unbanded and unlaminated syenite. At the contact with the naujaite, which is well exposed, the syenite shows no decrease in grain size. In the valley section between the 100—200 m contours the syenite is intruded by numerous veins and sills of lujavrite.

The contact of the augite syenite with the naujaite is marked by a zone of white feldspathic rock some 10 cm in diameter. Chemical etching and staining of the rock surfaces in the field shows that this white zone and the white rims surrounding the clove-brown feldspars in the type rock consists of a potassium-rich feldspar. Figure 10 shows a typical view

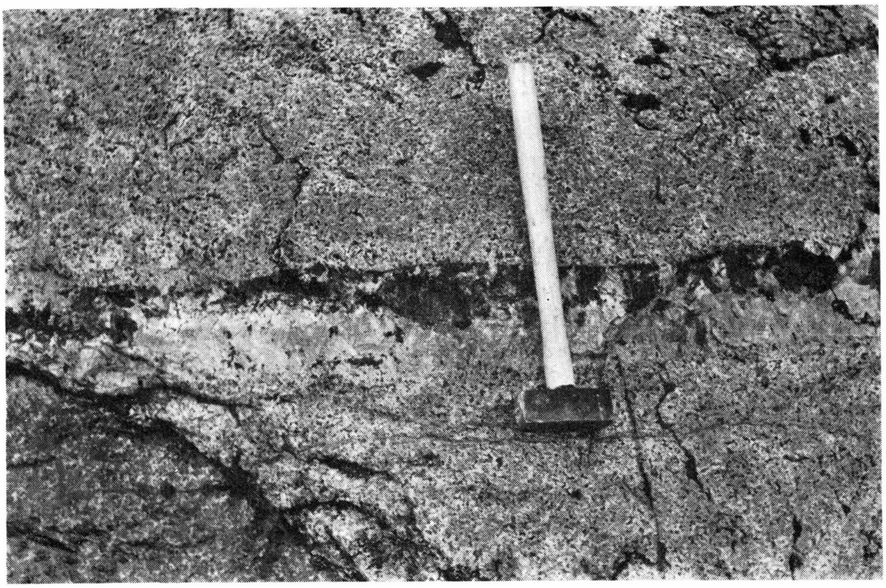

Fig. 12. Band of pegmatite in the augite syenite. Within the pegmatite the mafic and leucocratic minerals occur along opposite sides of the pegmatite. Narssaq Elv. 220 m.

of the contact along which a coarse grained pegmatite, composed of arfvedsonite, aegirine and feldspar, is developed in the naujaite (Fig. 11). The naujaite is fine-grained with the development of rather equidimensional minerals; it is noted that at this contact zone the eudialyte is absent and the normally developed poikilitic texture is lost. The field relations show that the naujaite crystallised later than the augite syenite and that pegmatite developed along the contact. Additional evidence for the later consolidation of the naujaite is the development of eudialyte along micro-cracks in the augite syenite together with aegirine. In the vicinity of the augite syenite-naujaite contact narrow dykes, from 10 to 20 cms in width, of "naujaite-like" rock cut the augite syenite. In addition, although the augite syenite is not banded or laminated, it contains certain curious non-linear but sharply defined bands of pegmatite. These bands are striking in that they show no features of chilling, and the feldspathic minerals grow in from one surface and the mafics from the other as seen in Fig. 12. The pegmatite bands dip steeply parallel to the contact of the intrusion. The only other feature parallel to these bands are very fine micro-cracks containing eudialyte and felted aegirine.

Although inclusions of country rock are rare at the augite syenite-naujaite contact, large inclusions of a feldspar- (oligioclase) rich rock occur at the outer contact with the volcanics. The feldspar-rich rock may be divided into two types.

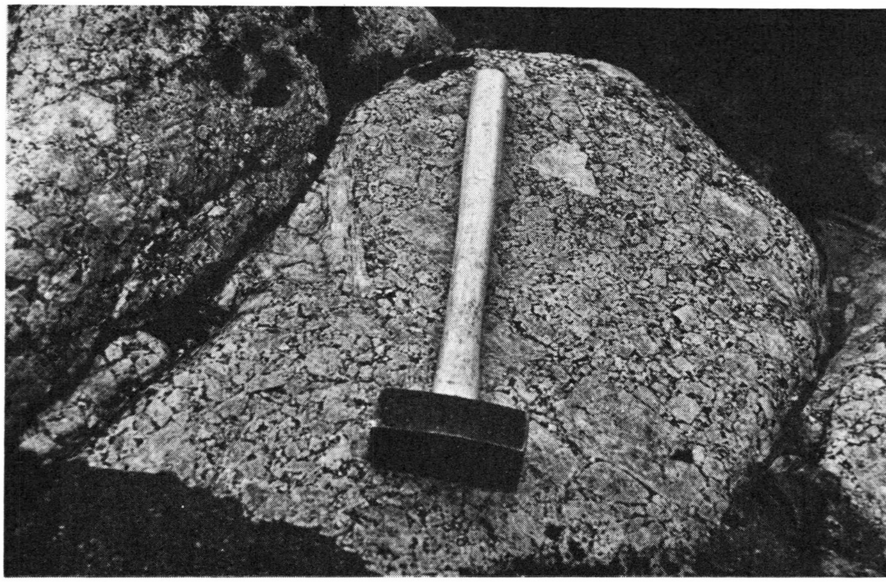

Fig. 13. Feldspar rock developed as zenoliths just within the marginal augite syenite. Narssaq Elv. 190 m.

a) One variety has narrow rather equidimensional feldspars measuring up to 15 by 5 cm in width, and packed closely together. In the occasional intercrystal spaces small patches of gabbro neasuring a few centimetres in diameter are present Fig. 13.

b) The above feldspar rock contains xenoliths of a second feldspar-rich rock. The feldspars in this case are clove coloured and the crystals smaller than those of the white variety. The feldspars tend to be somewhat lamellar in habit and intercrystal gabbro is absent.

At the head of the Narssaq Elv small inclusions of an augite syenite type rock occur in the lujavrite, but in this northern area the rocks are partly covered by glacial deposits and ice.

The eastern margin of the intrusion from the Narssaq Glacier to Tunugdliarfik consists of naujaite intruded by black and green lujavrite in contact with the Gardar volcanics. At the contact a non-poikilitic syenite is present containing nepheline and olivine. Hand specimens of this syenite bear a close resemblance to Ussing's pulaskite.

III) The Upper Contact and Rocks of the Augite Syenite.

Originally the upper part of the Ilímaussaq intrusion was composed of augite syenite. The chilled augite syenite and the typical coarse-grained type are now preserved beneath the erosion relic cap of volcanics in the north-western part of the intrusion, whereas to the north-east the augite syenite is absent beneath the volcanics.

At the contact with the volcanics the augite syenite is the fine-grained chilled variety which is typically non-porphyritic although occasional phenocrysts of a purple feldspar have been observed.

The constituent minerals are cryptoperthite, a trace of nepheline, augite with narrow aeigrine-augite rims, olivine, ophitic brown hornblende, iron ore, biotite, fluorite and apatite.

The chilled facies of the augite syenite can usually be traced around the contact with the volcanics, although in several areas the exposures are inaccessible or covered by scree. At the contact of the syenite with the volcanics, fragments of the volcanics occur as angular inclusions in the syenite. Local feldspathisation of the volcanics has been observed at a few localities. The chilled rock passes inwards into a feebly developed pegmatitic horizon. The grain size then increases and the typical coarse-grained syenite is present.

The constituent minerals of this syenite are, a rather altered perthite, augite, aegirine augite, olivine, iron ore, biotite, apatite and abundant fluorite. Fresh nepheline is absent although small intercrystal areas contain some secondary material probably after nepheline.

A few metres below the contact with the volcanics, large xenoliths of a feldspar rock and gabbro, derived from a sill-like body in the volcanics, are present. The augite syenite is chilled against the xenoliths giving rise to local flow patterns. In addition, the syenite veins these xenoliths, which fall into three groups:

1) A coarse-grained plagioclase rock containing narrow horizons of "spongy" olivine. Although multiple twinning is visible in the feldspar of the hand specimens, the feldspar in thin section is completely altered.

2) A layered gabbro consisting of mafic and leucocratic bands.

The lower part of the mafic zone is composed of olivine and augite. Passing upwards the amount of augite increases relative to the olivine. With an increase in feldspar the augite-rich rock gradually becomes an almost pure feldspar rock. Each unit is about 10 cm thick. Unfortunately the feldspar is rather altered, but the augite and some of the olivine is very fresh.

In an examination of this rock in thin section, there appear to be two feldspars. One is a plagioclase feldspar (oligoclase) of which a few clean areas still remain, whereas the other feldspar shows no twinning and is generally very altered. In addition to olivine, augite, and apatite, a little quartz is present in intercrystal areas. It is possible that this quartz was introduced from the granite which is only 1—2 m below.

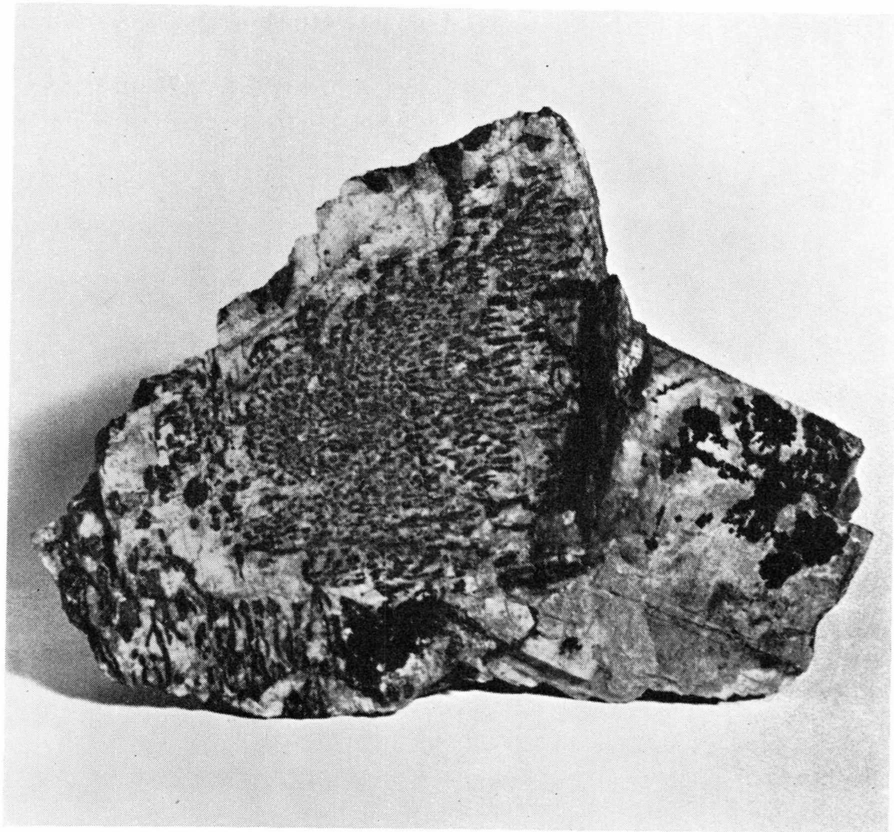

Fig. 14. Intergrowth of feldspar and olivine in pegmatite of the upper augite syenite at an altitude of 800 m to the north-east of the eastern end of Taseq. Natural size.

3) There is also a rather leucocratic gabbro with well laminated feldspars.

With the exception of the more resistant chilled augite syenite the main mass of the upper augite syenite is covered by steep scree. Three traverses have been made across the scree slopes to the north and north-east of Taseq. In this area the upper part of the syenite is generally fine-grained, and local olivine-rich bands a few millimetres thick are augite common. Below this horizon dactylographic textures are developed in a medium- to fine-grained rock in which pegmatitic patches are numerous. The feldspars in these patches are generally clove brown in colour with narrow, white feldspar rims, a feature common to the nordmarkitic variety of augite syenite. At an altitude of 800 m to the N.E. of the eastern end of Taseq a large pegmatite is present in fine-grained syenite. The pegmatitic feldspars are up to 80 cm long and are intergrown with olivine to form "myrmekite-like" structures. In thin section the olivine, is fresh and shows well developed cleavage and orientated inclusions of iron ore.

The olivines undoubtedly grew inwards or upwards from a surface of feldspar. The feldspar enclosing the olivine shows no twinning, but within it, sheaves and patches of albitic feldspar are present. Apatite is restricted to inclusions in the olivines and does not appear to occur in the feldspar. A typical example of the olivine myrmekite is given in Fig. 14.

The lower facies of the upper augite syenite are leucocratic and coarse-grained. As the upper contact with the granite is approached the syenite contains small widely dispersed crystals of quartz and local narrow quartz veins. In places along the augite syenite-granite contact and along fault zones and shear planes there is intense red colouration and abundant purple fluorite. The contact of the augite syenite with the granite is very sharp and the granite is chilled against the syenite. Below the granite sheet augite syenite is still present for at least 10 metres before a very altered and recrystallised rock is reached marking the upper facies af the agpaitic sequence.

PETROLOGY AND CHEMICAL COMPOSITION OF THE AUGITE SYENITES

From the studies of the augite syenites in the field a small, but carefully selected number of specimens were collected for thin section examination and for chemical analyses. As far as could be judged these specimens represent the main varieties of augite syenite and a brief description of the thin sections is given: —

I) Rocks representative of the outer fine-grained (chilled) facies of the augite syenite.

These chilled rocks are dark in colour, medium-grained, granular in texture and have no preferred orientation of the constituent minerals. At the actual contact with the country rock local flow patterns have been observed over a distance of a few centimetres. Acicular apatite and iron ore were the first minerals to crystallise followed by a fayalitic olivine, clove coloured titaniferous augite containing orientated inclusions of iron ore, brown hornblende and finally a cryptoperthitic slightly

Fig. 15. Perpendicular augite rock. Feather growth of augite. Natural size.

zoned alkali feldspar. Traces of nepheline and possibly a devitrified brown glass are present in some sections. Textural relations indicate that these were formed later than the feldspar. The mafic minerals are segregated in groups associated with rims of brown mica surrounding the iron ore. In the upper chilled augite syenite the pyroxene has a narrow rim of aegirine-augite and in rare instances hornblende. At a few localities feather-like crystals of pyroxene growing inwards and at right angles to the cooling surface indicate the existence of temporary inner walls of relatively solid augite syenite. This feature occurs mainly at the junction of the undifferentiated outer chilled augite syenite with the inner layered sequence (Fig. 15).

II) Rocks representative of the main part of the augite syenite.

These rocks are leucocratic and coarse-grained with the characteristic segregation of the mafic minerals into isolated clots. The outer part of the sequence is layered, whereas the inner part is not-layered although locally the segregation of the mafic and leucocratic minerals into bands has been observed.

The rocks are composed of the same mineral constituents as the chilled variety. The main difference is an increase in the amount of nepheline and brown hornblende, and an almost constant marginal replacement of the augite by aegirine. Fluorite becomes a prominent accessory mineral and has crystallised over a wide range. The central portions of the feldspars are still essentially cryptoperthites, but are marginally exsolved to give rise to a braid type of exsolution feature, associated with antiperthite and a little albite. The feldspars may be compared to the patch-pegmatite variety of the chilled augite syenite in which the feldspars are exsolved. It appears probable that the exsolution of the feldspars and general alteration of the mafic minerals is due to an increase in water and other volatile constituents of the final interprecipitate or pore liquid. In the layered sequence the upper facies of the leucocratic bands are more altered relative to the over-lying mafic bands.

III) Inner facies of the augite syenite adjacent to the naujaite.

Apart from being more leucocratic, hand specimens of the augite syenite within 0—10 m from the naujaite contact are not very different from the normal facies. However, in thin section the original cryptoperthite is replaced by an antiperthite and albite, and the olivine is almost totally replaced by iron ore, brown mica, aegirine, aegirine-augite, and green hornblende. In a few cases discrete crystals of aegirine and arfvedsonite are present. The aegirine occurs also as oriented inclusions within the feldspar. This is a feature of the agpaitic rocks. Nepheline is present in greater amounts and locally contains orientated inclusions. Apatite remains the main accessory mineral, but early eucolite, late analcite and sodalite are also present in some sections. At the immediate contact with the naujaite the augite syenite contains feldspar, eudialyte, catapleite, aegirine and sodalite along joint planes.

In conclusion, the following changes have been observed when passing in from the chilled augite syenite to the naujaite;

1) increase in the amount of exsolution of the alkali feldspar;
2) increase in the amount of nepheline;
3) increase in the amount of hornblende;
4) gradual increase in the amount of orientated inclusions in the olivines and in the breakdown of the olivines into aggregates of amphibole, mica and iron ore;
5) increase in the development of aegirine rims around the titaniferous augite and the brown mica rims around the iron ore;
6) crystallisation of primary eucolite, analcite and sodalite near the contact with the naujaite.

Chemical Analyses.

The chemical analyses, modal analyses and Niggli numbers representative of the Ilímaussaq augite syenite are given in Table 1. and can be compared with Ussing's original analyses and those of other augite syenites in Table 2.

The analyses will be described as follows: —

a) Chilled augite syenite,
  a) Marginal chill zone, Kangerdlugssuaq, nos. 33452, 33390, 33391.
  b) Upper chill zone, Nákâlâq, no. 33662.
b) Facies of the normal augite syenite, nos. 33320, 33321, 33323, 33326.
c) Inner facies of the augite syenite, nos. 33327, 33329.
d) Augite syenite from the Narssaq Elv, no. 33173.
e) Ussing's type augite syenite (Ussing, 1912).

a) Chilled augite syenite.

Allowing for sampling errors in the field, these four analyses are regarded as being representative of the chilled marginal augite syenite of Ilímaussaq. It is important to realise that the Ilímaussaq augite syenite

Table 1. Chemical Analyses of the Ilímaussaq Augite Syenites.

%	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
SiO_2	54.0	53.3	54.3	54.05	57.3	57.5	57.5	57.5	58.0	56.1	62.2	55.79
Al_2O_3	16.4	14.8	17.3	15.34	16.1	17.1	17.4	17.3	16.1	17.3	17.3	15.76
Fe_2O_3	5.4	2.8	3.0	2.53	2.7	1.8	n.d[1])	3.9	2.6	3.0	1.6	1.60
FeO	5.7	6.1	7.1	8.42	6.2	6.9	n.d	3.9	6.2	4.9	4.5	7.56
MnO	0.2	0.2	0.2	0.23	0.2	0.2	0.3	0.2	0.2	0.3	0.2	0.14
MgO	1.5	2.9	1.7	2.00	0.3	0.9	n.d	0.9	0.4	1.6	0.4	0.41
CaO	4.3	5.1	4.4	4.40	3.4	1.9	n.d	1.7	2.9	3.1	1.1	3.70
Na_2O	5.5	6.5	5.5	4.74	7.2	5.8	5.4	6.0	6.0	5.8	7.4	7.72
K_2O	4.5	4.5	5.1	4.81	5.0	5.1	5.0	5.3	5.0	4.9	5.3	4.34
TiO_2	2.0	2.2	0.5	1.90	1.1	1.1	1.1	1.0	1.6	1.9	0.6	1.81
P_2O_5	0.5	0.6	0.2	0.89	0.2	0.4	0.3	0.8	0.4	0.2	0.2	0.36
H_2O	0.4	0.6	0.6	0.81	0.6	0.5	n.d	0.5	0.5	0.5	0.3	0.52
Total	100.4	99.6	99.9	100.12	100.3	99.2	(87.0)	99.0	99.9	99.6	101.1	99.71
BaO incl. in CaO	0.4	0.5	0.4	0.17	0.2	0.5	n.d	n.d	0.8	0.5	0.2	0.2
ppm												
Ga^{+3}	30	30	10		30	30	30	30	30	10	30	30
Li^{+1}	10	10	50		15	30	20	n.d	60	20	40	25
Zr^{+4}	500	300	300		500	300	300	n.d	1500	80	200	300
Y^{+3}	tr	tr	tr		30	tr	tr	n.d	50	tr	tr	10
La^{+3}	50	20	0		30	30	30	n.d	50	tr	30	20
Sr^{+2}	300	300	300		250	400	250	n.d	400	200	250	300
Rb^{+1}	200	150	100		150	200	150	n.d	200	100	200	400

[1]) n.d. = not determined.

Table 1. (cont.)

MODE VOL.%	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
Feldspar ...	72.6	71.3	63.2		77.7	62.4	73.0	83.7	80.0	84.2	c.89	
Nepheline ..	0.3	2.7	2.5		tr.	tr.	3.5	5.7	5.0	tr.	0	
Augite	12.1	7.7	14.8		14.0	5.9	7.7	0	3.0	7.8		
Olivine	4.7	9.9	5.6		1.8	1.4	1.1	0	1.4	1.0		
Amphibole .	3.8	1.6	7.4		2.0	23.7	11.3	7.3	7.0	0.5	c.11	
Ore	5.6	5.3	5.1		3.8	2.5	1.8	2.2	1.1	5.7		
Fluorite....	tr.	tr.	tr.		tr.	2.9	tr.	0	tr.	0		
Apatite	0.9	1.5	1.4		0.6	1.2	1.6	1.1	2.5	0.8		
Sodalite....	0	0	0		0	0	0	tr.	tr.	0		
Eucolite ...	0	0	0		0	0	0	tr.	tr.	0	0	

Table 1. (cont.)

Niggli numbers

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
si.	160	151	154	162	184	194	–	200	197	225	178	197
al.	28.7	25.3	29.5	26.9	31.0	34.1	–	36.0	32.0	32.4	37.0	33.0
fm.	33.3	33.5	31.6	36.3	25.0	29.0	–	26.0	26.0	28.6	21.0	17.0
c.	13.7	15.2	14.1	14.0	12.0	6.9	–	6.0	11.0	11.1	4.0	14.0
alk.	24.4	26.1	24.8	22.8	32.0	30.0	–	32.0	31.0	29.0	38.0	36.0
ti.	4.5	4.8	1.0	4.3	2.7	2.8	–	0.3	4.1	4.6	1.7	4.9
p.	0.7	0.7	0.2	1.1	0.2	0.8	–	3.0	0.7	0.2	0.2	0.6
k.	0.4	0.3	0.4	0.4	0.3	0.4	–	0.4	0.4	0.4	0.3	0.3
mg.	0.2	0.4	0.2	0.3	0.1	0.2	–	0.2	0.1	0.3	0.1	0.7

1. (G.G.U. No. 33452) Chilled augite syenite Ilímaussaq. Anal. E. I. Hamilton
2. (G.G.U. No. 33390) – – – – – – –
3. (G.G.U. No. 33391) – – – – – – –
4. (G.G.U. No. 33662) – – – – – H. Wiik
5. (G.G.U. No. 33320) Inner facies of upper augite syenite – E. I. Hamilton
6. (G.G.U. No. 33321) Normal coarse-grained augite syenite – – –
7. (G.G.U. No. 33323) – – – – – – – –
8. (G.G.U. No. 33326) Inner facies of augite syenite near contact with naujaite – – –
9. (G.G.U. No. 33327) – – – – – – –
10. (G.G.U. No. 33329) Chilled facies of nordmarkitic augite syenite – – –
11. (G.G.U. No. 33173) Nordmarkitic augite syenite – – –
12. (Usssing 1912) Ussing's original analyses of the augite syenite (Ussing 1912, p. 190) – C. Winther(1912)

represents a group of rocks in which either nepheline or quartz are present as primary products of crystallisation. This has resulted in a large number of very similar, if not identical, rocks being given separate names, often based on a geographical location. It is not the purpose of this work to become involved in the existing complex nomenclature, so that in comparing the Ilímaussaq augite syenite to augite syenites from other areas, the original nomenclature will be retained. Chemical analyses of the chilled augite syenite are given in Table 1. nos. 1—4.

The chilled augite syenite is the most basic member of the augite syenite represented in the Ilímaussaq intrusion. In the neighbouring intrusion of Igaliko (Ussing, 1912) the marginal Korok variety of augite syenite may represent a more basic differentiate of the Ilímaussaq type. In the Korok type, alkali feldspar is associated with some oligoclase, a feature characteristic of the larvikites in the Oslo area. By analogy with the Oslo larvikites the augite syenite of Korok may be regarded as approaching the monzonitic group of rocks. According to Barth (1944) the ratio of alkali feldspar to oligoclase is almost 1:1. In the Ilímaussaq rocks plagioclase (oligoclase) has been observed in a few sections, but

Table 2. Chemical analyses of various syenites.

%	1.	2.	3.	4.	5.
SiO_2	54.20	53.71	54.41	57.44	64.76
Al_2O_3	15.73	15.37	16.50	17.30	17.13
Fe_2O_3	3.67	3.28	4.63	3.48	1.87
FeO	5.40	5.72	2.70	4.61	1.25
MnO	0.70	0.14	n.d	0.26	0.19
MgO	3.40	1.58	2.20	1.42	0.33
CaO	8.50	5.20	7.53	6.20	1.48
Na_2O	3.07	6.48	4.58	4.63	5.80
K_2O	4.42	4.11	3.74	2.96	5.70
TiO_2	0.40	3.40	2.60	1.42	0.70
P_2O_5	0.50	0.52	0.30	0.50	0.11
H_2O	0.50	0.78	1.25	0.08	0.41
TOTAL	100.49	100.29	100.44	100.51[1]	100.01[2]

plus 1 — F. 0.03, Cl. 0.03, FeS_2 0.15
2 — SrO 0.09, ZrO_2 0.11, Cl 0.02, S 0.06.

Niggli numbers

si.	146	166	162	179	269
al.	25	28	28.5	32	42
fm.	35	26.1	27	27.5	13
c.	24.5	17.3	24	20.5	6.5
alk.	15.5	28.6	20.5	20	38.5
ti.	0.8	8.0	5.8	3.3	2.2
p.	0.6	0.7	0.4	0.7	0.2
k.	0.5	0.3	0.4	0.3	0.4
mg.	0.4	0.3	0.4	0.2	02.

No. 1. Monzonite, Monzoni Berg, Fassatal, S. Tyrol.
Brøgger, W. C. 1895 Sk. Vidensk. Selsk. Kristiania, M. N. Kl. 19.
No. 2. Augite Syenite, Igaliko, S. W. Greenland.
Ussing, N. V., 1912, p. 243.
No. 3. Doréit, Madagascar, Lacroix, A.
Mineralogie de Madagascar 3, 1923. p. 328.
No. 4. Kjelsasite, S. Norway. Brøgger, W. C. Sk. Vidensk.
Selsk. Kristiania, M. N. Kl., 1933. p. 45.
No. 5. Nordmarkite, S. Norway, Brøgger, W. C., Z. Krist 16., 1890. p. 54.

altogether only three crystals have been seen. In all cases the plagioclase is present as a corroded relict within the alkali fedlspar and not as exsolution lamellae.

A typical chemical analysis of a monzonite is given in Table 2, No. 1. (Mode monzonite: Vol % Plagioclase zoned An_{68}—An_{35} 33 %. Orthoclase 32 %. Diopside 24 %. Lepidomelane 6 %. Ore quartz, apatite, zircon, sphene, 5 %. Tröger, 1935, vol %). The calcium content of the

Ilímaussaq rock appears to be just below the limit required for the primary precipitation of a plagioclase feldspar, and under the cooling conditions, plagioclase was not exsolved from the primary alkali feldspar. In some of the extrusive forms of monzonite the sodium content increase relative to the calcium but still maintains a plagioclase:alkali feldspar ratio of 1:1. An example of this type of rock is the Doréit (Table 2, No. 3) described by Lacroix (1923). From the published analyses it would appear that a difference of less than 1 % in the total lime content of a rock can give rise either to a rock containing only alkali feldspar or to one containing a mixture of plagioclase and alkali feldspar in the ratio 1:1. Another interesting variety is the so-called highwoodite (Johannsen 1938, Pirsson 1905) associated with pulaskite and containing labradorite (25 % by volume) poikilitically enclosing a soda feldspar (33 % by volume). It is essential to differentiate between the formation of primary plagioclase and plagioclase formed by later exsolution from a parent homogeneous feldspar.

In the author's opinion the chilled facies of the Ilímaussaq augite syenite represents the original magma modified by alkalies, volatiles and by a possible accumulation of minerals with a higher melting point such as iron ore, olivine and pyroxene. It would seem probable that if the original magma is represented by a rock type, it is the coarse variety of augite syenite found just within the chilled facies. The original magma could represent a stage in the differentiation of a parental alkali magma approximating to the sequence monzonite to larvikite.

By nature a residual magma is relatively small in volume and if strictly applied to the Ilímaussaq pluton would necessitate the presence at depth of a large volume of a more basic rock. The author regards the main Ilímaussaq augite-syenite as a magma exhibiting certain residual characters, such as the impoverishment in lime and magnesium, but not a magma complimentary to more basic rock types at depth.

An alkaline magma of the augite-suenite type could be pictured as being derived by a process of "sweating out" of the alkali elements, combined with the total or partial assimilation of pre-existing rocks. The more undersaturated rock types such as naujaite and lujavrite may represent differentiates of the original local magma, a concept that is partly supported by the distribution of trace elements.

b) Facies of the normal augite syenite.

The inner facies of the chill zone consists of typical augite-syenite. It is composed of a well layered sequence passing inwards to a poorly layered, coarser grained augite-syenite. The analysed specimens were taken from a nonlayered locality, but it is impossible to be completely certain that the samples represent true non-layered augite-syenite.

A typical feature of this group of syenites is the presence of nepheline and the absence of quartz. A comparison of these syenites with those from the Oslo area shows that they are similar in composition to the larvikites. Quartz-bearing types such as the kjelsasites, and nepheline-rich varieties such as the lardalites are absent. However, the larvikites, as described by BARTH (1944) cover a wide range in composition; of the seven analysed specimens six contain quartz (1—5 %) and one contains nepheline (4.5 %). Apart from the larvikites, the Ilímaussaq augite-syenites may be compared with the group of rocks covered by the general term pulaskite. Typical analyses of these related rocks are given in Table 2.

c) Inner facies of the augite syenite.

This coarse-grained variety is found adjacent to the later naujaite. The chemical analyses (Table 1, Nos. 8—9) of these rocks are not very different from the main mass of the augite syenite. The main difference is the increase in feldspar, nepheline and hornblende and the replacement of olivine and pyroxene by brown and green amphibole. Of the accessory minerals apatite is practically absent and typical agpaitic minerals such as sodalite, natrolite, eudialyte and eucolite are present in small amounts. Whereas the sodalite crystallised late, the other accessories crystallised at an early period. At the actual contact with the naujaite, coarse-grained naujaite is developed along joint planes in the augite syenite. Apart from this local feature, thin veins of aegirine derived from the naujaite cut the augite syenite for considerable distances from the contact zone. As in the case of this and other intrusions, the first foreign material to be introduced into a pre-existing rock indicates a movement of mafic material ahead of any alkali metasomatism.

d) Augite syenite from the Narssaq Elv.

This variety of augite syenite may be described as a leucocratic augite syenite and distinguished from other types by the presence of a clove-coloured feldspar surrounded by a white feldspar rim. Apart from these differences the textural sequence from the chilled to the typical rock type is identical to that seen in the type area to the south at Kangerdluarssuk fjord. In the Narssaq Elv area the country rock consists of Gardar volcanics. The chilled augite syenite is highly altered and contains large amounts of albite and aegirine. Passing inwards, the fine-grained chilled facies develops isolated pegmatitic patches, while the dark coloured chilled facies is rapidly replaced by a much lighter coloured rock in which the clove coloured feldspars predominate. Within this facies narrow mafic bands are developed and a few orientated lamellar feldspars are seen. In this section the main minerals are alkali feldspar, titanaugite, aegirine-augite, brown amphibole, relict olivine, iron ore, brown mica, fluorite and apatite. Although nepheline and quartz have not been identified in the thin sections, rare quartz grains have been seen in hand specimens of the main facies of the syenite, and altered nepheline in the chilled zone. This variety of augite syenite is similar in texture, chemical and mineral composition to an umptekite or nordmarkite. In the analysed specimens, (Table 1). No. 10 represents fresh chilled syenite, and No. 11 the normal type. From the field evidence the nordmarkitic variety of the augite syenite is an integral part of the marginal syenite, but it is also very similar to the nearby nordmarkites. Although sandstone fragments have not been found enclosed in the syenite it would appear possible that this facies of the marginal syenite has been formed by the reaction of augite syenite with sandstone derived from the Gardar formation. Typical analyses of nordmarkite (83 $^0/_0$ feldspar; 7 $^0/_0$ quartz; 3 $^0/_0$ aegirine-augite; 2 $^0/_0$ sphene; apatite, ore, zircon; Trøger, 1935, vol. $^0/_0$.), and umptekite (84 $^0/_0$ feldspar $\pm$ cancranite $\pm$ nepheline; 15 $^0/_0$ arfvedsonite aegirine; 1 $^0/_0$ sphene $\pm$ apatite ore; Trøger, 1935, vol. $^0/_0$.), are similar to this facies of the Ilímaussaq augite syenite.

Conclusions.

From the data obtained, the following tentative conclusions are drawn:—

1) As already stated by Ussing (1912) the augite syenites represent the oldest rocks of the intrusion. They are chilled against the country rock, but do not show any decrease in grain size towards the later agpatites.

2) The pegmatitic augite syenite probably represents the local accumulation of trapped water and volatiles; or it may represent the first stage in the build-up of water and volatiles moving outwards under a thermal diffusion gradient. Upton (1960) has suggested that an original fine-grained chilled zone to the Kûngnât intrusion has been destroyed by the outward thermal diffusion of water and alkalies. Alternatively the pegmatite may represent an alkali-rich liquid derived from the selectively rheomorphosed country rock (granite) that has locally permeated the chilled augite syenite.

3) In the main augite syenite, apart from the chilled zone, there is not very much variation in chemical and mineral composition. The main trend appears to be an increase in the amount of nepheline of the inner facies together with crystallisation under more aqueous conditions.

4) The potash-rich rims surrounding the central clove-coloured feldspar of the Narssaq Elv augite syenite may represent enrichment of potassium relative to sodium in the final intercrystal liquid. However, the possibility of contamination cannot be excluded. Of the chilled augite syenite only that represented by Anal. No. 4 (Table 1) contains $K_2O > Na_2O$.

5) In view of the complex nomenclature relating to this type of syenite and the small variation in mineralogical and chemical composition of the rocks studied, it is suggested that USSING's original term, augite syenite, be retained but prefixed by the appropriate mineral modifier, quartz or nepheline.

6) The marginal augite syenite as developed at the roof of the intrusion consists of a normal chilled facies, followed by a poorly developed medium- to coarse-grained augite syenite. It is noticeable that these upper rocks are somewhat altered even though they may appear fresh in the handspecimen. Beneath the latter rocks the development of a pegmatitic variety is common. This rock consists of a coarse pegmatite intermixed with a fine-grained "granophyric like" syenite with local banding. The altered nature of these rocks and the abundant pegmatite suggest crystallisation under rather aqueous or volatile (F, Cl) conditions. The accumulation of alkalies, water and volatiles derived from the differentiation of the augite syenite was probably concentrated at this high level of the intrusion beneath an "impervious" capping of volcanics.

PULASKITE

Before discussing the recent examination of the pulaskite of the Ilímaussaq intrusion it is pertinent to briefly compare and relate it to other similar rocks. The term "pulaskite rocks" is used here to cover pulaskites, larvikites and umptekites. Although all these rocks show certain definite similarities, there are differences. For example, the Ilímaussaq pulaskite (Ussing, 1912, p. 120—124) differs from the typical pulaskite in that arfvedsonite or aegirine-augite in many specimens of the rock is more abundant that the biotite, but it resemples typical pulaskite in all essentials.

The pulaskite, (Fourche Mountain, Arkansas) as originally described by Williams (1891) is considered as a trachytic form of a nepheline syenite. In texture it is intermediate between hypidiomorphic granular and porphyritic. The lineation of the feldspars gives a trachytic appearance to the rock. The main rock-forming minerals are orthoclase, biotite, augite with aegirine rims, amphibole (arfvedsonitic), a little nepheline, rare sodalite, accessory sphene, apatite, magnetite, fluorite, and analcite. Plagioclase feldspar, quartz and zircon are absent. Of the mafic minerals arfvedsonite predominates, and pyroxene and biotite are present in small quantities. As in the case of the marginal syenites of the Ilímaussaq intrusion, the mafic minerals are concentrated together in small groups.

The type pulaskite is finer grained than Brøgger's (1890) larvikite. While differing from it in the shape of its feldspars, it bears a close relation to pulaskite. The type pulaskite occurs as a wide dike-like mass associated with trachytic, and semi-porphyritic textures. It is worthwhile noting that it contains segregated veins of pegmatitic material. This is a typical feature of the outer facies of the Ilímaussaq marginal syenite.

The sequence of intrusion in the Fourche Mountains, Arkansas, began with the injection of a fine-grained pulaskite with a trachytic texture. Judged from the description (Williams, 1891), it is possible that this represents a chilled marginal syenite. The pulaskite was followed without any appreciable time interval by the intrusion of nepheline syenite. The nepheline syenite is regarded by Williams as being intermediate between Brøgger's lardalite and larvikite. These rocks were followed by the intrusion of fourchite dikes (Williams, 1891, p. 107—110). The final stage of the intrusion is marked by the formation of pegmatite and miarolitic dikes of syenitic material, before the earlier rocks had entirely cooled. It is interesting to note that among the miarolitic dikes, quartz syenites are present. In the nearly intrusion of Saline County the main rock type is nepheline syenite which has a border facies of pulaskite.

According to the presence or absence of nepheline, HATCH, WELLS and WELLS (1949) advocate that in view of the significance of nepheline, it is desirable to differentiate between the saturated and undersaturated varieties of pulaskite. If nepheline is present then the rock should be called a "nepheline pulaskite".

In the case of the Oslo rocks, BRØGGER (1890) described the larvikites as composed of soda orthoclase or soda microcline, a little titaniferous augite or aegirine-augite, lepidomelane, barkevikite, olivine with accessory titano-magnetite, large euhedral apatite crystals, zircon, and minor amounts of nepheline and sodalite. Quartz is absent, and plagioclase is restricted to a perthitic intergrowth with soda-orthoclase. BRØGGER recognised the unmixing of soda plagioclase and orthoclase, and called the rocks larvikites. BARTH (1944) described equal amounts of plagioclase and alkali feldspar indicating that the rock is nearer an alkali monzonite. The larvikites differ from the pulaskite in having a typical larvikitic texture, the presence of two feldspars and olivine, and in predominance of arfvedsonite. MUIR and SMITH (1956) and SMITH and MUIR (1958) describe the initial intrusion of larvikite in such a way that a little primary plagioclase was formed, followed by the crystallisation of the rhomb feldspars, and then the unmixing of the "anorthoclase" into monoclinic potash feldspar and oligiclase. In the latter paper, the term anorthoclase is replaced by soda-rich sanidine, and the larvikite feldspars are described as antiperthites composed of oligoclase and orthoclase or microcline.

RAMSAY (1894) gave the name umptekite (Umptek (Khibina), Kola Peninsula, Russia) to the marginal facies of the foyaite intrusion of Umptek. A similar rock associated with canadite has been described by QUENSEL (1914) from Almunge, Sweden. Umptekite is a rather leucocratic rock containing microperthite, arfvedsonitic amphibole, aegirine, rosenbuschite, biotite, aenigmatite, låvenite, sphene, apatite and magnetite. In addition, nepheline and sodalite may be present in accessory amounts. Ramsay considered that when amphibole is present the rock should not be called an augite syenite.

RAMSAY used the name umptekite because the rocks did not show the typical texture of BRØGGER's larvikite, or the trachytic structure of WILLIAM's pulaskite. Umptekite is further defined by the almost complete absence of nepheline and the predominance of an arfvedsonitic amphibole over pyroxene. Apart from these differences the rock is very closely related to the pulaskites.

Field description of the Ilímaussaq pulaskite (northern area).

The pulaskite of the Ilímaussaq Intrusion forms a "sheet-like" body which covers the uppermost part of the agpaitic syenite complex. On the northern side of Tungdliarfik fjord it is overlain by quartz syenites, granites, marginal augite syenite, and the volcanics.

Macroscopically the pulaskite is similar to the typical coarse-grained augite syenite of the border group. The rock may be described as coarse-grained, generally leucocratic, with the mafic minerals concentrated in clusters between the crystals of feldspar. The feldspars tend to be orientated, although the pulaskite is typically unlaminated. The major minerals are; feldspar consisting of intergrowths of microcline and albite, nepheline and pseudomorphs after nepheline in varying amounts, arfvedsonitic amphibole, aegirine, aegirine-augite, biotite, olivine, aenigmatite, Accessory fluorite, eudialyte, iron ore and apatite are found. (Because the rock has such a variable mineral composition it is difficult to describe the various types under one heading). The feldspars contain abundant acicular inclusions of aegirine and subordinate arfvedsonite that impart a greenish colour to the feldspars, a common feature of the agpaitic rocks. In spite of its variable composition the pulaskite is similar in appearance to the marginal syenite occurring at a fairly constant layer, above the sodalite foyaite in the contral part of the northern area.

In a few localities the pulaskite has pegmatitic patches which pass down into the sodalite foyaite. In the area to the north of Tunugdliarfik fjord the pulaskite is uniformly present and the thickness varies from a few meters up to about 40 m. Where the foyaite is absent the lower facies of the pulaskite are replaced by the later sodalite foyaite. While the replacement texture are often complex, in some areas (Traverse B) patches of pegmatite consisting of the minerals present in the sodalite foyaite, particularly large crystals of eudialyte, are present in the pulaskite.

To the south-east of Taseq the naujaite is overlain by a rock resembling the pulaskite and foyaite. It is rather leucocratic, coarse-grained and contains nepheline. The contact with the naujaite is sharp and irregular. From the field evidence it would appear that in this instance the later naujaite replaced the pulaskite. The pulaskite may be considered as a contaminated facies of the augite syenite produced by between the accumulation of alkalies and volatiles at the top of the later agpaites and the augite syenite.

No new analyses of the type Ilímaussaq pulaskite described by Ussing (1912) have been made, but the development of a pulaskite facies in the transition naujaite-granite is given in the chemical analyses based on Traverse A (see page 52). Chemical analyses of various pulaskite-type syenites are given in Table 3.

Table 3. Chemical analyses of various pulaskite-type syenites.

%	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
SiO_2	60.03	60.20	57.88	63.09	62.16	57.44	58.89	59.50	57.80	63.71
Al_2O_3	20.76	20.40	14.80	18.44	16.82	19.43	17.34	19.29	18.82	16.59
TiO_2	n.d.	0.14	1.23	0.45	0.38	1.97	0.24	0.70	1.15	0.86
ZrO_2	n.d.	tr.	n.d.	0.06	0.03	n.d.	0.15	n.d.	n.d.	n.d.
Fe_2O_3	4.01	1.74	5.86	2.90	1.53	1.69	2.77	1.65	1.60	2.92
FeO	0.75	1.88	3.71	1.36	1.54	2.70	2.13	2.32	3.50	0.66
MnO	tr.	tr.	0.15	tr.	0.09	0.25	0.16	0.03	0.14	0.90
MgO	0.80	1.04	none	0.16	1.43	1.16	1.56	1.10	1.48	0.90
CaO	2.62	2.00	2.71	1.00	3.79	2.66	4.22	2.53	3.72	3.11
BaO	n.d.	tr.	n.d.	n.d.	0.44	n.d.	0.48	n.d.	0.17	n.d.
SrO	n.d.	n.d.	n.d.	n.d.	tr.	n.d.	n.d.	n.d.	0.13	n.d.
Na_2O	5.96	6.30	9.12	7.25	5.09	6.48	6.72	5.97	6.48	8.26
K_2O	5.48	6.07	3.06	5.23	6.39	4.28	4.00	5.78	3.97	2.79
P_2O_5	0.07	0.15	none		0.35	0.60	0.32	0.34	0.55	n.d.
CO_2	n.d.	none	none		none	n.d.	n.d.	0.28	0.10	n.d.
H_2O^+		0.23	0.90	0.62	0.24		0.52	0.84	0.64	
H_2O^+ + H_2O^-	0.59					1.03				0.19
H_2O^-		0.10	0.23	0.21	0.05		0.15	0.12	0.02	
Pb	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.14	n.d.	n.d.	n.d.
F	n.d.	n.d.	n.d.	n.d.	0.04	n.d.	0.08	0.04	0.04	n.d.
Cl	n.d.	0.09	none	n.d.	0.02	tr.	0.19	tr.	0.05	n.d.
S	n.d.	none	n.d.	n.d.	n.d.	n.d.	0.17	n.d.	0.03	n.d.
$(YCe)_2O_3$	n.d.	n.d.	n.d.	n.d.	tr.	n.d.	n.d.	n.d.	n.d.	n.d.
SO_3	n.d.	0.13			n.d.	n.d.	0.14	0.02		
Total	101.07	100.47	99.65	100.77	100.39	99.69	100.37	100.51	100.39	100.89

Nos. 1 – 8 Pulaskite
9 Larvikite
10 Umptekite

1. J. F. Williams. Original analyses of pulaskite. Arkansas Geol. Survey (1891) Vol. II, pp. 70, 1891. Anal. R. N. Brackett, J. P. Smith.
2. H. S. Washington. Foyaite-Ijolite S. of Magnet Cove. Journ. Geol. Vol. IX, p. 609, 1901. Anal. H. S. Washington. (Same locality as No. 1).
3. N. V. Ussing. Geology of the Country around Julianehaab. Medd. Grønland, Bd. 38, p. 124, 1912. Anal. C. Winther.
4. H. S. Washington. Salem Neck. Journ. Geol. Vol. VI. p. 806, 1898. Anal. H. S. Washington.
5. B. C. King. Cnoc Nan Cuilean. Q. J. G. S. Vol. 98, p. 160, 1942. Anal. B. C. King.
6. F. O. Adams. Mount Johnson, Quebec. The Monteregian Hills. Journ. Geol. Vol. XI. p. 271, 1903. Anal. F. Adams.
7. O. J. Adamson. The Norra Karr District. Geol. Foren. i Stockholm. Forh. Vol. 66, pp. 113—255. 1944. Anal. N. Sahlbom.
8. E. S. W. Simpson. Okonjeje Igneous Complex. Trans. Geol. Soc. S. Afr., Vol. LVII, p. 173, 1954. Anal. E. S. W. Simpson.
9. W. C. Brøgger. Larvikite from Larvik, Norway. Eruptivgest Krist. VII. p. 59, 1933. Anal. O. Røhr.
10. W. Ramsay. Endomorphe Modificationen des Nephelinsyenites. Fennia. 11. No. 2. p. 205, 1894. Anal. W. Petersson.

Note added in proof.

After the author completed the mapping of the northern part of the intrusion during the summer of 1959, J. Ferguson mapped the southern part of the intrusion in 1961. From these results a difference was revealed between the author's mapping of the pulaskite and foyaite in the north and his in the south. Ferguson (1962) regards the foyaite as an inner differentiate of the augite syenite, and the pulaskite as a hybrid rock produced by the mixing of an augite syenite and alkaline granite magma. Such an explanation may explain why the pulaskite is always present as a well defined layer. From the distribution of these two rocks in the north it is impossible to separate them without having examined in detail the exposures in the southern area. The author has visited the southern part of the complex, but the time spent in the field was far too short for any detailed studies. In the northern part of the intrusion the foyaite, as defined by Ferguson, is only present at a few localities and most certainly can be regarded as an inner differentiate of the augite syenite, but any original rock sequence is almost obliterated by the pulaskite, quartz syenite and granite which are associated with the inner facies of the augite syenite. In the author's opinion the inner facies of the augite syenite consists of generally nepheline bearing syenite which has been partly replaced by the later agpaitic sequence, and still later granite.

Where used in this paper, the term "foyaite" refers to a rock present at the contact of the inner facies of the augite syenite with the sodalite foyaite. Most of the textures are of a replacement type, in which minerals characteristic of the agpaitic rocks are present in variable amounts.

At the time that this work was carried out, not many translations of Russian papers describing the very similar Khibina-Lovozero intrusion were available. Since this work was finished in early 1960 many Russian papers have become available, and in a later publicatlon the author will compare the geochemistry of Ilímaussaq with that of the Khibina-Lovozero intrusion. Particular reference will be paid to the mode of occurrence and genetic relation to other alkaline rocks, together with a discussion of the agpaitic index.

THE AGPAITIC ROCKS OF THE ILÍMAUSSAQ INTRUSION

The agpaitic rocks are composed of Ussing's stratified part of the complex. Ussing was of the opinion that a complete transition exists between the arfvedsonite granite-quartz syenite-pulaskite-foyaite-sodalite foyaite-naujaite-breccia zone-lujavrite and kakortokite. It has now been shown by the author that, in the northern area at least, the arfvedsonite granite is not part of a transition series, but is in fact a later intrusion. The hybrid quartz syenite appears also to be a separate intrusion earlier than the granite but later than the agpaitic rocks. In this paper the term transition series is used to describe rocks occurring between the augite syenite and agpaites.

The actual relation of the quartz syenite to the granite presents many difficulties. These are partly due to the very bad exposures in the upper part of the intrusion and the similarity between the quartz syenite and augite syenite in the field.

I) Sodalite Foyaite.

For the purpose of this paper. Ussing's (1912) description of the field relations of these rocks is adequate. However, some new observations and a general description of the rocks will be given.

The sodalite foyaite is easily recognised in the field by the tabular nature of the feldspars which show no preferred orientation. Sodalite is present as early dodecahedra enclosed within the feldspar, but is more typically idiomorphic towards the mafic minerals or eudialyte, or is interstitial. Both the feldspar and the nepheline contain micro-inclusions of aegirine or arfvedsonite. Nepheline is abundant mainly in interstitial spaces. An exception to this is seen at the top of the sodalite foyaite in Traverse B. Here the nepheline forms large prismatic crystals measuring up to 15—20 cm×3×3 cm whereas the mafic minerals and eudialyte occur in intercrystal spaces. Local rounded patches of pegmatite contain radiating clusters of aegirine associated with analcite and polylithionite. Eudialyte is present in varying amounts, whereas aegirine and arfvedsonite are present in large amounts. The accessory minerals include aenigmatite, rare astrophyllite (as growths on aegirine) polylithionite and fluorite.

Olivine is a common constituent of the sodalite foyaite at its contact with foyaite on Traverse E. In the field the olivine is recognised as small circular areas of a black mineral surrounded by a narrow zone of iron-staining. In thin section the fayalite is almost totally converted to opaque iron oxides. The amount of olivine decreases from the top of the sodalite foyaite downwards. At some horizons olivine is concentrated along planes parallel to the general parting of the rocks. The distribution of the olivine suggests that the later intrusion of the sodalite foyaite has "corroded" the earlier foyaite releasing olivines which locally sank into the crystallising sodalite foyaite. The rare eudialyte found in the foyaite was probably introduced from the sodalite foyaite.

The sodalite foyaite is commonly cut by very narrow tinguaite dikes. The intrusion of lujavrite is very rare although aegirine analcite dikes up to a metre wide are not uncommon. In terms of the structure of the intrusion and relative age relations between the Ilímaussaq rocks, the intrusion of lujavrite is most important. The contact of the sodalite foyaite with naujaite is sharp, indicating a time interval between intrusion.

II) Naujaite.

The naujaite comprises the main exposed mass of the agpaitic rocks. On account of the coarse-grained nature of the rock, its poikilitic texture and the great variation in the mineral assemblage from place to place, it is difficult to describe the naujaite in simple terms. The typical naujaite texture is given in Fig. 16. Ussing's descriptions are adequate in a general sense and it is obvious that a more detailed description of this rock will only be possible after more field work, combined with the detailed study of the optical properties of the constituent minerals. The naujaite is far too coarse for any modal or chemical analyses to be representative. As an example of the variation due to grain size in thin section, the modal analyses (vol %) is given for three large sections (8×5 cm) taken from a sodalite-rich variety:

Slide	*Feldspar*	*Sodalite*	*Arfvedsonite*	*Aegirine*	*Eudialyte*
1	7.5	44.5	48.0	0	0
2	0.0	68.0	0	1.6	30.4
3	45.1	52.5	0	0.6	1.8

Of the major minerals sodalite (var. hackmanite) generally comprises about 50 % by volume, particularly in the lower facies of the naujaite.

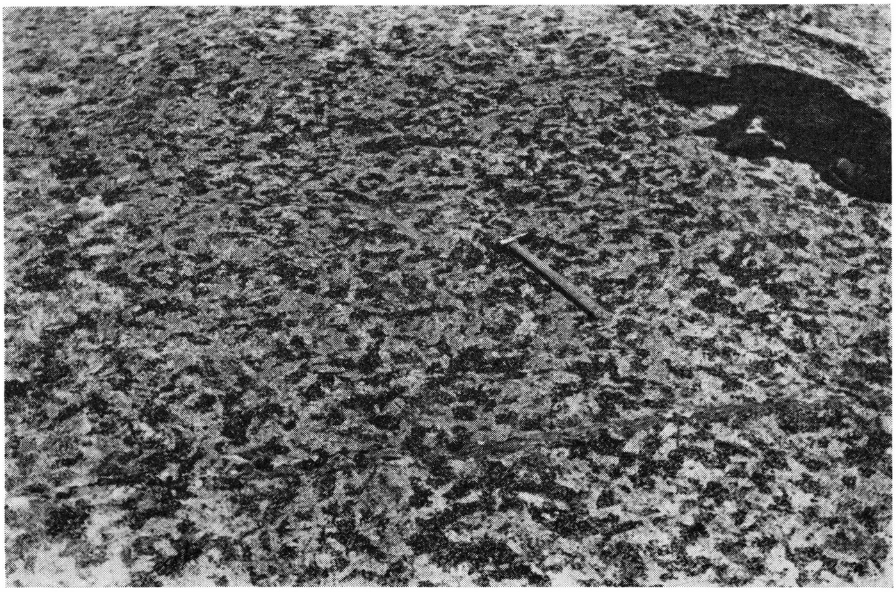

Fig. 16. Typical naujaite cut by narrow veins of aegirine and analcite derived from the later lujavrites. Taseq.

Fig. 17. Band of non-poikilitic pegmatite developed in poikilitic naujaite. Kangerdluarssuk fjord, north side.

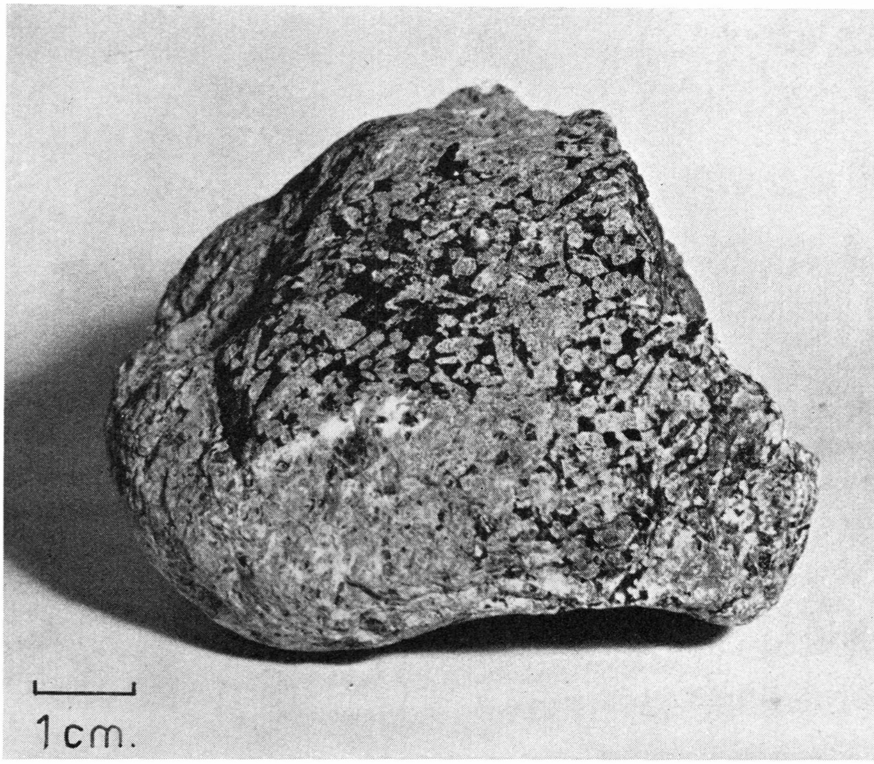

Fig. 18. Compact poikitilic naujaite showing prismatic sodalite pseudomorphs after nepheline.

Briefly, the main features seen during the recent field work were:

The naujaite is poikilitic in texture, the major minerals being full of crystals of sodalite. Occurring within the typical poikilitic naujaite are horizontal benches of non-poikilitic pegmatitic naujaite (Fig. 17). These pegmatites are conformable to the general parting of the naujaite. In addition there are somewhat transgressive pegmatites composed of feldspar and coarse anhedra of arfvedsonite, feldspar with arfvedsonite zeolite, steenstrupine, aegirine and lithia mica associated with albite.

Typical naujaite found in the lower part of the intrusion is composed of large feldspars full of sodalite crystals after nepheline; arfvedsonite, aegirine, eudialyte poikilitically enclosing sodalite, and abundant prismatic crystals of a grey to blue or green mineral regarded as nepheline in the field. These so-called "nephelines" are invariably prismatic (Fig. 18) and are at least three times longer than they are wide. In the naujaite pegmatite the nephelines are often up to 10 cm long and 1 cm wide. In view of the difficulty of obtaining good crystals of nepheline for chemical analyses many specimens were carefully collected from the

Fig. 19. The base of a mafic band developed in naujaite. Kangerdluarssuk Fjord.

intrusion. X-ray analyses and a preliminary optical study of these prismatic crystals showed that they were all sodalite. The blue types are full of micro-inclusions of arfvedsonite, and the green types are full of aegirine. It appears certain that in view of the crystal shape this mineral crystallised as nepheline, and was replaced by sodalite before the consolidation of the rock. It should be pointed out that nepheline has been observed in thin section, but is not always obvious in the hand-specimen. Naujaite found in the upper part of the intrusion contains well developed prismatic crystals of nepheline.

In the author's opinion banding in the naujaite is possibly widespread. Banding has previously been reported by SØRENSEN (1958, Figs. 7 and 5). In many cases the naujaite appears to be banded (Fig. 19) when viewed

Fig. 20. Diagram showing the growth of poikilitic aegirine in the mafic band.
Key: Black — Aegirine
Stippled — Sodalite
Dashed — Feldspar, Nepheline, Analcite.

from a distance, but upon closer examination of the outcrop banded features are difficult to see.

In view of the structure and texture of the naujaite, large scale good repetitive banding cannot be expected. In parts of the naujaite, careful observation shows that mafic bands composed of arfvedsonite and aegirine are not uncommon. In several areas narrow (25 cm) mafic bands have been observed. The base of these bands are composed of small prismatic and non-poikilitic concentrates of aegirine which passes up into poikilitic aegirine over a short distance (Fig. 20). Above the mafic band the amount of feldspar and eudialyte increases; then this zone passes up into average naujaite. Another feature related to the segregation of minerals is the concentration of arfvedsonite, aegirine, and sodalite with a little feldspar and eudialyte. Above this layer the amount of mafic minerals decreases and the rock is essentially composed of feldspar, sodalite and eudialyte.

At the margin of the intrusion, the naujaite exposed in the Narssaq

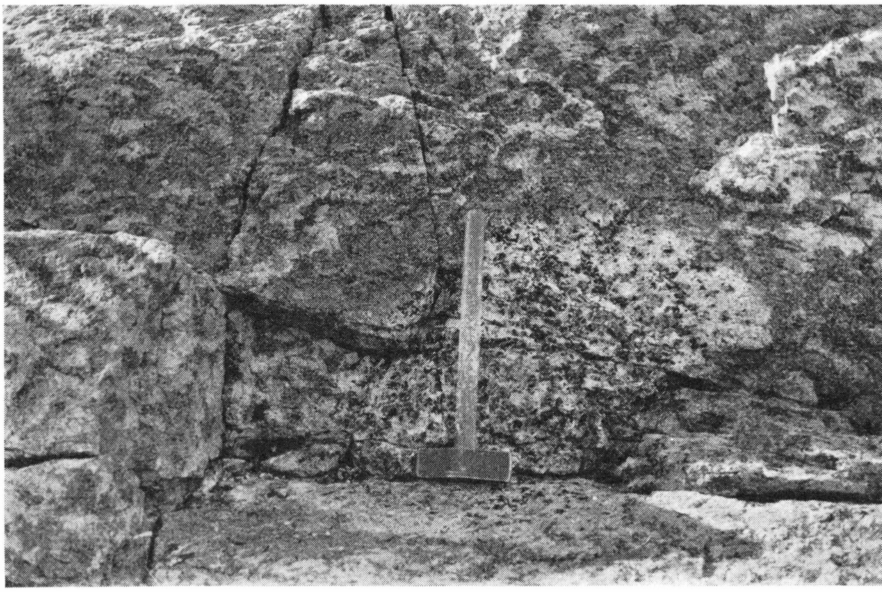

Fig. 21. Cognate inclusions of sodalite foyaite in naujaite. Kangerdluarssuk fjord.

Elv stream-bed at 200 m, shows good vertical banding. The bands, of which there are at least two cycles, show a mafic horizon passing up into an almost pure feldspathic horizon, the change taking place over a distance of 1 m.

At an altitude of about 300 m in the Narssaq Elv, rounded masses of naujaite, measuring up to 2 m in width, are enclosed in a very plate-like naujaite. The enclosing naujaite appears to flow around the rounded masses of naujaite. This indicates that rather coherent masses of naujaites were caught up in naujaite still capable of movement. It is suggested that these features are slump structures. The locality is very near the contact of the intrusion as is shown by the steep contact of naujaite with augite syenite and the vertical banding in the naujaite. In other areas rounded masses of sodalite foyaite present in the naujaite may be interpretated as similar slump structures (see Fig. 21).

A discussion as to the distribution of sodalite in the naujaite must await examination of the thin sections. At this stage, however, it may be said that small dodecahedral crystals of primary sodalite are intimately mixed with the prismatic sodalites pseudomorphing nepheline. The difference in crystal form is obvious if large sections of the rock are chemically stained. In the naujaite exposed in the Narssaq Elv, an almost pure sodalite rock is present. The rock consists of sodalite crystals in a matrix of aegirine and is easily recognised from a distance by the characteristic weathering.

The coarse-grained textures of the naujaite make it difficult to examine the textural relationships of the various minerals in thin section. Many thin sections have been examined and the general mineralogical characteristics given by Ussing (1912) are valid. Although most of the feldspars are composed of complex intergrowths of microcline microperthite it has become increasingly obvious that many of the central portions of the feldspars consist of cryptoperthite. The marginal alteration to analcite and natrolite may have resulted through the late stage concentration of alkalies, water and volatiles in the residual intercrystal liquid. The main sequence of crystallisation appears to be first sodalite (including sodalite after nepheline), nepheline, eudialyte, feldspar, aegirine, and finally arfvedsonite. The partially orientated aegirine microlites in the sodalites are absent around the margins of the crystals. Apart from the microlites the sodalites contain gas bubbles and rows of orientated bubble and dust inclusions. In some cases these rows of inclusions pass across several isolated sodalite crystals. Amongst the accessory minerals iron ore and apatite have not been observed. The main accessory minerals identified by X-ray powder patterns were rosenbuschite, steenstrupine, polylithionite, sphalerite, schizolite, microlite and neptunite.

The variations in the chemical analyses of the naujaites are controlled by the sporadic distribution of the major minerals. While sodalite generally comprises about 50 % by volume, the feldspar, aegirine, arfvedsonite, and eudialyte are often concentrated in different parts of the naujaite. Typically there are eudialyte clusters, surrounded and enclosed by feldspars. In this type of naujaite the mafics would only amount to 1 % by volume. Chemical analyses of the naujaites together with the qualitative distribution of the trace elements in rocks and minerals is given in Table No. 4. In Table No. 5 analyses Nos. 1—3, the effect of diffusion of some elements associated with the late stage thorium-rich steenstrupine is shown. Specimen No. 2 is of normal sodalite taken 10 inches from a pocket of steenstrupine. Specimen No. 3 is of an emerald green sodalite, taken adjacent the steenstrupine. From the semi-quantitative spectrographic analyses there appears to have been considerable diffusion of Li, Rb, Y, La, Zr and Pb from the steenstrupine into the adjacent sodalite.

III) Lujavrites-Kakortokites.

In this work the lujavrites are not studied in detail. They comprise the final residual magma derived from the agpaitic rocks and were intruded as late stage sills, dikes and veins. The final stage of the intrusion is marked by rather narrow dikes and veins predominantly

Table 4. Chemical Analyses of Naujaites.

%	1.	2.	3.
SiO_2	49.46	43.39	43.82
Al_2O_3	23.53	23.13	25.62
Fe_2O_3	3.04	3.62	2.66
FeO	1.02	3.24	0.40
MnO	0.17	tr.	0.25
MgO	tr.	none	0.06
CaO	0.80	0.56	0.70
Na_2O	14.71	19.68	18.45
K_2O	4.34	1.51	1.00
TiO_2	0.16	0.20	0.20
P_2O_5	none	none	none
ZrO_2	0.38	0.27	1.05
Cl_2	2.25	3.63	4.60
H_2O	1.38	1.57	2.40
TOTAL	101.24	100.80	101.21
Cl=O	.51	.82	1.01
TOTAL	100.73	99.98	100.20
ppm.			
Mo^{+4}	5	tr.	30
Li^{+1}	20	5	15
Y^{+3}	200	200	600
La^{+3}	150	100	800
Sr^{+2}	0	<30	100
Ba^{+2}	20	50	200
Rb^{+1}	320	200	155
Niggli numbers			
si.	142	109	118
al.	39.7	34.0	40.7
fm.	9.3	14	7.3
c.	2.4	1.6	1.9
alk.	48.6	50.4	50.1
ti.	.1	0.5	0.5
p.	0	0	0
k.	0.16	0.1	0.1
mg.	0	0	0.3

1., 2, G.G.U. No. 33157. Ussing's original analyses of the naujaite. Anal. C. Winther. Ussing 1912 p. 154.

3. G.G.U. No. 33158. Sodalite-rich naujaite. Anal. E. I. Hamilton.

Table 5. The distribution of some trace elements in some of the minerals from the agpaitic rocks.

No.		Mineral	Li.	Rb.	Cs	Mg	Sr	Ba	Mn	Ti	Y	La	Zr	Ga	Pb	Be. p.p.m.
1	333158	Sodalite A	15	15	0	100	0	0	100	<10	0	0	80	—	..	..
2°	–	Sodalite B	30	0	—	—	0	0	—	0	0	0	0	100	0	5
3°	–	Sodalite C	90	100	—	—	2	7	—	0	20	70	140	125	60	10
4	–	Eudialyte............	330	500	—	400	3000	2000	>1%	200	5000	1%	»1%	—	—	—
5	–	Aegirine	50	25	—	300	0	0	3000	3000	30	100	3000	—	—	—
6	–	Steenstrupine	100	5	..	2000	tr.	0	»1%	1500	>1%	»1%	>1%	—	—	—
7	33246	Feldspar.............	25	160	<5	90	—	—	—	10	30	100	200	—	—	—
8	–	Eudialyte............	330	160	0	300	100	100	8000	300	4000	5000	»1%	—	—	—
9	–	Aegirine	160	330	tr.	200	0	0	4000	3000	200	200	4000	—	—	—
10	33174	Feldspar.............	25	660	<5	90	100	5	900	20	100	200	500	—	—	—
11	–	Eudialyte............	50	20	0	300	200	400	1%	300	6000	5000	>1%	—	—	—
12	–	Mafics................	160	330	<5	600	..	0	1%	3000	200	200	1%	—	—	—

° Anal. by S. R. Nockolds; others by I. Sørensen.

Rock type

Nos. 1 — 6 Sodalite-rich naujaite, Ilímaussaq

Nos. 7 — 9 Sodalite foyaite-foyaite, Ilímaussaq

Nos. 10—12 Foyaite, Ilímaussaq

composed of aegirine and albite. The lujavrites are found mainly in the lower part of the naujaite and in the marginal areas of the intrusion. They are intrusive magmatic rocks and within them the earlier rocks of the Ilímaussaq intrusion occur as inclusions. WEGMANN's (1938) view that the lujavrites are metasomatically transformed porphyries cannot be accepted. SØRENSEN (1958) has suggested that the lujavrites were intruded into the older rocks not only as thin dikes, but also as larger masses in ring systems. Within the northern area covered by this paper there is no evidence for a system of ring structures related to lujavrites. In addition to brecciating the syenites, the lujavrites cut and include xenoliths of the country rock.

The lujavrites in the lower reaches of the Narssaq Elv form outwardly dipping sill-like masses. Along faults in the marginal syenite the augite syenite has developed a flaser structure and in places is intimately mixed with black and green analcite-aegirine lujavrite.

The kakortokites occurring in the southern part of the complex are very similar in chemical and mineral composition to the lujavrites. They differ from the lujavrites in being a coarser grained. A feature of the kakortokites is the remarkable layered structure, formed by crystallisation differentiation, possibly of the residual lujavrite liquid. The sequence is composed of black (rich in arfvedsonite), white (rich in feldspar) and red (rich in eudialyte) bands. The white bands are the thickest and most prominent members of the series, the black bands are thinner, the red thinner still and often lacking. Large and small angular inclusions of naujaite and augite syenite occur as inclusions in the kakortokites.

IV) Quartz Syenite.

It is difficult to accurately describe the distribution of the quartz syenites in the northern part of the Ilímaussaq intrusion, as the quartz is often not visible in the hand specimen. The distribution of the quartz syenites given in Plate 1 is based on field observations, and the study of thin sections.

Along the northern face of the intrusion a quartz-bearing syenite is present between the pulaskite and the soda granite. The upper part of the quartz syenite was mapped in the field; the lower part has been defined on the examination of thin sections.

It seems likely that the quartz syenite is developed either by metasomatism of the earlier rocks (particularly the augite syenite) by the later soda granite, or by the production of a contaminated augite syenite magma. The quartz syenite is associated with a considerable amount of alteration and recrystallisation of the feldspar and mafic minerals. The mafic minerals have recrystallised to give small radiating clusters of aegirine. In addition, granular aegirine-augite has developed together with fine-grained aggregates of iron oxides and purple fluorite. There are no chilled facies along the lower contact to the pulaskite-foyaite. At Ndr. Siorarssuit the quartz syenite is completely altered, iron stained and contains abundant fluorite.

In the exposures to the east of Taseq, quartz syenite is present as a rather thin sheet above the granite. Unfortunately, in this area the augite syenite is abundant and very similar to the quartz syenite in the hand specimen. The quartz syenite that in some places is present just below and just above the granite is considered to have formed by reaction between the granite and the adjacent rocks. The quartz syenite is not always readily recognised but a study of thin sections may show that it has a wider distribution.

At a higher level in the intrusion, on the plateau region of Nákâlâq, an intrusive quartz syenite is present. In this instance there is a recognisable difference between it and the augite syenite. The augite syenite weathers to a rusty brown colour and the exposures are covered by a sandy scree. The quartz syenite weathers to almost pure white. The difference in weathering has in this case proved to be a very reliable criteria for mapping these rocks. The marginal augite syenite occurs as rounded inclusions in the later quartz syenite which is chilled around them. Passing down towards traverse B, augite syenite is present and is underlain by granite and then quartz syenite. This area is mainly covered with scree and determination of the sequence of events in the few clean exposures is complicated by a breccia. The breccia zone occurs at the junction of quartz syenite and the granite. It is believed that the breccia is mainly restricted to the quartz syenite, which includes xenoliths of naujaite, sodalite foyaite, and syenites related to the pulaskites. Some of the naujaite inclusions in the breccia are up to 15 m long. The marginal parts (ca. 80 %) of these inclusions have been altered to an almost pure yellow-orange feldspar rock containing abundant purple fluorite, However, the cores of the inclusions consist of relatively fresh naujaite in which the poikilitic texture is preserved, the only evidence of alteration being the replacement of sodalite by fine aggregates of a black mineral.

The inclusions of pulaskite-like rock are rather fresh and angular in outline. The breccia zone is enriched in alkalies, F, Be, Sn, U and Th as shown by a preliminary semi-quantitative spectrographic analyses.

Slightly to the south-east of the quartz syenite at Nákâlâq, the syenite is cut by an aegirine granite. In addition to cutting, it also brecciates and veins the quartz syenite. There is faulting associated with the breccia and quartz, hematite and fluorite occur along joint planes.

In thin section the aegirine granite consists of microcline, quartz, aegirine-augite, arfvedsonite-riebeckite, astrophyllite, apatite, fluorite and an unknown colourless accessory mineral. The quartz contains orientated dustlike inclusions and shows strain extinction under crossed nicols. The rather equidimensional quartz grains have been replaced by feldspar, and occur as inclusions in feldspar. This granite shows some features similar to the soda granite of Iviangiussat.

Preliminary examination of the quartz syenite.

Quartz syenites have been recognised in the northern part of the Ilímaussaq pluton at levels above and below the granite. The lower facies are regarded as having formed by reaction of still warm augite syenite with the later intrusive granite. The upper facies are clearly intrusive into the augite syenite and contain altered inclusions of naujaite and sodalite foyaite.

In the hand specimen the quartz syenite is medium- to coarse-grained, leucocratic, with the mafic minerals occurring interstitially between the feldspars. In thin section alkali feldspar is replaced by later albite. Quartz is erratic in its distribution, but always occurs late in the crystallisation sequence. In some sections the quartz grains contain patterns of dust-like inclusions. Olivine is often present, but is normally altered to chlorite, green hornblende, iron ore and sphene. The latter mineral has not been found in other parts of the intrusion. The other mafic minerals are purple titaniferous augite, aegirine-augite with local patches of arfvedsonite that approaches riebeckite in composition and astrophyllite along the margins of the aegirine-augite. Green and brown hornblende when present may have cores of barkevikite. Sphene is the predominant accessory mineral and is associated with the breakdown of the mafic minerals. Other accessory minerals include apatite, polylithionite, elpidite (in close proximity to the granite) and rarely zircon.

Modal analyses of the quartz syenites are given below in volume percent.

G.G.U. No.	Feldspar	Quartz	Aegirine-augite	Arfvedsonite	Iron Ore
33249	66.0	4.5	27.5	0	2.0
33194	70.4	7.9	17.6	3.6	0.5
33586	70.0	13.4	13.2	2.8	0.6

The time of intrusion of the quartz syenite is tentatively placed as a post-agpaite, but pre-granite. The quartz syenite may be divided into three groups: —

1) The main mass of quartz syenite contains up to 10 % quartz and bears a great similarity to the Ilímaussaq augite syenite.

Table 6. Pulaskite and quartz syenite from Traverse A.

%	1.	2.	3.	4.	5.
SiO_2	57.88	—	57.5	56.1	63.0
Al_2O_3	14.80	—	14.9	15.4	12.4
Fe_2O_3.........	5.86	5.1	8.0	3.8	8.9
FeO	3.71	3.5	1.7	6.0	0.4
MnO	0.15	—	0.2	—	—
MgO	none	—	tr.	—	—
CaO	2.71	—	2.8	—	—
Na_2O	9.12	8.4	8.4	8.1	8.4
K_2O	3.06	5.4	5.6	5.4	5.5
TiO_2..........	1.23	—	0.2	—	—
ZrO_2	—	—	0.3	0.1	0.1
Cl_2	none	—	0.6	0.2	0.1
P_2O_5	none	—	tr.	—	—
CO_2	none	—	none	—	—
H_2O..........	1.13	—	0.4	—	—
TOTAL.......	99.65	(22.4)	100.6	(95.1)	(98.8)
ppm					
Ga^{+3}	20	10	20	10	50
Li^{+1}..........	25	50	40	20	80
Zr^{+4}..........					
Y^{+3}	100	300	100	600	100
La^{+3}	100	1000	200	1000	30
Sr^{+2}..........	30	100	30	50	60
Ba^{+2}	30	100	80	100	200
Rb^{+1}	400	400	300	400	400
Niggli numbers					
si.............	193		185		
al.	29		28.2		
fm............	26		24.6		
c.	9		9.7		
alk.	36		37.5		
ti.............	3		0.6		
mg.	0		0		
cl.............	0		3.3		
zr.	0		0.4		
k.............	0.2		0.4		

1. Pulaskite, Ilímaussaq. USSING N. V. 1912, p. 124. Anal. Chr. WINTHER.
2. (G.G.U. No. 33242), 3. (G.G.U. No. 33247), 4. (G.G.U. No. 33248) Pulaskitic rocks present between 846—870 m. Traverse A, "Transition" Series.
5. (G.G.U. No. 33249), Quartz syenite. 875 m. Traverse A. Anal. E. I. HAMILTON.

2) In the vicinity of the soda granite, some of the quartz syenite resembles the granite, particularly with regard to the accessory minerals, although quartz is less than 15 $^0/_0$ by volume. An analysis of this variety of quartz syenite is given in Table 6.

3) In a few cases quartz in abundant. It appears to have crystallised early and it is possible that the quartz syenite crystallised from an "augite syenite magma" that had assimilated quartz although the early crystallisation of quartz in this type of syenite is not uncommon.

Along the northern face of Nákâlâq at 1,000 m a white and red sandstone has been found in situ, and probably represents a sandstone horizon of the Gardar Formation. Local faults cutting the granite and volcanics also cut the small isolated outcrops of the sandstone. Although the immediate surroundings of the sandstone are obscured by scree, 4 m away the chilled facies of the augite syenite are surrounded by a fine-grained red altered rock. In thin section it consists of quartz, altered perthitic feldspar, calcite, chlorite and an almost black zircon. This facies may represent the local replacement of pre-existing sandstone in situ by either granite or modified augite syenite magma.

THE TRANSITION SERIES (HYBRID ZONE).

The transition series in USSING's sense consists of pulaskite, quartz syenite and soda granite. In addition, there are at a few places, according to USSING, gradual transitions from pulaskite down to foyaite, and sodalite foyaite to naujaite. In relation to the sequence above the pulaskite, a transition sequence does not generally exist in the sense implied by USSING, who visualised a gradual change from pulaskite to quartz syenite and finally granite.

The traverses numbered A, B, C, D, E, F, are given on the map (Plate 1).

I) Sequence A. (Fig. 22).

The rocks of this sequence are well exposed in a stream section.

Altitude in metres.

1,000 Marginal augite syenite consisting of: —
1) Very leucocratic variety.
2) Dark type with prominent olivine and ore minerals.
3) Pegmatitic type in which clove coloured feldspars are rimmed with white feldspar.
4) Mixed coarse and fine type with a dactylographic texture.
5) Leucocratic type with mafic bands less than 2 cms wide.

970 Iron stained augite syenite.
960 Augite syenite with xenoliths of almost pure feldspar rock.
920 Soda granite chilled against the overlying augite syenite. Chilled granite associated with small pegmatitic patches, mafic schlieren and narrow quartz veins.
880 Decrease in the amount of quartz, with a tendency for the quartz to form in small clusters.
870 Green syenite with a little quartz and rather platy partings.
850 Blue, eudialyte-free, compact, medium- to coarse-grained syenite. Possibly a variety of pulaskite.
846 Leucocratic rock, saccharoidal texture, eudialyte restricted mainly

Fig. 22. General view of the northern face of the Ilímaussaq intrusion looking towards the south-east. The small glacier marks the contact of the intrusion with the country rock of volcanics. Traverse A and F, are marked, also the lower level of the Transition Series.

to pegmatitic patches. Pegmatitic patches contain feldspar, nepheline, sodalite, aegirine and eudialyte.

835 Green syenite medium-grained with pegmatitic patches. Eudialyte restricted to pegmatite, small amounts in intercrystal spaces. The patches of pegmatite are surrounded by a zone of alteration in which prominent accicular aegirine is developed.

830 Blue, medium- to coarse-grained syenite with an even distribution of eudialyte. Possibly a variety of foyaite.

820 Platy sodalite foyaite. This rock is associated with a considerable amount of natrolite and analcite, particularly on joint faces.

805 Green syenite with the eudialyte. Restricted mainly to pegmatitic patches the margins of which show the development of acicular aegirine in from the walls of the "pocket".

800 Foyaite-sodalite foyaite with narrow crush zones.

780 Medium-grained compact foyaitic rock.

770 Sodalite foyaite passing down into naujaite.

Field relations show that the contacts of the various rocks seen in this traverse dip steeply towards the south at an angle greater than 80°.

The complete transition sequence is observed in Sequence A and as the exposed rocks were very fresh and free from scree this sequence was chosen for a more detailed study. Unlike many of the other transition series this one showed an apparent gradual change from the agpaitic rocks to the granites as decribed by Ussing (1912).

Petrology.

1) *c. 200 m — 760 m.*

The main rock present between these limits is naujaite that has been intruded by lujavrite veins, dikes and sills. The lower facies are rich in sodalite and may be described as a tawite. Between c. 400 m — 700 m naujaite is present, although the relative proportions of the major minerals varies from place to place. The two most common varieties are an eudialyte-sodalite-feldspar-rich facies and an arfvedsonite-aegirine-sodalite-rich facies. These two facies may represent the leucocratic and mafic bands seen in the layered naujaite, but in neither is there any preferred orientation of the major minerals. Poikilitic textures of the naujaite at this horizon are shown in Fig. 23A, B.

2) *760 m — 800 m.*

At 760 m naujaite is present, but at c. 765 m the poikilitic texture is lost and the rock becomes, in Ussing's terminology, a sodalite foyaite.

3) *800 m — 820 m.*

The lower facies of this zone consists of sodalite foyaite, but the mineral assemblage and textures are very variable. The upper facies reverts to normal sodalite foyaite with a slight preferred orientation of the feldspar crystals. In thin section the feldspars have a complex type of braided microcline twinning and are marginally replaced by analcite. Analcite is also present in intercrystal areas. Large crystals of nepheline are corroded and surrounded by analcite-natrolite coronas. Sodalite is associeted with the natrolite or occurs as discrete crystals. The most common mafic mineral is a well zoned aegirine with a narrow rim of aegirine-augite. Eudialyte is present in sporadic amounts and is partly replaced by catapleite. The accessory minerals include neptunite, schizolite, pyrolusite, microlite (probably chalcolamprite), and sphalerite.

4) *840 m — 846 m.*

In this zone the tendency to a preferred lamination of the feldspars is lost, the grain size becomes medium to coarse and the amount of mafic minerals increases; the eudialytes previously brown to dull red in colour become bright pink. The feldspar contains a central zone of cryptoperthite surrounded by a large corona of exsolved feldspar, analcite and sodalite. Sodalite and nepheline are almost totally replaced by intergrowths of analcite and natrolite. The arfvedsonite is surrounded, replaced or

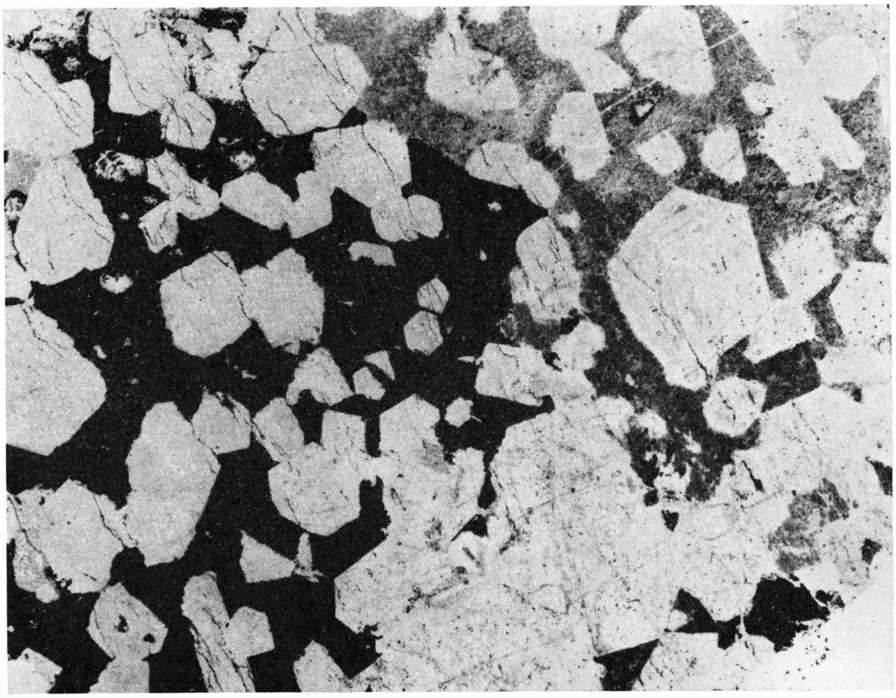

Fig. 23A. Sodalite, partly after nepheline, poikilitically enclosed by ænigmatite (black) and feldspar (dusty grey) in naujaite. This horizon corresponds to a mafic layer; eudialyte is practically absent and the sodalites are of variable sizes. Mag. X6.

rimmed by aegirine-augite which also occurs as microlites in the feldspar. Accessory minerals are lacking although small amounts of astrophyllite have replaced the pyroxene. In some areas nepheline is abundant, and although largely altered the rock may be regarded as an urtite, while the mafic counterpart, ijolite, is represented by areas rich in mafic minerals.

5) *846 m — 870 m.*

In this zone in the sequence the texture seen in the naujaites and sodalite foyaite are lost, and instead the rock becomes leucocratic, and saccharoidal in texture. Eudialyte previously one of the major minerals is here restricted to intercrystal areas and pegmatitic patches. The feldspar, a microcline perthite is surrounded by rims of sodalite and natrolite. Nepheline occurs as corroded inclusions in microlite-free sodalite, while the sodalite itself is surrounded by rims of natrolite and analcite. In some sections large porphyroblasts of nepheline have been observed. Aegirine is strongly zoned with deep green centres passing out to pale green margins. Three rock analyses from this horizon are given in Table 6. Nos. 2—4.

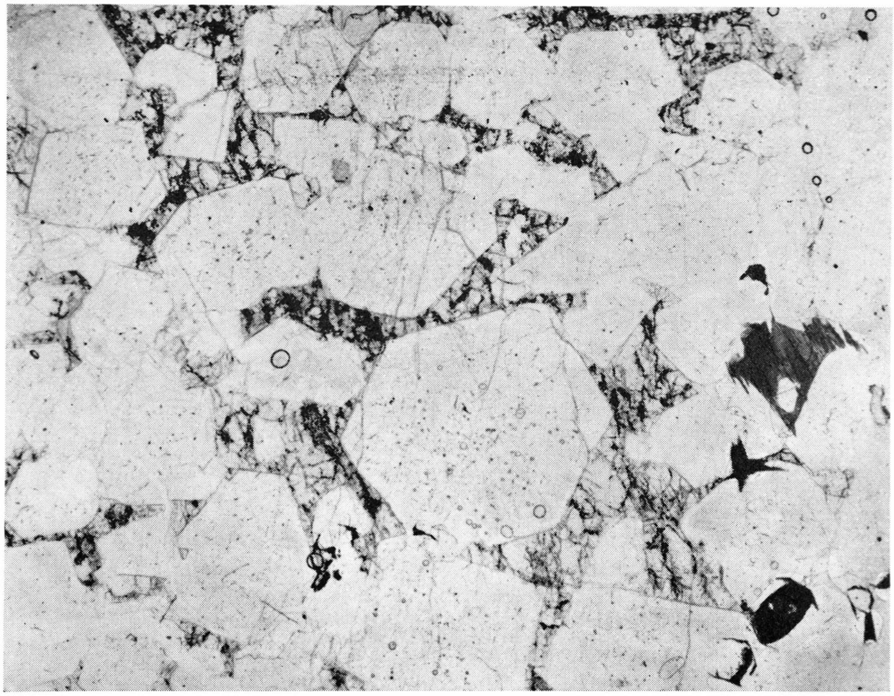

Fig. 23B. Sodalite and sodalite after nepheline, poikilitically enclosed by eudialyte (grey). This horizon corresponds to an eudialyte-sodalite-feldspar-rich leucocratic horizon in the naujaite. Mag. × 6.

6) *870 m — 880 m.*

Quartz appears within these limits and increases in amount upwards where the granite is encountered.

II) Sequence B.

The main difference between this traverse and the previous one is that the quartz syenite contains xenoliths of naujaite, sodalite foyaite, and pulaskite. Locally the quartz syenite is very rich in quartz and it is possible that at least some of it may be granite. If this should be the case then it would provide evidence that the quartz syenite and granite post date the agpaitic sequence. The area of xenoliths is partly covered with scree and the xenoliths themselves have been mineralised with the development of massive purple fluorite. The xenoliths appear as rounded masses of pink feldspar with fluorite developed in pockets and joint faces. It is only in the cores of the xenoliths that the original rock can be discerned. In the case of the naujaite the major minerals are altered but the poikilitic texture is retained. Some facies of the quartz syenite or

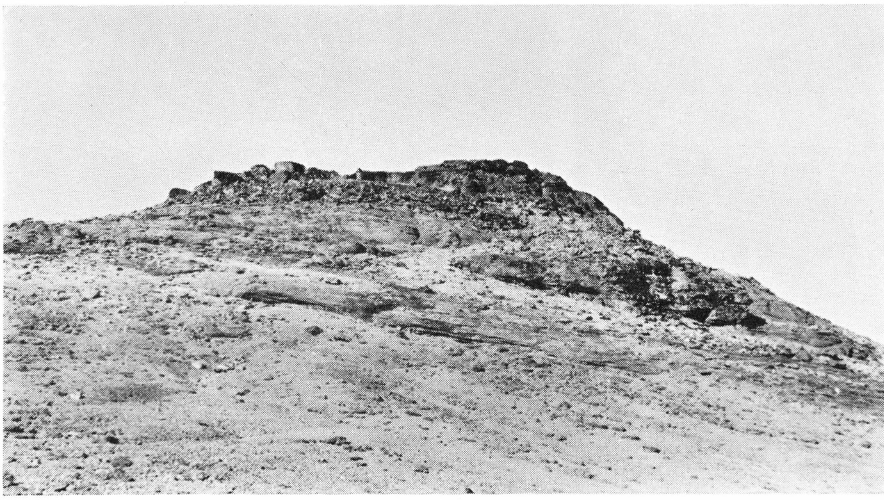

Fig. 24. General view of the Transition Series B. In the foreground naujaite passes up into platy sodalite foyaite. The latter is overlain by poorly developed pulaskite. The upper bluffs are formed of quartz syenite and soda granite. S. W. slope Nákâlâq.

possibly granite are fine-grained with acicular arfvedsonite. Photographs of the transition naujaite-sodalite foyaite-foyaite are given in Figs. 24 and 25.

III) Sequence C.

This sequence exhibits the same variation of rock types which were seen at Sequences A and B. In this traverse the pulaskite is well shown. The quartz syenite and lower facies of the granite are very altered. The alteration takes the form of the decomposition of the feldspar to pink secondary products, much iron staining, quartz veining and the presence of hematite and fluorite disseminated throughout the rock. The field relations suggest reaction between the granite and the underlying syenite.

The outstanding feature of this traverse is the well developed pulaskite, and the very sharp contact between the sodalite foyaite and naujaite.

IV) Sequence D.

This is one of the few exposures that are free from scree. In this traverse the main features seen were the sharp contact of naujaite with the sodalite foyaite, the gradual change of foyaite to pulaskite and the presence of altered olivines in the agpaitic rocks. From the field relations, the overlying pulaskite and foyaite seem to have been replaced by the underlying agpaitic rocks. The amount of replacement varies at different levels.

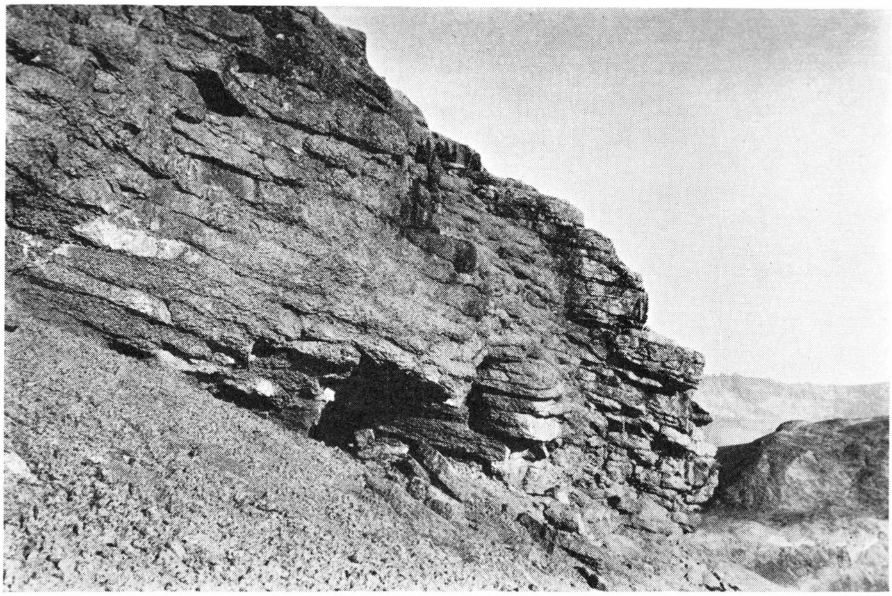

Fig. 25. Transition Series B showing naujaite overlain by sodalite foyaite. The naujaite weathers to give scree-covered slopes. S. W. slope Nákâlâq.

V) Sequence E.

This sequence forms the highest part of the intrusion, but the exposures are faulted, sheared, and much of the rock has been altered to secondary products. In spite of these difficulties the change from naujaite to granite is easily recognised in the field. The contacts dip steeply to the south.

THE ILÍMAUSSAQ GRANITE

In the northern area the time of emplacement of the granite cannot be accurately defined. In the south FERGUSON (1962) has suggested that the granite was emplaced after the crystallisation of the augite syenite-foyaite, but before the agpaites. In the author's opinion the granite is possibly the last intrusive phase of the Ilímaussaq intrusion.

In the southern area (FERGUSON 1962) very small granite stocks and sills of a soda granite have been intruded into the foyaite. FERGUSON regards these as representing the local penetration of the soda granite into the augite syenite sequence, and now occupying horizons both above and below the roof of augite syenite. While not disagreeing with this suggestion the author considers that the following considerations suggest a late stage intrusion of the granite.

1) The granites described by FERGUSON may not represent granite intruded from below, but rather from above and represent irregularities in the base of the granite sheet.

Although the roof of the intrusion and the overlying volcanics have been eroded from this area the roof cannot have been very far away. A common feature of the roof and margin of the intrusion is the formation of a soda granite formed by reaction between augite syenite magma and sandstone of the country rock. The rheomorphic granite is intrusive in nature and the granite described by FERGUSON may have been formed in such a manner.

2) The lujavrite is established as representing the final residual magma of the agpaites and the aegirine analcite veins as the final residual liquid of the lujavrite. Neither of these two cut the soda granite. However, lujavrite is not present in the upper parts of the intrusion which is associated with the granite.

3) The breccia present at 900 m on Traverse B does not appear to contain xenoliths of granite, but does contain xenoliths of the agpaites and pulaskite.

4) The quartz syenite present above the granite in the northern

Table 7. Chemical analyses of two rocks obtained from a silica-enriched zone in the naujaites.

%	1.	2.
SiO_2	67.17	65.9
Al_2O_3	17.66	—
Fe_2O_3	1.75	—
FeO	1.14	—
MnO	0.08	0.1
MgO	tr.	tr.
CaO	0.00	tr.
Na_2O	9.92	9.8
K_2O	3.20	3.7
TiO_2	0.17	0.2
P_2O_5	0.05	—
H_2O	0.24	—
TOTAL	101.38	—
Trace elements ppm.		
Mo^{+4}	10	
Li^{+1}	10	
Zr^{+4}	0.1 %	
Y^{+3}	500	
La^{+3}	300	
Sr^{+2}	20	
Ba^{+2}	50	

1. Chemical analyses Me Mouritzen, spectrographic analyses I. Sørensen, G.G.U. No.33499.
2. Partial analyses E. I. Hamilton, G.G.U. No. 33500.

area is intrusive into, and chilled against, the augite syenite. The examination of Traverse A suggests that the lower quartz syenite has been formed by the replacement of the pulaskite and the upper facies of the agpaitic sequence by a later granite. In the author's opinion the intrusion of granite was preceeded by the intrusion of a modified augite syenite magma. While the normal trend in the augite syenite magma is towards undersaturation, fractional crystallisation leading to a quartz-rich residium could be promoted by: —

a) Assimilation of sandstone in situ or at depth.
b) Assimilation at depth of granite country rock.
c) The development of two trends in the original augite syenite magma — one towards undersaturation and one towards saturation.

5) In the upper reaches of the Narssaq Elv at the 500 m contour, to the outcrop of granite below the Nákâlâq plateau, rocks enriched

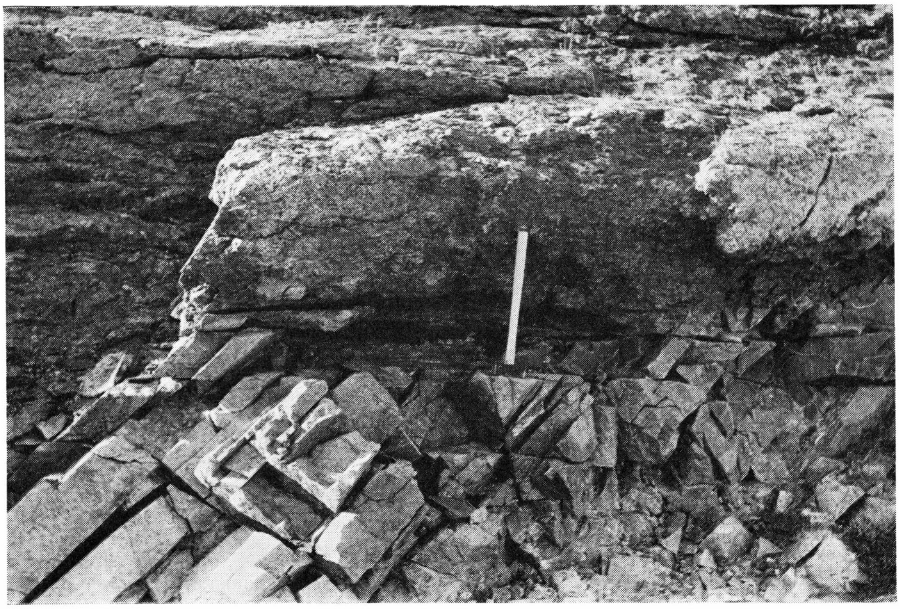

Fig. 26. Contact of granite overlain by quartz-bearing augite syenite. Eastern end of Taseq.

in silica are present along a poorly defined fault and crush zone. The analyses of some of these rocks which are present in the naujaite are given in Table 7. Although no granite has been found in situ this may be an indication that a granite was intruded after the crystallisation of the agpaitic sequence. It is possible that this silica-rich zone is related to the remelting of the granite country rock. The author is not of the opinion that this is valid as the agpaites would not have enough superheat to remelt a granite.

The Ilímaussaq soda granite may not be genetically related to the intrusion but derived by the selective remelting of country rock associated with large scale orogenic movements. Selective remelting on a large scale could give rise to a sodium- and iron-rich residual liquid. The presence of Be, Nb, U, Th, and rare-earths, in rather large amounts could be explained by complex transference (Shcherbina, 1956 a, b). The trace elements of the Ilímaussaq soda granite are similar to those of the agpaites.

The alkaline granite was emplaced, possibly as a sheet, in the upper region of the intrusion. The granite is transgressive in nature, its lower margin being limited by the quartz syenite or pulaskite and its upper margin by augite syenite, quartz syenite, or members of the Gardar Formation.

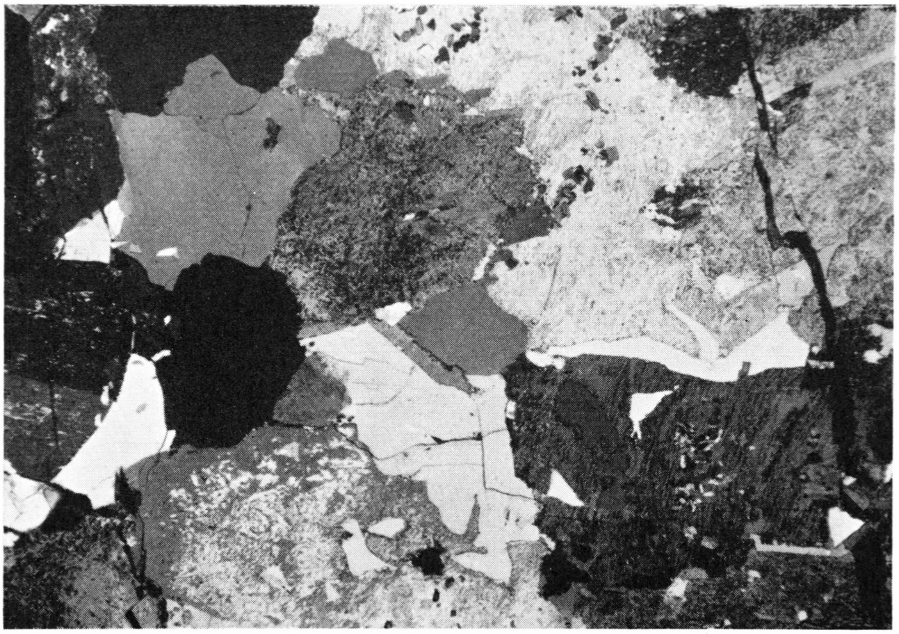

Fig. 27. Quartz-feldspar textures in granite. X-Nicols. Mag. × 10.

The Ilímaussaq soda granite is very homogeneous in terms of mineral constituents and texture, a feature sommon to many other similar rocks. Apart from mafic schlieren and pegmatite at the margins there is no preferred orientation of the major minerals. In the main mass of the granite, pegmatite is uncommon, but it is fairly widespread over a distance of a few metres below the upper margin of the granite. A striking feature of this granite that is not common to most soda granites is the development of an upper fine-grained chilled margin. No chilling has been observed at the lower margin. The main granite is green with black prismatic crystals of arfvedsonite. Quartz is present as somewhat rounded grains; several grains often forming conspicuous clusters. In addition, the green granite encloses areas of blue granite, but this does not appear to be related to any structural feature. The difference in colour of the granite is due to green aegirine or blue arfvedsonite microlites enclosed within the feldspar. In the chilled facies the mafic minerals are acicular in habit, calcite is sometimes present and a narrow zone (approximately 2—5 cm deep) of red altered rock containing fluorite, is present at the contact with the augite syenite. In the southern part of the granite outcrop north of Tunugdliarfik, the acicular chill is replaced by medium- to fine-grained granite with moss-like aegirine. In this area the contact with the overlying quartz syenite is very sharp as shown in Fig. 26.

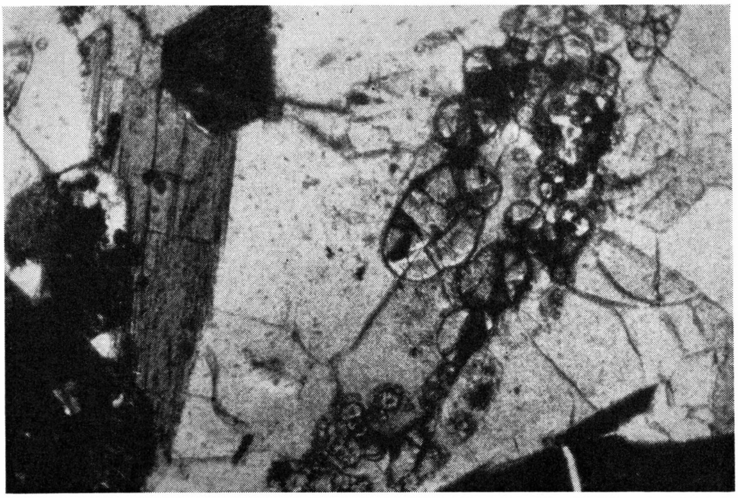

Fig. 28. Spherulitic elpidite between quartz grains of the Ilímaussaq soda granite. Mag. x 25. (This thin section is photographed through a cover of nuclear emulsion. The fine hair like lines associated with the elpidite are alpha particle tracks).

Although USSING described the granite of Ilímaussaq as a light greenish coarse-grained rock, the specimen taken for analyses is described as a fresh looking, light grayish-brown variety. USSING's original specimen has been examined and is without doubt an uncommon, altered variety; the brown colour is due to the alteration of the microlite inclusions in the feldspar to secondary iron oxides.

In thin section the granite is composed of alkali feldspar, quartz, arfvedsonite, aenigmatite, aegirine-augite, a brown amphibole, astrophyllite and accessory elpidite, epididymite, pyrochlore, leucosphenite, fluorite, calcite and rare zircon.

Brief descriptions of the analysed granites follow.

1) G. G. U. No. 33240. A green variety of the granite composed of alkali feldspar, quartz, arfvedsonite, aenigmatite, aegirine-augite, astrophyllite, with accessory elpidite, epididymite, fluorite and rare pyrochlore. The feldspar consists of early untwinned alkali feldspar, replaced by microcline perthite and later albite. Quartz and feldspar crystallised more or less simultaneously, although in some sections quartz occurs as rounded grains enclosed within feldspar. A photograph of the quartz-feldspar relationship is given in Fig. 27, and radiating clusters of elpidite associated with quartz are shown in Fig. 28.

2) G. G. U. No. 33241. A blue variety of the granite with arfvedsonite having a few cores of aenigmatite. Pyrochlore (surrounded by pleochroic haloes) and fluorite are the main accessory minerals.

3) G. G. U. No. 33250. This granite contains original untwinned feldspar

replaced by microcline and surrounded by granular albite. Arfvedsonite rimmed by aegirine-augite (Fig. No. 29) and accessory amounts of elpidite and pyrochlore.
4) G. G. U. No. 33239. This rock has fresh untwinned feldspar replaced by a mosaic of albite and quartz. The arfvedsonite rimmed with aegirine-augite contains cores of katophorite. Small amounts of aenigmatite are present together with elpidite and fluorite.
5) G. G. U. No. 33243. A medium-grained chilled facies of the chilled granite. The feldspar contains microlites of arfvedsonite and astrophyllite. The accessory minerals are calcite and elpidite.

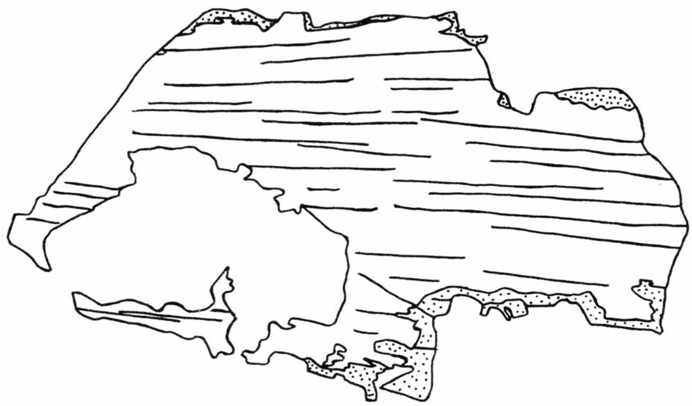

Fig. 29. Aegirine (stippled) replacing arfvedsonite. (G. G. U. 33240) Ilímaussaq granite, Mag. × 28.

6) G. G. U. Nos. 33243 and 33244. Both these specimens represent fine-grained chilled granite taken a few centimetres from the contact with the overlying augite syenite. The feldspar contains large amounts of albite, and the accessory minerals are predominantly pyrochlore and fluorite.

Two other types of granite not analysed are described.
a) One is an altered variety of granite exposed at 900 m above the eastern end of Taseq, just above the underlying foyaite. Quartz, from its form, can be seen to have crystallised early. It was followed by feldspar and then by early pale green hornblende surrounded by arfvedsonite which in turn has narrow rims of aegirine-augite partly altered to acicular astrophyllite. Most of this variety of granite has been altered by later hematite-fluorite mineralisation.
b) The other granite is a very rare bright red variety. It is fresh in thin section and the red colour is due to small prismatic grains of aenigmatite in the quartz. Slightly larger grains of aenigmatite also occur as inclusions in the arfvedsonite.

Mineralogy and Chemistry.

The main sequence of crystallisation of the Ilímaussaq granite was the simultaneous crystallisation of quartz and feldspar followed by the mafic minerals and finally by the accessory minerals.

In the main mass of the granite the alkali feldspar contains varying amounts of albite lamellae, but in the zone adjacent to the upper chilled granite layer the amount of albite lamellae and discrete crystals of albite increase. The relationship between the aegirine-augite- and arfvedsonite microlites present in the feldspar is interesting. In the main mass of the green granite aegirine-augite occurs as microlites in the feldspar while the main mafic mineral in this facies of the granite is arfvedsonite. In the case of the blue granite the reverse occurs. The feldspars present in the green granite have been separated and chemically analysed for total iron: Assuming that the feldspars contain negligible iron within the lattice the resulting iron content indicates the presence of 4—6 percent included aegirine-augite. This is a contributary factor in accounting for the high iron content of the Ilímaussaq granite compared with other similar granites.

The mafic microlites are prismatic, tend to be acicular in crystal form and in some cases could be regarded as slightly orientated inclusions. From the examination of the granite in thin section, it is suggested that the microlites were formed contemporaneously with the crystallisation of the feldspar and are in fact precursors to the main crystallisation of the mafic minerals. There is no evidence to suggest a secondary origin for these microlites by exsolution; in fact, the later albite which replaces the earlier potash feldspar is free from them. In the modal analyses given in Table 8 the percentage of mafic minerals does not include the microlites, as they are far too small and numerous for a modal analyses.

The crystallisation of aegirine as microlites (in a manner that may be described as saturation nucleation) followed by the crystallisation of arfvedsonite may be related to variations in the local water and volatile content and oxidation state of the magma. From the mineral assemblage it is concluded that the magma must have been relatively dry; mica and other hydrous minerals are typically absent. The breakdown of riebeckite in the presence of water at magmatic temperatures has been described by Tuttle and Bowen (1958). True riebeckites are absent in the Ilímaussaq granite, but the tentative extrapolation of the riebeckite data may be helpful in understanding the crystallisation of these arfvedsonites. The sequence of crystallisation shows that the initial formation of the mafic minerals (microlites) was in an environment unsuitable to the crystallisation of riebeckite (arfvedsonite) but which favoured crystallisation of aegirine-augite (acmite), this tentatively related to the water content of the magma in the initial stage. Following this, arfvedsonite formed from the rest-magma may have crystallised under more reducing conditions and a lower water content. As the pore spaces were further reduced by the growth of the arfvedsonites (zoned) the pore liquid was enriched in water which favoured the crystallisation of aegirine-augite which replaced the earlier arfvedsonite. Aegirine-augite rims surrounding arfvedsonite are a marked feature of the Ilímaussaq granite. Apart from the variations in the oxidation state and water content of the magma the effect of such active mineralisers such as fluorine and carbon dioxide must be taken into account.

Recently Tuttle and Bowen (1958) have described the Quincy granite with experimental data on the feldspars and amphiboles (riebeckite). By analogy to the Quincy granite, the Ilímaussaq granite, which is of the hypersolvus type, contains a primary K-Na-feldspar which is not of the completely unmixed variety indicating crystallisation in a rather dry environment. The exception to this is in the chilled facies of the granite in which two feldspars occur indicating a more aqueous environment at the margins which is to be expected.

The accessory minerals of the Ilímaussaq granite contain relatively large amounts of zirconium (elpidite), niobium (pyrochlore) and beryllium (epididymite). Elpidite which is the most common accessory mineral is mainly restricted to the margins of quartz crystals. This assemblage of accessory minerals is characteristic of many alkaline rocks and indicates the concentration of the constituent elements through the agency of complex formation. In the main mass of the granite zircon is typically absent, but in the narrow granite veins cutting the Gardar Formation zircon and possibly beryl have been found in mairolitic cavities.

Allowing for slight mineral variations from place to place, the homogeneous composition of the granites is supported by the chemical analyses given in Table 8. As may be expected, the chilled facies G. G. U. Nos. 33243, 33244 & 33586) show a relative enrichment in the rest elements zirconium, yttrium, lanthanum, cerium, cesium and lithium. In Table 9 a selection of alkaline granites is given for comparative purposes. In the general category of alkaline granites, arfvedsonite granites are not very common, instead aegirine or riebeckite granites predominate.

In the Nigerian granite province (Jacobson *et al.*, 1958) riebeckite granites account for only 12 % of the total varieties; biotite granites are the most abundant (56 %) followed by rhyolites (19 %), amphibole-fayalite granite (8 %) and a more basic granite (5 %). The biotite granites have chilled margins and mafic segregations at the margin similar to those seen at Ilímaussaq. The accessory minerals are typically thorite, monazite, xenotime, fluorite and ilmenite. The riebeckite granites on the

Table 8. Chemical Analyses of the Ilímaussaq Granites.

%	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.
SiO_2	70.59	72.65	72.98	71.80	72.50	73.40	70.40	74.00	71.93	72.50	72.32
Al_2O_3	12.38	10.05	10.75	10.71	10.11	10.16	9.50	9.17	10.11	9.78	10.27
Fe_2O_3	1.61	3.66	2.38	0.74	3.47	2.46	4.60	3.71	2.85	2.87	2.71
FeO	3.33	2.53	3.80	4.12	2.20	4.10	5.10	2.52	5.54	4.00	3.50
MnO	0.08	0.14	0.17	0.07	0.10	0.10	0.50	0.80	0.17	0.16	0.23
MgO	none	none	0.03	0.02	0.02	0.02	0.75	0.25	0.39	0.01	0.16
CO	0.93	0.72	0.71	0.90	0.50	0.70	0.50	0.80	0.22	0.40	0.67
Na_2O	6.95	4.56	4.66	6.00	4.75	6.00	4.35	3.40	3.81	6.40	5.17
K_2O	3.74	4.92	4.25	4.20	4.25	3.71	3.68	2.90	3.73	3.50	3.92
TiO_2	0.44	0.37	0.41	0.38	0.48	0.20	0.25	0.25	0.25	0.25	0.33
P_2O_5	tr.	0.01	0.30	tr.	0.59	0.11	0.10	0.10	0.03	0.11	0.18
H_2O	0.41	0.30	0.20	0.41	0.36	0.24	0.58	1.59	0.98	0.30	0.54
Total	100.46	99.91	100.64	99.35	99.33	101.20	100.31	99.49	100.01	100.28	100.00
ppm.											
Ga^{+3}	10	10	10	10	10	30	50	50	50	20	
Mo^{+4}	5	20	20	10	20	10	10	10	10	5	
Li^{+1}	50	25	25	50	25	90	80	80	90	70	
Zr^{+4}	3000	2000	2000	>1%	3000	1%	>1%	»1%	»1%	2500	
Y^{+3}	200	100	100	200	200	200	900	1000	900	1000	
La^{+3}	250	300	300	1000	100	500	2000	2500	3000	1500	
Sr^{+2}	<30	30	30	30	30	>30	100	100	90	<30	
Ba^{+2}	80	100	100	80	100	50	100	100	100	30	
Rb^{+1}	500	350	350	350	300	400	300	300	350	400	

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.
Mode Vol. %											
Quartz............	24		24	30	25	28	32	44	47	32	30
Feldspar..........	64		62	55	64	57	43	40	36	45	54
Arfvedsonite...... } Aegirine..........	12			15	11	14	22	14	15		15
Arfvedsonite......			12							16	
Aegirine..........			<.5							6	
Accessories........	(<1)		1.5	(<1)	(<1)	1	3	2	2	1	1

Average Niggli numbers si. 367, al. 31, fm. 27, c. 4, alk. 38, k. 0,34, mg. 0,44, ti. 1.2, p. 0.3.

1. USSING's arfvedsonite granite, Ilímaussaq. Original analyses C. WINTHER, 1912.
2. Normal green arfvedsonite granite. Anal. ME. MOURITSEN, 1958. G.G.U. No. 33240.
3. Normal green arfvedsonite granite. Anal. E. I. HAMILTON. G.G.U. No. 33240.
4. Normal green arfvedsonite granite. Anal. E. I. HAMILTON. G.G.U. No. 33399.
5. Blue arfvedsonite granite Anal. E. I. HAMILTON. G.G.U. 33241.
6. Variety of arfvedsonite granite. Anal. E. I. HAMILTON. G.G.U. 33250.
7. Medium-grained chilled granite. Anal. E. I. HAMILTON. G.G.U. 33243.
8. Fine-grained chilled granite. Anal. E. I. HAMILTON. G.G.U. 33244.
9. Fine-grained chilled granite 10 cm from contact. Anal. H. WIIK. G.G.U. 33586.
10. Variety of arfvedsonite granite. Anal. E. I. HAMILTON. G.G.U. 33239.
11. Average Ilímaussaq granite.

Table 9. Alkaline Granites.

%	1.	2.	3.	4.	5.	6.	7.	8.
SiO_2	69.80	73.93	70.40	70.25	70.04	73.68	71.24	76.23
Al_2O_3	5.10	12.29	7.85	8.75	10.53	11.05	13.78	11.35
Fe_2O_3	13.23	2.91	6.98	7.90	3.00	3.93	1.30	1.88
FeO	0.78	1.55	2.98	1.62	4.61	1.45	2.83	0.32
MnO	0.12	tr.	0.13	0.13	0.09	tr.	0.15	0.20
MgO	0.11	0.04	0.52	0.65	tr.	—	tr.	—
CaO	0.72	0.31	0.26	0.51	0.27	0.48	0.38	0.43
Na_2O	8.04	4.66	4.65	3.82	5.00	5.20	5.32	4.71
K_2O	0.22	4.63	4.25	4.12	4.36	4.05	5.10	4.57
TiO_2	0.34	0.10	0.13	0.86	0.20	0.57	0.68	0.27
P_2O_5	0.07	—	—	—	tr.	—	—	tr.
H_2O	0.77	0.41	0.25	0.75	0.80	0.25	tr.	0.39
ZrO_2	1.17	—	1.65	0.78	0.25	0.24	—	—
TOTAL....	100.47_1	100.83	100.05	100.14	99.15_2	100.90	100.78	100.35

plus 1 — Ce_2O_3 0.37 plus 2 — F 0.41; CO_2 0.07; SnO_2 0.10; ThO_2 0.03; RE 0.07; U_3O_8 0.02; Ta_2O_5 0.03; Nb_2O_5 0.33.

Mode Vol. %

	1.	2.	3.	4.	5.	6.	7.	8.
Quartz.....	30	30	—	—	—	—	—	30
Feldspar ...	26	60	—	—	—	—	—	62
Aegirine ...	43	0	—	—	—	—	—	} 6
Arfvedsonite	00	0	—	—	—	—	—	
Riebeckite .	0	10	—	—	—	—	—	..
Accessories .	1	0	—	—	—	—	—	1

Niggli numbers

	1.	2.	3.	4.	5.	6.	7.	8.
si.........	310	397	319	352	344	397	350	462
al.	13.3	39	21	26	30	35.3	40	40.5
fm.........	48	19.1	47.7	41	30	20.4	17	11.5
c.	3.2	1.6	1.1	1	2	2.9	2	2.5
alk.	35.5	40.3	30	32	38	41.6	41	45.5
ti.........	1.2	3.9	0.5	2.4	0.3	2.6	2.7	1.2
p.........	0.3	0.01	—	—	—	—	—	—
k.........	0.2	0.5	0.4	0.4	0.4	0.3	0.4	0.4
mg.	0.2	0.02	0.7	0.1	—	—	—	—
zr.	2.7	—	3.8	1.8	0.6	0.7	—	—

1. Rockallite. The composition of rockallite. H. S. WASHINGTON. Quart. Journ. Geol. Soc., London 1914, 70, p. 297. Anal. H. S. WASHINGTON.
2. Quincy granite. TUTTLE, O. F., BOWEN, N. L. 1958.
3. Arfvedsonite granite centre of aegirine granite dike. Ampasibitika Madagascar. A. LACROIX 1903. Nouv. Arch. Museum, Paris. II, p. 235. Anal. PISANI.
4. Aegirine border to No. 3. p. 235.
5. Albite Reibeckite Granite, Nigeria. British Geological Survey. The Petrography of some of the Riebeckite Granites of Nigeria, 1952, p. 33. Anal. K. E. BEER.
6. Comendite, Ilímaussaq. USSING, N. V. 1912, p. 224. Anal. C. WINTHER.
7. Soda granite, Iviangussat. USSING, N. V. 1912. p. 114. Anal. C. WINTHER.
8. Ekertie. Oslo. BRØGGER, W. C. Nyt. Mag. Natur. Vid. 44, p. 136, 1906.

other hand, which are peralkaline in comparison to the meta-aluminous biotite granites, show great textural variation with the development of spectacular marginal pegmatites. The accessory minerals include astrophyllite, pyrochlore, cryolite, thomsonolite, fluorite and ilmenite. The presence of pyrochlore and the replacement of the early potash feldspar by later albite are features similar to those seen at Ilímaussaq. In the granites of the Kuduru Hills (BAIN, 1934) a biotite granite contains sporadic patches of riebeckite granite indicating perhaps local more aqueous- or volatile-rich pockets.

In the Oslo area (BARTH, 1944) the alumina-deficient ekerites are similar to the Ilímaussaq granites, but aegirine is the main mafic mineral with subordinate riebeckite. The accessory minerals of the ekerites include astrophyllite and elpidite.

DIKES AND FAULTING

Dikes are not very numerous in the northern part of the intrusion. Five most common types observed are briefly described.

a) There is a fine-grained, black, flow banded, porphyritic dolerite.

b) There is also a fine-grained, red micro-syenite, which is generally very altered and iron stained.

c) Dense blue-black tinguaites were found.

d) A green, porcellaneous, spherulitic dike was studied in more detail. The major minerals of this dike are feldspar, aegirine and fluorite.

Table 10. Chemical Analyses of dike rocks.

%	1.	2.	3.
SiO_2	60.23	73.28	73.68
TiO_2	0.28	0.52	0.57
Al_2O_3	13.62	9.33	11.05
Fe_2O_3	7.47	4.40	3.93
FeO	4.17	2.52	1.45
MnO	0.28	0.14	tr.
MgO	0.28	0.30	none
CaO	0.74	0.16	0.48
Na_2O	9.65	4.40	5.20
K_2O	1.76	4.15	4.05
P_2O_5	0.13	0.00	none
H_2O^+	0.90	0.85	0.08
H_2O^-	0.05	0.07	0.17
TOTAL	99.56	100.12	*100.90

* inc. ZrO_2 0.24.

Niggli numbers

si.	208	394	389
al.	28	30	35
fm.	34	32	22
c.	2	1	3
alk.	36	37	40
ti.	0.8	1.9	3
k.	0.0	0.4	0.4
mg.	0.04	0.07	0

No. 1. G.G.U. 33506. "Soda-syenite" A. (Anal. H. B. Wiik).
No. 2. G.G.U. 33511. Comendite. (Anal. H. B. Wiik).
No. 3. Comendite. (Ussing, 1912. Anal. C. Winther).

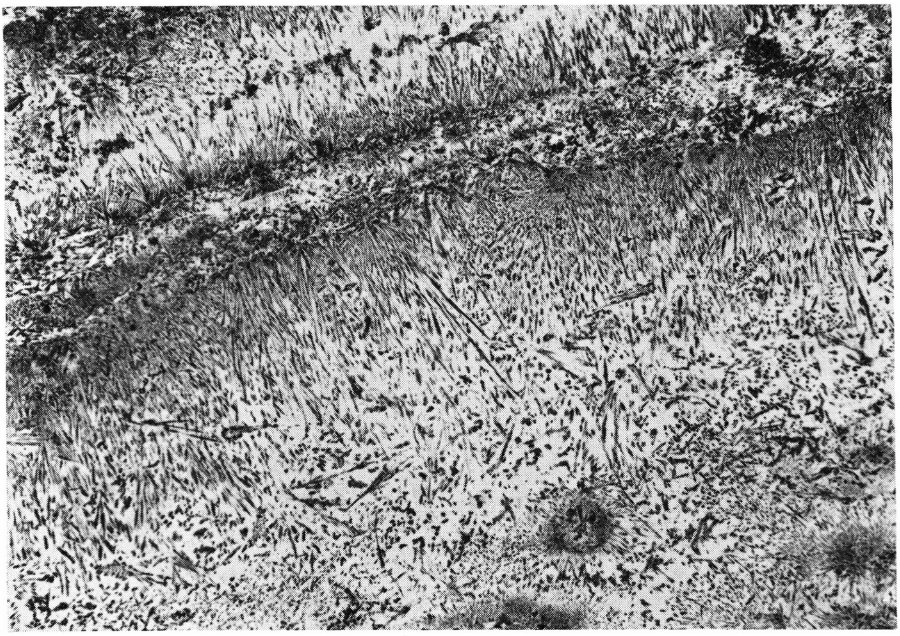

Fig. 30. Comendite — acicular arfvedsonite growing perpendicular to flow lines.

The grain size is so small that the positive identification of other minerals in the groundmass is difficult. The aegirine, which is of the prismatic habit, is concentrated in bands and patches together with fluorite. Some of these aegirine patches have marginal areas where aegirine forms a reticulate network that encloses the groundmass. This is taken as an indication that the mafic minerals were some of the last to crystallise. An analyses of this dike rock is given in Table 10, Col. 1.

e) In the vicinity of Narssaq, black spherulitic dikes with pronounced chilled margins are quite common. Apart from the colour difference they are similar to the green porcellaneous spherulitic dike. In thin section the major minerals seen are feldspar as discrete grains, acicular arfvedsonite, prismatic aegirine, quartz and small amounts of iron oxides. The textural features of this rock are shown in Fig. 30 and a chemical analyses in Table 10, Col. 2. From the textures, mineral composition and chemical analyses this dike resembles the Comendite type of soda granite.

The main fault lines cutting the northern part of the intrusion run parallel to the dike trend. The major fault that cuts the intrusion trends E—W, cuts the marginal syenite in the Narssaq Elv and then passes through Taseq. In the field the continuation of this fault to the south of Taseq is not obvious. Many of the fault zones contain fluorite, hematite and local mylonite.

THE GEOCHEMISTRY OF URANIUM AND THORIUM TOGETHER WITH THE DISTRIBUTION OF RADIOACTIVITY IN THE ILÍMAUSSAQ INTRUSION

Chemical procedures.

The uranium content of the Ilímaussaq rocks has been determined by the following techniques: —

a) Radioactivation analyses (Hamilton, 1959). In this particular method the rock powder is irradiated in a nuclear pile and the fission product Ba^{140} is chemically isolated. The barium-140 decays to the daughter La^{140} which after separation from the parent is used as a measure of the uranium content of the sample.

b) Fluorimetry (Hamilton, 1959). In the fluometric determination of uranium the mixed carbonate-fluoride flux was used (Grimaldi, 1952). The chemical yields of the separations were monitored by using a U^{233} spike and the amount of fluorescent quenching was determined by adding a known amount of uranium to the sample pad.

c) Thorium has been determined by extraction on Dowex 1 anion-exchange columns or by liquid extraction as described by Levine and Grimaldi (1958). After the separation the total thorium content of the sample was determined by spectrophotometry (Beckmann) using thoronol as the colouring complex. In the zirconium-rich samples it was necessary to remove zirconium before adding the thoronol.

The uranium and thorium content of the Ilímaussaq rocks compared to the sodium, potassium, lanthanum, yttrium and zirconium are given in Table 11.

The distribution of uranium and thorium (Table 11).

a) Augite syenites.

Specimens No. 1, and 2, represent fine- and coarse-grained facies of the augite syenite. The Th/U ratio shows slight thorium enrichment to the generally accepted Th/U ratio in igneous rocks of 3.5—4.0. Specimen No. 33452 was taken adjacent the country rock of Julianehåb granite and

Table 11. The distribution of uranium and thorium in the Ilímaussaq intrusion.

G.G.U. No.	Rock Type	SiO_2 %	Na_2O %	K_2O %	U ppm.	Th ppm.	Th/U	La ppm.	Y ppm.	Zr ppm.
	Augite Syenites									
33452	1 Chilled type	54.0	5.5	4.5	1.8	8.7	4.8	50	tr.	500
33390	2 Chilled type	53.3	6.5	4.5	1.2	6.6	5.5	20	tr.	300
33320	3 Normal augite syenite	57.5	5.8	5.1	1.2	5.8	4.8	30	tr.	300
33242	4 Inner facies of upper augite syenite	57.3	7.2	5.0	2.0	14.0	7.0	30	30	500
33190	5 Inner facies of upper augite syenite	56.0	5.7	4.8	2.3	14.5	6.3	—	—	—
33586	6 Chilled facies of nordmarkitic type	56.1	5.8	4.9	1.2	6.6	5.5	0	0	80
33173	7 Nordmarkitic facies	62.2	7.4	5.3	2.2	12.8	5.8	30	tr.	200
	Granites									
33240	8 Normal green granite	73.0	4.7	4.3	28	51	1.8	300	100	2,000
33241	9 Normal blue granite	72.5	4.8	4.3	20	50	2.5	100	200	3,000
33250	10 Variety of coarse granite	—	6.1	4.2	28	90	3.2	100	1,000	1%
33243	11 Medium-grained chilled granite	70.4	4.4	3.7	42	140	3.4	2,000	900	>1%
33244	12 Fine-grained chilled granite	74.0	3.4	2.9	58	250	4.3	2,500	1,000	»1%
	Agpaites									
33158	13 Sodalite-rich naujaite	43.8	18.5	1.1	22+	100	4.5	800	600	>1%
33235	14 Variety of naujaite-sodalite foyaite	50.0	14.1	3.8	nd.	28	—	30	30	100
33237	15 Variety of naujaite-sodalite foyaite	53.6	12.1	3.6	nd.	50	—	300	600	>1%
33238	16 Variety of naujaite-sodalite foyaite	57.9	9.9	4.3	50+	nd.	—	200	200	600
33245	17 "Foyaite" in transition series A	51.0	12.5	2.5	41+	160	3.9	400	300	>1%
33247	18 "Foyaite" in transition series A	57.5	9.6	3.3	22	35	1.6	200	100	3.000
33248	19 Contact zone agpaites/augite syenite	56.1	8.1	5.4	19	90	4.7	1,000	600	1%
33231	20 Contact zone agpaites/augite syenite	57.1	8.0	4.8	—	33	—	—	—	—
33249	21 Quartz syenite (augite syenite granite)	65.0	8.4	5.5	27+	50	1.9	30	100	1,800
33233	22 Arfvedsonite lujavrite, Narssaq Elv, 310 m	53.3	9.9	1.7	1,602+	6,500	4.1	3,000	1,000	1%
33292	23 Eudialyte (Narssaq Elv 400 m)	—	13.0	1.1	60	340	5.7	4,000	5,000	»1%

+ Analyses by radioactivation.

Analyst 1) E. I. Hamilton SiO_2, Na_2O, K_2O, U, Th.
2) I. Sørensen La, Y, Zr.

the slightly higher uranium and thorium content may reflect a marginal concentration of these elements, or the incorporation of back veined rheomorphic granite. The chilled zone of the nordmarkitic facies of the augite syenite in the northern part of the intrusion, is represented by Nos. 6 and 7, and the normal coarse-grained variety by No. 3 in Table 11. Compared to the normal chilled syenite this facies shows a two-fold enrichment in both uranium and thorium.

The distribution of uranium and thorium in the granite is partly controlled by the heterogeneous distribution of the accessory minerals. Apart from this sampling error, the granite is enriched in uranium relative to thorium. The average Th/U ratio in the augite syenite is 5.7, while in the granites (omitting the anomalous chilled facies No. 12) it is ca. 2.7. From the few analyses made on the granite there appears to be an increase in both uranium and thorium with a decrease in the amount of potassium and sodium; this is the reverse to the normal trend in igneous rocks.

The concentration of uranium and thorium in the chilled varieties of the Ilímaussaq granite probably represents the effect of the outward migration of these two elements, and the rock probably does not correspond to the original composition of the "granite magma".

It is difficult from total rock analyses to describe quantitatively the distribution of both uranium and thorium in the agpaitic rocks. Superimposed the scattered distribution of the accessory minerals there is the heterogeneous distribution of the major minerals audialyte, aegirine and arfvedsonite all enriched in uranium and thorium. The thorium to the uranium ratio of the naujaite and lujavrite is approximately 4, with the late stage lujavrite formed from the residual magma being greatly enriched in both uranium and thorium. The analyses of these rocks are given in Table 11, Nos. 13—23. In the transition series (Table 11, Nos. 17—21) the rocks have been formed by reaction of both granitic and agpaitic "emanations" upon pre-existing augite syenite. The thorium to uranium ratio of these rocks appears to be comparable to that in the granites.

From the thorium and uranium analyses the following conclusions are drawn: —

1) The augite syenite shows a slight preferential increase in thorium relative to uranium.

2) The uranium and thorium content of the granites increases with a decrease in the amount of potassium and sodium.

3) The agpaites appear to have a fairly normal Th/U ratio with a tendency towards thorium enrichment.

4) In Ussing's transition zone uranium is enriched relative to thorium.

5) The Ilímaussaq intrusion is relatively rich in thorium.

Table 12. Augite Syenite from the lower facies of the upper augite syenite. G.G.U. No. 33242.

Mineral	Mode Vol. %	Total no. tracks	% of alpha particles from rock	% of alpha particles from mineral	alphas/cm².sec.
Feldspar	77.7	348	51.5	100	4.0×10^{-5}
Feldspar	..	48	7.0	14	0.56×10^{-5}
Inclusions	..	271	40.0	70	..
Cracks	..	10	1.5	2	..
Alteration	..	19	3.0	6	..
Augite	14.1	68	10.0	100	0.45×10^{-5}
Augite	..	29	4.2	42	0.19×10^{-5}
Inclusions	..	15	2.2	22	..
Cracks	..	12	1.8	18	..
Alteration	..	12	1.8	18	..
Hornblende	2.0	16	2.3	100	..
Hornblende	..	10	1.5	66	..
Inclusions	..	3	0.4	17	..
Alteration	..	3	0.4	17	..
Apatite	0.6	168	24.6	100	2.6×10^{-4}
Apatite	..	115	17.0	68	..
Inclusions	..	23	3.3	14	..
Alteration	..	30	4.3	18	..
Ore	3.8	6	0.9	100	1.5×10^{-4}
Olivine	1.8	4	0.6	100	2.05×10^{-5}
Accessories	<.1	70	10.2	100	..

Total alpha particle radioactivity, 91 alpha/cm²

The distribution of radioactivity in the Ilímaussaq Intrusion.

The method used in this work and a bibliography of earlier works describing the nuclear emulsion method of analyses have been given by Hamilton (1957, 1959, 1960a). In the examination of the Ilímaussaq intrusion, granites, quartz syenite and two varieties of the augite syenite have been studied. Most of the Ilímaussaq rocks are far too coarse for analyses by the nuclear emulsion method and are perhaps more suitable for individual mineral analyses.

Table 13. Augite syenite adjacent to the naujaite. G.G.U. No. 33409.

Mineral	Mode Vol. %	Total no. tracks	% of alpha particles from rock	% of alpha particles from mineral	alphas/cm².sec.
Feldspar[1]	85.0	633	42.19	100	7.33 $\times 10^{-5}$
Feldspar	..	58	3.86	9.2	0.67 $\times 10^{-5}$
Inclusions	..	392	26.11	61.9	..
Alteration	..	183	12.20	28.9	..
Mafics[2]	10.0	146	9.73	100	1.44 $\times 10^{-5}$
Mafics	..	42	2.80	28.8	0.20 $\times 10^{-5}$
Inclusions	..	83	5.52	56.8	..
Cracks	..	5	0.34	3.4	..
Alteration	..	16	1.06	11.0	..
Intercrystal	..	54	3.60	100	..
Ore	1.1	0	0	0	..
Apatite	2.5	245	16.47	100	9.65 $\times 10^{-4}$
Unknown Accessory	<.1	393	26.20	100	..
Fluorite	<.1	27	1.81	100	..
Olivine	1.4	0	0	0	..

[1] Including 5% nepheline
[2] Pyroxene, amphibole, aenigmatite
Total alpha particle radioactivity: 382 alpha/cm².

Augite syenite (Table 12, 13).

These two samples represent the extreme differentiates of the augite syenite. While the accessory minerals are the most radioactive, the feldspar is more radioactive than the mafic minerals.

Quartz Syenite (Table 14).

Most of the radioactivity originates from the accessory minerals and from inclusions within the major minerals. Apart from the accessory minerals the next most radioactive minerals are the mafics, followed by the feldspar.

Granite (Tables 15, 16, 17, 18).

In the average green granite the accessory minerals are the most radioactive and are followed in order of decreasing radioactivity by

Table 14. Quartz syenite. G.G.U. No. 33194.

Mineral	Mode Vol. %	Total no. tracks	% of alpha particles from rock	% of alpha particles from mineral	alphas/cm².sec.
Feldspar	74.6	126	39.76	100	3.15×10^{-5}
Feldspar	..	33	10.40	27.0	0.83×10^{-5}
Inclusions	..	71	22.40	56.0	..
Cracks	..	22	6.95	17.0	..
Mafics	..	49	15.45	100	1.606×10^{-5}
Aegirine	13.1	12	3.78	24.5	5.205×10^{-5}
Fibrous Amphibole	9.1	27	8.52	55.0	..
Brown mica	..	10	3.15	20.5	..
Apatite	0.2	23	7.25	100	2.017×10^{-3}
Apatite	..	4	1.26	17.4	0.35×10^{-3}
Inclusions	..	19	5.99	82.6	..
Intercrystal	..	25	7.88	100	..
Quartz	2.9	0	0	0	..

Total alpha particle radioactivity: 144 alpha/cm².

Table 15. Aegirine soda granite. G.G.U. No. 33239.

Mineral	Mode Vol. %	Total no. tracks	% of alpha particles from rock	% of alpha particles from mineral	alphas/cm².sec.
Feldspar	55	147	12.03	100	2.94×10^{-5}
Feldspar	..	13	1.06	8.9	0.26×10^{-5}
Inclusions	..	102	8.35	69.1	..
Cracks	..	10	0.82	6.9	..
Alteration	..	22	1.80	15.1	..
Mafics	15	279	22.83	100	2.05×10^{-4}
Aegirine Arfvedsonite	..	63	5.15	22.6	..
Alteration	..	15	1.23	5.4	..
Aenigmatite	..	14	1.15	5.0	..
Alteration	..	187	15.30	67.0	..
Quartz	30	33	2.70	100	1.213×10^{-5}
Quartz	..	6	0.49	18	0.22×10^{-5}
Inclusions	..	27	2.21	82	..

Total alpha particle radioactivity: 255 alpha/cm².

Table 16. Typical soda granite. G.G.U. No. 33240.

Mineral	Mode Vol. %	Total no. tracks	% of alpha particles from rock	% of alpha particles from mineral	alphas/cm².sec.
Feldspar	62	698	16.1	100	10.97×10^{-5}
Feldspar	..	78	1.8	11.0	..
Inclusions	..	600	13.8	86.0	..
Cracks	..	20	0.5	3.1	..
Quartz	24	48	1.10	100	1.92×10^{-5}
Quartz	..	24	0.55	50	0.96×10^{-5}
Inclusions	..	24	0.55	50	..
Arfvedsonite	12	31	0.70	100	0.25×10^{-5}
Arfvedsonite	..	11	0.25	35	0.86×10^{-6}
Inclusions	..	18	0.40	58	..
Alteration	..	2	0.05	7	..
Accessories	1.5	107	2.47	100	6.95×10^{-4}
[1] A	..	42	0.97	40	..
[1] B	..	27	0.67	25	..
[1] C	..	36	0.83	35	..
Intercrystal	..	3404	..	100	66×10^{-3}
Intercrystal	5	12	0.25	0.3	..
Accessory-Intercrystal	..	3392	78.07	99.7	..
Emanation	..	..	..	..	..
Feldspar	F	38	0.87	100	..
Quartz	Q	17	0.40	..	..
Accessories	AC.	3	0.04	..	..

[1] Mineral not determined.

Total alpha particle radioactivity: 1089 alpha/cm².

feldspar, quartz and then the mafic minerals. Similarly, in the chill zone (Tables 17 and 18) the accessory minerals are the most radioactive but are followed by the mafic minerals and then by the feldspar and quartz. The high radioactivity from the quartz in the chilled granite is due to the intimate association of quartz with elpidite. The elpidite is the most radioactive mineral in the granites and is associated with several other radioactive minerals such as epididymite and leucosphenite. In the major minerals most of the radioactivity originates from the inclusions, and not (as far as microscopic examination allows using a magnification of c. ×1,000) from the actual mineral.

Changes in the ratio a/b (a = Total radioactivity from the feldspar, b = Total radioactivity from the feldspar-radioactivity in the feldspar from inclusions and cracks), have been used to compare nuclear emulsion

Table 17. Medium-grained chilled granite. G.G.U. No. 33243.

Mineral	Mode Vol. %	Total no. tracks	% of alpha particles from rock	% of alpha particles from mineral	alphas/cm²./sec.
Quartz	31.00	146	3.20	100	5.85 $\times 10^{-5}$
Quartz	..	22	0.50	15	0.88 $\times 10^{-5}$
Inclusions	..	124	2.70	85	..
Elpidite inclusions	4	2,088	45.90	100	8.5 $\times 10^{-2}$
Amphibole	22	1,006	22.10	100	7.6 $\times 10^{-3}$
Amphibole	..	20	0.40	2.0	0.15 $\times 10^{-3}$
Inclusions	..	167	3.70	16.4	..
Cracks	..	3	0.06	0.3	..
Alteration	..	816	17.90	81.3	..
Feldspar	43	238	5.2	100.0	9.0 $\times 10^{-4}$
Feldspar	..	9	0.2	7.6	0.34 $\times 10^{-4}$
Inclusions	..	220	4.8	92.4	..
Cracks	..	9	0.2	7.6	..
Intercrystal	..	248	5.4	100	..
Alteration	..	830	18.2	100	..

Total alpha particle radioactivity: 1,920 alpha/cm².

Table 18. Fine grained chilled granite. G.G.U. No. 33244.

Mineral	Mode Vol. %	Total no. tracks	% of alpha particles from rock	% of alpha particles from mineral	alphas/cm²./sec.
Quartz	44	942	9.91	100.0	13.73 $\times 10^{-4}$
Quartz	..	8	0.08	0.9	0.12 $\times 10^{-4}$
Inclusions	..	34	0.36	3.6	..
Elpidite inclusions	..	900	9.47	95.5	..
Feldspar	40	95	1.00	100.0	1.49 $\times 10^{-4}$
Feldspar	..	20	0.20	21.0	0.31 $\times 10^{-4}$
Inclusions	..	67	0.72	70.6	..
Cracks	..	8	0.08	8.4	..
Amphibole	10	243	2.47	100.0	15.6 $\times 10^{-4}$
Brown alteration	3	840 } 8110	85.40	100.0	17.74 $\times 10^{-2}$
Elpidite	..	7,270 }	..	..	..
Astrophyllite	3	116	1.22	100.0	24.87 $\times 10^{-4}$

Total alpha particle radioactivity: 1,920 alpha/cm².

data (Hamilton, 1960a). The analyses of the Ilímaussaq specimens gave the following results: —

G.G.U. No.	*Rock Type*	*a/b*
33243	Medium-grained chilled granite	26.5
33244	Fine-grained chilled granite	4.8
33240	Normal granite	9.1
33239	Normal granite	11.3
33194	Quartz syenite	3.8
33242	Augite syenite [1])	7.1
33409	Augite syenite [2])	11.1

[1]) Augite syenite from the lower facies of the upper augite syenite.
[2]) Augite syenite taken adjacent to the naujaite.

In the majority of previously described rocks (granites, basalts) the ratio a/b is approximately 1—3, values > 3 are represented by the late stage magmatic granophyres and granites. The ratio indicates the maximum amount of uranium and thorium present within the crystal lattice of the major minerals of a particular magma series.

Recently the distribution of uranium, thorium and radioactivity in igneous rocks has been described by Krylov (1958), Krylov and Atrashenok (1959), Smyslov (1958) and Whitfield *et al.* (1959). Although none of these authors deal with the syenites exclusively, Larsen (1960) has described the distribution of uranium and thorium in the undersaturated alkali-rich basalts of Honolulu, and in some of the alkaline rocks from Bear Paw Mountains. The uranium and thorium contents of only a few selected intrusions have been studied in moderate detail by Larsen. Whitfield *et al.* (1959) and Rogers and Ragland (1961) have attempted to compare the uranium- thorium- and potassium content, the Th/U and feldspar/plagioclase ratios the colour index, and the quartz content of a varied collection of granites and gneisses. In many of the graphical distribution diagrams, straight lines and curves have been related to a large scatter of the individual points. It is difficult, if not impossible, to obtain fundamental data relating to the geochemistry of uranium and thorium by comparing the uranium and thorium content of such different and unrelated sequences of rocks. This applies in particular to the granites of magmatic origin and in the case of metamorphic rocks we are immediately confronted with the problem of sampling. In magmatic environments we can regard the distribution of a particular element as homogeneously distributed throughout the original magma. However, the distribution and total amount of a particular element in a magma at a certain time or phase in its development may depend upon many factors related to its previous history. In the ideal case the original homogeneous distribution of a particular element is then modified by crystallisation, fractionation, the migration and diffusion of elements

Table 19. Distribution of uranium in the Lovozero intrusion.

Intrusive phase	*Rock types*	*Average uranium content ppm.*
First intrusive phase (Volume °/₀ rock 1°/₀)	Equigranular nepheline syenites Porphyritic nepheline syenites Poikilitic nepheline syenites	9.9
Second intrusive phase (Volume °/₀ rock 75°/₀)	Lujavrites Urtites Ijolites Foyaites	15.3
Third intrusive phase (Volume °/₀ rock 24°/₀)	Lujavrites containing eudialyte, lovozerite, and loparite Poikilitic sodalite syenite	19.7
Fourth intrusive phase	Monchiquite	2.8
	Average uranium content of the Lovozero massif (Saprykina, 1959)	16.0

under partial control of volatiles, alkalies, and structural features develuped within the solidifying magma and during the final hydrothermal phases. In the case of uranium, any initial homogeneity can be expected to disappear from the original magma by the time it has solidified. In the case of the metamorphic rocks there is the problem of the original distribution of uranium and thorium in the unmetamorphosed sequence upon which is superimposed the rearrangement of the elements during the metamorphic period. The metamorphic event can be regarded as an external stimulus applied to the pre-existing rocks, whereas in the case of the true magmatic rocks the final distribution of the elements has been at least partly controlled by internal stimuli. In metamorphic rocks the effect of migration of selected elements can in many instances be seen in the form of basic fronts and such features as alkali metasomatism. In other cases various elements migrate from one area to another, but the rocks commonly show no features from which the amount of migration can be judged. In the case where the metamorphic rocks actually becomes remobilised there is a link to the true magmatic rocks.

The distribution of uranium in the Lovozero alkaline massif has been described by Saprykina (1959) and the uranium content of the various intrusive phases is given in Table 19. The uranium content of the Ilímaussaq lujavrites are very variable compared to those of the Lovozero massif.

THE DISTRIBUTION OF POTASSIUM AND RUBIDIUM AND K/Rb RATIOS IN THE ILÌMAUSSAQ INTRUSION

The association of potassium and rubidium and their abundance in igneous rocks and meteorites has been described by AHRENS *et al.* (1952). From this work it was shown that the ratio K/Rb remains virtually unchanged when proceeding from rock type to rock type. Although this paper does not contain any data on syenites, the low K/Rb ratio found in rocks and minerals crystallising from small volume residual magmas is discussed. The enrichment of rubidium in relation to potassium in rocks that have crystallised from a highly differentiated magma is described by TAYLOR (1956). Rubidium enrichment in some post-orogenic granites and potash feldspars from the east of the Oslo fjord is also described by TAYLOR (1958).

The preferential enrichment of rubidium relative to potassium has been observed in the analysed total rock specimens from the Ilímaussaq intrusion together with an increase in rubidium in the latter differentiates. The maximum enrichment in rubidium is found in the late stage lujavrites. Of all the Ilímaussaq rocks those of the augite syenite suite appear to have a normal K/Rb ratio with a possible tendency to slight enrichment of potassium over rubidium. The total potassium contents and K/Rb ratios of the Ilímaussaq rocks are given in Table 20 and are compared to the distribution of Li, Cs, Ba, Sr, La, and Zr. The latter elements have been determined by spectrochemical analyses using GI as a standard.

The increased rubidium enrichment in some of the minerals from the agpaites and the granites is quite outstanding. A semi-quantitative spectrographic analyses of astrophyllite from a specimen of arfvedsonite lujavrite was kindly carried out by Dr. S. R. NOCKOLDS and gave the following results: —

Rb 4,500, Li, 250 Ba 3000, Sr 200, Ga 45, Sn 250, Zr 450, Co 30 ppm.

The tendency for a second cyclic build up of elements characteristic of the early augite suite, such as Ba, Sr, and Co, appears to be a trend seen in the lujavrites. An examination of some of the minerals from the agpaitic

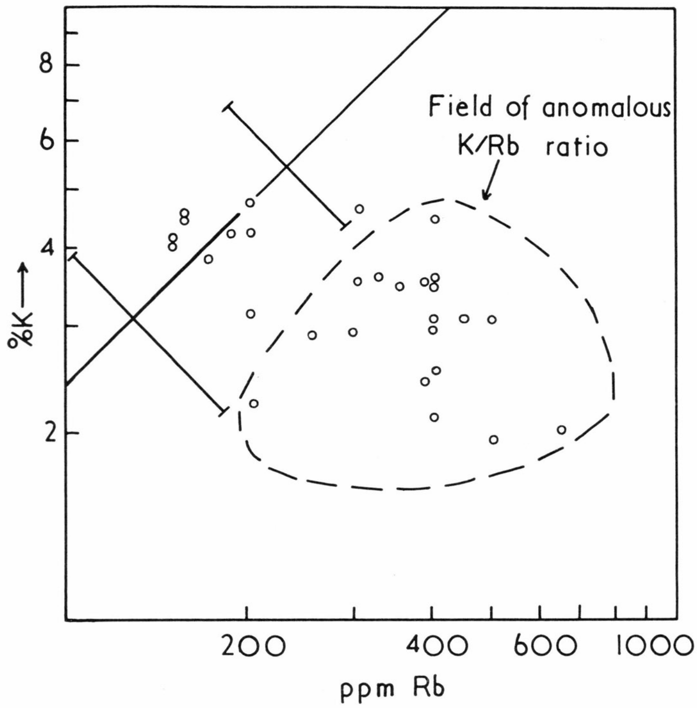

Fig. 31A. K/Rb ratio plot of Ilímaussaq rocks. The area of anomalous K/Rb ratios shows rubidium enrichment relative to potassium.

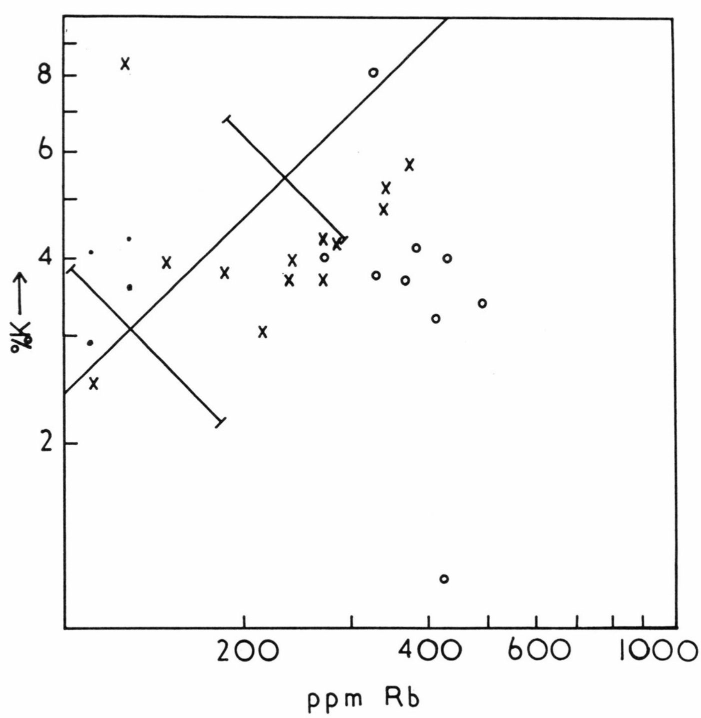

Fig. 31B. K/Rb ratio, plot of Lovozero rocks, Kola Pen., U. S. S. R.

Table 20. The distribution of Potassium and Rubidium in the Ilímaussaq intrusiom.

G.G.U. No.	Rock Type	%K	ppm. Rb	K/Rb	Li[1]	Cs[1]	Ba	Sr	La	Zr
	Augite Syenites									
33452	Chilled type	4.57	[1]200	229	10	tr.	5,000	200	50	500
33645	Chilled type	4.23	[1]185	229	50	0	1,000	300	0	300
16U	Ussing's augite syenite	3.60	400	90	25	0	2,000	300	20	300
33320	Normal augite syenite	4.23	200	212	30	0	5,000	400	30	300
33316	Normal augite syenite	4.07	150	271	20	0	3,000	250	30	300
33242	Inner facies of upper augite syenite	4.15	150	277	15	0	1,500	250	30	500
33448	Inner facies augite syenite/naujaite	4.51	[1]156	289	20	0	1%	400	50	1,500
33173	Nordmarkitic facies	4.46	[1]155	283	25	0	1,500	250	30	200
	Granites									
33240	Normal green granite	3.53	[1]394	90	25	tr.	100	30	300	2,000
33241	Normal blue granite	3.53	300	118	25	tr.	100	30	100	3,000
33239	Varieties of coarse granite	3.50	[1]350	100	50	tr.	80	30	1,000	>1%
33250	Varieties of coarse granite	3.49	[2]523	87	80	tr.	50	[2]10.6	1,000	1%
33251	Varieties of coarse granite	2.99	400	75	100	tr.	150	100	1,500	1%
33252	Varieties of coarse granite	3.10	400	78	90	tr.	50	<30	500	1%
1U	Ussing's granite	3.10	500	62	50	4	80	<30	200	3,000
33243	Medium-grained chilled granite	3.10	[1]449	69	80	tr.	100	100	2,000	>1%
33244	Fine-grained chilled granite	2.41	[1]385	63	80	4	100	100	2,500	>1%

	Agpaites									
6U	Ussing's naujaite	3.60	[1]320	113	20	1	20	0	150	2,500
7U	Ussing's naujaite	1.25	200	63	5	0	50	<30	100	3,000
33158	Sodalite rich naujaite	0.83	155	54	15	0	200	100	800	>1%
5U	Ussing's sodalite foyaite	2.12	400	53	20	2	30	100	100	2,000
4U	Ussing's foyaite	3.86	[1]170	227	10	0	1,500	600	150	2,500
3U	Ussing's pulaskite	2.54	400	64	25	2	30	30	100	2,000
33235	Variety of naujaite-sodalite foyaite	3.15	200	156	10	<5	10	60	30	100
33238	Variety of naujaite-sodalite foyaite	3.57	400	89	70	9	80	30	200	600
33237	Variety of naujaite-sodalite foyaite	2.99	[1]250	120	0	~ tr.	30	30	300	>1%
33245	Foyaite in transition series A	2.99	[1]297	101	80	4	30	30	400	>1%
33246	Foyaite in transition series A	2.24	200	112	100	2	50	30	600	>1%
33247	Contact zone agpaites/augite syenite	4.65	300	155	40	5	80	30	200	3,000
33248	Contact zone agpaites/augite syenite	4.48	400	112	20	8	100	50	1,000	1%
33221	Contact zone agpaites/augite syenite	4.01	[2]447	91	20	<5	50	[2]18.9	500	5,000
33249	Quartz syenite (augite syenite & granite)	4.57	400	114	80	tr.	200	60	30	1,800
11U	Ussing's arfvedsonite lujavrite	2.02	[1]623	32	170	2	50	50	3,000	1%
9U	Ussing's aegirine lujavrite	1.99	[1]500	40	50	2	150	100	2,500	>1%

Analysts: Rb, Li, Cs, Ba, Sr, La, Zr.
Semiquantitative spectropgaphic analysis by I. Sørensen, Copenhagen.
[1]Rb.
Quantitative spectrographic analysis by N. Garton, Oxford.
K.
Flame photometric analysis by E. I. Hamilton, Copenhagen.
[2]Rb, [2]Sr.
Isotope dilution analysis by E. I. Hamilton, Oxford.
For data on Ussing's specimens see Ussing, 1912.

Table 21. Potassium and Rubidium Content of the Lovozero Massif.

Rock type	*K.*	*Rb.*	*K/Rb.*
Rocks of the first complex (miaskitic).			
Nepheline syenites	4.3	128	336.0
Nepheline syenites	4.0	101	396.0
Nepheline syenites	2.9	101	288.4
Nepheline syenites	3.6	128	229.3
Rocks of the second complex (agpaitic).			
Ijolites-urtites	3.0	201	148.3
Ijolites-urtites	3.7	265	137.3
Foyaites	5.7	367	149.3
Foyaites	5.1	338	150.7
Trachytoidal foyaite	3.6	87	429.5
Leucocratic lujavrite	3.8	182	208.5
Leucocratic lujavrite	5.3	261	146.4
Leucocratic lujavrite	4.3	261	164.5
Melanocratic lujavrite	3.7	229	159.6
Melanocratic lujavrite	4.2	265	156.3
Mesocratic lujavrite	4.8	329	146.0
Amphibole lujavrite	3.9	146	259.5
Lujavrite with loparite	3.9	238	164.0
Urtite with loparite	2.5	110	226.6
Urtite with apatite and loparite	0.83	128	647.6
Malignite with loparite	4.3	277	158.6
Rocks of the third complex (agpaitic).			
Eudialyte lujavrite	4.0	320	125.6
Eudialyte lujavrite	4.0	411	97.7
Porphyritic juvite with loparite	4.0	265	150.0
Porphyritic lovozerite with lujavrite	3.7	366	110.9
Poprhyritic lovozerite lujavrite with lomonosovite	3.8	320	119.2
Porphyritic lujavrite with murmanite	4.2	375	112.8
Poikilitic sodalite syenite	2.8	83	338.8
Poikilitic sodalite syenite	3.2	82	383.8
Tavite	1.2	411	282.0

Original analyses see Gerasimovskii and Lebedev (1959).

rocks showed the following rubidium contents: feldspar 25—300 ppm, sodalite 0—15 ppm, eudialyte 20—500 ppm, polylithionite > 1,000 ppm.

From this data it is concluded that in the Ilímaussaq Intrusion the total rubidium content of the rocks increases in the sequence augite syenite, granite to agpaites, with the maximum enrichment in the lujavrites. In the same sequence of rocks the K/Rb ratio shows a normal ratio in the augite syenites, but an enrichment of rubidium relative to potassium in the granites and agpaites.

The distribution of potassium and rubidium in the Lovozero alkaline massif has been described by GERASIMOSKII and LEBEDEV (1959). In the first intrusive phase of the intrusion rubidium stays constant, but is depleted in the third stage. The average rubidium content of the intrusion is 260 ppm. but the present distribution of rubidium has been affected by zeolitisation. In addition there is no relation between potassium and rubidium, but rocks low in rubidium are also low in potassium. The potassium and rubidium content of the Lovozero massif is given in Table 21, and plots showing the K/Rb ratio of the Ilímaussaq rocks and those of Lovozero in Figs. 31 A and 31 B respectively.

From Table 21 it is evident that the maximum rubidium enrichment relative to potassium occurs in the third intrusive stage. In stage two there is an approximate correlation between an increase in potassium with an increase in rubidium.

GEOCHEMISTRY OF BERYLLIUM AND NIOBIUM IN THE ILÍMAUSSAQ INTRUSION

Beryllium.

Various aspects of the geochemistry of beryllium have been described by GOLDSCHMIDT (1954), BEUS (1956, 1955), RANKAMA and SAHAMA (1950), and SANDELL (1952).

Mineralogy.

The main beryllium-bearing minerals of the Ilímaussaq Intrusion are epididymite and leucophanite (USSING 1912). Beryllium enters also into the structure of the feldspars and mafic minerals in varying amounts. (Although beryl has not been identified with any certainty, a beryl-like mineral has been found in the pegmatitic veins of granite cutting the Gardar Formation). Other beryllium minerals such as helvite, danalite, and genthelvite found in the Lovozero intrusion have not been identified in Ilímaussaq although the chemistry of the rocks would indicate that they are present, particularly the zinc-bearing genthelvite. Chkalovite and beryllium sodalite have been found in late albite pegmatite (SØRENSEN, 1960).

Analytical procedure.

In this work the finely crushed rock powder was dissolved in a mixture of hydrofluoric and sulphuric acid and the hydroxides precipitated with ammonia. The interference of calcium and zinc was removed by using E.D.T.A. and 5 $^0/_0$ solution of potassium cyanide. The final end determination of beryllium was made fluorimetrically with morin, using the method of visual comparison against a narrow range of standards.

The ionic radius of beryllium is 1.13°A and that of the positive ion 0.34°A. Like aluminium, beryllium lies between a typical cation and the complex forming elements. It does not exist in the magma as a simple divalent ion but rather as complex ions $(Be0_4)^{-6}$ and substitution occurs between this complex and those of silica $(Si0_4)^{-4}$ and aluminium $(Al_20_4)^{-4}$.

Table 22. The beryllium content of the Ilímaussaq rocks, and other syenites.

Rock type	*Average ppm. Be.*	*Number of analyses.*
1) *Augite syenite*		
Chilled augite syenite (G.G.U. No. 33452)	0.1	4
Normal coarse-grained augite syenite (G.G.U. No. 33320) .	3.0	5
Augite syenite adjacent to the naujaite (G.G.U. No. 33316)	2.0	4
Augite syenite inclusion in the kakortokites (G.G.U. No. 33340)	5.0	3
Mean average:	2.5	..
2) *Granite*		
Fine-grained chilled granite (G.G.U. No. 33243)..........	30.0	2
Medium-grained chilled granite (G.G.U. No. 33244)	40.0	2
Normal coarse-grained granite (G.G.U. No. 33240)	24.0	9
Elpidite-rich variety of granite (G.G.U. No. 33244A)	40.0	2
Epididymite-rich variety of granite (G.G.U. No. 33251)...	65.0	2
Altered riebeckite-calcite granite (G.G.U. No. 33252)	60.0	2
Mean average:	43.0	..
3) *Agpaites*		
Naujaite (G.G.U. No. 33158)	23.0	4
Sodalite foyaite (G.G.U. No. 33233)	37.0	3
Foyaite (G.G.U. No. 33223)	25.0	2
Reaction zone foyaite-augite syenite (G.G.U. No. 33221)..	40.0	4
Arfvedsonite lujavrite (G.G.U. No. 33233)	35.0	3
Mean average:	30.0	..
4)		
Nordmarkite (G.G.U. No. 33526)	7.0	2
Narssaq granite (G.G.U. No. 33524)	15.0	2
Pantellerite dike (G.G.U. No. 33511)	20.0	3

Analyst: E. I. Hamilton

(continued).

Results.

The beryllium content of the Oslo essexites and larvikites is similar to that of the augite syenite suite of Ilímaussaq, while the agpaitic rocks compare favourably with the Oslo lardalites. The Ilímaussaq granite has a higher beryllium content than the Oslo granites, which is reflected by the greater abundance of beryllium-bearing minerals.

The average beryllium content of the Ilímaussaq rocks based on a total of 51 analyses is tabulated below.

Table 22. (cont.)

	Average ppm. Be.	*Number of analyses.*
Goldschmidt (*1954*)		
Dunite	nd.	..
Gabbro, basalts	2.0	..
Gabbro aplite	4.0	..
Granodiorite	2—4	..
Granites	2—20	..
Obsidianites	4—40	..
Nepheline syenites (15 types)	2—220	..
Oslo area		
Essexite	2.0	..
Larvikite	4.0	..
Lardalite	40.0	..
Foyaite	12.0	..
Ditroite	24.0	..
Nordmarkite	4.0	..
Granitite	12.0	..
Beus (*1958*)		*Range, ppm.*
Biotite granite	4.0	2—13
Two mica muscovite granite	9.0	2—17
Average U.S.S.R. granites	5.0	2—23
Acid extrusives	6.0	3—20
Syenites	7.0	3—14
Nepheline syenites (Mariupol)	6.0	4—8
Nepheline syenites (Botogolski)	4.0	3—10
Miaskites Ilmen	7.0	3—10
Vishnerogorski	4.0	2—5
Nepheline syenites Khibina	6.0	5—8
Nepheline syenites Lovozero	12.0	4—24

Rock Type	*Average Beryllium content ppm.*
1) Augite syenite	2.5
2) Granite	43.0
3) Agpaites	30.0

The detailed data of the Ilímaussaq rocks and analyses by Goldschmidt (1954) and Beus (1956) are given in Table 22.

Although no mineral analyses have been made on the Ilímaussaq rocks, Goldschmidt (1954) gave a value of 24 ppm. Be for an arfvedsonite from Kangerdluarssuk fjord. For the Oslo rocks he obtained the following results: — nepheline 120—240 ppm., soda-microline 12 ppm,

Table 23 A. The niobium content of the Ilímaussaq rocks.

Rock type	*Average niobium content ppm. Nb.*	*No. of analyses*
1) *Augite syenite*		
Chilled augite syenite (G.G.U. No. 33452)	6	8
Coarse augite syenite (G.G.U. No. 33201)	18	6
Nordmarkite facies (G.G.U. No. 33173)	8	8
2) *Nordmarkite Narssaq*		
Contact of nordmarkite to essexite (G.G.U. No. 33501)	46	2
Nordmarkite chilled facies (G.G.U. No. 33502)	39	4
Red nordmarkite (G.G.U. No. 33503)	14	2
Black dike cutting nordmarkite (G.G.U. No. 33504)	8	2
Syenite dike cutting nordmarkite (G.G.U. No. 33506)	7	2
Chilled pantellerite dike(G.G.U. No. 33511)	50	2
Centre of pantellerite dike (G.G.U. No. 33511)	20	2
3) *Narssaq granite* (G.G.U. No. 33505)	25	2
4) *Pyroxenite, Narssaq* (G.G.U. No. 33499)	50	4
5) *Ilímaussaq granites*		
Typical green granite (G.G.U. No. 33240)	447	6
Typical blue granite (G.G.U. No. 33241)	487	6
Elpidite-rich granite (G.G.U. No. 33244 F)	837	5
Medium-grained chilled granite (G.G.U. No. 33244)	1040	6
Fine-grained chilled granite (G.G.U. No. 33243)	1110	6
6) *Ilímaussaq quartz syenite*	156	6
Mineralised quartz syenite breccia (G.G.U. No. 33193)	1030	2
7) *Agpaites*		
Naujaite (G.G.U. No. 33158)	880	4
Sodalite foyaite (G.G.U. No. 33233)	1115	8
Foyaite (G.G.U. No. 33223)	1076	4
Contact foyaite to augite syenite (G.G.U. No. 33222)	595	4
Foyaite replacing augite syenite (G.G.U. No. 33226)	565	4
Contact lower granite to altered augite syenite (G.G.U. No. 33662)	593	4
Lujavrite, uranium-rich type (G.G.U. No. 33232)	1400	7
Arfvedsonite lujavrite (G.G.U. No. 33233)	555	3
8) *Minerals*		
Sodalite (G.G.U. No. 33158)	75	6
Eudialyte (G.G.U. No. 33158)	1342	8

Analyses by E. I. Hamilton.

Table 23 B.
Niobium content of rocks from the Lovozero massif.
Gerasimovskii *et al.* (1959).

Intrusive Phase	*Rock Type*	*Average Niobium content. ppm.*
First intrusive phase		
(Volume %₀ rock, 1%)	Nepheline syenite	317[1]
	Porphyritic nepheline syenites	360, 370, 330.
	Poikilitic nepheline syenites	280, 161, 225.
Second intrusive phase		
(Volume % rock, 75%)	Urtite	420.
	Ljolite urtites	365, 474, 90.
	Foyaites	459, 296, 565.
		360, 430.
	Lujavrite, leucocratic	720.
	– mesocratic	660.
	– amphibolitic	520, 625, 395.
	– + loparite	1,270, 1,200.
	– + eudialyte	1,113.
Third intrusive phase		
(Volume % rock, 24%)	Lujavrite + eudialyte	918, 497.
	Porphyritic lujavrite	338.
	Porphyritic lujavrite + murmanite	965.
	Porphyritic lujavrite + lovozerite	1,600.
	Poikilitic sodalite syenite	590, 365, 350.
	Tavite	400.
Fourth intrusive phase		
	Monchiquite	1,100, 985.
Average niobium content	of Lovozero massif.	700.

[1] Where original analyses were determined by wet chemical methods and X-ray spectrography the results have been averaged.

Average niobium content of igneous rocks, Rankama (1948).

Rock Type	*Average Nb_2O_5*
Monomineralic rocks	0.4
Ultrabasics	23.0
Eclogites	5.0
Gabbros	27.0
Diorites	5.2
Granites	30.0
Syenites	50.0
Nepheline syenites	450.0
Basic alkaline rocks	20.0

aegirine 400 ppm, barkevikite 220 ppm, lepidomelane 24 ppm. (Be); and for a nepheline from the Khibina intrusion 40 ppm Be.

Niobium.

Our present day knowledge of the distribution of niobium in various types of rock is based mainly on the detailed work of RANKAMA (1948). More recently quantitative data for alkaline rocks has been presented by GOLDSCHMIDT (1954), ESKOVA (1959), PAVLENKOV (1958) and GERASIMOVSKII *et al.* (1959). The close similarity between niobium and tantalum is reflected in thier geochemical distribution. In both elements the atomic radius (in 12 co-ordination) is 2.94°A and the ionic radius for niobium 0.69°A (Nb^{+5}) and for tantalum 0.68°A (Ta^{+5}). Apart from the niobium-tantalum association there is a strong similarity between niobium and titanium (Ti^{+4}), and zirconium (Zr^{+4}). Like beryllium, niobium does not exist in a magma as free positive ions but rather as the central atom of a complex anion. The effect of the complex formation is seen in many intrusion in which niobium has concentrated in the residual liquids and has not substituted for titanium in the early crystallisation of the iron ores. Although niobium and tantalum are almost identical in their geochemical behaviour, tantalum shows a preferential concentration in normal granites, while niobium concentrates in the residual liquids of syenites and nepheline syenites.

Mineralogy.

In the Ilímaussaq Intrusion the dominant niobium minerals are pyrochlore, microlite, epistolite and eucolite. Apart from the major niobium minerals, niobium is also present as a minor constituent in the many complex sodium, titanium, iron, rare-earth and zirconium minerals.

Table 23A presents the niobium content of the Ilímaussaq rocks. Table 23B shows the niobium content of the rocks forming the Lovozero alkaline massif and the average niobium content of igneous rocks.

Analytical Procedure.

The niobium was determined by a slightly modified form of the procedure given by WARD and MARRANZINO (1955). In the original method the technique of solution of the rock powder was suited to the fairly rapid determination of niobium in rocks in the field. In the present method 300 mg of finely ground sample was treated with a mixture of sulphuric and hydrofluoric acids and evaporated to dryness; this was separated and the final residue fused with 300 mgs of fused and powdered sodium bisulphate. The fused cake was dissolved in tartaric acid and the clear solution extracted with a mixture of ammonium thiocyanate and ethyl ether. The extraction of iron was reduced by the addition of stannous chloride. The addition of acetone to the ether extract inhibits the polymerisation of the thiocyanate and stabilises the colour for at least 20 hours. The niobium content of the samples was determined by means of a Beckmann spectrophotometer measuring at 385 mu. with reference to a previously prepared standard curve.

Results.

In the augite syenite suite niobium is relatively enriched in the coarse-grained facies; this increase is paralleled by the increase in sodium and zirconium. The nordmarkitic facies of the augite syenite show a slight enrichment in niobium. The niobium content of the Narssaq granite falls between that of the chilled augite syenite and the nordmarkitic facies of the augite syenite. The normal soda granite contains an average of 467 ppm. Nb. In the chilled facies of the granite there is a two-fold increase of niobium associated with the enrichment in beryllium, lithium, rare earths, uranium and thorium. The agpaites show a characteristic high niobium content as may be expected from the widespread occurrence of niobium-rich accessory minerals. At the contact of agpaites to augite syenite (Ussing's pulaskite), these soda-rich rocks show a high niobium content relative to the coarse-grained augite syenite. At this horizon pyrochlore is not present and the niobium is associated with the localised areas of eudialyte, and a white, altered, sodium-niobium-silicate that has not been identified. Only two analyses are given of the lujavrites and can only be regarded as indicating the approximate niobium content of these variable rocks.

ADDITIONAL NOTES ON THE DISTRIBUTION OF SOME ELEMENTS

Lithium.

The independant determination of lithium in some selected rocks was done by spectrographic analyses using G1 as an external standard. The results given below indicate a maximum enrichment in the granites, sodalite foyaite and lujavrite.

G.G.U. Rock No.	*Rock Type*	*Average ppm Li.*
33452	Chilled augite syenite	60
33374	Inner facies of augite syenite	65
33173	Nordmarkitic facies of augite syenite	40
33240	Normal granite	90
33244	Medium-grained chilled granite	100
33243	Fine-grained chilled granite	90
33222	Pulaskite-foyaite contact rock	90
33223	Sodalite foyaite	110
33174	Sodalite naujaite	50
33243	Arfvedsonite lujavrite	80

(Anal. N. GARTON, Oxford)

Gallium.

The gallium contents have been determined by quantitative spectrographic analyses and the results are compiled from at least four determinations of each rock type.

	Rock Type	*Average ppm Ga.*
	Augite syenite	30
	Granite	10
	Chilled granite	50
	Naujaite	10
So	Sodalite foyaite	< 10

(Anal. I. SØRENSEN, Copenhagen)

Tin.

No tin minerals have been identified and with a limit of detection by spectrographic analyses of 10 ppm this element has not been found in the main rock types. The only tin found in total rock analyses is from sodalite foyaite-naujaite breccia associated with the later intrusion of quartz syenite where a tin content of 200—300 ppm has been noted. This zone is associated with massive purple fluorite and actual tin-enriched minerals may be expected in this area. Preliminary analyses of some of the separated minerals from the intrusion contain tin, in particular the feldspar from the augite syenite (100 ppm Sn, anal. Nockolds), the eudialyte (200—300 ppm Sn., anal. Sørensen) and the steenstrupine 100 ppm Sn., anal. Sørensen) from the agpaites.

CONCLUSIONS

Conclusions regarding the petro-chemical development of the Ilímaussaq Intrusion cannot be made until the rest of the intrusion has been re-examined. At this stage, however, it is possible to outline the main sequence of events that occurred in the northern part of the intrusion.

1) The first phase in the intrusive sequence of Ilímaussaq is marked by the emplacement of the augite syenite suite of rocks. The augite syenite has an outer chilled facies and passes inwards to coarse-grained rocks. The outer facies are poor in nepheline while the amount of nepheline increases in the inner coarse-grained rocks. The inner facies are represented by a foyaite.

2) The second phase of intrusion resulted in the emplacement of the naujaite, sodalite foyaite, and lujavrites. The lujavrite is essentially crystallised from a residual liquid derived from the naujaite sequence.

3) The third phase of intrusion is probably marked by the intrusion of quartz syenite and soda granite. The quartz syenite was intruded after the previous agpaitic sequence, but its relation in time to the granite is uncertain. The granite has a pronounced upper chilled zone.

4) The hybrid zone from naujaite to granite as implied by Ussing does not exist, and Ussing's pulaskite probably represents a contaminated facies of the augite syenite developed beneath the upper augite syenite which forms a roof continuation of the marginal augite syenite sequence.

5) The author would agree with Ussing in that the alkaline rocks of Ilímaussaq were derived from two magmas; one the augite syenite magma giving rise to the basic outer facies and the inner more undersaturated differentiates, and the other a magma giving rise to the agpaites. The former magma may represent an earlier differentiate of the latter. The sequence augite syenite (which is covered by many names such as pulaskite, umptekite, or simply syenite) and foyaite was followed by the intrusion, without any appreciable time interval, of the agpaites and granites. This is a fairly common sequence seen in alkaline intrusions throughout the world. In some cases the syenites are genetically related to more basic rocks such as the essexites or gabbros and it is possible to trace the development of a potential alkaline magma within a small area.

In the Ilímaussaq Intrusion it would appear that the volatiles have been retained by the magma during its development and have not been lost.

6) The following sequence of events is suggested for the emplacement of the Ilímaussaq intrusion —

a) The intrusion of an augite syenite magma contemporaneous with block faulting and cauldron subsidence.
b) As the central block sank a magma chamber was gradually formed into which the volatile-rich agpaites were intruded. Reaction with the augite syenite gave rise to the hybrid pulaskite. Crystallisation of the agpaites gave rise to the partially layered naujaites. Although it is improbable that a rock representative of the original undersaturated magma now exists, the sodalite foyaite may be regarded as approaching the original composition.
c) The direction of cooling of the agpaites was inwards resulting in the formation of a pocket of residual liquid, the lujavrites.
d) The lujavrites differentiated at lower levels to form the layered kakortokites.
f) As the confining pressure of the "lujavrite pocket" was exceeded the magma explosively brecciated the surrounding naujaite. Contemporaneous with brecciation there was a general slumping which gave southerly dip to the banding in the naujaite.
g) The next event was the intrusion of a hybrid magma from which the quartz syenites crystallised.
h) A sheet of soda granite was intruded next.

APPENDIX

Silicate Analyses.

The silicate analyses carried out by the author were made by methods of rapid silicate analyses described by SHAPIRO and BRANNOCK (1956) and RILEY (1958), except for the determination of aluminium.

In this paper each analysis was carried out using two standards. One was prepared from pure chemicals, the other involved the use of a rock of known and similar composition to the unknown sample. The artificial standard was used to check the separation and method. Calculations as to the amount of an element present were made by comparison to the standard rock. In addition, standard rocks were checked against the artificial standards.

Aluminium.

A large number of the rocks examined contain one per cent or more of zirconium, and other elements, that lead to errors in the final colourimetric determination by use of alizarin red-S.

Aluminium was determined with good reproducability by a volumetric method, described by H. L. WATTS, 1958. In a highly basic solution, aluminium forms soluble aluminate, and iron and titanium precipitate as hydroxides. When aluminium reacts with fluoride, the hydroxide which combines with the aluminium can be released by titration with standard acid. The titration can be preformed in the presence of the precipitated hydroxides. Interference from calcium can be eliminated by precipitating it as the oxalate. By limiting the sample size, aluminium can be determined in the presence of silicon dioxide. The method is fast, precise, and accurate. If large amounts of zirconium are present a correction factor can be determined. In practice this was not necessary. Although the determination of aluminium can be carried out in the presence of silicon dioxide, the silica was removed by decomposing 200 mg of rock in a mixture of hydrofluoric and nitric acids.

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Preliminary Geological Map
of the Northern Part of
THE ILÍMAUSSAQ INTRUSION
SW Greenland
by Eric Hamilton. Mapped in 1957 and 1959
Topographical map by the Geodetic Institute, Copenhagen
1:40.000
0,1 0 1 2 km
Heights in metres
Contour interval 100m
Granite
Alkali granite
Agpaitic Syenites
Lujavrite
Zone of lujavrite brecciating naujaite
Foyaite
Sodalite foyaite
Naujaite
Syenites
Quartz syenite
Pulaskite
Marginal syenite
Gabbro
Gardar continental series
Alluvium
Dykes
Faults
Dips
Ice
Traverse across transition series
45°55'
60° 57'
Ilímaussaq
Narssaq Elv
Nákâlâq
Taseq
Ndr. Siorarssuit
Igdlúnguaq
TUNUGDLIARFIK