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THE ILÍMAUSSAQ BATHOLITH

A REVIEW AND DISCUSSION

BY

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WITH 18 FIGURES IN THE TEXT

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Abstract.

The Ilímaussaq batholith was examined and described in a masterly way by N.V. Ussing in the first years of this century. During the last few years the region has been re-examined and this work is still being carried out. It is based on maps far superior to those used by Ussing.

This paper is a summary of the present knowledge of the geology of the batholith. Ilímaussaq is one of many plutonic bodies in the alkaline province of South Greenland. Its formation was preceded by the accumulation of sandstone, extrusion of lavas, and block movements. The country rock consists of granite.

Ussing divided the plutonic rocks of Ilímaussaq into two groups: 1) the unstratified complex made up of fairly normal rocks as augite syenite, essexite, nordmarkite, and arfvedsonite granite; 2) the stratified, peralkaline, agpaitic nepheline syenites: sodalite foyaite, naujaite, kakortokite, and lujavrite. These rocks are often rich in sodalite and eudialyte.

The marginal borders of the batholith are transgressive. The agpaites are overlain by almost horizontal beds of porphyries. The stratified part of the complex is saucer-shaped.

According to Ussing the batholith was formed in two stages; in the first stage the unstratified rocks crystallized, in the second the agpaites were intruded and partially replaced the unstratified rocks. The differentiation of the agpaites has later been discussed by Fersman and Backlund. Wegmann considered the nepheline syenites to be of metasomatic origin.

The Ilímaussaq batholith is compared with other regions of alkaline rocks. On this basis and in the light of new field data the magmatic and metasomatic modes of formation of the batholith are discussed. Much more field work is, however, still necessary before more final conclusions can be reached.

In addition to Ussing's interpretation of the genesis of the batholith a somewhat different magmatic explanation is put forward. Augite syenite is considered to be the primary magma. A part of this magma was trapped under an impermeable roof and huge amounts of volatiles were accumulated in the magma during its crystallization, especially in its upper part (cf. Säther, *45*). The sodalite-rich naujaite crystallized in the upper part of the magma, the banded kakortokite at a deeper level. In a later phase, subsidence of parts of the batholith occurred and in this stage the melanocratic and schistose lujavrite was formed. This rock can be compared with tinguaites and may then be considered to be magmatic, but it may also be regarded as a metasomatic rock especially formed in the most deformed parts of the complex.

Wegmann's view that essexite, nordmarkite and porphyries are metasomatically transformed into nepheline syenites is discussed. It is supported by the finding of a pillow structure in the lujavrite. As an alternative the writer suggests that the metasomatism has acted upon an older plutonic body made up of augite syenite and foyaite, etc.

In the writer's opinion the combination of magmatic and metasomatic processes is in best agreement with the field observations.

INTRODUCTION

During the last few years detailed geological examinations have been undertaken by Grønlands geologiske Undersøgelse (the Geological Survey of Greenland) on the Ilímaussaq batholith in the Julianehaab District, South Greenland.

The Ilímaussaq batholith—so named by N.V. USSING in his classical description of the region—was visited by this eminent geologist in the years of 1900 and 1908. During two short field seasons he was able to map the geology of the whole region. On this basis he described the most important rock types and discussed in a masterly way the petrogenesis of the region.

Many years have now passed since USSING carried out his field work on the Ilímaussaq batholith, but the geologists now working in the area do not feel this lapse of time, so plentiful are USSING's observations, so precise his descriptions. Even though the first geological mapping of the batholith was done so brilliantly, there is, of course, still a lot of work to be done in the area. New topographical maps make a more detailed geological mapping possible and there are rock varieties not described by USSING. Also the structural relations are far from solved.

The geological re-mapping of the batholith has not yet been completed. The present paper is therefore not a conclusive discussion of the batholith, but the author regards it as a review of the interesting geology of the batholith and a discussion based on USSING's observations and on observations undertaken during the last few years. The reason for the publication of this paper at an early stage in the mapping is that the author's work in Denmark will prevent him from continuing his field work in the years to come, and he therefore wishes to put forward for discussion the views on the genesis of the batholith arrived at during his work on the batholith. The paper may further serve as an introduction to the papers on minor problems within the batholith which will be published before the geological map.

I am indebted to professor, dr. T. F.W. BARTH, dr. CHR. OFTEDAHL and dr. O. ADAMSON in Oslo, and to professor, dr. A. NOE-NYGAARD, Mr. A. BERTHELSEN, Mr. J. BONDAM, Mr. K. ELLITSGAARD-RASMUSSEN, dr. E. HAMILTON, and Mr. F. L. JACOBSEN, in Copenhagen for discussions of the geology of Ilímaussaq and the problem of the origin of the alkaline rocks.

For the excellent working facilities during the field seasons in Greenland I am most grateful to the staff of the Geological Survey of Greenland, especially to Mr. J. BONDAM, the leader of the mapping of the Ilímaussaq batholith.

I wish to express my appreciation to Mrs. R. LARSEN for drawing the maps and to Mr. A. KIILERICH for preparing the photographs for publication.

The Mineralogical Museum of the University of Copenhagen in february 1958.

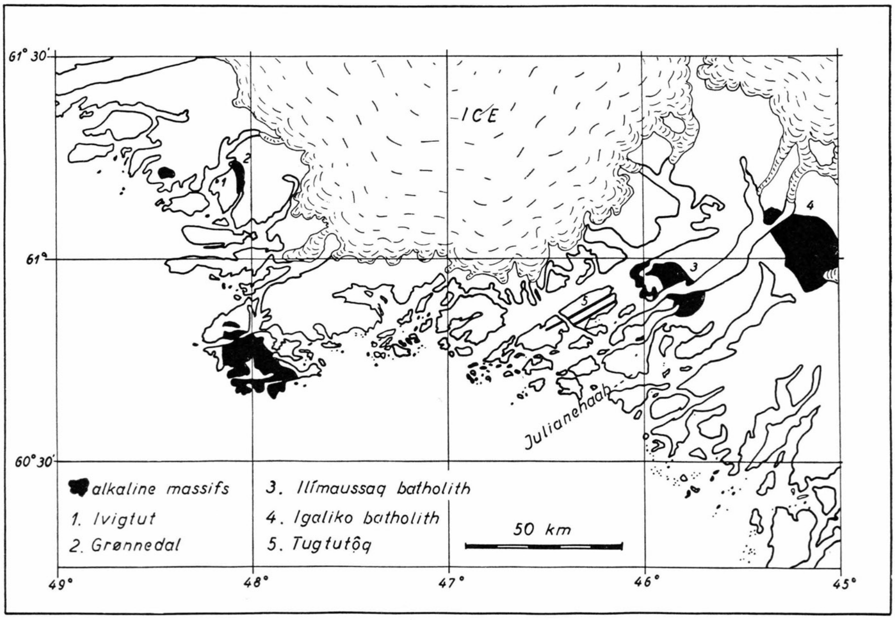

Fig. 1. General map of the Julianehaab area showing the location of the Ilímaussaq and the Igaliko massifs and other alkaline bodies. The two big dykes on the island of Tugtutôq (5) are also indicated.

THE GEOLOGY OF THE ILIMAUSSAQ BATHOLITH

As mentioned by Ussing (*55*) and Wegmann (*56*) South Greenland is rich in plutonic bodies of alkaline type. The region may therefore be termed an alkaline province.

There are rocks of miaskitic type (as defined by Fersman, *21*, p. 69) and of agpaitic type (as defined by Ussing, *55*, p. 341 and Fersman, *21*, p. 69). Examples of the first group are found at Grønnedal (Callisen, *15*), in the Igaliko batholith (Ussing, *55*), and in parts of the Ilímaussaq batholith. The agpaitic rocks are known so far only from Ilímaussaq.

The two big massifs Ilímaussaq and Igaliko (fig. 1) are both situated at the Tunugdliarfik Fjord in a region characterized by block faulting and they are associated with a thick series of volcanic rocks (porphyries) and sandstone, rocks preserved in an area made up of older granite (Julianehaab granite) due to down faulting. The sandstone and its overlying lavas are older than the plutonic rocks. The lavas have unfortunately not yet been made the subject of a more detailed study.

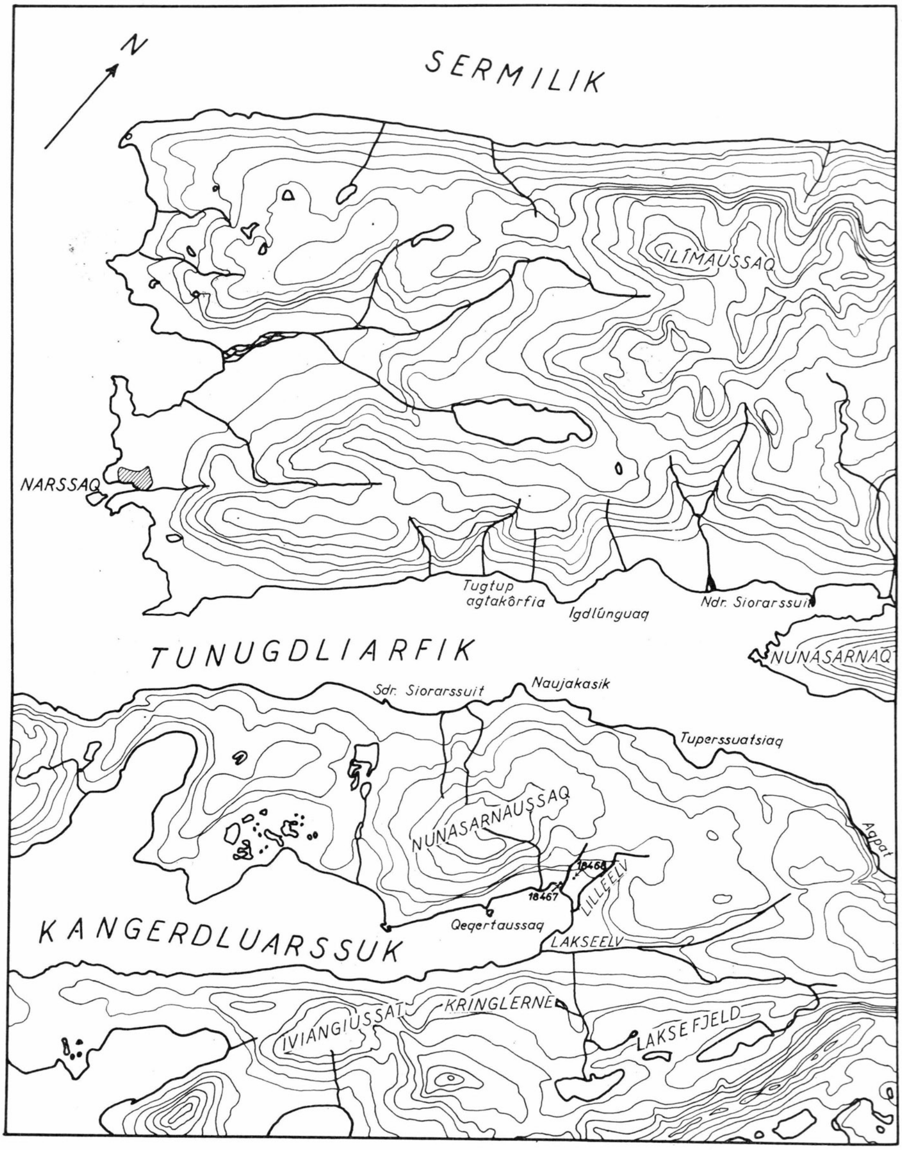

Fig. 2. Topographical map of the Ilímaussaq area. The map has been based (with the kind permission of the Geodetic Institute, Copenhagen) on a preliminary map in 1 : 50.000 (copyright Geodetic Institute, Copenhagen). The map has been reduced to a scale of ca. 160.000, equidistances are 100 m.

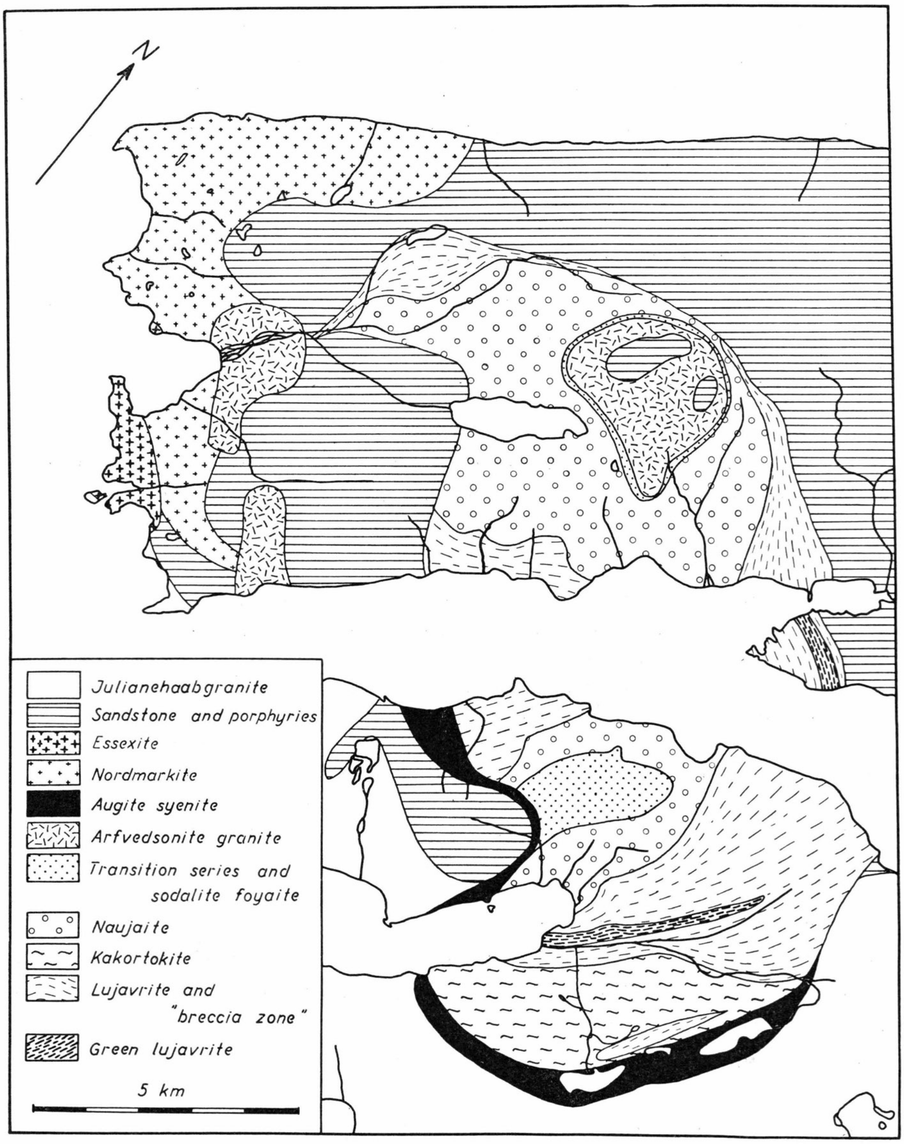

Fig. 3. Geological sketch map of the Ilímaussaq batholith based on Ussing's map with topographical corrections according to the map of fig. 2 and with a few minor corrections. As mentioned in the introduction, the Geological Survey of Greenland is undertaking a re-mapping of the batholith.

The two plutonic bodies mentioned above are cut by a limited number of dykes, but dykes (and sills) are common in the country rocks. USSING (*55*) has described the following types of dykes: diabase, monzonite porphyry, augite syenite, hedrumite, nepheline porphyries, tinguaite, and sölvsbergite.

The Rocks of the Ilímaussaq Batholith.

The batholith was divided by USSING into an older unstratified and a younger stratified part.

A. The unstratified part of the complex is composed of the rocks essexite, nordmarkite, arfvedsonite granite and augite syenite.

The **essexite** and **nordmarkite** occur to the west of the main part of the batholith and they appear to form independent bodies.

The essexite is coarse to very coarse-grained, but it is fine-grained against the sandstone. The components are: labradorite, soda orthoclase, augite, olivine, hornblende, biotite, apatite and iron ore. The name essexite is sometimes as in the present case used to describe orthoclase-bearing olivine gabbro. If the name is restricted to gabbro containing feldspatoids, syeno-gabbro or the term essexite gabbro used by WEGMANN (*56*) would be a more appropriate name for this particular rock, than the term essexite used by USSING.

The nordmarkite is younger than the essexite. It has fine-grained borders against the porphyries into which it sends apophyses. It is composed of perthitic alkali feldspar (often surrounded by a rim of albite), augite, ægirine-augite, biotite, hornblende, apatite, a small amount of ægirine, arfvedsonite, and ænigmatite.

The arfvedsonite granite occurs as an almost horizontal (partial) cover above the stratified part of the complex to the north and south of the Tunugdliarfik Fjord (USSING, *55*, pp. 70 and 109). Downwards there is a gradual transition via syenitic rocks (USSING's transition series) into the nepheline syenites of the stratified part of the complex. There are pegmatitic veins parallel to the transition zone and numerous apophyses penetrate into the overlying porphyry.

The granite is composed of microperthite, quartz, arfvedsonite (often brown in the central parts of the grains, green along the margins), ægirine (often as a rim around the arfvedsonite), ænigmatite and zircon.

A smaller body of arfvedsonite granite is found near Narssaq adjacent to sandstone, porphyries, and nordmarkite. It has the same minerals as mentioned above, and in addition augite as a subordinate constituent.

The augite syenite is found along the south and south west borders of the stratified part of the complex. It has also been found locally in the north western border of the complex (USSING, *55*, pp. 85 and 86) and in the north east border (JACOBSEN, personal information). A white augite syenitic rock has been observed by USSING (*55*, pp. 87 and 88) above the arfvedsonite granite to the south of the Ilímaussaq mountain. Inclusions of augite syenite have been found in the stratified rocks, especially in the kakortokite. In one place on the south coast of Kangerdluarssuk there are inclusions of sandstone in the augite syenite with a granitic zone of reaction separating the two rocks.

The augite syenite has fine-grained borders against Julianehaab granite and sandstone and may carry quartz close to these rocks. Apophyses of the rock have been found in the country rocks.

The rock is composed of perthitic soda orthoclase, augite, olivine, hornblende, biotite, apatite, iron ore and occasionally of ægirine augite, arfvedsonite, quartz, and ænigmatite? The rock may show a faint banding.

Augite syenite is the marginal rock in the known part of the Igaliko batholith, around which there, according to USSING, are many dykes of augite syenite and of the related hedrumite. They may be up to 40 m thick. BONDAM (*9*) has mentioned augite syenite from two big dykes on the island of Tugtutôq to the west of the Ilímaussaq batholith (fig. 1). The dykes point towards the batholith.

B. The stratified part of the complex is in the ideal section from top to bottom composed of: arfvedsonite granite – quartz syenite – pulaskite – foyaite – sodalite foyaite – naujaite – "breccia zone" (see p. 19) – lujavrite with kakortokite. The bottom of the complex is not seen, hence USSING's term batholith. There are gradual transitions between the members of the sequence, but the kakortokite has inclusions of naujaite and the lujavrite inclusions of naujaite and kakortokite.

The transition series includes quartz syenite, pulaskite and foyaite and shows gradual transitions from quartz-bearing to nepheline-bearing rocks. It is up to 40 m thick and occurs to the north and south of Tunugdliarfik. USSING (*55*, p. 341) has described gradual transition from the marginal augite syenite to the pulaskite in Nunasarnaussaq.

The minerals are: quartz (in the upper part), nepheline (in the lower part), perthitic microcline (often with marginal albite), ægirine augite, biotite, arfvedsonite, ægirine and ænigmatite. The foyaite contains in addition: sodalite, olivine, eudialyte, apatite and iron ore. The ægirine augite may have rims of ægirine. The foyaite is coarse-grained, trachytoid, and it resembles the khibinite of the Khibina Tundra, the Kola Peninsula.

The sodalite foyaite forms a zone, 2—150 m thick, between transition series and naujaite.

The components are: microcline-microperthite, nepheline, sodalite, arfvedsonite, ægirine, eudialyte, biotite, and ægirine augite. The rock is rich in

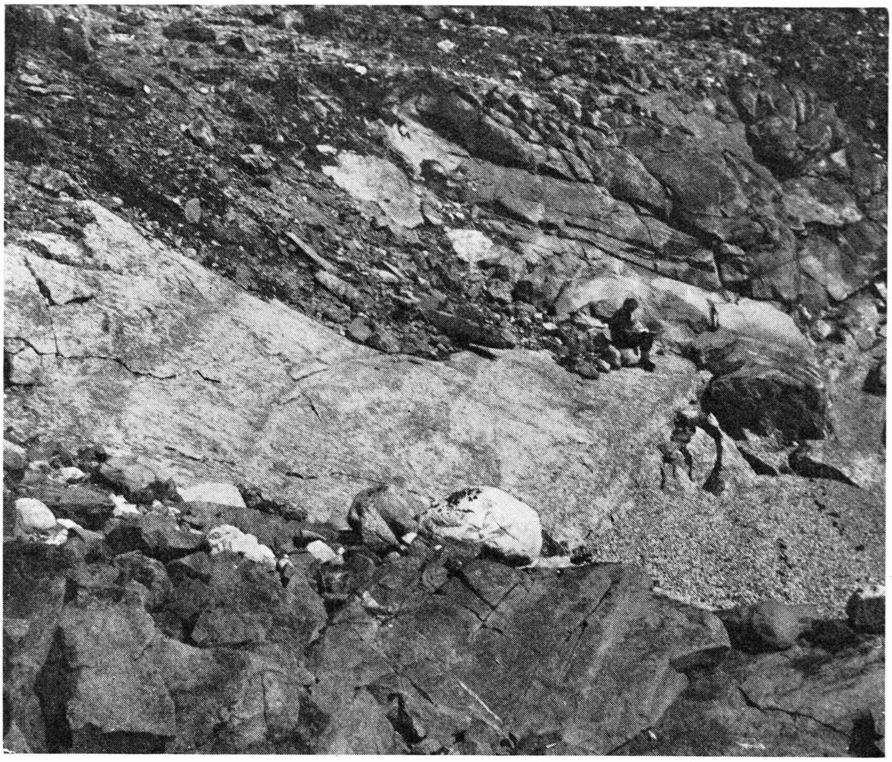

Fig. 4. Banding in the naujaite at Igdlúnguaq. The naujaite (white) is enclosed in lujavrite (black) of the "breccia zone". See further figs. 5 and 10.

minerals containing volatiles and rare elements, in addition to the sodalite and eudialyte mentioned above, there are rinkite, lithium mica, steenstrupine, and fluorite. The order of crystallization is, according to USSING, feldspar, eudialyte, nepheline, ægirine, and arfvedsonite. The sodalite is older as well as younger than the feldspar. The ægirine augite has rims of ægirine.

The naujaite is a very coarse-grained nepheline syenite with a peculiar poikilitic texture: small crystals of sodalite are enclosed in the other minerals of the rock. In the summer of 1957 an irregular banding was observed in the naujaite at Igdlúnguaq and at Qeqertaussaq. It is caused by the variation in the content of eudialyte, dark minerals and light-coloured minerals, so that red, black and white layers are developed (figs. 4 and 5). There is no regular repetition of the layering and it seems to be of local importance only. Normally the texture of the naujaite is fairly massif.

The constituents are in the apparent order of crystallization: sodalite, nepheline, eudialyte, microcline microperthite, ægirine, and arfvedsonite. Minor constituents are: ænigmatite, rinkite, rosenbuschite, molybdenite,

Fig. 5. Banding in naujaite. Close up of fig. 4. The dark layers are rich in arvedsonite.

sphalerite, lithium mica, and apatite. The eudialyte is present in large grains with numerous inclusions of sodalite. The smaller grains of eudialyte are generally well-developed crystals.

The lujavrite is the most fine-grained nepheline syenite of the complex. It shows a wide range in grain size, texture, structure, colour, and composition. The texture may vary from massive to a pronounced lineation produced by the parallel arrangement of prismatic crystals of ægirine and/or arfvedsonite. The rocks may show foliation with wavy and glistening planes of foliation. Some varieties are strongly schistose. As pointed out by Ussing (*55*, p. 39) and Wegmann (*56*, p. 76) the lujavrite resembles most of all the crystalline schists, in particular amphibolites.

Ussing described two main types, a green rock rich in ægirine, and a black one rich in arfvedsonite. The occurrence of the black rock is more widespread than that of the green lujavrite. The two varieties usually form independent masses but they may in places occur together,

Fig. 6. Banding in the kakortokite of Kringlerne. In centre a mass of altered naujaite conformably enclosed in the kakortokite (F. L. JACOBSEN phot.).

as on the north coast of Tunugdliarfik where the green rock is present as bands or inclusions in the black rock.

Thin veins of lujavrite cut the naujaite.

The lujavrite has inclusions of altered augite syenite (or perhaps essexite), porphyries, naujaite, and kakortokite. The inclusions are often deformed and more or less recrystallized.

The minerals are: arfvedsonite and/or ægirine, laths of microcline and/or albite, crystals of nepheline and eudialyte, and in minor quantities: sodalite, sphalerite, britholite, ænigmatite, schizolite, astrophyllite, naujakasite, steenstrupine, monazite, and fluorite. The feldspar laths, the columnar crystals of nepheline, and the platy crystals of eudialyte are arranged parallel to the prisms or needles of ægirine and arfvedsonite. The laths of feldspar and the needles of ægirine may be broken. Thus movements have played an important rôle during the formation of the lujavrite (see further p. 36).

The kakortokites occur in the southern part of the complex called Kringlerne. They are coarse-grained rocks with a pronounced foyaitic texture. They show a pronounced, almost horizontal stratification or banding caused by the alternation of layers of different colours: black (rich in arfvedsonite), red (rich in eudialyte) and white (rich in feldspar and nepheline). The white layers are the thickest and most prominent

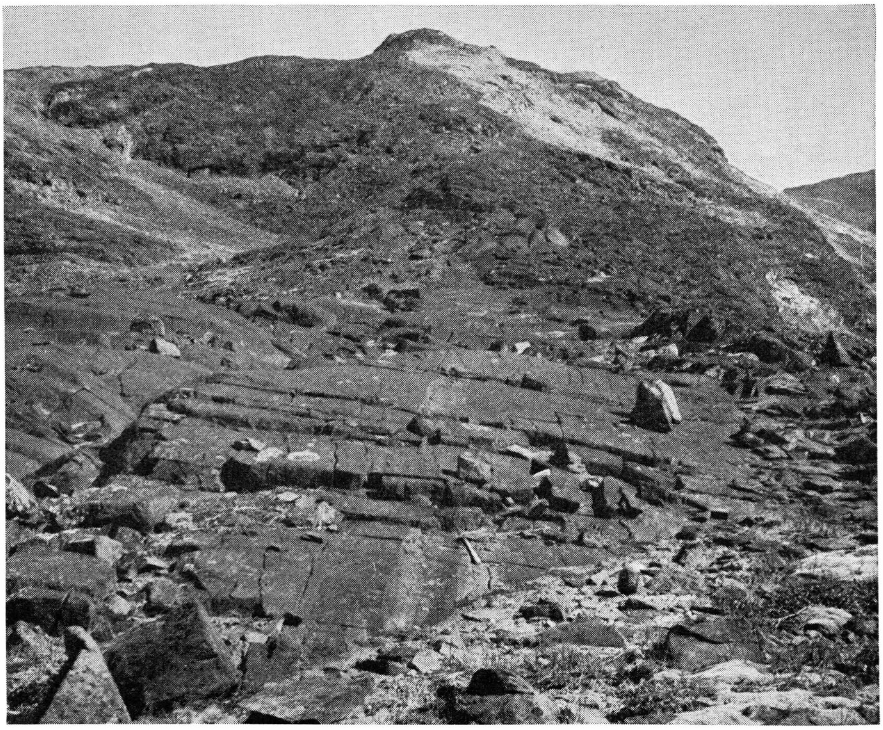

Fig. 7. Tectonized inclusions of kakortokite (at the hammer) in green lujavrite between Lakseelv and Lilleelv. In background lujavrite with inclusions of naujaite.

members of the series, the black layers are thinner, the red layers thinner still and often lacking.

The kakortokite in Kringlerne has inclusions of augite syenite and strongly altered naujaite (fig. 6).

The minerals are: crystals of nepheline and eudialyte, large laths of microcline (with rims of albite), small laths of albite, arfvedsonite, ægirine, ænigmatite, sodalite, biotite, rinkite, and iron ore.

In addition to the large mass of kakortokite in Kringlerne, kakortokitic rocks have been found in a number of other places. At Agpat Ussing (*55*, p. 71) found a 100 m thick dyke of kakortokite in the border between lujavrite and sandstone. The kakortokite is unbanded and rich in sodalite and eudialyte. The writer paid a short visit to the locality in 1957 and found boulders of the kakortokite, but the rock is not exposed on the shore. In this place the lujavrite is much disturbed and rich in fluorite.

In 1955 Jacobsen found inclusions of kakortokite in the lujavrites between Agpat and Tuperssuatsiaq and in 1956 Bondam found a dyke of kakortokite in the naujaite of Tuperssuatsiaq. In 1955 and 1957 the writer studied inclusions of banded and unbanded kakortokite in the lujavrite at the head of Kangerdluarssuk between Lilleelv and Lakseelv. These inclusions are conformably enclosed in lujavrite, towards the north they are more or less horizontal, towards the south, in the ridge to the north of the valley of Lakseelv, the inclusions and the foliation of the lujavrite (in this place green with black poikiloblasts of arfvedsonite) have a north western dip of ca. 50° (fig. 7). In some of these inclusions (from the northern part of the area in question) there is evidence of gravitative accumulation of the black crystals of arfvedsonite. There is a gradual increase in the number of black crystals from the upper white, to the lower black part of the horizontal inclusion. In the same area of inclusions of kakortokite in lujavrite there are also inclusions of coarse-grained rocks which have features in common with kakortokite as well as naujaite. The naujaitic features of these rocks are the coarse grain-size and the large poikilitic prisms of arfvedsonite. In common with the kakortokites are the poorness in sodalite and the richness in well developed crystals of eudialyte. The poikilitic inclusions in the arfvedsonite are—as in the kakortokite—of small laths of feldspar.

Near the mouth of the brook to the north of Lilleelv there are veins in the naujaite that have kakortokitic composition.

In the material collected by USSING there are kakortokitic rocks from Nunasarnaq on the north coast of Tunugdliarfik.

The Border of the Batholith.

In the northern part of the area the alkaline rocks are in part covered by porphyries. According to USSING the contact is irregular and generally parallel to the horizontal layering of the porphyries and the stratified nepheline syenites.

The marginal contacts are transgressive and steep and they may be associated with faulting. The following rocks of the complex have borders on the country rocks: augite syenite, essexite, nordmarkite, arfvedsonite granite, naujaite, lujavrite, and kakortokite. The augite syenite, essexite and the nordmarkite show fine-grained border zones, the other rocks do not show any decrease in grain size towards the borders and they may even be more coarse-grained there. USSING (op. cit. pp. 73, 75, 169, and 176) has described endomorphic contact zones of ægirine- and arfvedsonite lujavrites in the north eastern part of the batholith. These contacts have not been re-visited during the last years, but it is known that faulting plays a rôle in these places. In thin section the rocks recall the fine-grained lujavrites found in recrystallized zones of crushing in the lujavrites in other parts of the region. Further field studies are

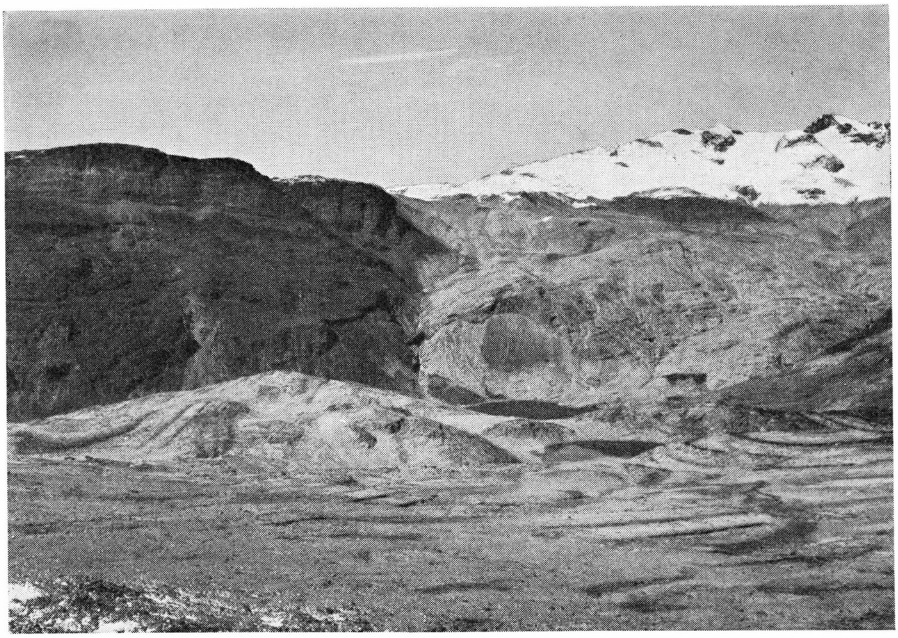

Fig. 8. View from Kringlerne towards the north. In the foreground: kakortokite, centre left: the mountain Nunasarnaussaq with sandstone and sills of diabase, centre right: naujaite overlain by sodalite foyaite. The water in centre is the head of Kangerdluarssuk. In background the snow-covered mountains to the north of Tunugdliarfik (F. L. Jacobsen phot.).

necessary in order to decide whether the fine-grained rocks described by Ussing are due to chilling or to recrystallization.

According to Ussing the arfvedsonite granite and the lujavrite send apophyses into the country rocks.

Inclusions of sandstone and porphyries have been found in the alkaline rocks.

The sandstone and porphyries adjacent to the batholith may be contact metamorphosed and there may be a development of crocidolite in the surrounding Julianehaab granite.

Ussing (op cit., p. 55) mentions a small intrusive body of a fine-grained arfvedsonite lujavrite exposed over an ellipsoidal area of many square meters and surrounded by Julianehaab granite. It is found on the east side of the mountain Iviangiussat at an altitude of about 550 m. Iviangiussat is situated to the west of the plateau of Kringlerne.

The Structure of the Batholith.

The layering of the stratified part of the batholith is due to the foliation and schistosity of the lujavrites, to the banding and jointing

Fig. 9. The lujavrite immediately below the kakortokite of Kringlerne in the tributary to Lakseelv, alt. ca. 80 m. There are vein-like inclusions of kakortokite in the lujavrite.

of the naujaite, and to the banding of the kakortokites. The stratification is almost horizontal in the central part of the batholith (and parallel to the regional stratification of sandstone and porphyries), but it becomes steeper outwards and is along the borders of the complex parallel to the vertical contacts. The sheets of which the batholith is composed are therefore saucer-shaped.

The banding of naujaite and kakortokite is horizontal or almost so in the larger masses of these rocks. In the "breccia zone" the banding of the naujaitic inclusions in the lujavrite may be inclined as shown in fig. 4.

Towards the junction between the kakortokite of Kringlerne and the marginal augite syenite the banding disappears and along the vertical border there is a zone of coarse-grained kakortokite with vertical, eudialyte-rich pegmatites and with inclusions of augite syenite. The junction between the kakortokite of Kringlerne and the underlying lujavrite was described by USSING (*55*, p. 47). There is in places a gradual transition, in other places a more abrupt one, the lower lujavrite having conformable inclusions of kakortokite immediately under the junction. The lowermost part of the kakortokite is white and shows no banding.

In 1957 the writer studied the junction between the kakortokite

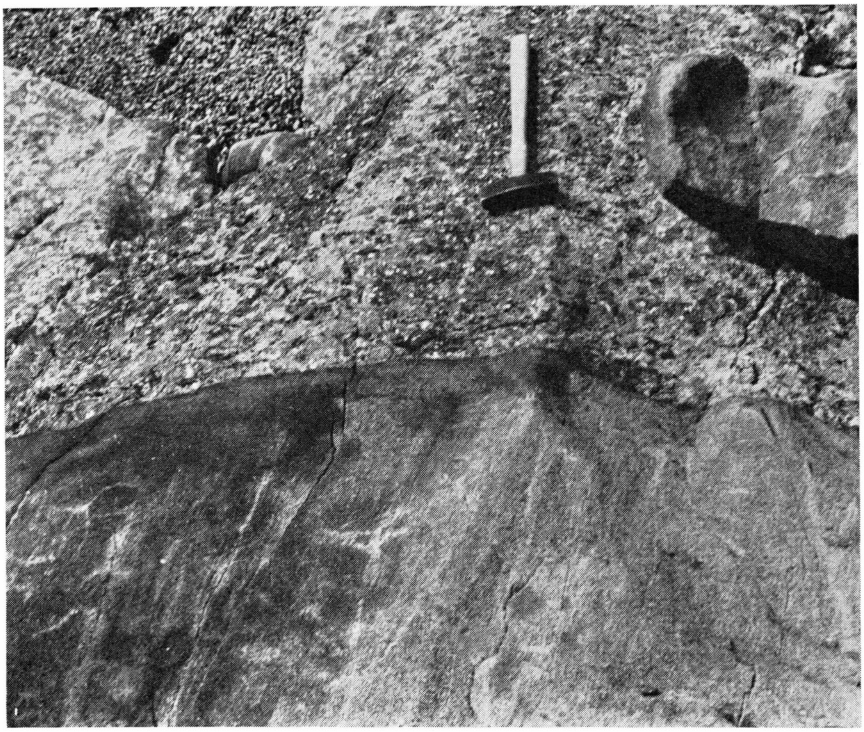

Fig. 10. Sharp contact between banded naujaite (background) and black lujavrite (foreground). There is a thin, black, arfvedsonite-rich zone between the two rocks. The lujavrite has white lines in continuation of the banding of the naujaite. Same locality as fig. 4, p. 12. Fig. 10 shows the border between naujaite and lujavrite behind the geologist of fig. 4.

and lujavrite in two places on the north slope of Kringlerne. At an altitude of about 100 m there is a 20 m thick layer of kakortokite in the black lujavrite. The latter has many small inclusions of kakortokite, most often arranged parallel to the foliation of the lujavrite, but in places also developed as thin veins. The lower border of the kakortokite of Kringlerne is found at an altitude of 150 m. This kakortokite is white, unbanded, the underlying lujavrite is black and resembles a fine-grained black kakortokite. Both rocks are rich in eudialyte. There are small inclusions of kakortokite in the lujavrite, some of them are vein-like and may be folded (fig. 9).

The "breccia zone" between naujaite and lujavrite is made up of large and small blocks of naujaite enclosed in lujavrite and there is in many places a thin black zone rich in arfvedsonite between the two rocks (fig. 13). The lineation and foliation of the lujavrite are parallel to the borders of the inclusions, but there may be instances where the lineation is almost perpendicular on the border (fig. 10) In some places

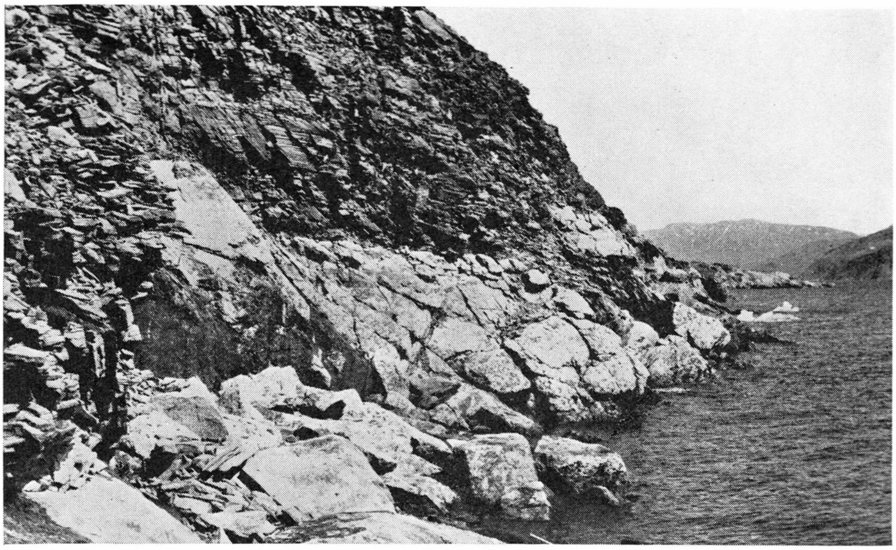

Fig. 11. The "breccia zone" at Tugtup agtakôrfia. Lenses of naujaite (with zones of deformation) enclosed in strongly schistose lujavrite.

there is a strongly developed schistosity in the lujavrite of the breccia zone (fig. 11).

The inclusions of naujaite in the lujavrite are cut by veins of lujavrite and they may show a more or less pronounced recrystallization and may even be replaced by the lujavrite.

The foliation of the lujavrite is generally horizontal or nearly so, but variations in the orientation of its planar structures are common. As mentioned by USSING the foliation of the lujavrite changes from horizontal to vertical towards the east and south east borders of the batholith. A further zone of steeply inclined lujavrite is found in the ridge to the north of the Lakseelv where a zone of green lujavrite dips at about 50° towards the north (fig. 12). Its inclusions of kakortokite are arranged parallel to this structure. Towards the south of this zone is the kakortokite of Kringlerne with almost horizontal banding, towards the north lujavrite and naujaite with a slight northern dip.

Steep or vertical foliation of the lujavrites are found in many places in the breccia zone. Folds in the lujavrite are not uncommon.

Later Alterations.

The nepheline syenites are often strongly altered. Analcime and acmite are the most common secondary minerals. The alteration is most pronounced in and around zones of deformation. Fluorite often occurs in these zones.

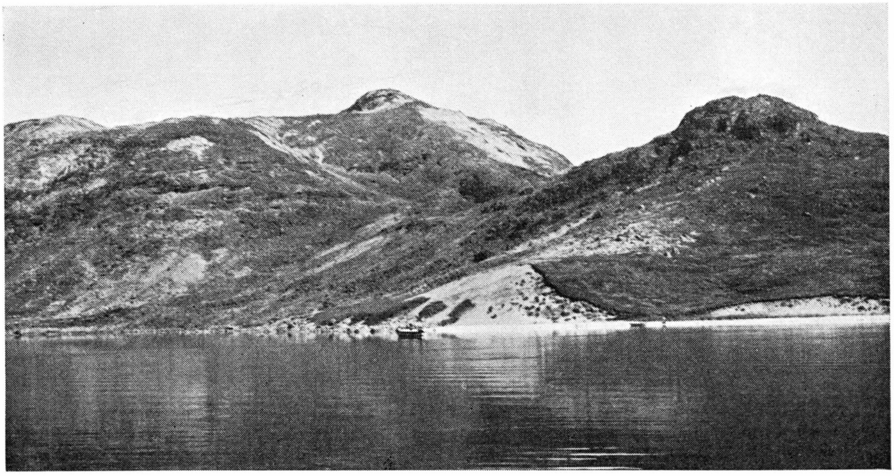

Fig. 12. The head of Kangerdluarssuk between Lakseelv (just to the right of the photo) and Lilleelv (just to the left of the photo). To the left: fairly flat-lying lujavrite with inclusions of naujaite and kakortokite. To the right: zone of steeply dipping green lujavrite with inclusions of kakortokite.

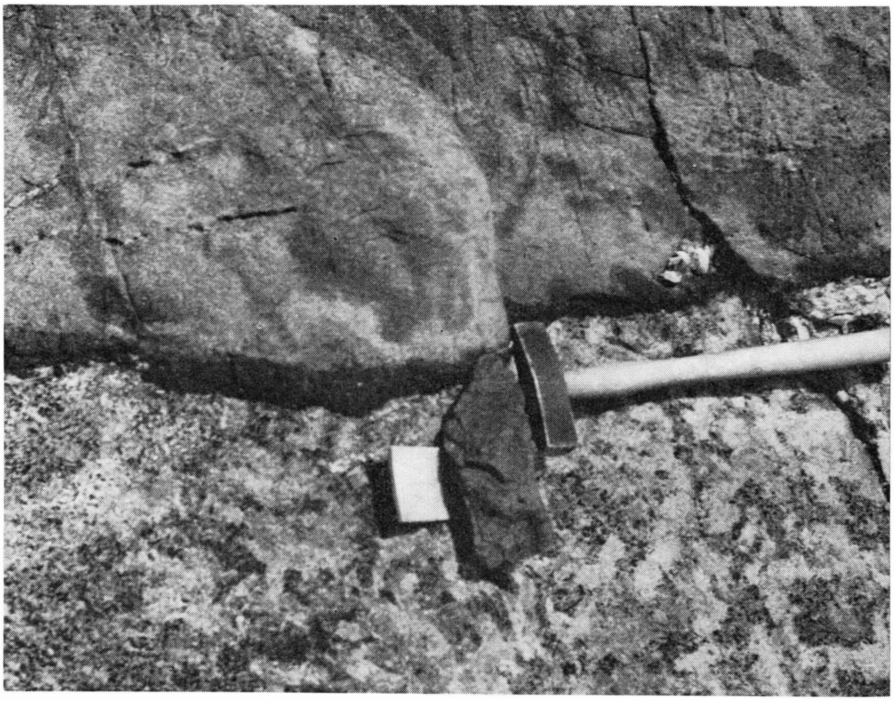

Fig. 13. Black, arfvedsonite-rich zone in lujavrite where this rock borders on naujaite (white). The poikilitic texture of the naujaite is well seen to the right. Igdlúnguaq.

Petrogenesis.

According to USSING the batholith was formed in two stages. In the first stage the unstratified part of the complex intruded into the Julianehaab granite, the sandstone and the porphyries. In the second stage the stratified rocks (the agpaites) intruded and partly replaced the unstratified rocks and parts of their surroundings by "stoping".

USSING was the first to discuss the differentiation of agpaitic rocks, that is according to his definition alkaline rocks with $\frac{na + k}{al} \geq 1.2$; na, k, and al being the relative number of ions of Na, K, and Al in the rocks. The first minerals to crystallize are the sodium-aluminium-silicates, feldspar, nepheline and sodalite. From the fact that all the agpaitic rocks are composed of the same minerals and from the gradual transition between many of them USSING concluded that the horizontal stratification was caused by fractional crystallization and gravitational separation of the minerals. The first formed light minerals accumulated at the top of the magma chamber, while the lower part of the magma was enriched in the constituents of the dark and heavy minerals.

The primary agpaitic magma was by USSING calculated to be composed of 1 part of sodalite foyaite, 3 parts of naujaite, 5 parts of lujavrite, and 1 part of kakortokite. This composition corresponds closely to that of the sodalite foyaite. The layer of sodalite foyaite was explained by USSING by means of a comparison with the conformable pegmatites of the naujaite. These pegmatites lack, as the sodalite foyaite, the poikilitic texture of the naujaite and they occur along the partings of the latter rock. The sodalite foyaite might therefore be taken as an intrusion of the original magma in fractures formed by contraction in the upper part of the batholith.

The pulaskite could then be regarded as the result of reactions between the foyaite and the acid roof of the batholith, but as emphasized by USSING (op. cit. p. 341) the pulaskite may be related to the augite syenite since gradual transition between these two rocks has been observed.

The saucer shape of the stratification, the "breccia zone" between naujaite and lujavrite, and the structure of the lujavrite were according to USSING caused by a subsidence of the central part of the complex. The structure of the lujavrite was considered as a flow structure formed during crystallization of a magma rich in volatiles at low temperature and over a solid and passive substratum.

USSING explained the banding of the kakortokite as a result of variation in pressure in the magma chamber, a variation that might be connected with igneous surface activity of a very fluid magma.

FERSMAN (*21*) regarded the crystallization as a result of gravitative differentiation and the banding of the kakortokite was caused by slight variation in a magma of almost anchi eutectic composition. He emphasized the importance of the agpaitic differentiation with an early separation of Na-minerals and the production of a residual liquid rich in Zr, rare earths, Nb, Ti, P, etc.

BACKLUND (*3*) compared Ilímaussaq with a number of similar occurrences of alkaline rocks in other parts of the world. The agpaitic crystallization resulted in an accumulation of the first formed crystals at the top of the magma chamber. The volatiles were prevented from escaping and the first formed minerals were therefore pneumatolytically altered. At the same time fenitization and assimilation of the country rocks took place. In this way arfvedsonite granite, augite syenite, nordmarkite, (and umptekite in Kola) were formed. In Ilímaussaq the temperature of the final consolidation was so low that no incongruent melting of the acmite-ægirine took place. In other areas where the acmite was decomposed, rocks rich in calcite, apatite and iron ore were formed (carbonatites, apatite rocks, and kimberlite pipes). The concentration of Zr in the agpaites was explained by BACKLUND by means of assimilation of granite. The Julianehaab granite is fairly rich in zircon.

WEGMANN (*56*, pp. 74—80) gives a somewhat different interpretation of the history of the Ilímaussaq batholith. There was first an intrusion of essexite, nordmarkite, and arfvedsonite granite. These rocks, and their country rocks (especially the porphyries), were later penetrated by solutions and volatiles. The porphyries were transformed into lujavrite, the essexite into naujaite, and the nordmarkite into foyaite and pulaskite. "This conversion and the addition of material increased the volume of the rocks, bending the deeper parts downwards" (op. cit. p. 80). A boudinage structure was formed with boudins of naujaite in a matrix of lujavrite. The augite syenite is considered to be limited to a large fault along the western and southern margins of the massif. As to the kakortokite WEGMANN does not support USSING's view, but his observations "did not yet suffice to form a sufficiently reliable basis of another explanation."

DISCUSSION

I. On a Magmatic Origin of the Ilímaussaq Batholith.

The batholith is as so many other alkaline rock complexes found in a region characterized by germanotypic tectonics and the formation of the nepheline syenites was also in this region preceded by the extrusion of lavas.

Agpaitic nepheline syenites appear to be rare. Lists of the known occurrences are given by FERSMAN (*21*) and BACKLUND (*3*). In most complexes of nepheline syenites the main rocks are foyaites and augite syenites (larvikite, umptekite, and pulaskite). Well-known examples are: the Oslo Region (BARTH, *5*), Serra de Monchique (KRAATZ-KOSCHLAU and HACKMANN, *30*), Fourche Mountains (WILLIAMS, *57*), and Ditro (STRECKEISEN, *52* and *53*). Examples of the "normal" kind of nepheline syenites are in South Greenland: the Grønnedal Massif (CALLISEN, *15*) and the Igaliko Batholith (USSING, *55*).

Lavas of foyaitic and augite syenitic compositions are known from many regions and there is therefore no doubt that magmas of these compositions exist.

The crystallization of the above-mentioned "normal" nepheline syenites is miaskitic according to FERSMAN (*21*) and GERASIMOVSKY (*24*), that is, the order of crystallization described by ROSENBUSCH and BOWEN. The miaskites may in the main rocks contain zircon, but very rarely more complex minerals. If eudialyte or eukolite are present in such plutonic complexes it is always in pegmatitic dykes and veins, examples are: The Oslo Region (BRØGGER, *11*), Otero Co., New Mexico (CLABAUGH, *16*), Bearpaw Mountains, Montana (PECORA, *40*), Seiland, Northern Norway (BARTH, *4*) and Magnet Cove, Arkansas (WILLIAMS, *57*, and LANDES, *33*).

Tinguaites and other alkaline dykes are found in and around the nepheline syenites. They may as emphasized by ROSENBUSCH (*44*) and JOHANSEN (*26*) contain rare minerals as låvenite, mosandrite, astrophyllite, katapleite, sodalite, etc., and according to these two writers zircon and apatite are rare in these rocks. They do not mention eudialyte and eucolite as constituents of these rocks, but occurrences of these minerals in tinguaites have been mentioned by: WILLMANN (*58*, p. 384) from North Africa (together with lujavrite), STOBBE and MURRAY (*50*) from Arkansas, and BORDET, FREULON, and LEFRANC (*10*) and KARPOFF (*27*) from North Africa. Thus KARPOFF has from Adrar Tidjerazrazzé described foyaite surrounded by phonolites. Both contain eudialyte and the phonolite carries further astrophyllite, haüyne, katapleite, and ænigmatite. It also has inclusions of foyaite.

Of nepheline syenitic occurrences resembling Ilímaussaq will be mentioned below: Mt. Ord Range in Texas, the Kola Peninsula, Pilandsberg in Transvaal, Norra Kärr in Sweden, and Iles de Los in French Guinea.

Mt. Ord Range, West Texas, (OSANN, *38*) is a body of nepheline syenite which shows some architectural resemblance to Ilímaussaq. It forms a laccolith in limestone and has a fine-grained marginal zone. The nepheline syenite contains augite, biotite, some låvenite and a slight amount of zircon, to mention minerals important in this connection. Towards the top of the laccolith there is a decrease in grain-size and a simultaneous increase in the amounts of nepheline, sodalite, and ægirine. Augite, biotite and låvenite may be lacking, but an eudialyte-looking mineral and possibly rosenbuschite occur. In the fine-grained upper border zone of the laccolith there is less nepheline and sodalite, but ægirine, "eudialyte" and ænigmatite are present. In the main rocks there is—as in Ilímaussaq—a concentration of nepheline and sodalite in the upper part, although this zone—contrary to Ilímaussaq—is more fine-grained. There are in the area other bodies of nepheline syenite which may contain a good deal of zircon. Phonolitic lavas and tinguaitic dykes also occur.

In the **Kola Peninsula** there are two very large bodies of nepheline syenite, both of them agpaitic.

The largest of them, **Khibina,** is characterized by ring-shaped structures. Primary banding is common within the different rock complexes of which the marginal ones are the oldest, the central ones the youngest. There are eruptive breccias between the rocks of the different complexes. For instance there are inclusions of the marginal umptekite in the khibinite, the predominant rock of the outer part of Khibina. This feature recalls the relationship between augite syenite and kakortokite. Foyaitic rocks form the central part of Khibina. The main rocks of the complex show some resemblance to the foyaite and less pronounced to the sodalite foyaite of Ilímaussaq.

Fine-grained, in part gneissic ægirine-nepheline syenites with parallel needles of pyroxene intersect the main rocks of Khibina in vertical bands (RAMSAY and HACKMANN, *43*, p. 84) and they may according to the same writers (p. 85) have inclusions of the main rocks. They contain eudialyte and astrophyllite and they may have concentrations of rare earth metals and thorium (in rinkolite and lovchorrite) according to ELISEEV, OGINSKY, and VOLODIN (*18*, p. 73) and AFANASYEV (*2*, p. 116). Some if not all of these gneissic nepheline syenites are found as cone sheets or ring dykes. In one cone sheet there is according to ELISEEV etc. (*18*) a thick interbanded complex of ijolite-urtite, malignite, and lujavrite. These gneissic or banded, partly fine-grained nepheline syenites resemble as to mode of occurrence some of the lujavrites of Ilímaussaq.

Khibina is rich in pegmatites, conformable as well as true veins and dykes. They may be strongly deformed showing gneissic structures. They are rich in rare minerals. According to FERSMAN (*21*) the magmatic phase is separated from the pegmatitic by the formation of radiating masses of ægirine. In the subsequent hydrothermal phase ægirine and zeolites are formed. The last-mentioned formations correspond probably to the felt-like ægirine mentioned by RAMSAY (*43*, see further p. 36).

The whole complex is cut by tinguaites and other alkaline dykes. The tinguaites may be characterized by a high radioactivity, U and Th being associated with Nb, Ti, and rare earths (FERSMAN, *22*, p. 94).

The **Lovozero massif** is stratified. Its rocks remind of the lujavrite and kakortokite of Ilímaussaq (namely lujavrites) and also of the naujaite (tawite). The lujavrite of Lovozero, poor in eudialyte in its lower part, rich in the upper, is somewhat more coarse-grained than the lujavrite of Ilímaussaq and differs from the kakortokite in having small needles of ægirine (RAMSAY, *41*, and *42*).

The order of crystallization was according to ELISEEV, ZÉLENKOV, NÉFEDOV, SAKHAROV, and OUNXOV (*19*): 1) poikilitic nepheline syenite (tawite), 2) stratified complex of urtite, foyaite, and lujavrite, and 3) eudialyte lujavrite with intrusive contacts to the stratified complex. The stratification of the massif is saucer-shaped as in Ilímaussaq with horizontal banding in the central areas. This succession is reminiscent of that found at Ilímaussaq. A different interpretation has been given by VOROBYEVA in FERSMAN (*23*). The stratified complex of urtite, foyaite etc. is intrusive into the lujavrite, and the tawite is a secondary rock formed along vertical and horizontal fractures.

Geochemically Khibina and Lovozero differ from Ilímaussaq in containing great quantities of Ti and P. These elements are almost lacking in the main rocks of Ilímaussaq. The contents of Nb and rare earths in Kola also appear to be higher than those found in Greenland.

Pilandsberg, Transvaal, (SHAND, *47*) is a thick laccolith under a cover of tuff. The earliest intrusive rocks are red foyaite and syenite. Subsidence of a solid core of these rocks caused later magma to well up along its edges and lujavrite, white and green foyaite, and tinguaite crystallized in a ring structure. The lujavrite (BROUWER, *13* and *14*) contains eucolite and it has eucolite pegmatites. Thus the lujavrite in this occurrence appear to take part in a ring dyke.

Norra Kärr in Sweden (ADAMSON, *1*) is a small stock 1200×400 m in area. Its main rock is the dense green grennaite which may be described as a rock intermediate between lujavrite and tinguaite. It has a pronounced lineation and foliation caused by the parallel arrangement of the needles of ægirine. This foliation is conformable to the outer border of the stock. There are phenocrysts of eudialyte and/or katapleite, and eudialyte is often present in the groundmass.

The grennaite has inclusions of coarse-grained nepheline syenites, partly agpaitic, partly pulaskitic.

The surrounding granite is fenitized in a zone up to 100 m wide. Volatiles have thus played an important rôle during the formation of the stock.

In Iles de Los, French Guinea (LACROIX, *31* and *32*) there is a complex built up of nepheline syenites. Some of them are agpaitic, namely the ægirine nepheline syenites with one or more of the minerals: låvenite, astrophyllite, sodalite, and poikilitic arfvedsonite. Eudialyte is rare in the main rocks, more common in lujavritic varieties. The pegmatites contain eucolite, sodalite, astrophyllite, leucophane, serandite, and other minerals. Eucolite is only found where låvenite and other Zr-silicates are lacking. There are also nepheline syenitic and monzonitic rocks with black amphibole. They are of more "normal" type than the agpaitic rocks and contain augite, biotite, zircon, haüyne and/or noseane, and the rare minerals hjortdahlite (guarinite) and rinkite. The nepheline syenites are cut by tinguaitic dykes which may contain sodalite, rosenbuschite and eudialyte. The last-named may be present as phenocrysts. Katapleite is an alteration product of the eudialyte, but may also occur as phenocrysts (corresponding to the relations of the grennaite from Norra Kärr).

There are a few more areas of agpaitic and eudialyte-bearing nepheline syenites, but the writer has had no access to any detailed descriptions of these occurrences.

If the occurrences of nepheline syenites mentioned above are magmatic the rocks of the Ilímaussaq batholith may also be.

Table 1. Chemical analyses of rocks from the Ilímaussaq Batholith. (Ussing, *55*).

	Essexite Narssaq	Augite syenite Nunasar-naussaq	Nordmarkite Narssaq	Arfvedsonite granite Ilímaussaq	pulaskite N. Siorars-suit.	Foyaite Nauja-kasik
	%					
SiO_2	46.10	55.79	58.17	70.59	57.88	56.31
TiO_2	3.34	1.81	2.09	.44	1.23	2.82 (TiO₂ + ZrO₂)
ZrO_2	—	—	—	—	—	
Al_2O_3	18.59	15.76	16.07	12.38	14.80	20.11
Fe_2O_3	2.63	1.60	1.30	1.61	5.86	3.93
FeO_2	6.68	7.56	5.04	3.33	3.71	1.45
MnO	.05	.14	.07	.08	.15	.60
MgO	3.23	.41	1.20	—	—	.36
CaO	9.86	3.70	3.42	.93	2.71	.62
Na_2O	6.22	7.72	7.41	6.95	9.12	8.76
K_2O	.63	4.34	4.65	3.74	3.06	4.65
H_2O^+	.80	.18	.41	.21	.90	1.13
H_2O^-	.11	.34	.19	.20	.23	—
Cl	—	—	—	—	—	.15
P_2O_5	1.41	.36	.42	tr.	—	.13
CO_2	—	—	—	—	—	—
	99.65	99.71	100.44	100.46	99.65	101.02
Cl = 0						.03
						100.99

The rocks of the unstratified part of the batholith are very similar to the rocks of igneous complexes of other regions and augite syenitic and nepheline syenitic lavas are known from many places, not only oceanic, but also continental. Thus in the Oslo Region (BARTH, *5* and *6*) extrusion of basalts and rhomb porphyries was followed by the formation of plutonic rocks. BARTH has described a differentiation series from kjelsåsite (augite monzonite) to larvikite (augit monzonite). From larvikite the series branches into two differentiation series, an acid one via nordmarkite to alkali granite, and an undersaturated one via nepheline syenite (lardalite) to nepheline syenite pegmatites. The latter are rich in rare minerals with Zr, Nb, Ti, Th, etc., e. g. eukolite and mosandrite.

The chemical analyses published by USSING (see table 1) arranged in the order essexite, augite syenite, nordmarkite and arfvedsonite granite show a regular variation that might be caused by differentiation of a common magma. This magma is considered by the writer to be augite syenitic for the following reasons: augite syenite occurs along the margins of the batholith and may show fine-grained contacts against the country rocks; it is found as inclusions in the agpaites; augite syenite occurs in big dykes in many parts of the regions, as at Tugtutôq, and it occurs according to USSING's preliminary examination of the Igaliko batholith, as a marginal facies of that massif. Furthermore the augite syenite resembles the larvikites and pulaskites that are so common in other alkaline complexes, thus larvikite occupies about $^1/_3$ of the area taken up by the plutonic rocks of the Oslo Region.

The basic rocks essexite and its associated magnetite pyroxenite may be early differentiates of the augite syenitic magma, but they may also, as in the Oslo Region (BARTH, *5*) be independent intrusions. However, the essexite, augite syenite (in part) and the nordmarkite appear to be formed by multiple intrusions. The arfvedsonite granite may as suggested by USSING be an acid differentiate of the magma or a hybrid product formed through assimilation of sandstone. But it might also according to BACKLUND be regarded as a fenitic rock formed at the expense of sandstone and Julianehaab granite.

In the Igaliko batholith the marginal augite syenite surrounds a core of fairly normal foyaite. Rare elements and minerals are so far only known from the pegmatites in the augite syenite at Narssârssuk. These pegmatites may be associated with partly assimilated sandstone. In the Ilímaussaq batholith the rare minerals are also found in the central part of the batholith.

On the origin of the agpaitic rocks: USSING divided the magmatic history of the Ilímaussaq batholith into two phases. The agpaites belonged to a second phase and they intruded into and replaced the nonstratified rocks. As an alternative explanation the writer would like to advance the view that the main part of the batholith was formed during a magmatic and a late- or post magmatic phase.

To the first phase belongs the emplacement of most of the rocks of the batholith. The crystallization of the primary augite syenitic magma was in the western part of the area of fairly normal type. The volatiles of the magma apparently escaped during the crystallization, possibly in connection with volcanic processes at the surface. In the eastern and larger part of the batholith, however, the crystallization followed a somewhat different path. The augite syenite, which crystallized along the margins, and a resistant cover prevented the volatiles from escaping so that they were accumulated in the upper part of the magma.

BACKLUND (*3*, p. 11), when discussing the agpaitic type of differentiation, operated with volatiles accumulated at the top of the magma since the layer of the first formed minerals prevented the volatiles from escaping. These minerals were pneumatolytically altered and the cover was fenitized. WEGMANN (*56*, p. 82) pointed out that the volatile components accumulated under the heavy cover of the porphyries "in stead of causing explosions, might have caused chemical reactions with the heated rocks of the roof and have thereby initiated the series of transformations which resulted in the formation of lujavrites and naujaites. A further indication is the high gas content of the younger dykes". The idea of gases accumulated under an impervious roof has also been put forward in the writers explanation of the formation of the cryolite at Ivigtut situated ca. 150 km to the west of Ilímaussaq (*49*). In that case fluorides seem to have played a similar rôle as chlorides in Ilímaussaq.

The concentration of the volatile materials at the top of the magma may have been brought about by the mechanism discussed by SÄTHER (*45*). H_2O, CO_2, Cl, F, fluorides of Ti, Zr, and Nb, and the alkali metals rose through the magma by means of diffusion (cf. also KENNEDY, *28*). These volatiles correspond in composition to the residual solutions and gases made responsible for the formation of many pegmatitic, pneumatolytic and hydrothermal veins. Where they as in Ilímaussaq are "locked in" they take part in the crystallization of the magma. The differentiation may then have taken place as follows:

In the upper transition zone from arfvedsonite granite (fenite?) via quartz syenite, pulaskite (corresponding in composition to augite syenite), foyaite to sodalite foyaite the succession of rocks is of fairly normal type. The pulaskite is believed to represent the primary magma and quartz syenite and arfvedsonite granite are then reaction products with the roof. The crystallization of pulaskite was followed by the formation of foyaite (as in the Igaliko batholith and the Oslo Region) and the following sodalite foyaite then represents the approximate composition of the magma at the time when the concentration of volatiles in the magma was so high that volatiles began to take part in the crystallization of the magma.

The augite syenite and the pulaskite have almost identic chemical compositions (see table 1), the only differences being that the pulaskite is slightly richer in SiO_2, Na_2O and Fe^{+3}, and slightly poorer in CaO, K_2O and Fe^{+2} than the augite syenite. The mineralogical differences are more pronounced and the two rocks have different types of feldspar and of dark minerals. There are as mentioned on p. 11 gradual transition between the two rocks. The said differences may be accounted for by the different positions of the two rocks in the batholith. The augite syenite crystallized along the margins, the pulaskite at the top of the magma where volatiles played an important rôle. Evidence of reactions between the marginal augite syenite and the volatiles trapped in the magma is found on the northern shore of Kangerdluarssuk (USSING, *55*, p. 58) where the syenite is altered along joints and fractures to coarse-grained rocks, occasionally eudialyte-bearing, and associated with green felt-like ægirine.

The sodalite foyaite is fairly coarse-grained; even coarser is the naujaite which is the next rock to crystallize. At this stage of the crystallization the concentration of volatiles in the upper part of the magma was so high that pegmatitic conditions prevailed. The naujaite is therefore rich in volatiles (3.63 $^0/_0$ Cl has been determined), rich in "rest elements", and rich in conformable eudialyte pegmatites (fig. 14). The sodalite is partly a primary constituent of the naujaite, partly a secondary one being formed by pneumatolytic alteration of the nepheline. In this connection it can be mentioned that the sodalite in the lardalite of the Oslo Region is considered to be a primary mineral, while it in Ditró (STRECKEISEN, *53*) and in the tawite of the Kola Peninsula is interpreted as a secondary mineral.

The upper rocks, rich in light minerals, may well have been formed according to USSING's agpaitic type of crystallization, that is, the first formed light minerals, nepheline, feldspar, and sodalite were concentrated at the top of the magma.

The foyaite and the sodalite foyaite occupy an intermediate position between the agpaites and the more normal rocks and they have minerals in common with both rock types. In common with the first mentioned rocks are sodalite, nepheline, eudialyte, arfvedsonite, and ægirine. In common with the last-mentioned are: olivine, apatite, ægirine augite, biotite, and ænigmatite. The ægirine augite of the two rocks often has an outer rim of ægirine and the potassium feldspars have rims of albite, both these features being evidence of reaction between the first formed minerals and the residual liquid rich in Na.

As to the feldspars, the augite syenite and the nordmarkite may have homogeneous alkali feldspars, but perthites are more common. The microline of the nordmarkite may show cross hatching, plagioclase is present partly as intergrowths with the alkali feldspar and partly as independent grains. In the arfvedsonite granite and in the rocks of the transition series perthites with

Fig. 14. Flat-lying eudialyte pegmatite in the naujaite of Qeqertaussaq. In background the northernmost part of the head of Kangerdluarssuk with naujaite and to the extreme right black lujavrite.

irregular twin structure occur. These feldspars are often albitized and small laths of albite may be present. The foyaite and the sodalite foyaite have microcline of the characteristic agpaitic habit (Ussing, *55*, fig. 15, p. 159) and occasionally albitized. Naujaite, kakortokite and lujavrite all have agpaitic microcline, perthitic in the naujaite and albitized in the kakortokite. Ussing (*54*) has studied some of the feldspars of the rocks and more information is to be found in his memoir on the batholith. It is, however, to be hoped that supplementary examinations of the feldspars and of the other rock-forming mineral series may be undertaken.

The kakortokites: Light-coloured rocks rich in feldspar and nepheline are predominant among the kakortokites and the magma responsible for the formation of the banded series of kakortokites may therefore (apart from volatiles and other components lost during the crystallization) have had a chemical composition corresponding to that of the white kakortokite.

The kakortokite is composed of the same minerals as the other agpaitic rocks of the batholith. As the sodalite foyaite and naujaite it has automorphic grains of feldspar and nepheline, but its eudialyte is present in better developed crystals than in the two mentioned rocks. The arfvedsonite and ægirine are in all three rocks allotriomorphic and the large prismatic grains of arfvedsonite may in naujaite and kakortokite enclose feldspar (and also sodalite in the naujaite)[1]).

The chemical compositions of sodalite foyaite and white kakortokite are very similar, the most pronounced difference being the ZrO_2 content and the differences in SiO_2, Al_2O_3, and Na_2O caused by the sodalite of the sodalite foyaite (see table 2). A sodalite-bearing kakortokite as the one at Agpat should then have a sodalite foyaitic composition.

Table 2. Chemical analyses of rocks from the Ilímaussaq Batholith (USSING, *55*).

	Sodalite foyaite Tuperssuatsiaq	Naujaite Kangerdluarssuk	Kakortokite (white) Kringlerne	Kakortokite (average) Kringlerne (USSING, p. 182)
SiO_2	49.38	49.46	51.62	51.82
TiO_2	.63	.16	.44	.35
ZrO_2	.61	.38	1.70	2.05
Al_2O_3	17.31	23.53	15.63	13.68
Fe_2O_3	4.20	3.04	6.06	7.32
FeO	5.25	1.02	4.98	7.27
MnO	.08	.17	.33	.57
MgO	.53	tr.	tr.	.09
CaO	2.23	.80	3.13	3.06
Na_2O	13.87	14.71	10.09	9.75
K_2O	2.55	4.34	4.19	3.92
H_2O^+	1.30	1.38	2.12	—
H_2O^-	.16	—	—	—
Cl	1.68	2.25	.17	.16
P_2O_5	—	—	—	—
CO_2	—	—	—	—
	99.78	101.24	100.46	100.04
Cl = 0	.38	.51	.04	.04
	99.40	100.73	100.42	100.00

From these facts the writer concludes that a kakortokitic, sodalite foyaitic magma once occupied a large volume of the batholith. The uppermost part of the magma soon became so enriched in volatiles that the pegmatoid naujaite crystallized. In the lowermost visible part of the batholith the less coarse-grained, foyaitic kakortokite crystallized

[1]) The kakortokite may contain a considerable amount of ænigmatite, a mineral which is also found in the rocks of the transition series, in the sodalite foyaite and in the naujaite. The related minerals cossyrite and rhönite occur in alkaline lavas on Pantellaria near Sicily, in France, Germany, and Kenya.

from a magma fairly rich in volatiles, since the rocks are markedly miarolitic (Ussing, *55*, p. 180) and since the kakortokite is coarse-grained and rich in pegmatites where bordering on the augite syenite. As mentioned on p. 16 there has at Lakseelv been found rocks intermediate between naujaite and kakortokite as inclusions in lujavrite.

The formation of the upper transition zone and of the sodalite foyaite, naujaite, intermediate rock between naujaite and kakortokite, and the kakortokites took in the writers opinion place in the main crystallization phase of the batholith. Apart from the rocks of the transition series all the rocks of the complex are made up of the same minerals and their chemical compositions do not differ very much. There may, as it should be expected, be a slight enrichment in SiO_2, CaO and iron oxides in the kakortokite. Thus the chemical composition of the magma was, except for the content of volatiles, almost constant during a vertical height of several hundred meters.

The kakortokite has inclusions of much altered naujaite conformably enclosed between the bands of the kakortokite (fig. 6). Since the latter rock is fairly fresh around the inclusions it is reasonable to assume that the upper naujaite—at least in part—crystallized earlier than the lower kakortokite. The vein of kakortokite in naujaite observed by Bondam (see p. 15) and altered veins of kakortokitic rocks in the naujaite at the brook to the north of Lilleelv (which will be described in a later publication) also point in this direction.

As mentioned on p. 12 there is a faint banding in the naujaite. The banding of the kakortokite is more pronounced, but not regular. As emphasized by Ussing (*55*, p. 356) the sequence black, red and white is not always developed. Especially the red bands are thin and they are often lacking. Also the black layers are thin. It may therefore be stated that there was during the crystallization of the white kakortokite at intervals a separation of black, and more rarely of red layers. According to Ussing presure variations were responsible for the banding. Yoder's recent experimental work (*59*) seems to support the view that variations in the water pressure of the magma may result in the alternating crystallization of different mineral assemblages. As mentioned on p. 16 there is evidence of gravitative accumulation of crystals of arfvedsonite in the kakortokite and gravitative differentiation may therefore also have played a rôle during the formation of the banding. More field work is, however, necessary in order to solve the problem of the banded kakortokites.

On the origin of the lujavrites: Tinguaitic dykes are common in many alkaline complexes, but there are very few younger dykes in Ilímaussaq. Tinguaites are according to Shand (*48*, p. 471) fine-grained

Fig. 15. Thin *en echelon* veins of lujavrite in the naujaite of Qeqertaussaq. To the left a white, analcime-filled fracture parallel to the veins of lujavrite.

equivalents of lujavrite and they frequently contain eudialyte as the latter. As mentioned on p. 24 eudialyte and other rare minerals have been reported from tinguaites of many regions.

Thin veins of lujavrite are found in the naujaite in many places and it might therefore be suggested that the lujavrites of Ilímaussaq correspond to the late tinguaites of other regions (fig. 15).

On p. 33 the writer suggested that the sodalite foyaite, naujaite and kakortokite were formed in the main phase of agpaitic differentiation. All these rocks—except the thin bands of black kakortokite—are leucocratic. There is a great similarity in the mineralogy and chemical composition of the melanocratic black kakortokite and the arfvedsonite lujavrite (table 3). The main difference between the two rocks is to be

Table 3. Chemical analyses of rocks from the Ilímaussaq Batholith (USSING, *55*).

	Ægirine lujavrite Kangerdluarssuk	Ægirine lujavrite Tuperssuatsiaq	Arfvedsonite lujavrite Nunasarnaq	Kakortokite (black) (Kringlerne)
SiO_2	53.74	53.44	56.64	48.90
TiO_2	.50	.30	.30	} 1.96
ZrO_2	1.63	1.00	—	
Al_2O_3	14.02	18.64	16.10	7.85
Fe_2O_3	10.63	9.38	4.90	11.46
FeO	1.71	.86	6.86	13.32
MnO	.36	.10	.57	1.11
MgO	tr.	—	—	.38
CaO	1.18	.79	.39	1.95
Na_2O	9.02	12.10	11.50	7.40
K_2O	4.77	2.43	1.00	3.23
H_2O^+	3.40	1.12	1.54	1.80
H_2O^-	—	.34	.04	—
Cl	n.d.	.12	—	—
P_2O_5	—	—	tr.	.03
Co_2	—	—	—	—
	100.96	100.62	100.29[1]	99.39
Cl = O		.03		.01
		100.59		99.38

[1] including 0.45 % Nb_2O_5.

found in their different grain-sizes. Another difference is that the kakortokite has albitized microcline and in addition small independent laths of albite, while the lujavrite has laths of the same size of the two feldspars. The two rocks differ from the upper agpaites in having two feldspars.

If as stated on p. 29 the crystallization started from an augite syenitic magma the crystallization of the upper leucocratic rocks should result in the formation of a more melanocratic rest magma. Evidence of the existence of such a magma is the thin bands of black kakortokite and the resemblance between this rock and the black lujavrite may be taken as support of the presence of a lower melanocratic rest magma.

The lujavrites occur as dykes in the naujaite and also make up the lowermost visible part of the batholith. The lujavrites have inclusions of the older rocks and they show most often a pronounced lineation and foliation. It is therefore suggested that the *mise en place* of the lujavrite was associated with a phase of deformation and especially with a subsidence of parts of the complex. The lujavrites intruded into fractures in the older rocks not only as thin dykes, but also as larger masses i ring systems. *A zone including the steep lujavrite in the ridge to the nort* *of Lakseelv, the strongly deformed lujavrite at Agpat, and the steep lujavrite at Nunasarnaq may be a part of such a ring system.* Green lujavrites are prominent in many places in this zone.

This subsidence is a probable explanation of the distribution of the rocks of the batholith, for instance that kakortokite forms a large mass in the southern non-subsided part of the batholith, while naujaite occurs in the same altitude in its northern subsided part.

The lujavrites in the ring system are rich in inclusions of the older rocks and some assimilation has taken place. "Lujavritization" has also occurred in many places in the "breccia zone" and in the kakortokite of Laksefjeld.

Similar phenomenae of subsidence as the one discussed above have been described from the Oslo Region (OFTEDAL, *37*) and from a number of places in South Africa, for instance Pilandsberg (SHAND, *47*), Spizkop (STRAUSS and TRUTER, *51*) and Messum (MATHIAS, *35* and *36*). In the ring systems of the three last-mentioned examples there are schistose foyaites (eudialyte-bearing lujavrites in Pilandsberg) and tinguaites.

The lujavrites as metasomatic rocks: In the discussion above the lujavrites were interpreted as eumagmatic formations. A metasomatic origin of the lujavrite will be discussed below as a transition to the next paragraph dealing with a metasomatic origin of the whole batholith.

The naujaite and kakortokite are often cut by green zones with felt-like ægirine and analcime as the main constituents. Displacements have in many cases taken place along these zones and they are therefore interpreted as recrystallized zones of deformation. Similar green zones have been described from Khibina and Lovozero of the Kola Peninsula (RAMSAY and HACKMANN *43*, pp. 86, 88, and 94). According to FERSMAN (*21*) this felt-like ægirine ("third generation ægirine") is of hydrothermal origin and it was also in Ilímaussaq formed under hydrothermal conditions, as will be discussed in a later publication.

The green felt-like rocks may show transitions to green lujavrites.

The thin veins of black lujavrite in the naujaite may have inclusions of green felt-like rocks in their central zones (USSING, op. cit. p. 157 and new observations). These inclusions show that the black lujavrite is younger than the deformation which was the cause of the formation of the green zones.

As it is seen in fig. 16 veins of black lujavrite and pegmatitic rocks rich in analcime (and/or albite) may occur contiguous in fractures in naujaite. These observations place the formation of the lujavrite in a late stage of the history of the batholith. The pegmatites may be slightly younger than the lujavrite since they in places replace the lujavrite.

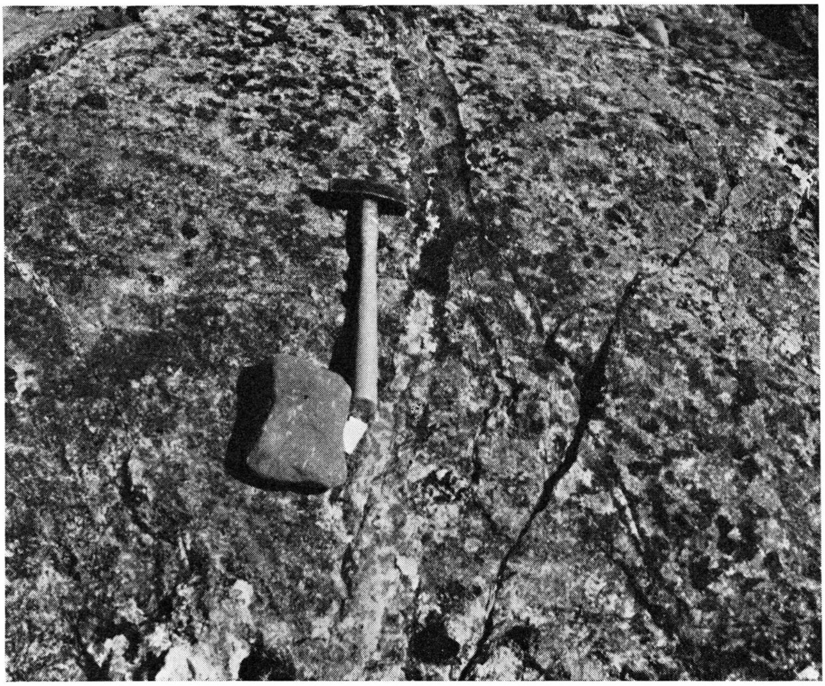

Fig. 16. Lujavritic vein in naujaite, Igdlúnguaq. At the head of the hammer the vein branches into two veins composed of analcime and lujavrite.

As mentioned on p. 20 there is in the ridge to the north of Laxeelv a thick zone of green lujavrite with steep dip and "out-rolled" inclusions of kakortokite (fig. 7). When studied in thin section the lujavrite resembles the kakortokite very much, having the same columnar crystals of nepheline and the same platy crystals of eudialyte as that rock. It differs from the kakortokite in having two feldspars and a great multitude of needles of ægirine. This green lujavrite may therefore be interpreted as a deformed and recrystallized kakortokite. This view is supported by the presence of narrow green zones in the kakortokite of Kringlerne which in thin section show great resemblance to the abovementioned green lujavrite. It is therefore reasonable to assume that the green lujavrite to the north of Laxeelv has been formed by recrystallization of kakortokite. The green lujavrite from Laxeelv has poikiloblastic crystals of arfvedsonite[1]).

The inclusions of naujaite in the lujavrite of the "breccia zone" are often strongly recrystallized into a coarse-grained pegmatitic rock

[1]) In this case, as in the inclusions of green lujavrite enclosed in the thin veins of black lujavrite mentioned above, arfvedsonite was formed later than the ægirine. During still later processes of alteration the arfvedsonite may be replaced by akmite.

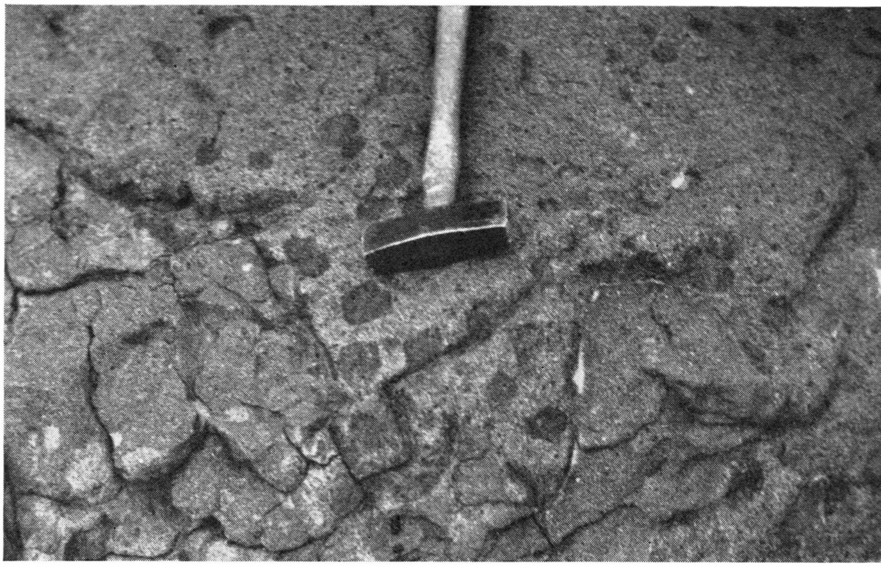

Fig. 17. Small, partly "digested" inclusions of green lujavrite (dark) in black lujavrite. The easternmost point of Tugtup agtakôrfia.

with the main components analcime and sodalite. Associated with these rocks and enclosed in the surrounding lujavrite are coarse-grained dark rocks composed of the same components as the lujavrite. These inclusions may be interpreted as recrystallized naujaite since they have inherited minerals and textures from the naujaite. These rocks may be digested by the more fine-grained lujavrites.

Finally should be mentioned that green felt-like zones are unknown from fractures in lujavrite. As mentioned above inclusions of the green rock are enclosed in veins of lujavrite in the naujaite.

Inclusions of green lujavrite in black lujavrite are not uncommon (fig. 17). They may be found in all stages of digestion.

From the above it may be concluded that the naujaite and the kakortokite during a period of deformation have recrystallized into green rocks and that the latter may be replaced by the black lujavrite. The deformation was most probably—as also stated by USSING and WEGMANN—caused by subsidence of parts of the complex. The recrystallization of the deformed zones may then be either late- or post magmatic. The recrystallization took place in the presence of volatiles. These volatiles may come from deeper portions of the magma where they may have been locked in until they were released during the period of subsidence. They may perhaps also have been introduced into a partly crystallized magma from exterior sources (cf. LEHMANN, *34*).

The metasomatic origin of the lujavrite will be further discussed in the next paragraph.

II. On a Metasomatic Origin of the Ilímaussaq Batholith.

Many examples have been described of the metasomatic formation of alkaline rocks, especially by means of fenitization around carbonatites. An outstanding example is Alnö in Sweden where syenites and nepheline syenites have been formed through fenitization of migmatites and there are in the complex cone sheets and ring dykes of carbonatites (von Eckermann, *17*).

Many examples of fenitization have been reported from Africa. Mathias (*35* and *36*) has discussed the genesis of the Messum complex in South Africa. An original volcano was built up of basaltic lavas and rhyolitic tuffs. Subsidence took place between ring fractures and the basalts have therefore dips towards the centre of the complex. The outer ring dyke consists of granite. In the central part of the volcano, probably in a system of ring dykes, foyaite was intruded and the surrounding rocks were fenitized. There are also tinguaitic ring dykes with radial offshoots.

In the **Spitzkop complex** near Messum (Strauss and Truter, *51*) there is a central intrusion of ijolite surrounded by different types of fenites. The complex is cut by ring dykes of foyaite, often banded or schistose and with steep planar structures. The foyaite may be lujavritic, but rare minerals are absent. In addition there are cone sheets of foyaite, tinguaite and syenite and radial dykes of micro ijolite and foyaite. A body of carbonatite is interpreted by Shand (*46*) as an inclusion of sedimentary dolomite, while Strauss and Truter interpreted it as a carbonatitic ring dyke.

In the two complexes mentioned a phase of deformation was accompanied by fenitization and the formation of ring dykes and cone sheets. The two complexes are almost free from rare minerals. **Pilandsberg** mentioned on p. 26 may be a similar formation, but it should be pointed out that an eudialyte-bearing foyaite makes up the greater part of the complex and that, to the outside of the complex, there are big dykes of eudialyte foyaite which do not cut the complex. The green foyaite and the eudialyte lujavrite form, according to Shand (*47*), a ring dyke around a subsided area. Pilandsberg is situated where a dyke swarm intersects the axis of the Bushveld syncline.

In these three complexes the first rocks to be formed were more leucocratic than those formed in later stages. This sequence recalls that found in Ilímaussaq.

All the complexes mentioned are composed of rings and they may be interpreted as multiple intrusions accompanied by metasomatic alterations of the country rocks. The Khibina massif of Kola (cf. p. 25) has a similar structure and ring dykes and cone sheets are prominent. This complex is also a multiple intrusion. The Ilímaussaq and Lovozero complexes are stratified and of a somewhat different structure.

Some occurrences of syenite and nepheline syenite are interpreted as results of regional metamorphism.

Thus B. C. KING (*29*) has described syenites from Bechuanaland formed at the expense of granitic rocks. The syenites may be mobilized and then have fluidal texture.

GUMMER and BURR (*25*) have described nepheline syenites from the classical area in **Bancroft, Ontario, Canada.** These rocks are assumed to be formed by nephelinization of horizons of impure calcareous sediments. The transformation is dependent on the tectonical structure. Gradual transitions from para-gneiss to nepheline syenite may be seen. Zircon and an eucolite-like mineral have been found in the nepheline syenite. OSBORNE (*39*) has examined nepheline gneiss from the same region. It occurs at irregular intervals in a zone where gneisses meet the amphibolites and limestones of the Grenville series. Calcite and calc-silicate minerals as diopside, grossularite, vesuvianite, and scapolite are present in some of the nepheline syenites. The nepheline gneisses are interpreted as gneisses altered by alkaline solutions or perhaps *lit par lit* intruded by nepheline syenite.

According to VAN BILJON (*7* and *8*) some of the nepheline syenites of **Transvaal** are metasomatic rocks occurring in a zone where compression and faulting were prominent. The bodies of nepheline syenite occur in the continuation of horizons of limestone shale.

The structural relationship of the lujavrite in Ilímaussaq may be compared with the ring systems in the African complexes mentioned above and with examples from Kola (the gneissoid nepheline syenites mentioned on p. 25) and from the Oslo region.

According to BRØGGER (*11*, p. 105 etc.) the larvikite of the **Oslo region** is in places brecciated by schistose nepheline syenite of the same composition as lardalite (cf. p. 28). This rock was named ditroite by BRØGGER. It has parallel needles of ægirine and resembles a metamorphic rock. The ditroite has inclusions of larvikite and there may be a gradual transition between the two rocks. BRØGGER regards this as a result of assimilation of fragments of larvikite in the ditroite. The latter rock contains melinophane, zircon, pyrochlor, and BRØGGER (op. cit., p. 138) suggests that there may be a transition from the schistose nepheline syenites to the pegmatites of the region[1]). In a later paper BRØGGER (*12*) mentions a 200—250 m thick dyke in Bratholmen. It is a ditroite with xenoliths of larvikite.

Of further importance for the present problem are the eucolite-bearing dykes of **Wausau, Marathon Co., Wisconsin,** (STOBBE and MURRAY, *50*) and the eudialyte pegmatites of **Bear Paw Mountains, Montana** (PECORA, *40*).

In the first-named area, dykes of syenite and nepheline syenite (partly lujavrite) were formed through replacement and recrystallization of shear zones in the roof of a granite batholith (cf. also EMMONS, *20*). The eucolite was found in fine-grained, schistose lujavrite. In the second area eudialyte

[1]) According to CHR. OFTEDAHL (personal information) these rocks may be interpreted as recrystallized zones of deformation in the larvikite. The crushed larvikite reacted with alkaline solutions and recrystallized into ditroite.

occurs in complex and clefted pegmatites in the upper slopes and near the summit of the Rocky Boy mountain. The eudialyte is associated with fibrous ægirine and lamprophyllite. PECORA considers these formations to be post magmatic.

These two examples and the eucolite-like mineral mentioned by GUMMER and BURR (*25*) show that eudialyte and eucolite may be formed by processes other than magmatic crystallization.

Wegmann's hypothesis: When WEGMANN advanced his "migmatitic hypothesis" on the formation of the Ilímaussaq batholith in 1938 (see p. 23) it was the first application of such views on the problem of the formation of large masses of nepheline syenite. As mentioned above metasomatic processes have now in a number of cases been claimed to be of importance in the formation of alkaline rocks.

WEGMANN'S very interesting hypothesis was used as a working hypothesis by the present writer when he first visited the Ilímaussaq region. Much evidence can be found in support of the hypothesis, but there are also features which are difficult to explain in this way. The writer has therefore changed his opinion on the genesis of the complex several times during his work in the region.

As stated in the last part of the preceding paragraph there is much evidence in favour of the view that the lujavrite is metasomatic. The rock greatly resembles a metamorphic rock, but has not yet been treated as such, except for very restricted areas. It is to be hoped that a detailed examination of the structure of the lujavrites may be undertaken, also "by means of the methods which especially aim at petrofabrics" (WEGMANN, op. cit., p. 75).

According to WEGMANN the nepheline syenites of Ilímaussaq were formed through metasomatic transformation of essexite, nordmarkite and porphyries. These three rock groups gave rise to naujaite, foyaite and lujavrite, respectively. Inclusions of augite syenite and an essexite-looking rock have been found in the lujavrite, but separate inclusions of naujaite and "essexite" have been found a few cm apart without any traces of naujaitization of the "essexite". Inclusions of augite syenite have also been found in the kakortokite. Inclusions of porphyries in lujavrite will be further discussed on p. 44.

Lujavrite as well as naujaite occur in contact with porphyries. The porphyries are somewhat altered in contact with the nepheline syenites and there are apophyses of lujavrite in the porphyries at Nunasarnaq. As mentioned on p. 36 the distribution of the rocks may be taken in favour of the view that the metasomatic processes accompanied a subsidence of a part of the pre-nepheline syenitic complex. Almost all the nepheline syenites are found in direct contact with the country rocks.

The metasomatism was then caused by the impregnation of the subsided complex with volatiles.

WEGMANN (op. cit. p. 78) regards the augite syenite to be limited to large faults on either side of Kangerdluarssuq. According to USSING's and the writers observations the augite syenite is definitely older than the nepheline syenites since it occurs as inclusions in these rocks. The foyaitic texture and the banding of the kakortokite is very difficult to explain on the basis of WEGMANN's and any other metasomatic hypothesis.

WEGMANN's discussion of the relationship between naujaite and lujavrite is very stimulating and the writer agrees in principle to his structural interpretation, but not to the view (op. cit. p. 76) that "it is not the lujavrite that has brecciated the naujaite, but this "brecciating" has taken place later" than the formation of the two rocks. The writer has found many examples of lujavrite cutting and replacing naujaite (see p. 20).

Metasomatic transformation of a foyaitic intrusion into the rocks of Ilímaussaq: The writer (*49*) has formerly discussed how a granitic stock was selectively altered by impregnation of volatiles into the body of cryolite at Ivigtut. The formation of the peculiar rocks of Ilímaussaq could be explained in a similar way. According to this attempt at explaining the problem there was first an igneous complex resembling the Igaliko batholith, that is, with marginal augite syenite and central foyaite. Nordmarkite and alkali gabbro and -granite were probably also constituents of the complex. During tectonic processes the complex was penetrated by volatiles either originating in deeper parts of the magma or also introduced from exterior sources. The augite syenite (except small areas), the foyaite, essexite, nordmarkite, etc., and parts of the country rocks were metasomatically altered into naujaite, sodalite foyaite (and possibly arfvedsonite granite). The lujavrite may then have been formed either by recrystallization of zones of deformation, or also by recrystallization of the basic rocks of the original complex. Some of the veins of lujavrite in the naujaite may then be recrystallized veins of tinguaite. The schistose or gneissoid nepheline syenites of Kola, Oslo, Spitzkop, and Pilandsberg, and the eucolite-bearing dykes of Wisconsin are occurrences that have features in common with the lujavrite of Ilímaussaq.

This mode of interpretation corresponds closely to USSING's explanation of the development of the batholith, if his second (and replacing) magmatic phase is made metasomatic.

But also according to this hypothesis it is difficult to explain the formation of the banding of the kakortokite. It is difficult to imagine

Fig. 18. "Pillows" of green lujavrite enclosed in black lujavrite. Ca. 400 m to the west of Tugtup agtakôrfia, alt. ca. 90 m.

how a banding of the primary rocks could have survived the metasomatic alterations without any obliteration of this primary structure. And if the banding is not primary it is still more difficult to see how it could have been formed.

Pillow structure in the lujavrite: In the summer of 1957 the writer found in the mountain wall immediately to the west of Tugtup agtakôrfia a small area in the lujavrite made up of small pillow-shaped balls (fig. 18). The balls consisted of green lujavrite and the matrix, restricted to thin "veins" consists of black lujavrite. The balls showed features that could be interpreted as moulding of one pillow upon an adjacent one. Upwards and downwards the pillow-area grades into black lujavrite with a few small inclusions of green lujavrite. Farther to the east in the same mountain wall at Nunarssuatsiaq Wegmann (*56*, fig. 40) found remnants of volcanic breccias in the lujavrite and still farther east Ussing found inclusions of porphyries at Nunasarnaq. To the west of the pillow area there are in the wall strongly altered and partly digested inclusions of augite syenite and/or "essexite" in the lujavrite.

These very interesting features may be explained in one of the following ways:

1) The inclusions support WEGMANN's view and they may then be regarded as pre-lujavritic volcanic rocks and structures.

2) In Magnet Cove, Arkansas (LANDES, *33*) there is in the alkaline body a "rim" of contact metamorphosed sediments. LANDES has interpreted these rocks as sedimentary layers along and between which the intrusion took place.

In the nepheline syenite massif of the Lovozero Tundra (cf. p. 26) there is a persistant horizon of Devonian hornfels in the lujavrite.

The pillows and the volcanic breccia of Ilímaussaq may then be remnants of a recrystallized and partly replaced horizon of volcanic rocks in the batholith.

3) Inclusions of older rocks are not uncommon in Ilímaussaq. Sandstone inclusions have been found in the augite syenite on the southern shore of Kangerdluarssuk where the sandstone cover of the Julianehaab granite originally may have been situated at least 900 m above the present position of the inclusions. There is therefore (USSING, op. cit. p. 299) strong evidence in favour of a subsidence of the sandstone inclusions in the magma. In addition the nepheline syenites contain inclusions of porphyry, augite syenite, and possibly essexite. These rocks, the volcanic breccia and the pillows may all be remnants of blocks having sunk down in the magma.

4) The volcanic breccia and the inclusions of porphyry are found in the ring system discussed on p. 35. This zone of lujavritization may have been formed in the border of or just outside of the nepheline syenite massif and this may explain the presence of these inclusions.

5) On p. 36 it was shown that green lujavrite could be formed by recrystallization of older deformed rocks. The green rock is later replaced by the black lujavrite. If this is the case the "pillow structure" may represent an intermediate stage in the replacement of the green rock by the black lujavrite.

III. Conclusions.

In the preceding chapter the magmatic and metasomatic modes of explaining the formation of the Ilímaussaq massif were discussed. Much more field work will have to be carried out before a more conclusive discussion can be undertaken. In the present state of knowledge of the geology of Ilímaussaq the writer prefers the combination of magmatic and metasomatic processes dealt with on pages 27 to 38. This explanation faces two difficult problems. The one is the formation of a magma of such a peculiar type, the other the serious "space problem" since, according to this explanation, there must have been a magma chamber of considerable vertical and horizontal extension. Ilímaussaq, however, has these problems in common with many other igneous complexes. No attempt to discuss these problems will be made at this place, but reference should be made to BARTH's discussion of the origin of the magmas of the Oslo region (*6*).

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