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South Greenland, with information from seven bore holes

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Contribution to the Mineralogy of Ilímaussaq no. 109

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Cover photo: In the foreground, the site of bore hole IV on the south coast of Tunulliarfik. The bore hole is marked by a white circle and is located in arfvedsonite lujavrite. In the background, the north coast of Tunulliarfik showing the westernmost part of the Ilímaussaq complex in contact with Gardar volcanics in the extreme left side. Bore hole II is located in the ravine in the centre. The mountain wall to the right is made up of arfvedsonite lujavrite enclosing rafts of naujaite (white) and overlain by naugaite. The coastal cliff behind the iceberg is Tuttup Attakoorfia.

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Abstract

John Rose-Hansen and Henning Sørensen. Geology of the lujavrites from the Ilímaussaq alkaline complex, South Greenland, with information from seven bore holes. – Contribution to the Mineralogy of Ilímaussaq no. 109. Meddelelser om Grønland Geoscience 40. Copenhagen, Danish Polar Center, 2002.

Lujavrites, melanocratic agpaitic nepheline syenites, are the most highly evolved rocks of the Ilímaussaq alkaline complex, South Greenland. They have elevated contents of U. U-rich occurrences at Kvanefjeld in the northern part of the complex have been extensively drilled. Lujavrites from other parts of the complex were examined in seven bore holes, I to VII, in 1962 in an evaluation of the U potential of the complex. The study presents a general overview of the geology of the lujavrites, the distribution of various types of lujavrite and the structure of the complex partly based on the information obtained from the study of drill cores I-VII. The lujavrites are sandwiched between the roof and floor series of the complex. The drill cores penetrate the lower part of the roof series and present an incomplete section through the lujavrites. The lowermost lujavrites are dominated by aegirine lujavrites, cumulitic rocks directly succeeding the rocks of the floor series. The overlying arfvedsonite lujavrites intrude the lower part of the roof series.

The alternation of aegirine- and arfvedsonite-bearing lujavrites and the formation of layering are interpreted to be caused by changes in the physico-chemical conditions of the lujavritic magma, especially changes in P_{H_2O} and fO_2. Villiaumite, NaF, has only been found in drill cores from high levels in the complex. Naujakasite, which is a common constitutent of the hyper-agpaitic lujavrites at Kvanefjeld, has not been observed in drill cores I-VII. This may be linked to its formation at higher levels in the complex than represented by these drill cores. The lujavrites of bore holes I-VII have with few exceptions moderate contents of U.

Keywords: agpaitic, crystallization differentiation, drill cores, Greenland, Ilímaussaq, lujavrite, nepheline syenite

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Introduction

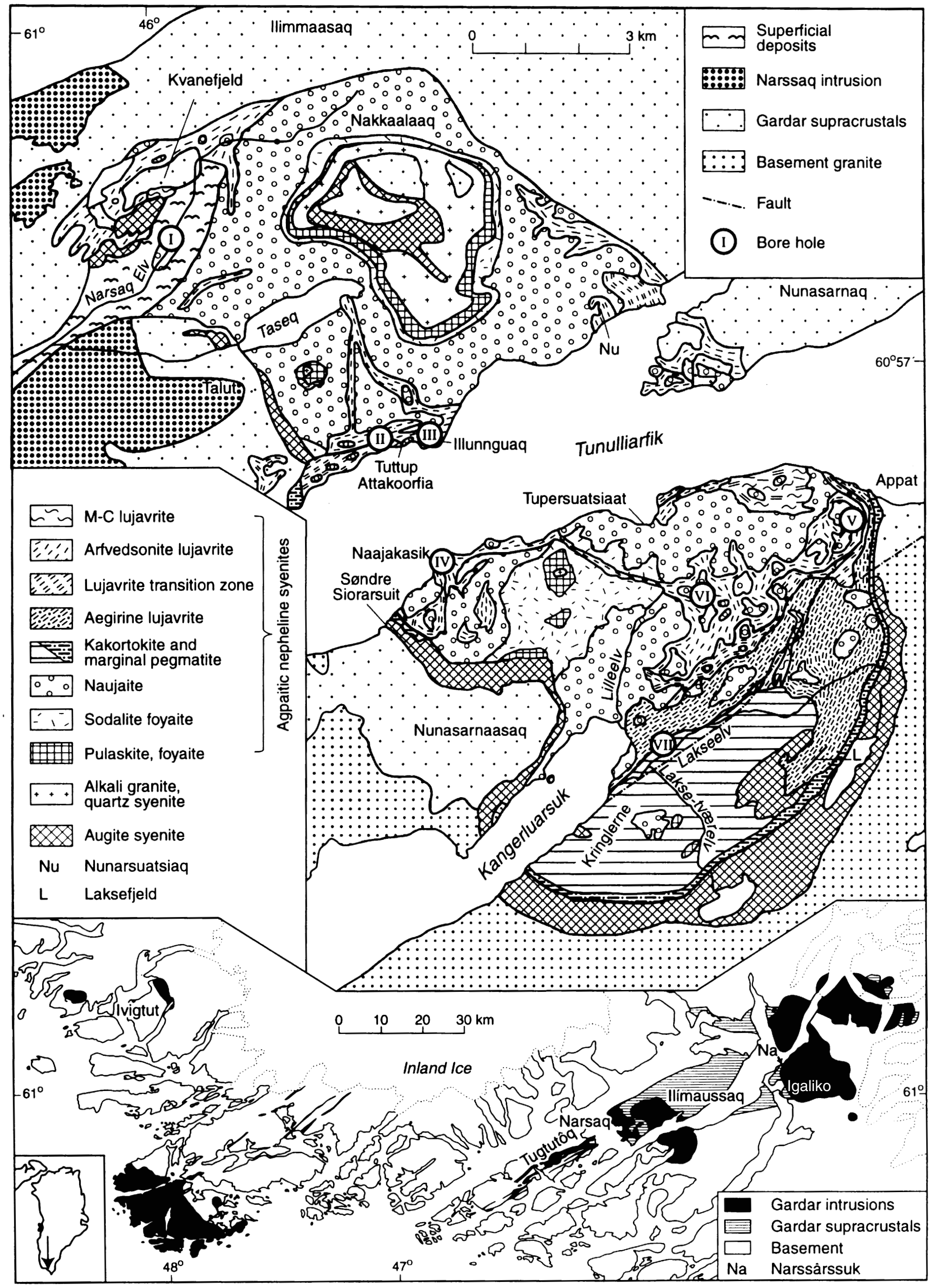
The lujavrites are agpaitic to hyper-agpaitic nepheline syenites characterized by exceptionally high contents of rare elements such as Li, Be, Nb, Ta, Zr, Hf, REE, U and Th and by a corresponding wealth in rare minerals. Their most prominent occurrences are the Lovozero alkaline complex, Kola Peninsula, Russia, and the Ilímaussaq alkaline complex, South Greenland. Because of the economic potential of these rocks, detailed studies including diamond drilling have been undertaken in Lovozero as well as in Ilímaussaq. (Ilímaussaq is the internationally well-established name of the geological occurrence, whereas the mountain, which gave name to the complex, in modern authorised spelling is Ilimmaasaq, cf. Fig. 1). There is an extensive literature on the mineralogy, petrology, geochemistry and economic geology of the Ilímaussaq lujavrites. Examples are: Ussing (1912); Sørensen (1962); Ferguson (1964, 1970); Gerasimovsky (1969); Sørensen et al. (1969, 1974); Piotrowsky & Edgar (1970); Sood & Edgar (1970); Engell (1973); Bohse & Andersen (1981); Kunzendorf et al. (1982); Konnerup-Madsen & Rose-Hansen (1982); Larsen & Sørensen (1987); Bailey (1995); Bailey et al. (2001) and Khomyakov et.al. (2001).

The Ilimaussaq complex (Fig. 1) is one of a number of intrusive complexes in the Gardar igneous province (1300 to 1130 Ma). The newest data give an age of about 1160 Ma for the complex (Sørensen 2001). The complex was formed during three intrusive stages: 1. augite syenite which is preserved as a partial rim around the marginal contacts and in the roof of the complex; 2. a stage of alkali granite and alkali syenite preserved in the roof and as xenoliths in the underlying rocks from stage 3; and 3. the main intrusive stage made up of a roof series, an intermediate series and a floor series. The roof series consists from the roof downwards of pulaskite, foyaite, sodalite foyaite and naujaite, of which the two last-named rocks are of agpaitic composition, that is peralkaline nepheline syenites characterised by the presence of complex silicate minerals like eudialyte and rinkite (Ussing 1912). The exposed part of the floor series consists of layered agpaitic nepheline syenites, kakortokites. The intermediate series is made up of lujavrites sandwiched between the roof series and the floor series. The major rock types of the complex are presented in Table 1, for a recent review of the geology of the complex, see Sørensen (2001).

The Ilímaussaq lujavrites are melanocratic rocks. Most of them are fine-grained and laminated, but there is also a medium- to coarse-grained variety (M-C lujavrite) showing foyaitic texture. Black varieties, arfvedsonite lujavrites, are rich in arfvedsonite, green varieties, aegirine lujavrites, are rich in aegirine. Eudialyte is the main carrier of rare elements in the lujavrites. Strongly persodic varieties are called hyper-agpaitic lujavrites. Instead of eudialyte they contain steenstrupine and they are rich in rare minerals such as naujakasite, villiaumite and ussingite (Sørensen 1997; Sørensen & Larsen 2001; Khomyakov et al. 2001). Table 2 presents a list of the rare minerals mentioned in the text.

The lujavrites of several parts of the complex have contents of uranium and thorium of economical interest. The till now most interesting occurrences are located at Kvanefjeld in the northern

Fig. 1. Geological map of the Ilímaussaq alkaline complex with location of bore holes I to VII. Based on Ferguson (1964) and Andersen et al. *(1988).*



part of the complex (Fig. 1) (Sørensen et al. 1969, 1974).

The present study reviews the geology of the Ilímaussaq lujavrites and is partly based on the information provided by the examination of seven drill cores from a hitherto unpublished drilling programme and on information obtained during the study of more than 300 thin sections of samples from these drill cores kept at the Geological Institute, University of Copenhagen.

Table 1. The major rock types of the Ilímaussaq complex.

rock type	texture	essential minerals	minor minerals
augite syenite	hypidiomorphic to xenomorphic granular, massive or layered, medium to coarse	alkali feldspar, olivine, ferrosalite, ferropargasite	titanomagnetite, apatite, biotite, pyrrhotite
pulaskite and foyaite	massive, medium to coarse, platy feldspars	alkali feldspar, fayalite, hedenbergite, aegirine-augite, katophorite, nepheline	apatite, aenigmatite, titanomagnetite, biotite, fluorite, eudialyte
sodalite foyaite	foyaitic, coarse	alkali feldspar, nepheline, sodalite, aegirine-augite, katophorite, fayalite	apatite, aenigmatite, titano magnetite, eudialyte, rinkite, fluorite, biotite, steenstrupine
naujaite	poikilitic, coarse to pegmatitic	alkali feldspar, sodalite, nepheline, aegirine, arfvedsonite, eudialyte	rinkite, aenigmatite, fayalite, apatite, polylithionite, sphalerite, pectolite, villiaumite
kakortokite	laminated, layered, medium to coarse	alkali feldspar, nepheline, eudialyte, aegirine, arfvedsonite	sodalite, aenigmatite, rinkite, fluorite, löllingite
lujavrite	laminated, fine-grained, sometimes layered or massive, medium to coarse	microcline, albite, nepheline, sodalite, analcime, naujakasite, aegirine, arfvedsonite, eudialyte	steenstrupine, monazite, britholite, villiaumite, sphalerite, pectolite, lovozerite, vitusite, polylithionite, ussingite, lueshite, neptunite
alkali granite, quartz syenite	hypidiomorphic granular, medium to coarse	alkali feldspar, quartz, aegirine, arfvedsonite	aenigmatite, elpidite, zircon, ilmenite, pyrochlore, neptunite, fluorite

Table 2. Rare minerals mentioned in the text and in Table 1.

Aenigmatite	$Na_2Fe_5TiSi_6O_{20}$
Astrophyllite	$(K,Na)_3(Fe^{2+},Mn)_7Ti_2Si_8O_{24}(O,OH)_7$
Britholite-(Ce)	$(Ce,Ca)_5(SiO_4,PO_4)_3(OH,F)$
Catapleiite	$Na_2ZrSi_3O_9 \cdot 2H_2O$
Elpidite	$Na_2ZrSi_6O_{15} \cdot 3H_2O$
Epistolite	$Na_5TiNb_2(Si_2O_7)_2(O,F)_4 \cdot 5H_2O$
Eudialyte	$Na_{15}Ca_6Fe_3Zr_3Si(Si_{25}O_{73})(O,OH,H_2O)_3(OH,Cl)_2$
Lovozerite	$Na_2Ca(Zr,Ti)Si_6(O,OH)_{18}$
Lueshite	$NaNbO_3$
Monazite	$(Ce,La,Nd,Th)PO_4$
Murmanite	$Na_3(Ti,Nb)_4O_4(Si_2O_7)_2 \cdot 4H_2O$
Nacareniobsite-(Ce)	$Na_3Ca_3(Ce,La)(Nb,Ti)(Si_2O_7)_2OF_3$
Naujakasite	$Na_6(Fe,Mn)Al_4Si_8O_{26}$
Neptunite	$KNa_2Li(Fe^{2+},Mn^{2+})_2Ti_2Si_8O_{24}$
Pectolite	$Na(Ca,Mn)_2Si_3O_8(OH)$
Perovskite	$(Ca,Na)(Ti,Nb)O_3$
Polylithionite	$KLi_2AlSi_4O_{10}(F,OH)_2$
Pyrochlore	$(Ca,Na)_2Nb_2O_6(OH,F)$
Rhabdophane	$(Ce,La)PO_4 \cdot H_2O$
Rinkite	$(Ca,Ce)_4(Na,Ca)_3(Ti,Nb)(Si_2O_7)_2(O,F)_4$
Sodalite	$Na_4Al_3Si_3O_{12}Cl$
Steenstrupine-(Ce)	$Na_{14}Ce_6Mn_2Fe_2(Zr,Th)(Si_6O_{18})_2(PO_4)_7(OH)_2 \cdot 3H_2O$
Ussingite	$NaAlSi_3O_8 \cdot NaOH$
Villiaumite	NaF
Vitusite-(Ce)	$Na_3(Ce,La, Nd)(PO_4)_2$

Drilling programmes in the Ilímaussaq complex

Danish state agencies have undertaken core drillings in the Ilímaussaq complex with the purpose of establishing the uranium potential of the complex. A total of sixty nine bore holes were drilled in 1958, 1969 and 1977 within or immediately adjacent to uranium-bearing rocks of the Kvanefjeld plateau in the northern part of the complex (Fig. 1), with a total core length of 10.7 km. A drilling programme in 1962 was aimed at lujavrite occurrences elsewhere in the Ilímaussaq complex. It comprised seven holes, I to VII, located where additional information about the uranium distribution in lujavrites was considered to be important (Fig. 1). The drill cores have been described in internal reports, see review by Bondam (1995).

Commercial companies have carried out core drillings in the southern part of the complex with the aim of evaluating the potential of eudialyte-rich kakortokite and lujavrite: two short holes in 1985, nine holes totalling 415 m in 1988 and 37 holes totalling 1883 m in 1989 (Le Couteur 1990). The results of these drillings have not been published.

Sørensen et al. (1969, 1974) discussed the drill cores from 1958 and 1969 and presented a general account of the Kvanefjeld uranium deposit; Kunzendorf et al. (1982) described the distribution of characteristic elements in drill cores from the northern part of Kvanefjeld; and Bailey & Gwozdz (1994) and Bailey (1995) studied the distribution of lithium and layering in drill core VII from 1962.

The analyses of the drill cores from 1962 revealed only moderate uranium contents. The subsequent exploration activities in the Ilímaussaq complex were therefore confined to the much more promising occurrences on the Kvanefjeld plateau. The 1962 drill cores were consequently stored at Research Establishment Risø, Roskilde, Denmark and no follow-up activities were envisaged. In connection with the examination of drill cores from Kvanefjeld, we also made a description of the 1962 drill cores and collected samples representative for the rock successions met in the drill cores.

Bore holes I to VII

This section brings a brief description of drill cores I to VII and of their location (Figs 1, 2). The detailed descriptions are presented in an appendix.

The seven holes were vertical or nearly so and were drilled to a depth of 200 m below the surface. The total radioactivity was later determined by gamma-logging

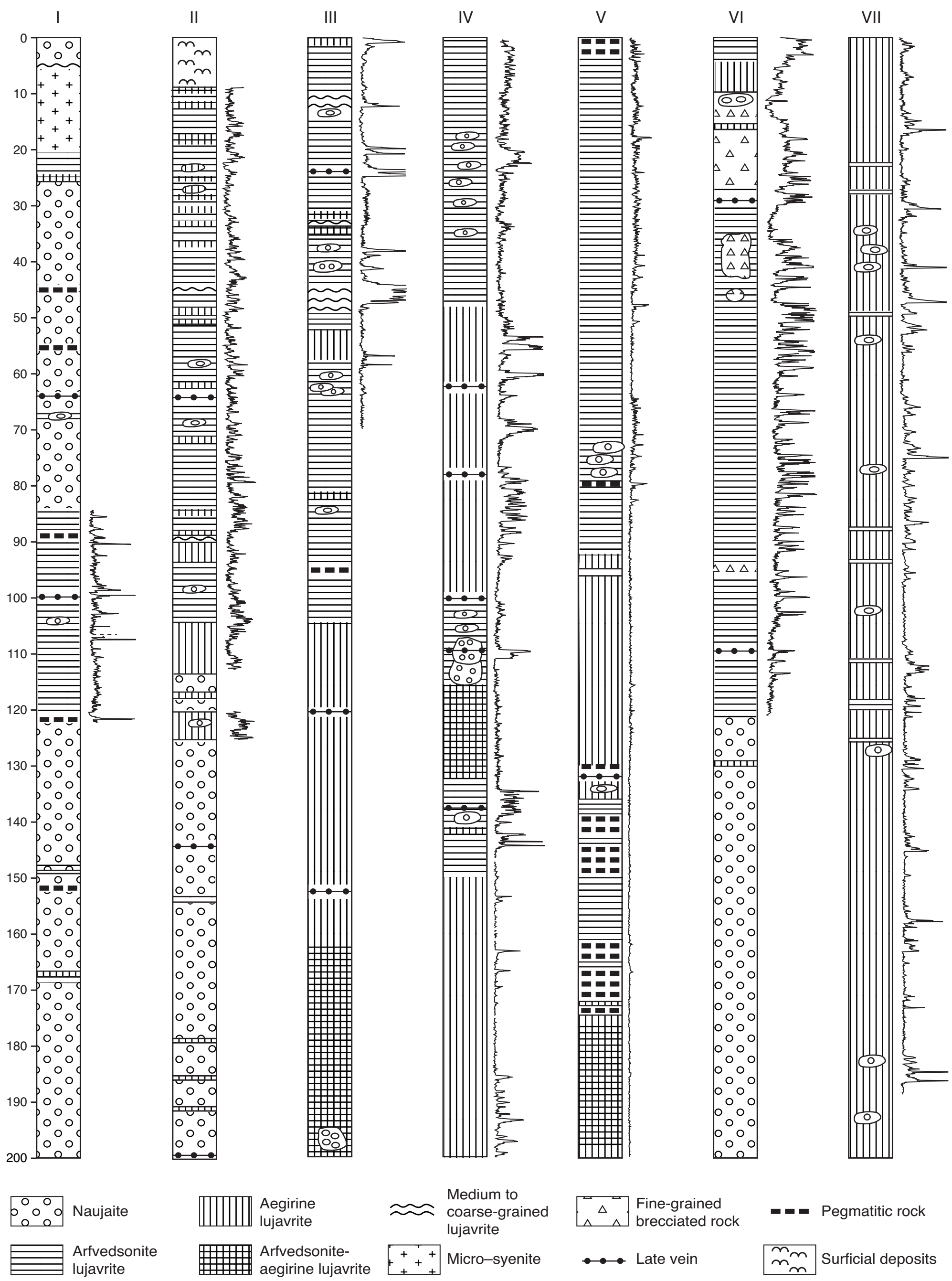


Fig. 2. Drill cores I to VII with simplified indication of rock types and gamma-logs (cf. the more detailed description of the drill cores in the appendix). The logs are shown without scale because of intercalibration problems.

of the bore holes (Fig. 2). The logging met difficulties because of partial blockage of the holes by fallen rocks. The logs are therefore incomplete. Our subsequent study of the cores and the logs has unfortunately shown that there are problems with the calibration of the logs. This makes comparison of logs from different bore holes problematical and is most clearly seen in a comparison of drill cores V and VI and the data for the U contents of the drill cores presented in Table 3. The differences can not be referred to the contributions by Th and K to the total gamma activity, since the Th/U ratio of most rocks is lower than one, as will be described in a later part of the study, and the contribution by K is negligible. We have therefore decided to include in Fig. 2 the parts of the logs which represent the lujavrite sections of the bore holes (except the lower part of bore hole III which could not be logged), but without a scale. This gives an impression of the variation of radioactivity with depth in the bore holes.

The water-soluble mineral villiaumite (NaF) has been found in drill cores I and II, but not in cores III-VII. It is of widespread occurrence in drill cores from the Kvanefjeld plateau. When present, it is generally found at depths greater than 50 m in the cores which means that it has been washed out from the uppermost parts by circulating surface water. The drilling operation has only dissolved insignificant amounts of villiaumite.

Bore hole no. I

This hole is located at tachymetric point 212 in the Narsaq Elv Valley at the foot of the Kvanefjeld mountain at altitude 292.4 m a.s.l., a few metres to the north of the river (Fig. 1).

The exposed rock is at this place naujaite rich in sodalite and nepheline and poor in eudialyte and mafic minerals. It has many irregular pegmatitic patches and is intersected by thin veinlets of felted aegirine, albite and analcime. The contact zones of these veinlets are locally rich in steenstrupine, monazite and sphalerite which also occur in tension cracks in the felted aegirine. The naujaite is intersected by sheets of fine-grained arfvedsonite lujavrite. These again are cut by pegmatitic veins which have arfvedsonite-aegirine along the margins and cores made up of plates of white microcline up to several cm long.

A sheet of a dense grey to black alkali microsyenite occurs in the river bed about 20 m to the south of the bore hole and is intersected by the bore hole in the depth interval 5.66–21.35 m (Fig. 2) indicating a thickness of about 16 m. The microsyenite most probably forms a nearly horizontal sheet-like intrusion in the naujaite and is described in a separate paper (Rose-Hansen & Sørensen 2001).

The drill core is dominated by naujaite which is intersected by sheets of arfvedsonite lujavrite and by veins of albite-analcime-natrolite which often contain steenstrupine crystals and Li-mica.

Villiaumite occurs at the depth of only 3-3.5 m which is the closest to the surface this water-soluble mineral has been found in the complex. The naujaite contains scattered grains of villiaumite from a depth of 145 m to the bottom of the core. At 154.00 the naujaite contains fluorite as well as villiaumite.

Bore hole no. II

The bore hole is located on a scree-covered slope ca. 1 km to the west of Tuttup Attakoorfia on the north coast of Tunulliarfik at an altitude of 80 m a.s.l. (Figs 1, 2, 3).

The bedrock near the drilling site consists of a breccia of xenoliths of naujaite enclosed in and intruded by laminated arfvedsonite lujavrite. The xenoliths vary in size from a few cm to many hundred metres. The naujaite of the larger

Fig. 3. The north wall of Tunulliarfik showing the lujavrite-naujaite breccia zone with rafts of naujaite (white) enclosed in lujavrite (black). Above the lujavite, naujaite overlain by sodalite foyaite and in right side of photo of alkali granite, augite syenite and basalts from the roof. Bore hole II is located to the left of the gorge in the extreme left side of the photo, bore hole III on the small point Illunnguaq in the right hand side of the photo. Tuttup Attakoorfia is the low black coastal cliff in centre of photo (cf. Fig. 1).

xenoliths is generally unaltered, with the exception of the contact zones against lujavrite where it is recrystallized. The smaller xenoliths of naujaite are generally recrystallized. The lujavrite is intersected by albite-analcime veins containing steenstrupine, sphalerite, epistolite, pectolite, Li mica, etc.

The slope to the north of the bore hole, between 80 and 150 m a.s.l., is made up of a series of brown steenstrupine-rich arfvedsonite lujavrites with some horizons rich in rounded xenoliths of green aegirine lujavrite (see Sørensen 1958, p. 43; 1962, pp. 63-65, 83-88).

The upper 9.15 m of the bore hole penetrates the surficial deposits. Below this depth the core consists of alternating horizons of arfvedsonite and aegirine lujavrites and of horizons of arfvedsonite lujavrite with rounded enclaves of aegirine lujavrite. From a depth of 91.40 m, the lujavrites contain xenoliths of strongly altered naujaite and are cut by analcime veins. The lujavrite sequence is from 114 m to the bottom of the hole underlain by naujaite. The sequence of alternating black and green lujavrite with xenoliths of naujaite is exposed along the shore of the fjord to the south of the bore hole.

This drill core brings important information about the relationship between naujaite and lujavrites and between the green and black lujavrites. Felted aegirine and deformation in the contacts between lujavrites and naujaite bodies show that the emplacement of the lujavrites was preceded by deformation, fracturing and deposition of felted aegirine in fractures in the naujaite.

The aegirine lujavrite is intersected by veins of arfvedsonite lujavrite and occurs as rounded xenoliths in this rock. These features indicate that there was an episode of brecciation and fracturing between the emplacement of the two types of lujavrite, though there are also cases of gradual transition between the aegirine and arfvedsonite lujavrites.

Villiaumite is present in the lujavrites from 61 to 70 m and 76-89 m. The naujaite contains villiaumite from 145 to 174 m and from 196 m to the bottom of the hole. The villiaumite may be associated with fluorite. The lujavrites in several horizons are rich in mm-sized holes, indications of the former presence of villiaumite or more likely of other water-soluble minerals.

Bore hole no. III

The site of this hole is a trigonometrical point near Illunnguaq on the north coast of Tunulliarfik (Figs 1, 2, 3). The bedrock at the site is a laminated arfvedsonite lujavrite rich in spheroidal bodies up to 25 cm across. These bodies are concentrically zoned with a core macroscopically identical to the lujavrite outside the bodies and with white rims rich in brown aegirine (Fig. 14). A paper discussing these bodies is in preparation.

Adjacent to the lujavrite with the spheroidal bodies the arfvedsonite lujavrite contains numerous xenoliths of naujaite. They vary from unaltered bodies with sharp contacts to strongly altered rocks rich in analcime and natrolite. The lujavrite is cut by veins of albite and/or analcime with steenstrupine, epistolite, pectolite, sphalerite, etc. To the east of the bore hole there are areas made up of coarse-grained rocks which may be lujavrite pegmatites or medium- to coarse-grained lujavrite. They have prismatic grains of arfvedsonite and aegirine and stellar aggregates of these minerals in a matrix of analcime.

This drill core is made up of arfvedsonite lujavrite, aegirine lujavrite and aegirine-arfvedsonite lujavrite which all have xenoliths of naujaite. The core shows examples of gradual transitions of aegirine lujavrites into aegirine-arfvedsonite and arfvedsonite lujavrites by increasing contents of arfvedsonite coupled with decreasing contents of aegirine. Hydrothermal veins cut naujaite and lujavrite.

The naujaite xenoliths are bleached and recrystallized. The arfvedsonite and aegirine are often replaced by aggregates of very fine-grained biotite. The eudialyte is always replaced by catapleiite, analcime, pigmentary material, etc. The eudialyte of the lujavrites is also generally strongly altered into catapleiite, etc.

It is a characteristic feature that biotite is present not only as a secondary mineral in the naujaite but is also associated with arfvedsonite and brown aegirine in the lujavrites and forms schlieren in some lujavrites.

Bore hole no. IV

This hole is located on a small rocky shelf at Naajakasik on the south coast of Tunulliarfik close to the west contact of the complex (Figs 1, 2, 4). The bedrock is a weakly laminated, fine-grained arf-

Fig. 4. The south side of Tunulliarfik showing the westernmost part of the Ilímaussaq complex. The right hand side of the photo shows basalt overlying sandstone in Nunasarnaasaq (cf. Fig. 1). The steep wall is the contact between the country rocks and crumbling augite syenite which on the plateau is in contact with naujaite overlain by sodalite foyaite (light grey). Bore hole IV is located on the small point Naajakasik in centre of photo which is made up of lujavrite with xenoliths of naujaite. The mountain ridge in the background is Killavaat (Redekammen) made up of basement granite intersected by dolerite dykes.

Fig. 5. The south side of Tunulliarfik showing the eastern part of the Ilímaussaq complex. Appat is located on the extreme left side of the photo (cf. Fig. 1). In the right side of the photo, the complex is made up of naujaite (light grey) veined by lujavrite (black), the left hand side is made up of a complicated mixture of lujavritic rocks with xenoliths of naujaite. Bore hole V is located on the plateau on the left side of the photo.

vedsonite lujavrite which is separated from the contact by a zone of aegirine lujavrite rich in large xenoliths of naujaite. The dip of the lamination of the lujavrites is about 30° toward the N and the E.

The drill core consists of alternating lujavrite and naujaite cut by analcime veins. Fine-grained, weakly- to well-laminated arfvedsonite lujavrite predominates in the upper part of the core, aegirine lujavrite in the lower part.

Fig. 6. Bore hole V is located in the foreground in naujaite intruded and enclosed by arfvedsonite lujavrite. The black rock in the middleground is aegirine lujavrite I and II tapering out along the east contact of the complex (cf. Fig. 1). Appat is located to the immediate left of the photo. The background is the basement granite in Killavaat mountain.

Fig. 7. The plateau at Appat made up of arfvedsonite lujavrite (black) with naujaite xenoliths (light grey). In the background, Illerfissalik Mountains (1752 m), part of the Igaliko alkaline complex.

Medium- to coarse-grained lujavrite is also present. The arfvedsonite lujavrite is by far the richest in naujaite xenoliths.

As in drill core III, the naujaite xenoliths are strongly altered, arfvedsonite and aegirine often being replaced by biotite; eudialyte and sodalite are generally replaced by alteration products.

Bore hole no. V

This hole is located close to the east contact of the complex, *c.* 1 km WSW of Appat, a few metres to the southwest of the small lake at 300 m a.s.l. (Figs 1, 2, 5, 6, 7). The bedrock is a strongly altered naujaite xenolith enclosed in well-laminated and fissile, arfvedsonite lujavrite rich in eudialyte. The dip of the lamination is about 45° W, that is towards the interior of the complex. There is a considerable variation in strike direction because the many xenoliths of naujaite are wrapped by the lamination of the lujavrite. The naujaite has pockets of natrolite and sphalerite and is cut by white and red veins of albite and natrolite. These veins have contact zones of prismatic grains of arfvedsonite oriented at right angle to the walls of the veins. The lujavrite is also cut by such veins, against which it is strongly altered.

A little to the south of the drill hole, the naujaite and lujavrite are cut by many shear zones striking N-S. These fractures are coated by Fe-Mn oxide minerals. A similar coating is observed on shear zones in the supracrustal Gardar rocks at Nunasarnaq (Hansen 1968).

The drill core consists of lujavritic rocks with xenoliths of naujaite which are generally rich in secondary analcime and natrolite. These rocks are intersected by late hydrothermal veins.

The predominant lujavrite is a laminated arfvedsonite lujavrite with well-developed layering, parts of the drill core have closely spaced thin layers of nepheline-rich rocks. As in other cores, arfvedsonite lujavrite dominates the upper part, aegirine lujavrite the lower. Fig. 6 shows the exposed aegirine lujavrite a few hundred metres to the east of the bore hole. Aegirine lujavrite is met at depth 90 m in the drill core confirming the above-mentioned westward dip of the lamination.

Bodies of coarse-grained felsic rocks rich in crystals of nepheline, sodalite, microcline and eudialyte and with strongly varying contents of aegirine

Fig. 8. The south side of Tunulliarfik between the sections shown in Figs 4 and 5. Tuper-ssuatsiaat is the bay on the left side of the photo (cf. Fig. 1). On the right side of the bay, the complex is made up of naujaite veined by lujavrite, on the left side by lujavrite overlain by naujaite. The plateau is made up of lujavrite with xenoliths of naujaite. Bore hole VI is located on the plateau behind the bay.

and arfvedsonite occur as larger masses in the lujavrites and present a special problem to be discussed in a later section.

Bore hole no. VI

The site of the drill hole is in the large area of lujavrite referred to as the Tupersuatsiaat area in the earlier literature (e.g. Buchwald & Sørensen 1961). These lujavrites are enriched in uranium and form a structural culmination. The drill site is close to the small lake located 2700 m WSW of Appat at 320 m a.s.l. (Figs 1, 2, 8, 9).

The bed rock is a weakly to unlaminated arfvedsonite lujavrite with irregular cm-large brown spots rich in brown aegirine and with yellow-brown alter-

Fig. 9. The plateau at the site of bore hole VI is made up of arfvedsonite and naujakasite lujavrite (both black) with xenoliths of naujaite (white) forming part of the breccia zone. Background, the north coast of Tunulliarfik showing from left to right: basalts, the westernmost and central parts of the Ilímaussaq complex, cf. Fig. 3.

Fig. 10. The head of Kangerluarsuk. The site of bore hole VII is on the ridge running from the lower left corner to the right hand side of the photo (cf. Fig.1). The wall facing the river Lakseelv is from foot to top made up of the transitional layered kakortokite, aegirine lujavrite I and II and at the right side of the photo of the transitional and arfvedsonite lujavrites (black) which intrude the roof of naujaite (white) and contain xenoliths of naujaite. The layering of the transitional layered kakortokite and the aegirine lujavrite is clearly seen. The naujaite is overlain by sodalite foyaite and foyaite (left background). The foreground is made up of layered kakortokite.

ation products after sphalerite. Fine-grained lujavrite varieties predominate, but there are also medium-grained lujavrites. The lamination has a steep dip. Near the drill site the lujavrite encloses many xenoliths of naujaite which are often cut by veins of felted aegirine.

The drill core is composed of arfvedsonite lujavrite, minor aegirine lujavrite, naujaite and brecciated masses of dense black rocks with white prismatic phenocrysts of pectolite up to 1 cm long. All rocks are intersected by hydrothermal veins.

The naujaite varies from practically unaltered and rich in eudialyte, locally up to 85 vol.%, to strongly altered rocks rich in analcime and natrolite without eudialyte and with arfvedsonite altered into biotite. There are thin pegmatitic horizons with up to 5 cm long prismatic grains of arfvedsonite and large crystals of eudialyte.

This drill core shows that the lujavrite is underlain by naujaite and that arfvedsonite lujavrite predominates over aegirine lujavrite. The emplacement of the arfvedsonite-bearing lujavrite was preceded by aegirine lujavrite.

Bore hole no.VII

The drill hole is located ca. 1 km NE of the mouth of Lakseelv (Figs 1, 2, 10, 11) at an altitude of 120 m on the ridge of aegirine lujavrite. The core has been examined in detail by Bailey (1995) in a study of cryptorhythmic and macrorhythmic layering of lujavrite and by Bailey & Gwozdz (1994).

The bedrock at the drilling site is a fine-grained aegirine lujavrite with larger poikilitic grains of arfvedsonite up to 0.5 cm across, the variety called aegirine lujavrite I by Bohse & Andersen (1981). This rock passes gradually into the underlying transitional layered kakortokite which is exposed about 140 m to the south of the bore hole according to the maps by Henriksen (personal information 1993) and Bailey (1995), see also Fig. 10. The dip on the surface is about 60° NW. The top of the bore hole is located in the middle part of aegirine lujavrite I. Extrapolation of the boundary zone from the surface towards the vertical bore hole indicates that the bore hole does not reach the lower contact of this lujavrite. The aegirine lujavrite is generally strongly fissile due to the arrangement of acicular aegirine and

Fig. 11. The continuation to the north of the section seen in Fig. 10. The foreground is made up of layered kakotokite. The aegirine lujavrite is seen to the left in the ridge facing the river. It is to the right overlain by transitional and arfvedsonite lujavrites, the last-named sending sheets and dykes into the overlying naujaite (grey). The Lakseelv valley.

feldspar laths in the plane of lamination. The lujavrite shows microfolding, the direction of the fold axis is 94-100°. Adjacent to the drill site the lujavrite contains small xenoliths of naujaite. There are pegmatitic veins having large crystals of arfvedsonite and eudialyte, the latter being concentrated in the central parts of the veins.

In addition to aegirine lujavrite, the drill core is composed of naujaite, a little arfvedsonite lujavrite and kakortokite-like rocks. The aegirine lujavrite is in many horizons brecciated and penetrated by zones of felted aegirine.

Andersen et al. (1981a, b) and Bailey et al. (1981) have studied the transition from kakortokites to lujavrites including aegirine lujavrite I (Fig. 12). Based on the examination of drill core VII they have demonstrated the presence of a number of eudialyte-rich horizons in aegirine lujavrite I and have also elaborated the Zr-Y-U stratigraphy of the southern part of the Ilímaussaq complex. The eudialyte-rich layers are also described by Le Couteur (1990) and Henriksen (personal information 1993)

Bailey & Gwozdz (1994) examined the distribution of Li in the minerals and rocks of drill core VII. The lujavrite contains 80-200 ppm Li which is concentrated in the intercumulus zeolites and arfvedsonite. Arfvedsonite contains 2200 ppm Li. The amount of intercumulus material increases upwards in the core.

Arfvedsonite lujavrites	150-300 m	Arfvedsonite lujavrite
Lujavrite transition zone	35 m	Upper layer of aegirine lujavrite II
	25 m	Lower layer of arfvedsonite lujavrite
Aegirine lujavrites	85 m	Aegirine lujavrite II
	80 m	Aegirine lujavrite I
Kakortokites	40 m	Transitional layered kakortokite
	35 m	Slightly layered kakortokite
	210 m	Lower layered kakortokite (exposed part)

Fig. 12. Schematic representation of the standard kakortokite-lujavrite stratigraphy according to Andersen et al. (1981b).

Structure and evolution of the Ilímaussaq complex

Ussing (1912) showed that the rocks in the agpaitic part of the Ilímaussaq complex have the structural form of flat saucers piled one upon another and that at the eastern and perhaps also the northern contact, the marginal parts of the saucers are bent almost vertically upward parallel to the contact against the country rocks. The steeply dipping rocks along the east contact consist of lujavrites. We now know that also the northern contact zone at Kvanefjeld and in the foothills of the Ilimmaasaq mountain (Fig. 1) is dominated by lujavritic rocks (Sørensen et al. 1969, 1974). The saucer-shaped layers and the steeply dipping contact zones were explained by Ussing (1912) as a result of subsidence of the central part of the complex.

Ussing (1912) established the major features of the stratigraphy of the Ilímaussaq complex. The first intrusive phase of augite syenite was partially replaced by the subsequent formation of the stratified agpaitic part of the complex and only remained as a partial marginal rim. Ferguson (1964) and Hamilton (1964) demonstrated that remnants of augite syenite also occur near the roof of the complex (Fig. 1) and Sørensen et al. (1969, 1974) that large masses of augite syenite are enclosed in the lujavrites of the south-west part of the Kvanefjeld plateau. According to Nielsen & Steenfelt (1979) these masses of augite syenite lie very close to their original position.

Based on almost continuous exposures at the head of Kangerluarsuk and to the south of Appat (Fig. 1), Andersen et al. (1981b) and Bohse & Andersen (1981) established the stratigraphy of the floor series and lujavrites of the intermediate series of the complex (Fig. 12), from the lowest exposure upwards: lower layered kakortokite, slightly layered kakortokite, transitional layered kakortokite, aegirine lujavrite I, aegirine lujavrite II, lujavrite transition zone, arfvedsonite lujavrite. There is a gradual transition from the kakortokite of the floor series of the complex into the aegirine lujavrites (cf. Fig. 10) and again a gradual transition from the aegirine lujavrites via transitional lujavrites into arfvedsonite lujavrites.

The lowermost part of the lujavrite sequence is made up of cumulitic rocks, whereas the uppermost lujavrites occur as dykes and sheets which intersect the overlying naujaite (Fig. 11). This mixed association of naujaite and lujavrite was described by Ussing (1912) as the breccia zone: large angular blocks of naujaite are injected and engulfed by lujavrite (Figs 3, 7, 9), but apparently they lie more or less undisturbed, their partings being in a parallel position and parallel to the partings of the overlying unbroken naujaite.

At Kvanefjeld, it may be concluded from the study of surface exposures and drill cores that, before the emplacement of the lujavrites, this part of the complex consisted of augite syenite and of pulaskite, foyaite and naujaite from the roof series. The marginal contact against the volcanic rocks to the north was made up of naujaite and naujaite border pegmatite. Intermittent emplacement of lujavritic melts took place in nearly vertical zones during several periods of deformation and faulting of the roof series rocks, the augite syenite and the volcanic rocks resulting in the formation of an intrusion breccia (Sørensen et al.

1969, 1974; Nielsen & Steenfelt 1979). The occurrence of xenoliths of pulaskite and foyaite in the lujavrite in the foothills of Ilimmaasaq to the east of Kvanefjeld (Rose-Hansen et al. 1977) confirms that the northern part of the complex was made up of roof series rocks prior to the emplacement of the lujavrite.

In the south slope of the Kvanefjeld plateau facing the Narsaq Elv valley, it is seen that the large masses of augite syenite of the southwestern part of the plateau are underlain by naujaite. Nevertheless, the lujavrites intruding and overlying the augite syenite have xenoliths of naujaite, foyaite and volcanic roof rocks, all three often present within a limited part of an outcrop or drill core. This shows that the lujavritic melt has transported fragments of naujaite and foyaite upwards, whereas gabbro fragments from the volcanic roof have sunk into the lujavritic melt. In drill cores, lava xenoliths in lujavrite have been observed below xenoliths of augite syenite and naujaite at depths greater than 300 m below the present surface. This may not necessarily mean that lava fragments have sunk deep into the lujavritic magma. Another possibility is that screens of volcanic roof rocks have been present in the zones of deformation through which the lujavritic melts ascended and have been engulfed by the lujavrite. In such cases the fragments from the volcanic roof are left in a more or less *in situ* position.

Information from bore holes I-VII

The drill cores from the Kvanefjeld plateau (Sørensen et al. 1969, 1974; P. Nyegaard personal information 1979) and the seven drill cores described in the present study supply important additional information on the structure of the complex and on the geology of the lujavrite series. The bore holes at Kvanefjeld are located close to the north contact of the complex and penetrate lujavrites from a very high stratigraphical level immediately below the volcanic roof. The bore holes described in the present study penetrate rocks from lower stratigraphical levels made up of naujaite and lujavrites.

Bore holes IV and V (Figs 1, 2, 13). These two bore holes are located at rather low stratigraphical levels close to the west and east contacts of the complex, respectively. At the two sites, the contact against the country rocks is made up of the kakortokitic border pegmatite followed inwards by aegirine lujavrite II and arfvedsonite lujavrite. The drill cores consist almost entirely of lujavrites, arfvedsonite lujavrite dominating the upper parts, aegirine and arfvedsonite-aegirine lujavrites the lower parts. The two drill cores have very few and small xenoliths of naujaite in spite of the presence of large masses of naujaite at the two drilling sites. There are no xenoliths of the other roof series rocks or volcanic rocks from the roof.

Drill core IV is from the top downward composed of 48 m arfvedsonite lujavrite, 50 m aegirine lujavrite, 51 m arfvedsonite lujavrite and arfvedsonite-aegirine lujavrite and at the bottom 51 m aegirine lujavrite (Fig. 2). This succession may be correlated with the abovementioned standard stratigraphical sequence (Fig. 12) established by Andersen et al. (1981 b): the lowermost part of the arfvedsonite lujavrite, the transitional lujavrite zone composed of the upper aegirine lujavrite II and the lower arfvedsonite lujavrite, and at the bottom aegirine lujavrite II.

Drill core V is from the top downward composed of 90 m arfvedsonite lujavrite, 46 m aegirine lujavrite, 60 m arfvedsonite lujavrite and arfvedsonite-aegirine lujavrite and 3 m aegirine lujavrite. This succession may also represent the lower part of the arfvedsonite lujavrite, the transitional lujavrites and the uppermost aegirine lujavrite II of the abovementioned standard sequence. The interpretation of the lujavrite stratigraphy of drill cores IV and V is in excellent agreement with the detailed information about the lujavrites found in the geological map by Andersen et al. (1988).

As mentioned in a previous section, drill core V differs from the other drill cores in containing xenoliths of pegmatitic rocks rich in nepheline, sodalite, microcline and eudialyte and with varying contents of arfvedsonite, aegirine and other minerals. The rocks differ from naujaite in having separate crystals of especially nepheline and eudialyte and in lacking the characteristic poikilitic texture; they differ from the kakortokites in the lack of igneous lamination. They are most probably engulfed fragments of border pegmatite. Alternative interpretations are: (1) they may have been formed by recrystallization of xenoliths of naujaite; (2) they may represent an independent intrusive phase formed after the formation of naujaite and kakortokite and before the lujavrites as proposed by Sørensen (1958) for sim-

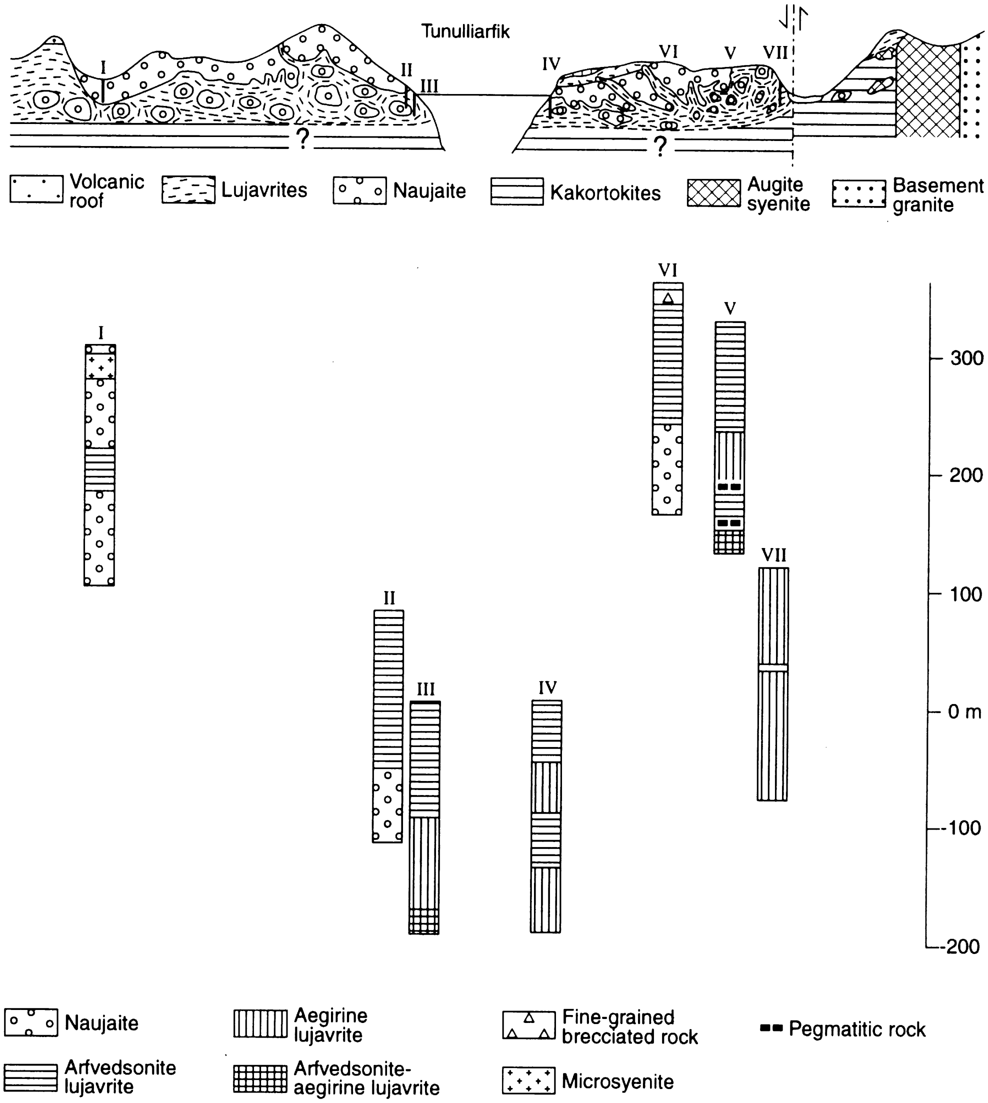


Fig. 13. Composite diagram showing the position of bore holes I to VII in a schematic NW-SE section through the Ilímaussaq complex.

ilar rocks found as xenoliths in aegirine lujavrite at the head of Kangerluarsuk and presented as naujaite on the geological map by Andersen et al. (1988); or (3) they may represent lujavrite pegmatites. As these pegmatitic rocks are found only in bore hole V, is is most likely that they are related to the local environment, that is the contact with the border pegmatite.

Bore holes I, II and III: These three bore holes are located in the northern half of the complex and represent rather high stratigraphical levels.

Drill core I (Figs 1, 2, 13) is made up of naujaite and covers the lower part of the main horizon of naujaite, that is the lower part of the naujaite lying between the sodalite foyaite and the naujaite-lujavrite breccia zone. There are sheets of arfvedsonite lujavrite and subordinate aegirine lujavrite, the former enclosing xenoliths of naujaite. The bore hole is located in the Narsaq Elv Valley at 292 m a.s.l. The 200 m long core ends in naujaite at 92 m a.s.l. The naujaite horizon reaches the altitude *c.* 450 m in the south wall of the Kvanefjeld plateau to the west of the drilling site and more than 700 m at Nakkaalaaq to the east of the site. This means that the naujaite horizon is more than 600 m thick. This compares well with earlier estimates of the thickness of the naujaite: Ussing (1912) 200-600 m, Ferguson (1970) 600-800 m, and Andersen et al. (1981) 600 m.

Bore holes II and III are both located on the north coast of Tunulliarfik at the altitudes 80 and 5 m a.s.l., respectively (Figs 1, 2, 3, 13).

Drill core III is in the uppermost 100 m made up of arfvedsonite lujavrite with thin sheets of aegirine lujavrite. This is underlain by 60 m aegirine lujavrite and 40 m arfvedsonite-aegirine lujavrite cut by a few sheets of arfvedsonite lujavrite. The section may be correlated with the lower part of the arfvedsonite lujavrite and the transitional lujavrite of the standard sequence of Andersen et al. (1981b) and Bohse & Andersen (1981).

The upper part of drill core II is made up of arfvedsonite lujavrite with rounded xenoliths of aegirine lujavrite and a few veins of medium- to coarse-grained lujavrite or of lujavrite pegmatite. This sequence cannot be correlated with the standard succession of Andersen et al. (1981b). Assuming that there is no major fault zone between the sites of bore holes II and III, Fig. 13 indicates that the lujavrite of drill core II may be regarded as an upward extension of the arfvedsonite lujavrite seen in drill core III. The horizon of arfvedsonite lujavrite with its xenoliths of naujaite and aegirine lujavrite is accordingly at least 175 m thick. The lower part of drill core II, from *c*. 35 m to 120 m below sea level, consists of naujaite which is intersected by thin sheets of aegirine lujavrite and is interpreted as a raft of naujaite in lujavrite. The core ends in naujaite.

The naujaite-lujavrite breccia zone seen in the north face of Tunulliarfik (Fig. 3) displays a shallow dip towards the east; the overlying main mass of naujaite reaches the coast line a few hundred metres to the east of Illunnguaq (Fig. 1). The fact that naujaite only occurs as small xenoliths in the lujavrites of core III most probably means that this hole is located in a vertical zone of lujavrite between larger masses of naujaite.

Bore hole VI: This hole is located in the central part of the main area of lujavrite to the south of Tunulliarfik (Figs 1, 2, 9, 13). The uppermost *c*. 120 m of the core is made up of arfvedsonite lujavrite with minor aegirine lujavrite and a single xenolith of naujaite. The lowermost *c*. 80 m of the core is made up of naujaite with a few sheets of aegirine lujavrite. The hole terminates in naujaite at 120 m a.s.l. The drilling site is in lujavrite with many large xenoliths of naujaite, that is, it is located in the naujaite-lujavrite breccia zone (Fig. 9). As seen in Fig. 13, bore holes VI and V are located at almost the same altitude, but direct correlation between them is problematical because the last-named bore hole is situated near the east contact of the complex where the lujavrites are bent upward towards the contact. The same applies to the relation to bore hole IV located near the west contact. The considerable difference in altitude between bore holes IV and VI indicates, however, that the arfvedsonite lujavrite reaches high levels in the breccia zone. North of Tunulliarfik, the combined information from bore holes II and III and from the geological map indicates that the total thickness of the arfvedsonite lujavrite, the breccia zone included, may exceed 300 m. This is a higher value than the earlier estimates of 150 m for the main arfvedsonite lujavrite (Andersen et al. 1981b) and 200 m for the lujavrites overlying the aegirine lujavrite (Ferguson 1970).

Drill core VI differs from the other cores in the presence of brecciated masses of a very fine-grained black rock with phenocrysts of pectolite enclosed in a very fine-grained matrix of lujavritic mineralogy. These masses appear to be engulfed and partly digested by the enclosing arfvedsonite lujavrite. The origin of the fine-grained black rock is uncertain. In thin section, it texturally and mineralogically looks like very fine-grained lujavritic rocks displaying a pronounced trachytic texture. It may, however, also be recrystallized xenoliths of microsyenitic dyke rocks intersecting the naujaite but emplaced before the lujavrite. Microsyenitic minor intrusions are known to transect naujaite and aegirine lujavrite but are transected by arfvedsonite lujavrite (Ferguson 1964; Rose-Hansen & Sørensen 2001). In consideration of the rather high level in the complex, it might be envisaged that the fine-grained rocks are stoped blocks from the volcanic roof of the complex which have sunk into the lujavrite. This implies, however, that the lujavrites here have penetrated through the overlying roof series of naujaite, for which there is no direct field evidence.

Bore hole VII: This bore hole is located in rather steeply dipping and strongly tectonized aegirine lujavrite I (Figs 1, 2, 10, 11, 13) and represents the deepest level in the intrusion penetrated by bore holes I-VII. The deformation is most probably connected with the activity in the fault zone in the Lakseelv valley about 200 m to the south of the drilling site. The aegirine lujavrite contains a number of thin sheets of arfvedsonite lujavrite and xenoliths of naujaite.

There are horizons of coarse-grained rocks made up of plates of microcline arranged around crystals of eudialyte and round aggregates of natrolite interpreted to be secondary after nepheline. They have interstitial prismatic and acicular crystals of arfvedsonite and aegirine. These coarse-grained rocks grade into the adjoining aegirine lujavrite and most probably represent a pegmatitic facies of this rock. It should, however, be pointed out that the coarse-grained rocks texturally recall the kakortokites from which they first of all differ in having aegirine and arfvedsonite as interstitial grains. The arfvedsonite may form poikilitic grains as in the aegirine lujavrite.

The examination of drill cores I to VII thus confirms the field observation that arfvedsonite lujavrite generally occurs at a higher stratigraphical level than aegirine lujavrite, but that sheets of the latter are intercalated in the main sequence of arfvedsonite lujavrite. The relationship between the aegirine and arfvedsonite lujavrites will be discussed in more detail in a later section.

Medium- to coarse-grained lujavrite (M-C lujavrite), which forms large masses at Kvanefjeld (Sørensen et al. 1969) and at Appat (Andersen et al. 1988), is only observed as thin veins in drill cores I-VII. In general, it it impossible to decide if these veins should be interpreted as lujavrite pegmatites or as belonging to an independent phase of M-C lujavrite. The veins often occur close to naujaite xenoliths and may also be interpreted as products of a reaction between naujaite and lujavritic melt as proposed by Sørensen (1962).

In conclusion, drill cores I to VII do not represent a continuous section through the Ilímaussaq complex (cf. Fig. 12). They provide information about the lower part of the naujaite horizon, the naujaite-lujavrite breccia zone, the main arfvedsonite lujavrite horizon, the lujavrite transition zone, very probably aegirine lujavrite II and certainly aegirine lujavrite I.

Correlation across Tunulliarfik

The fjord Tunulliarfik, which divides the complex into a northern and a southern part, is located in a pre-Ilímaussaq fault zone. The basement granite and its cover of Gardar sandstone and volcanics are downfaulted to the north of the fjord (Fig. 1, see also the maps of Ferguson 1964; Allaart 1973; Kalsbeek et al. 1990). The fault zone was apparently inactive or nearly so during or after the emplacement of the Ilímaussaq complex. The boundary between the naujaite and the overlying sodalite foyaite may be regarded as a stratigraphical marker horizon. It is located about 300 m above sea level on the north side of the fjord and about 100 m on the south side as illustrated by the geological map of Ferguson (1974). Both places are located in the central part of the complex and are characterised by an almost horizontal orientation of this boundary and other major planar structures in the agpaitic rocks. This may indicate that the part of the Ilímaussaq complex lying to the south of the fjord has been down-faulted about 200 m compared to the part lying to the north of the fjord. However, the sagging of the central part of the complex invoked already by Ussing (1912) may explain the difference in altitude of the boundary between sodalite foyaite and naujaite on the two sides of the fjord. A major fault zone is located in the Lakseelv valley and Kangerluarsuk fjord in the southern part of the complex (Fig. 1). The northern side of this fault is according to Bohse et al. (1971) downfaulted about 350 m compared to the southern fault block. The displacement along the Lakseelv fault zone in the southern part of the complex appears to involve the layered kakortokite and the aegirine lujavrites according to Bohse et al. (1971). In addition to the major fault, small scale faulting is observed all over the complex and there are major zones of fracturing and hydrothermal alteration, as for instance the red zone intersecting naujaite and lujavrite on the north coast of Tunulliarfik (Ussing 1912: 77) and similar zones marked on the map of Ferguson (1974). Little if any displacement has taken place along the last-named zones of fracturing.

Correlation of the lujavrite stratigraphy across Tunulliarfik is difficult because of the absence of indisputable marker horizons in the lujavrite series. To the north of Tunulliarfik, the contact between the arfvedsonite lujavrite of the breccia zone and the overlying naujaite is located at about 200 m a.s.l., locally more than 300 m a.s.l., whereas to the south of the fjord it lies between 300 and 400 m a.s.l. according to the geological map of Ferguson (1964), see also the map of Andersen et al. (1988). This difference in altitude can, however, easily be explained by the dip of the planar structures towards the centre of the complex and by the fact that the lujavrites around bore hole VI occupy an updomed structure. Furthermore, the lujavrite of the breccia zone intrudes the naujaite which explains that it attains different stratigraphical levels in different parts of the complex.

There are several boundaries between aegirine lujavrite and arfvedsonite lujavrite: the boundary between aegirine lujavrite II and the transitional lujavrite, and boundaries between the aegirine and arfvedsonite lujavrite units within the transitional lujavrites and against the overlying arfvedsonite lujavrite. Furthermore, drill cores I-VI show horizons of aegirine lujavrite within the arfvedsonite lujavrite. In drill core II, xenoliths of aegirine lujavrite are enclosed in arfvedsonite lujavrite, an indication of arfvedsonite lujavrite intruding aegirine lujavrite and the wedging out of horizons of aegirine lujavrite. These features make correlations based on boundaries between the two lujavrite types highly problematical. Bore holes III and IV are both located near sea level on opposite sides of Tunulliarfik (cf. Fig. 12). In an earlier section it has been proposed that a boundary between arfvedsonite lujavrite and aegirine lujavrite located at the depth 105 m in drill core III and at 48 m in drill core IV may correspond to the boundary between arfvedsonite lujavrite and transitional lujavrite in the standard stratigraphy of the lujavrites. This difference in altitude can be explained by the location of bore hole IV in the contact near part of the complex characterised by a steep orientation of the planar structures of the rocks.

In conclusion, there has been little if any fault movement between the northern and southern parts of the complex during and after formation of the agpaitic rocks.

The relations between aegirine and arfvedsonite lujavrites

Aegirine lujavrite dominates the lower parts of drill cores III, IV and V where it forms large masses with xenoliths of naujaite and thin veins intruding the naujaite xenoliths. The fractures intruded by the aegirine lujavrite veins were often occupied by crusts of felted aegirine, a feature also seen in the case of veins of arfvedsonite lujavrite intruding naujaite and interpreted to be fracture fillings formed prior to the emplacement of the arfvedsonite lujavrite magma (Sørensen 1962). Arfvedsonite lujavrite dominates the upper parts of the drill cores as larger masses and as veins in naujaite.

Two types of relations between aegirine lujavrite and arfvedsonite lujavrite are observed in the drill cores:

(1) There is a gradual transition from aegirine lujavrite to arfvedsonite lujavrite, that is the crystallization of aegirine is succeeded by crystallization of arfvedsonite. This may appear as an alternation of green and black parallel layers (cf. Ferguson 1964, figs 33, 34), where individual layers vary in thickness from mm-size to several cm. The arfvedsonite grains of the arfvedsonite lujavrites very often contain tiny inclusions of acicular aegirine which shows that aegirine in many cases was the first of the two minerals to form. In both types of lujavrite, aegirine and arfvedsonite are interstitial to nepheline and platy crystals of microcline and/or albite and generally occur as prismatic grains, which may be bent. Aegirine may also occur as felted masses of tiny acicular grains. In aegirine lujavrite, arfvedsonite often occurs as oikocrysts measuring up to more than 1 cm and enclosing especially feldspar and aegirine in smaller grains than in the surrounding rock, an indication of the onset of crystallization of arfvedsonite at an intermediate stage of consolidation of the melt. Nepheline generally occurs as larger grains in the aegirine lujavrite than in the arfvedsonite lujavrite.

The arfvedsonite-aegirine lujavrite represents a 'frozen' state of transition from magmatic crystallization of aegirine into crystallization of arfvedsonite, that is a transition from aegirine lujavrite to arfvedsonite lujavrite. There is also a late-magmatic transition in the opposite direction, brown aegirine (acmite in the earlier literature on the complex) replacing arfvedsonite in rocks in which the felsic minerals are replaced by analcime, and in some rocks also by natrolite.

(2) The arfvedsonite lujavrite of drill core II has rounded enclaves of aegirine lujavrite. In some cases it looks as if the arfvedsonite lujavrite infiltrates the aegirine lujavrite parallel to the igneous lamination of the latter. In other cases the arfvedsonite encloses fragments of aegirine lujavrite and also fragments of felted aegirine, which means that the aegirine lujavrite was tectonized before or in connection with the emplacement of the arfvedsonite lujavrite. The frequent occurrence of xenoliths of aegirine lujavrite in arfvedsonite lujavrite adjacent to naujaite xenoliths indicates that the naujaite was invaded by aegirine lujavrite prior to the emplacement of the arfvedsonite lujavrite. Arfvedsonite lujavrite intrusive into aegirine lujavrite has often a concentration of arfvedsonite in the contact against the last-named rock which may be enriched in white mica adjacent to the arfvedsonite lujavrite.

As pointed out in the preceding paragraph, the alternation of green and black parallel layers may in some cases be a result of infiltration of arfvedsonite lujavrite along the lamination of the aegirine lujavrite, but in others it may be governed by periodic changes in the physico-chemical conditions of consolidation of the lujavrite melts which determine whether aegirine or arfvedsonite crystallizes.

These observations show that the physico-chemical conditions responsible for the formation of arfvedsonite instead of aegirine in some cases changed gradually or in a periodical way; in others the arfvedsonite lujavrite represents an independent pulse of magma.

The relations between aegirine and arfvedsonite are determined by temperature, activities of water and silica and oxygen fugacity (Sørensen 1962; Larsen 1976; Markl et al. 2001). Aegirine is formed at a relatively high temperature in lujavritic melts unsaturated in water. Rising contents of water and lower temperature favour the formation of arfvedsonite. The brown aegirine substitutes for arfvedsonite (and in cases also for aegirine) when oxygen fugacity increases in a water-saturated system dominated by the low-temperature crystallization of analcime and brown aegirine (Markl et al. 2001).

Layering in the lujavrites

Drill cores I-VII show that layering in the arfvedsonite lujavrite is more widespread than formerly known.

In addition to the the above-mentioned alternation of layers of green and black lujavrite, drill cores I to VII show the following types of lujavrite layering: (1) layering caused by alternation of finer and coarser grained layers, (2) layers rich or poor in arfvedsonite, (3) alternation of layers rich in nepheline and layers rich in microcline, (4) alternation of layers rich in albite or microcline, and (5) thicker layers of homogeneous laminated arfvedsonite lujavrite alternating with thin light-coloured layers, most commonly rich in nepheline. Especially drill core V shows that layering occurs in much thicker sequences of lujavrite than mentioned by Ferguson (1964) and that it is not confined to the boundary zone between green and black lujavrite but is a characteristic feature of the main mass of arfvedsonite lujavrite.

The alternation of coarser- and finer-grained rocks is a common phenomenon in the Ilímaussaq complex. A characteristic example is the alternation of pegmatitic and normally grained layers in the foyaite of the roof zone (heterogeneous foyaite of Ferguson (1964)) which is explained by changes in fluid pressure in the magma chamber (Sørensen & Larsen 1987).

The other types of layering are all seen in drill core V. The alternation of light-coloured layers rich in nepheline, up to 2 cm or more thick, and darker layers of more homogeneous arfvedsonite lujavrite, up to 10 cm or more thick, are especially well-developed in this drill core. A more detailed description and discussion of these types of layering is in preparation.

Mineralogy of the lujavrites

The co-existence of independent grains of Na-poor microcline and K-poor albite is a characteristic feature of the Ilímaussaq lujavrites and is evidence of a low temperature of crystallization (Ussing 1912; Larsen & Sørensen 1987). The examination of many thin sections of lujavrites from the drill cores has demonstrated a great variation in the mutual proportion of the two feldspars, albite-rich layers without microcline alternate with microcline-rich layers without albite and with layers with two feldspars. This represents a type of mineral layering. A more detailed study of the variation in the proportion of feldspars would require a number of closely spaced thin sections that exceeds our present possibilities.

Eudialyte, a type mineral of agpaitic nepheline syenites, is a rock-forming mineral in the lujavrites and naujaite. The eudialyte crystals of drill cores I to VII are, however, often strongly altered into catapleiite, aegirine, micaceous minerals, neptunite, analcime, carbonate minerals, etc. Pseudomorphs after eudialyte are common in the rocks of the complex. In naujaite, the large crystals of eudialyte are generally altered, whereas small crystals, when present, are often perfectly fresh.

Britholite is one of the most common accessory minerals in the examined thin sections of lujavrites. Steenstrupine has been observed in only a few thin sections of arfvedsonite lujavrite, in drill cores I-VII it is mainly found in hydrothermal veins.

Ussingite is a very rare constituent in the examined thin sections of arfvedsonite lujavrite. Naujakasite has not been observed in the seven drill cores, in strong contrast to the Kvanefjeld area in which the hyper-agpaitic naujakasite lujavrite is observed in almost half of the drill cores. Naujakasite lujavrite outcrops, however, close to bore hole VI and also occurs at Tupersuatsiaat (Petersen & Andersen 1975; Khomyakov et al. 2001).

The examination of the drill cores has shown that vitusite is more widely distributed in arfvedsonite lujavrite than hitherto known. Unaltered grains of vitusite are present in some rocks, more common are very fine-grained aggregates of monazite/rhabdophane which have been demonstrated to be pseudomorphs after vitusite (Pekov et al. 1997). There are also coarser-grained clusters of monazite crystals which were described by Danø and Sørensen (1959, plate 1, fig. 1). These clusters may form a network which poikilitically encloses minerals of the matrix. It is unclear if also these monazite aggregates are secondary after vitusite or perhaps another REE-rich phosphate mineral.

Unaltered grains of lovozerite have been observed in a few thin sections of arfvedsonite lujavrite, but widespread grains of the same size and form as lovozerite and composed of unidentified black pigmentation may be altered grains of lovozerite.

Naujakasite, steenstrupine, ussingite, lovozerite and vitusite are typical minerals of the hyper-agpaitic lujavrites of the Ilímaussaq complex (Sørensen & Larsen 2001). Of these minerals, only vitusite is of some importance in the drill cores examined by us, though its place in most samples is taken by monazite and rhabdophane pseudomorphing the vitusite grains. It is also to be remarked that the hyper-agpaitic mineral villiaumite, which is of widespread occurrence in the Kvanefjeld drill cores, has been observed only in drill cores I and II and not in III or the bore holes located to the south of Tunulliarfik. These observations indicate that hyper-agpaitic conditions were attained only locally in the parts of the Ilímaussaq complex where the seven bore holes are located. This contrasts with the Kvanefjeld area where hyper-agpaitic naujakasite lujavrite is very common and may be at least partly explained by the difference in stratigraphical position in the complex: the Kvanefjeld lujavrites and the lujavrites of bore holes I and II were formed at a stratigraphically higher level in the intrusion than the lujavrites of bore holes III–VII. Khomyakov et al. (2001) have demonstrated that at Ilímaussaq hyper-agpaitic minerals and rocks are formed under extreme per-sodic conditions

The widespread occurrence of biotite as an alteration product of arfvedsonite in naujaite xenoliths and the enclosing arfvedsonite lujavrite shows that biotite is a much more common mineral in the complex than hitherto known. Finch et al. (1995) have discussed the occurrence of late-magmatic biotite from a number of intrusions of the Gardar province, but they excluded the Ilímaussaq complex from the study because of its peralkaline nature which was thought to prevent the formation of biotite. The occurrence of biotite in naujaites and lujavrites of drill core III recalls, however, closely the occurrences in the Gardar complexes examined by Finch et al. (1995) and is most likely a result of the interaction of late-magmatic fluids with the primary magmatic minerals. The occurrence of biotite shows that the late magmatic fluids, which were the cause of the alteration of the arfvedsonite, were potassic. It should be emphasized that in addition to the potassic branch of late- to post-magmatic alteration of arfvedsonite, there is also a sodic branch represented by brown aegirine replacing arfvedsonite and analcime and natrolite replacing the felsic minerals.

Uranium content of the lujavrites

At the time of drilling in 1962 it was known that some of the lujavrites of the Kvanefjeld area in the northern part of the Ilímaussaq complex had high uranium contents, whereas other of the Kvanefjeld lujavrites had low contents. Elevated U contents had, however, also been found in other parts of the complex (Bondam & Sørensen 1959; Buchwald & Sørensen 1961). A major purpose of the 1962 drilling programme was to examine the U contents of lujavrites elsewhere in the complex. The total radioactivity of the rocks was measured by gamma-logging of the bore holes (Fig. 2). However, calibration problems make the direct correlation from bore hole to bore hole impossible, as mentioned in an earlier section. Therefore, the logs of Fig. 2 only show the variation in gamma activity with depth in the individual bore holes, but without a common scale. Samples of the cores were chemically analysed for U (the method is described by Sørensen 1960). Parts of the cores were also analysed by a gamma-ray spectrometer equipped with a conveyor belt for automatic scanning of the radiometric equivalent of the U concentration over fixed core lengths of 1 m (Løvborg et al. 1972) (Table 3).

Table 3 shows that U concentrations higher than 200 ppm are indeed rare. High concentrations are confined to arfvedsonite lujavrite, contact zones between arfvedsonite lujavrite and naujaite and between arfvedsonite lujavrite and aegirine lujavrite, and to pegmatites and hydrothermal veins carrying steenstrupine. The highest concentrations are found in bore hole VI. This bore hole and the neighbouring Tupersuatsiaat uranium anomaly (Bondam & Sørensen 1959; Sørensen 1974) are located in a structural culmination which very probably functioned as a collector of residual liquids enriched in U.

Sørensen (1971) reported the results of 3388 gamma spectrometric field measurements of the Th and U contents of the lujavrites of the complex. The mean values of U, Th and Th/U for some selected areas vary within the following limits: arfvedsonite lujavrite U 130-250 ppm, Th 115-170 ppm, and Th/U 0.68-0.92. The corresponding values for aegirine lujavrite are: U 80-110 ppm, Th 95-180 ppm, Th/U 1.15-1.61.

J. C. Bailey (personal information 2000) has undertaken partial analyses of samples from drill cores I-VII by conventional XRF techniques using powder pellets (Andersen et al. 1981a). The results from drill core VII have been published by Bailey & Gwozdz (1994) and Bailey (1995); results from other cores by Andersen et al. (1981a). Some values for U, Th and Th/U are presented in Table 4. They conform rather well with the data in Table 3. The variation in arfvedsonite lujavrite is 42-272 ppm U, 42-543 ppm Th and Th/U 0.23-2.47, average 1.16 (21 analyses); in aegirine lujavrite 24-83 ppm U, 50-134 ppm Th, Th/U 1.24-2.44, average 1.71 (9 analyses). The values for U and Th in Table 4 are generally lower than the above-mentioned values reported by Sørensen (1971). This can most probably be explained by different methods of analysis, field gamma spectrometry by Sørensen (1971) and XRF analysis by Bailey (Table 4). Both data sets agree, however, that arfvedsonite lujavrite only exceptionally has lower U and Th contents than aegirine lujavrite and that aegirine lujavrite generally has higher Th/U ratios than arfvedsonite lujavrite.

Table 3. Uranium concentration measured in selected drill core samples (in ppm). Explanation: **Rt:** rock type, * samples analysed by γ-ray spectrometry, average of 1 m scan, other analyses by chemical analyses. **Al**: arfvedsonite lujavrite, **Ae**l: aegirine lujavrite, **Ms**: microsyenite, **N**: naujaite, **Lv**: late veins, **Fbr**: fine grained brecciated rock**, #** together with late veins.

Core I		Core II		Core III		Core IV		Core V		Core VI		Core VII	
Depth Rt	U	Depth Rt	U	Depth Rt	U	Depth Rt	U	Depth Rt	U	Depth Rt	U	Depth Rt	U
3.99N	71	11.63Al	70	3.95Al	42	7.65Al	145	4.78Al	80	3.50Al	690	1.68Ael	20
8.15Lv	42	14.23Al	43	14.23Al	43	10.67Al	77	17.73Al	203	9.92Ael	180	7.60Ael	20
20.00Ms	100	19.75Al	80	33.57Al	38	21.08Al	62	30.30Al	295	16.03Fbr	300	30.19Ael	45
21.73Al	112	30.70Ael	80	39.60Al	83	40.22Al	64	47.82Al	255	22.01Fbr	256	40.80Ael	10
25.36P	508	40.60Al	107	45.29Al	159	53.00Ael	45	55.38Al	47	27.30Al	120	40.85Ael	10
30.65N	65	50.00Al	65	51.75Al	130	59.93Ael	83	70.28Al	164	37.03Al	550	47.00Ael	25
41.73N	35	80.65Al	108	55.13Al	17	65.40Ael	68	76.78Al	216	49.49Al	247	51.64Ael	20
60.45N	15	82.66Al	125	58.45Al	102	69.51Ael	55	109.55Al	57	67.62Al	125	60.70Ael	25
73.60N	60	88.40Al	130	64.72Al	57	80.73Ael	40	171.90P	35	79.10Al	120	63.48*Ael	28
85.95Al	40	89.65Ael	83	67.19Al	60	92.25Ael	48			90.39Al	187	70.05Ael	26
91.05Al	20	103.79Al	113	76.40Al	68	120.92Al	52			103.18Al	135	72.85Ael	20
92.44Al	200	110.62Ael	65	79.38Al	80	142.54Al	27			120.01Al	90	74.72Ael	30
102.55Al	35	113.35Ael	42	161.48Ael	47	152.90Ael	20			125.92N	30	81.20Ael	30
117.35Al	86	124.70Ael	38			182.90Ael	40			166.69N	30	82.00Ael	20
125.60N	56	127.21N	20							184.55N	20	86.54Ael	30
139.51P	35	132.51N	10									90.02Ael	30
152.50N	25	143.31Ael	35									112.02Ael	25
168.64Al	156	157.46N	12									120.57*Ael	31
190.35N	25	169.90N	37									127.40*Al	31
		171.75N	60									132.26*Ael	46
		180.20N	20									134.33*Ael	41
		199.15N	54									136.27*Ael	30
		200.00N	15									138.20*Ael#	30
												140.13*Ael#	34
												141.10*Ael#	40
												144.91*Ael	34
												154.80*Ael	35
												185.63 Ael	25

The Th/U ratio is highest in the uranium-rich arfvedsonite lujavrites.

The U-rich lujavrites at Kvanefjeld and Tupersuatsiaat have steenstrupine as a major mineral (Buchwald & Sørensen 1961). This mineral is practically absent from the lujavrites of bore holes I-VII.

Eudialyte contains 50-600 ppm U (Wollenberg 1971; Bailey et al. 1983) and is the major rare element containing mineral in most of the Ilímaussaq agpaitic rocks. But eudialyte is a subordinate mineral in most drill core samples examined by us and is generally altered into catapleiite and other minerals. Its place in many samples is taken by grains of the size and shape of eudialyte crystals but composed of unidentified black pigmentation in a matrix of analcime. Autoradiography has demonstrated that altered eudialyte grains occasionally show the same a-track intensity as steenstrupine (Buchwald & Sørensen 1961). The same study showed that monazite, britholite and lovozerite are also weakly radioactive. Monazite contains 100-2000 ppm U and up to 12 000 ppm in late

Table 4. Selected trace element analyses of lujavrites from drill cores I to VI. AL = arfvedsonite lujavrite, GL = aegirine lujavrite, MC = medium- to coarse-grained lujavrite, * = mineralized lujavrite.
(XRF analyses kindly placed at our disposal by J.C. Bailey, Geological Institute, University of Copenhagen).

bore hole no.	depth in hole	height above/ below sea level	rock type	U	Th	Rb	Sr	Y	Zr	Th/U	Zr/U	Zr/Y	Rb/Sr
I	98.7 m	193.3 m	AL	102	79.1	273	75.4	761	4930	0.8	48.3	6.5	3.6
–	118.0 m	174.0 m	AL	174	85.4	821	121.3	1630	11160	0.5	64.1	6.9	6.7
II	13.2 m	66.8 m	AL	69.4	125	706	80.9	807	8130	1.8	117.1	10.1	8.7
–	16.7 m	63.3 m	AL	71.1	127	672	85.4	889	8160	1.8	114.8	9.2	7.9
–	17.5 m	62.6 m	AL	77.6	192	525	68.8	520	3680	2.5	47.4	7.1	7.6
–	17.7 m	62.4 m	AL	70.3	137	468	60.8	516	3720	2.0	52.9	7.2	7.7
–	18.0 m	62.1 m	AL	113	104	688	71.4	795	6310	0.9	55.8	7.9	9.6
–	21.8 m	58.3 m	AL	92.0	92.5	799	85.3	905	8160	1.0	88.7	9.0	9.4
–	23.7 m	56.4 m	AL	60.1	67.8	536	52.7	509	4000	1.1	66.6	7.9	10.1
–	50.1 m	29.9 m	AL	65.9	134	721	80.2	794	8330	2.0	126.4	10.5	9.0
–	176.6 m	–96.6 m	GL	24.1	58.9	477	80.3	1236	8806	2.4	365.4	7.1	5.9
III	157.9 m	–152.9 m	GL	35.2	50.1	588	74.9	757	6180	1.4	175.6	8.2	7.9
IV	5.3 m	–0.3 m	AL	192	141	699	116.8	1590	11060	0.7	57.6	7.0	6.0
–	12.5 m	–7.5 m	AL	104	111	580	66.0	902	6470	1.1	62.2	7.2	8.9
–	39.6 m	–34.6 m	AL	49.0	64.5	670	52.4	405	4630	1.3	94.5	11.4	12.8
–	47.4 m	–42.4 m	GL	58.7	109	705	54.9	675	4890	1.9	83.3	7.2	12.8
–	49.7 m	–44.7 m	GL	56.3	120	530	68.4	786	5560	2.1	98.8	7.1	7.7
–	56.1 m	–51.1 m	GL	72.8	126	417	52.1	680	5080	1.7	69.8	7.5	8.0
–	79.0 m	–74.0 m	GL	82.9	134	603	82.7	1030	7440	1.6	89.7	7.2	7.3
–	84.4 m	–79.4 m	AL*	434	4113	738	47.9	1640	1080	9.5	2.5	0.7	15.4
–	96.8 m	–91.8 m	GL	63.9	79.2	763	72.3	890	6840	1.2	107.0	7.7	10.6
–	103.7 m	–98.7 m	AL	41.6	41.6	402	65.1	749	5910	1.0	143.2	7.9	6.2
–	120.5 m	–115.5 m	AL	42.6	47.2	453	85.6	1020	7950	1.1	186.6	7.8	5.3
–	148.9 M	–143.9 m	MC	45.5	56.7	507	98.2	1210	9830	1.1	216.0	8.1	5.2
–	167.9 m	–162.9 m	GL	40.5	53.9	622	88.9	1070	8650	1.3	213.6	8.1	7.0
–	195.7 m	–190.7 m	GL	38.1	61.2	563	97.6	1230	9900	1.6	259.8	8.0	5.8
V	13.1 m	286.9 m	AL	125	103	776	77.8	742	4800	0.8	38.4	6.5	10.0
–	19.9 m	280.1 m	AL	118	106	865	72.9	858	5400	0.9	45.7	6.3	11.9
–	20.3 m	279.8 m	AL	212	126	1165	92.8	1180	7440	0.6	35.1	6.3	12.6
–	69.1 m	231.0 m	AL	272	63.8	515	64.5	510	3820	0.2	14.0	7.4	8.0
–	69.5 m	230.5 m	AL	130	76.7	859	103.6	1350	9600	0.6	73.8	7.1	8.3
–	96.4 m	203.6 m	AL	48.1	57.6	449	65.6	754	5640	1.2	117.3	7.5	6.8
VI	1.8 m	318.2 m	AL	239	543	556	35.9	1010	3170	2.3	13.2	3.1	15.5
–	6.0 m	314.0 m	GL*	248	1114	1005	44.2	1300	5420	4.5	21.9	4.2	22.7
–	41.1 m	258.9 m	AL*	126	n.d.	1151	85.0	938	6040	–	47.9	6.4	13.5
–	96.9 m	223.1 m	AL	n.d.	116	834	68.6	1090	6850	–	–	6.3	12.2

veins (Wollenberg 1971; Bailey et al. 1983). The moderate U contents of the lujavrites of drill cores I-VII can be related to this mixture of weakly radioactive minerals and to interstitial, easily leachable material which is partly associated with altered grains of eudialyte (Bailey et al. 1983).

Geochemical stratigraphy

Andersen et al. (1981a, fig. 3) proposed that the Zr/U and Zr/Y ratios can be used as indicators of stratigraphical level in the kakortokite-lujavrite series. The Zr/U ratio decreases upwards in this rock sequence. The Zr/Y ratio is nearly constant in the kakortokite-aegirine I part, it decreases from aegirine lujavrite I to aegirine lujavrite II and is nearly constant throughout the overlying lujavrite series, though distinctly lower in the Kvanefjeld naujakasite lujavrite. The Zr/U stratigraphy of the arfvedsonite lujavrite is, however, based on rather few (nine) samples.

Table 4 presents the available geochemical data on lujavrites from drill cores I-VI, the data for drill core VII have already been published by Bailey & Gwozdz (1994) and Bailey (1995). Table 4 shows that there is a tendency towards a decrease in the Zr/U ratio upwards in the thicker sequences of arfvedsonite lujavrite. This trend is also suggested by the results of a fission-track examination of eudialyte from the floor series of the complex which demonstrated an increase in the U content of eudialyte up through the kakortokite and lujavrite sequence (Steenfelt & Bohse 1975). Eudialyte is the main carrier of Zr and U in the kakortokites and the lower part of the lujavrite series (Bailey et al. 1983). The reported contents of U in eudialyte from kakortokite and lujavrite are rather constant over considerable depth intervals (Steenfelt & Bohse 1975, table 1). Also Table 4 shows that the Zr/U ratio of the lujavrites is rather constant over some depth intervals in drill cores II and IV, but that generally it varies in an irregular way throughout the drill cores which may be partly explained by the widespread alteration of eudialyte in the lujavrites of the drill cores. This makes the use of the Zr/U ratio as stratigraphical indicator problematical. There is undoubtedly an enrichment in U and a decrease in Zr in the stratigraphically uppermost arfvedsonite lujavrites of the drill cores (as is also the case in the hyper-agpaitic naujakasite lujavrites). In the U-rich rocks of the Kvanefjeld plateau and the Tupersuatsiaat U anomaly, eudialyte is substituted by steenstrupine (cf. Bondam & Sørensen 1959; Sørensen et al. 1974; Khomyakov et al. 2001) which explains the low Zr/U ratios in these rocks (Andersen et al. 1981a). But steenstrupine is practically missing in the major part of the lujavrite sequence.

Contrary to the marked variation in Zr/U ratios, the Zr/Y and Rb/Sr ratios in lujavrites show very little variation with stratigraphical level in the complex with the U-rich rocks in the upper part of bore hole VI as the most marked exception (Table 4).

In order to explain the above-mentioned variation in element ratios, the following points should be considered:

1. The lujavrites most probably did not consolidate in one continuous magma chamber but in separate shallow sub-chambers (Andersen et al. 1981a; Larsen & Sørensen 1987) which makes a correlation across the whole complex difficult. This view is corroborated by the variation in thickness of the naujaite part of the roof zone and of the lujavrite-naujaite breccia zone, and by the observation of Guttenberg & Le Couteur (1992) and Bailey (1995) that the lujavrites at the head of Kangerluarsuk thin out in a way indicating that the overlying naujaite here and there extended unusually far down, cf. the geological map of Andersen et al. (1988).

2. The examination of a large number of thin sections of arfvedsonite lujavrite from drill cores I-VI has shown that the main carrier of Zr, Y and U, eudialyte, in most cases is altered and in many rocks is substituted by black pigmentation. Furthermore, the Zr-rich mineral lovozerite and its alteration products are unevenly distributed in the lujavrites of the drill cores, as are the U-and Y-bearing minerals britholite and vitusite/monazite. The Zr/U and Zr/Y ratios depend on the changing proportion of the minerals containing Zr, U and Y and on the degree of late magmatic alteration. The rather constant Zr/Y ratio indicates that Zr and Y are not separated during the breakdown of eudialyte, except in the most evolved rocks. The variations in Zr/U can be partly explained by varying proportions of the U-bearing minerals, partly by the mobility of U.

In drill cores II and IV, the U content is practically constant over considerable vertical thicknesses of arfvedsonite lujavrite, whereas the Th content and the Th/U ratio vary in a more irregular way with stratigraphical position in the complex (Table 4).

The Th/U ratio of the arfvedsonite lujavrites is generally less than 1, whereas it is higher than 1 in the aegirine lujavrites (Sørensen 1971; Bailey et al. 1983). The Th/U ratios listed in Table 4 show the same general trend, but a number of the arfvedsonite lujavrite samples have Th/U ratios higher than 1. This is explained by variation in the proportion of U-Th-bearing minerals and in the conditions of late- and post-magmatic alteration of the minerals. The Th/U ratio is around 3 or higher in the steenstrupine-carrying arfvedsonite and naujakasite lujavrites from Kvanefjeld (Sørensen et al. 1974).

The slight variation in the Rb/Sr ratio throughout the drill cores presents a problem. Sr is especially located in eudialyte, Rb in the felsic minerals with the highest contents in microcline (Bailey et al. 2001). The most evolved lujavrites have high Rb, low Sr, the highest Rb/Sr ratios (Table 4) and show a simultaneous enrichment in Rb and U. The last-named feature may be a result of fractional crystallization if Rb and U have similar bulk partition coefficients in these volatile-rich highly evolved magmas. But, as pointed out by Andersen et al. (1981a, fig. 3), Larsen & Sørensen (1987) and others, fractional crystallization cannot alone explain the formation of the evolved lujavrites, other processes such as volatile transfer of elements must have been involved in the formation of the most evolved lujavrites. The rather constant Zr/Y and Rb/Sr ratios throughout large parts of the arfvedsonite and aegirine lujavrites penetrated by bore holes I–VI lend support to the view of Andersen et al. (1981a) that the lujavrites consolidated as closed systems which retained the original element ratios also in rocks where the mineralogical carriers of these elements were disintegrated.

Crystallization of the lujavritic magma

Andersen et al. (1981a, b) and Bohse & Andersen (1981) have demonstrated that there is a gradual transition from the lower layered kakortokite through the slightly layered and transitional layered kakortokite into aegirine lujavrite and arfvedsonite lujavrite (Figs 10, 11, 12). The transition from kakortokite to lujavrite is characterized by aegirine substituting arfvedsonite, by microcline perthite being substituted by co-existing laths of microcline and albite, and by a decreasing grain size of the rocks. Up through the lujavrite sequence arfvedsonite dominates again over aegirine but, as discussed in the present study, there is a recurrence of aegirine in an erratic way.

The lujavritic magma developed beneath a roof of naujaite. It may be imagined that there was a steady stream of residual liquid and volatiles towards the top of the magma and that the very fluid lujavritic magma consolidated from the bottom upwards while more and more of low-melting components were incorporated into the residual melt (Larsen & Sørensen 1987). This explains the above-mentioned enrichment in U and Rb in the stratigraphically highest lying lujavrites. It is in this connection worth noting that villiaumite has only been found in drill cores I and II which represent the highest stratigraphical levels of the seven drill cores and that the lower-lying levels of lujavrite, especially the aegirine lujavrite, have comparatively lower U contents (Fig. 2, Tables 3, 4). The most evolved lujavrites, such as the villiaumite-bearing hyperagpaitic naujakasite lujavrite, are especially abundant in the Kvanefjeld area, that is at a very high stratigraphical level in the Ilímaussaq complex.

The examination of drill cores I to VII has revealed distinct variations in the mineralogy of the lujavrites which confirms the field observations of Bohse & Andersen (1981). In addition to the above-mentioned alternation of arfvedsonite- and aegirine-rich rocks, the mutual proportions of nepheline, microcline, albite and sodalite vary to the extent that horizons of arfvedsonite lujavrite may be dominated by one or two and even three of these minerals. The variations in mineralogy are caused by changes in the physico-chemical conditions during the formation of the lujavritic sequence. These changes may at least partly be related to the successive spalling-off of rafts of naujaite from the roof of the magma chamber which very probably were accompanied by a pressure relief and loss of volatiles from the crystallizing magma. The accompanying changes in P_{H_2O} and oxygen fugacity can explain at least some of the observed mineralogical variation such as the crystallization of arfvedsonite or aegirine and the formation of layers rich in nepheline.

Kogarko & Romanchev (1983) emphasized the agpaitic order of crystallization, the crystallization of felsic before mafic minerals which according to Ussing (1912) is a characteristic feature of agpaitic nepheline syenites. In their view, this means that agpaitic magmas were undersaturated in water and other volatiles corresponding to a P_{H_2O} less than 0.2 kbar. At higher P_{H_2O} mafic minerals also became liquidus minerals. Larsen & Sørensen (1987) have, however, pointed out that many agpaitic rocks are cumulates and that the melts from which kakortokite formed were anchieutectic systems having nepheline, microcline, arfvedsonite and eudialyte on the liquidus: They estimated that the Ilímaussaq magma contained 4 wt.% H_2O + F under a confining pressure of around 1 kbar.

Conditions are less clear with regard to the lujavrites. In the aegirine lujavrite as well as the arfvedsonite lujavrite large crystals of nepheline, sometimes also of sodalite, are conformably wrapped by smaller crystals of feldspar, eudialyte, arfvedsonite and/or aegirine. The straightforward interpretation is that nepheline and sodalite crystallized earlier than the matrix minerals, an example of the agpaitic order of crystallization. The nepheline crystals, however, have inclusions of especially feldspar, arfvedsonite and aegirine in much smaller grains than in the matrix, an indication of a more or less simultaneous nucleation of the minerals coupled with a faster growth of nepheline (and sodalite) than of the other rock-forming minerals. These features may be explained by the above-mentioned changes in physico-chemical conditions during the formation of the lujavrites. For instance, in petrogeny's residua system, nepheline-kalsilite-SiO_2-H_2O, decreasing P_{H_2O} favours the crystallization of nepheline (cf. Gittins 1989). The high sodalite contents of some lujavrites may be explained by partial assimilation of naujaite xenoliths.

The examined drill cores show that the late formation of analcime and natrolite is a widespread phenomenon in lujavrites and naujaite. The solubility of water in silicate melts increases with increasing contents of alkali ions. This may result in the transition of melts into hydrothermal fluids (Kogarko 1977). There may therefore have been a continuity from late- to post-magmatic formation of these minerals (see also Markl et al. 2001).

Conclusions

The naujaite part of the roof zone of the Ilímaussaq complex is at least 600 m thick and the arfvedsonite lujavrite part of the lujavrite sequence (including naujaite xenoliths and intercalated aegirine lujavrite) at least 300 m thick, the last-named figure is higher than earlier estimates.

It has been known for a long time that the lower part of the lujavrite sequence is made up of aegirine lujavrite, the upper part of arfvedsonite lujavrite. The drill cores have brought more detailed knowledge of the transitions between these two types of lujavrite, especially the alternation of aegirine- and arfvedsonite-rich lujavrites.

The naujaite xenoliths enclosed in lujavrites are in the lower part of the breccia zone injected by sheets of aegirine lujavrite, but in the major part of this zone by arfvedsonite lujavrite in conformity with the predominance of aegirine lujavrite at low stratigraphical levels and arfvedsonite lujavrite at higher levels.

Changes in the physico-chemical conditions during the formation of the lujavrites, especially variations in water and volatile pressure and oxygen fugacity, are regarded to be responsible for mineralogical changes such as the alternation of arfvedsonite and aegirine and the formation of nepheline-rich layers in the arfvedsonite lujavrite. These changes may, at least partly, be related to pressure relief caused by fracturing of the naujaitic roof of the lujavrite magma chamber and the loosening of large angular rafts from it.

Biotite is demonstrated to be of much more widespread occurrence in the Ilímaussaq complex than formerly known. It is assumed to have been formed by late-magmatic alteration of arfvedsonite and aegirine. The presence of biotite and neptunite indicates that the late-magmatic fluids were enriched in K. There is, however, in the examined lujavrites also a late-magmatic sodic stage characterized by the formation of brown aegirine and analcime/natrolite.

There are geochemical and mineralogical differences between lujavrites which may be related to their stratigraphical position in the complex. Villiaumite, NaF, is for instance only found in drill cores from the upper levels of the complex. Hyper-agpaitic lujavrites are similarly especially abundant near the roof of the complex, as it is seen at Kvanefjeld, and also occur in comparatively high-level structural culminations as at Tupersuasiaat close to bore hole VI.

The lujavrites of bore holes I-VII have very rare grains of steenstrupine, the major uranium-bearing mineral of the arfvedsonite lujavrites and the hyper-agpaitic naujakasite lujavrites which form the uranium deposits at Kvanefjeld and in the up-domed region between bore hole VI and Tupersuatsiaat. The lujavrites of drill cores I-VII have consequently low U contents.

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Appendix

Description of the drill cores

Description of core I (Fig. 2):

0-4.80 m: Fresh naujaite rich in eudialyte.

4.80-5.66 m: Medium- to coarse-grained lujavrite or lujavrite pegmatite with sharp contact against the overlying naujaite and with masses of aegirine-rich albitite containing eudialyte and monazite and thin zones of felted aegirine. The albite occurs as plates and sugary-grained aggregates. There are fragments of earlier albitite rimmed by small crystals of natrolite. The pegmatitic rock has stellar groups of arfvedsonite crystals growing toward the albitite in the contact on the underlying microsyenite. Pectolite and sphalerite are minor components and analcime an interstitial mineral. Zoned crystals of steenstrupine and clusters of monazite occur in a cutting analcime vein. The medium- to coarse-grained lujavrite is at 5.03-5.16 m in contact with a steeply dipping sheet of aegirine lujavrite consisting of albite, clusters of acicular aegirine, eudialyte crystals, aggregates of monazite crystals and sphalerite.

5.66-21.35 m: fine-grained alkali microsyenite with phenocrysts of alkali feldspar, clinopyroxene and neptunite. The upper contact is sharp and is marked by a thin white albite zone which passes gradually into the underlying fine-grained rock. This rock shows colour variation from black over grey to white, partly because of almost horizontal layering, partly because of wavy lighter coloured albite-rich zones which penetrate the darker coloured rock. The groundmass of the fine-grained rock consists of microcline laths and sugary albite in varying proportions. There are short prismatic grains of arfvedsonite and aegirine, also in strongly varying proportions. The arfvedsonite contains inclusions of aegirine which in other cases occur as rims on arfvedsonite grains. Neptunite is of widespread occurrence, as phenocrysts and in the groundmass, often as oikocrysts enclosing the feldspars. Pectolite occurs as prismatic grains which are also often oikocrysts. Eudialyte is a very rare component. At 13.33 m there is an intersecting pegmatite vein (or medium to coarse-grained lujavrite) with large crystals of arfvedsonite, nepheline, sodalite, eudialyte and with interstitial analcime and natrolite containing flakes of astrophyllite. The lowermost part of the microsyenite from 20.0 to 21.35 m is greenish due to the content of green clinopyroxene and it is at 21.20 m cut by an albite vein containing steenstrupine.

21.35-21.43 m: rather coarse-grained albitite containing eudialyte and monazite and with radiating groups of arfvedsonite crystals growing toward the microsyenite. The contact on the underlying arfvedsonite lujavrite is sharp.

21.43-24.53 m: arfvedsonite lujavrite with xenoliths of augite syenite and naujaite. It shows horizontal lamination and is made up of albite, arfvedsonite, aegirine, nepheline, eudialyte, monazite and sphalerite. It is without feldspathoids in the upper contact zone. The rock is full of holes, most probably after dissolved villiaumite. It is separated from the augite syenite by a zone of albite-analcime. Against the naujaite the lujavrite is coarse-grained and made up of plates of albite, large prismatic grains of arfvedsonite, aggregates of aegirine and crystals of eudialyte under alteration into catapleiite. 21.86 and 22.22 m: The lujavrite is rich in grains of vitusite under transformation to monazite/rhabdophane. The hand specimens show yellow aggregates of monazite measuring up to 0.5 mm across. These yellow aggregates were earlier described as erikite but are now known to be secondary after vitusite (Pekov et.al. 1997).

24.53-24.92 m: aegirine lujavrite without holes.

24.92-84.25 m: naujaite. The upper part of the naujaite is altered and cut by thin veins of albite, analcime and natrolite with steenstrupine crystals up to 0.5 cm across and small grains of galena. The naujaite is also intersected by green lujavrite rich in eudialyte, crystals of steenstrupine, up to 1 cm across, and yellow monazite aggregates, and by many veins of medium- to coarse-grained lujavritic rocks. They often contain thin zones or sheets of fine-grained arfvedsonite lujavrite and may be pegmatites expelled from the larger masses of arfvedsonite lujavrite or reaction products between lujavrite and naujaite (cf. Sørensen 1962).

The pegmatitic veins are from a few centimetres to a few metres thick and appear to be more or less horizontal. They consist of large often corroded crystals of nepheline, plates of microcline and prismatic or acicular grains of arfvedsonite, often as stellar groups. Large crystals of eudialyte are generally strongly altered into catapleiite, whereas small eudialyte crystals are perfectly fresh. There are large grains of sodalite. The arfvedsonite may be partly altered into brown aegirine. There are also in some rocks prismatic grains of aegirine with inclusions of arfvedsonite. Minor minerals are neptunite, pectolite, sphalerite, perovskite, Li mica, monazite and steenstrupine. There is interstitial albite, analcime and natrolite.

The pegmatitic rocks occur at the levels:

45.95-46.32, 51.53-51.85, 54.50-54.82, 55.90-56.50, 64.67-64.76, and 71.63 m.
65.00-65.95 m: the naujaite is strongly altered.
68.07-69.32 m: lujavrite vein with inclusion of altered naujaite (68.90-69.20).
72.43-74.95 m: recrystallized naujaite.
82.10 m: vertical vein of arfvedsonite lujavrite, the adjacent rock is rich in Li-mica.

84.25-122.50 m: arfvedsonite lujavrite cut by albite veins and rich in nepheline in hanging wall. The lamination dips 20-30°. The major components are albite, microcline, arfvedsonite, nepheline and eudialyte. Minor minerals are aegirine, sodalite, monazite, sphalerite, perovskite, fluorite and neptunite,

84.50-84.60 m: analcime vein with eudialyte.
84.92-85.48 m: xenolith of strongly altered naujaite cut by analcime vein with steenstrupine.
87.42-87.50 m: naujaite xenolith.
89.35-89.50 m: analcime pegmatite.
100.56-101.03 m: albite vein with sphalerite crystals.
101.40-101.50 m: albite vein with steenstrupine.
104.20-104.40 m: strongly altered naujaite with steenstrupine.
105.20-105.50 m: albite-analcime-natrolite vein.
111.42 m: inclusion of altered naujaite.
120.12-122.50: pegmatite rich in arfvedsonite.

122.50-198.00 m: naujaite which, like the naujaite at higher levels, is intersected by veins of pegmatitc rocks at the depth intervals:

124.75-125.05, 137.50-143.00, 152.90-153.04 and 191.50-191.95 m.

148.54-148.73, 150.70-150.90 m: thin sheets of arfvedsonite lujavrite associated with pegmatitic rock.

167.00 m: steenstrupine in naujaite.

167.55-167.95 m: aegirine lujavrite with aegirine crystals and felted aegirine, near horizontal lamination.

168.20-169.80 m: arfvedsonite lujavrite sheet with concentration of brown aegirine in upper contact zone. Near horizontal lamination. Associated pegmatitic rock contains steenstrupine and crystals of natrolite, several cm long.

Description of core II (Fig. 2):

0-9.15 m: loose cover.

9.15-114.95 m: the lujavrite sequence.
This section is made up of alternating horizons of aegirine-, arfvedsonite- and aegirine-arfvedsonite lujavrites varying in thickness from a few cm to several metres. The lamination is generally near horizontal.

The aegirine lujavrite of the upper part of this section is massive and without the pronounced lamination and fissility of aegirine lujavrite type I and II described by Bohse & Andersen (1981). It also lacks the poikilitic grains of arfvedsonite of these rocks and the shiny planes of lamination. The aegirine lujavrite of the lower part of the section shows shiny planes of lamination in which there are prismatic crystals of arfvedsonite.

The massive aegirine lujavrite of the upper part of this section shows an intergranular texture defined by prismatic grains of aegirine which show no preferred orientation. There are larger grains of nepheline, often showing corroded outlines, in a finer-grained matrix of microcline, albite, very small crystals of eudialyte and interstitial analcime and natrolite. Arfvedsonite may be entirely lacking; if present it occurs as tiny grains which may form partial overgrowths of aegirine. Sphalerite and britholite are minor components.

The arfvedsonite lujavrite is generally fine-grained and with near horizontal lamination. Locally, the lamination is disturbed around xenoliths of green lujavrite and naujaite. The arvedsonite lujavrite is made up of short prismatic grains of arfvedsonite, laths of microcline and albite, small nepheline crystals, eudialyte and here and there sodalite. Minor components are sphalerite, perovskite, britholite and vitusite. In most examined thin sections the vitusite is transformed into rhabdophane. Some rocks contain aggregates of monazite crystals which may be pseudomorphs after vitusite. Villiaumite or holes after villiaumite are found in some sections of the core and are missing in others.

The arfvedsonite lujavrite is in places medium- to coarse-grained with stellar aggregates of arfvedsonite needles, several cm across. The coarser-grained varieties are found close to naujaite xenoliths in the lujavrite and may form veins made up of marginal arfvedsonite crystals, often growing at right angle to the contacts, and central parts made up of analcime, sodalite, natrolite, steenstrupine, sphalerite, monazite and in places also eudialyte which is partially altered into catapleiite. At 90.90 m there are aggregates of larger crystals which are uniaxial positive, possibly catapleiite. At 104.70 m the central part of such veins is made up of corroded crystals of nepheline and arfvedsonite, a rock which petrographically should be termed an ijolite.

There are also arfvedsonite-aegirine lujavrites which appear to be mixtures of the above-mentioned two types of lujavrites. They are made up of the larger grains of aegirine and nepheline of the aegirine lujavrite and a matrix of arfvedsonite lujavrite minerals, including vitusite which at depth 20.85 m forms an accumulation of fresh crystals in the arfvedsonite-enriched part of an arfvedsonite-aegirine lujavrite. The vitusite is associated with sheaths of fibrous britholite. Arfvedsonite forms overgrowths on the prismatic grains of aegirine. From the textural relations it appears that there has been a transition from aegirine to arfvedsonite lujavrite. This could have been a progressive process due to changes in the conditions of crystallization, first of all increasing contents of volatiles favouring the formation of arfvedsonite. But it could also be a result of infiltration of the partly consolidated aegirine lujavrite by the volatile-rich magma responsible for the formation of the arfvedsonite lujavrite.

Some contacts between green and black lujavrite are sharp, the two rocks being unmodified right up to the contact. In other cases there is a thin zone of albite, analcime, etc. between the two rocks or there may be a concentration of arfvedsonite in the marginal part of the arfvedsonite lujavrite. The aegirine lujavrite of the upper part of the drill core is also cut by arfvedsonite lujavrite, analcime veins and by fractures filled with red earthy natrolite. There are patches of a dense green rock with the same mineralogy as the aegirine lujavrite. In several horizons the arfvedsonite lujavite contains densely packed ellipsoidal xenoliths of aegirine lujavrite which are conformably wrapped by the laminated arfvedsonite lujavrite.

9.15-10.00 m: nepheline-rich aegirine lujavrite with lamination dipping ca. 30°. It is intersected by veins of laminated nepheline-rich arfvedsonite lujavrite made up of alternating laminae of fine- and medium-grained rocks and is separated from the underlying arfvedsonite lujavrite by a cm-thick zone of felted aegirine with natrolite.

10.00-10.15 m, 25.13-25.30, 28.10-28.75, 41.72-43.90, 62.60-62.82, 64.23-64.28, 94.30, 97.35-101.90: arfvedsonite lujavrite with ellipsoidal xenoliths of aegirine lujavrite.

25.42 m: arfvedsonite lujavrite sends veins into the overlying aegirine lujavrite and contains inclusions of the latter.

27.0-28.10 m: the aegirine lujavrite is rich in ellipsoidal bodies of finer-grained green lujavrite.

45.92-47.50 m: veins of medium-grained lujavrite with concentration of arfvedsonite along contacts and an analcime core with steenstrupine crystals, up to 1 cm across.

62.05-62.10 m: arfvedsonite lujavrite rich in albite and with ellipsoidal xenoliths of aegirine lujavrite.

64.90-65.02 m: horizon of arfvedsonite lujavrite with sharp contact against the overlying aegirine lujavrite and diffuse lower contact against aegirine lujavrite. At 64.90 m analcime vein with concentration of aegirine along contact. It contains yellow aggregates of monazite.

70.46 m: inclusion of dense grey rock in arfvedsonite-aegirine lujavrite.

71.85 m: sharp contact between aegirine and arfvedsonite lujavrite, the arfvedsonite lujavrite is enriched in arfvedsonite in the contact zone.

89.14-91.03 m: aegirine lujavrite cut by medium-grained arfvedsonite lujavrite and showing an increasing content of arfvedsonite toward the underlying arfvedsonite lujavrite.

91.13-91.70 m: the arfvedsonite lujavrite contains xenoliths of felsic rocks which may be altered foyaite or naujaite. The same rock is found at 100.30 m.

91.70-94.30 m: aegirine lujavrite, locally rich in arfvedsonite and cut by veins of arfvedsonite lujavrite.

105.04, 110.70-111.05, 111.05-112.50 m: the aegirine lujavrite shows shiny fracture surfaces.

112.50-114.95 m: aegirine lujavrite with shiny fracture surfaces and xenoliths of altered naujaite.

114.95-200.00 m: naujaite. It shows a considerable variation with regard to mineral composition, state of alteration and veining by lujavrites and pegmatites. The poikilitic arfvedsonite grains are generally substituted by brown aegirine (acmite) with minor biotite but in some horizons by aggregates of biotite flakes. Aegirine occurs as larger poikilitic grains but is in some rocks present as a network of small acicular grains between the larger sodalite grains. The sodalite grains may be completely fresh, but there are all stages of transition into rocks where sodalite is substituted by analcime and natrolite. Nepheline is present as larger grains which may enclose sodalite. The same applies to larger plates of microcline. The large poikilitic grains of eudialyte are generally substituted by aggregates of catapleiite, fluorite, pectolite and Li-mica. Small crystals of eudialyte may be entirely fresh. Minor components are pectolite, sphalerite, apatite, Li-mica, fluorite, perovskite and in some horizons villiaumite.

The naujaite is in many horizons infiltrated by aegirine lujavrite which appears as schlieren of acicular aegirine, plates of microcline, small eudialyte crystals and analcime and natrolite substituting the original felsic minerals of the naujaite.

117.40-117.87 m: strongly folded aegirine lujavrite containing xenoliths of strongly altered and sheared naujaite with schlieren of biotite and acicular aegirine.
120.07-120.14 m: sheet of aegirine lujavrite with densely packed crystals of analcime.
121.75-127.14 m: aegirine lujavrite rich in analcime and with inclusions of naujaite and altered gabbro.
144.10-144.20 m: analcime vein rich in catapleiite.
From 145.35 m: scattered grains of villiaumite, at 154.07 and 156.65 m associated with fluorite.
146.13 m: aegirine lujavrite with villiaumite.
150.16 m: breccia with angular white fragments in pegmatitic matrix containing villiaumite.
154.07 m: infiltration of lujavrite into recrystallized naujaite containing villiaumite and fluorite.
176.56-177.90 m: aegirine-arfvedsonite lujavrite with shiny fracture surfaces. It contains larger prismatic grains of arfvedsonite and acicular aegirine. There are inclusions of altered naujaite.
178.07-185.10 m: schlieren of aegirine lujavrite in altered biotite-rich naujaite.
180.97 m: unidentified mineral in altered naujaite. It occurs as irregularly-shaped grains showing sector extinction. It is uniaxial positive or has a small 2V, refractive index around 1.66, birefringence first-second order colours.
191.70 m: aegirine lujavrite in naujaite.
199.25 m: analcime vein with steenstrupine and brown aegirine.
199.50 m: lujavrite in naujaite.

Description of core III (Fig. 2):

0.0-1.0 m: aegirine lujavrite dominated by prismatic grains of aegirine which may be partly overgrown by arfvedsonite. There are corroded grains of nepheline, plates of microcline and strongly altered grains of eudialyte in a matrix of analcime. The rock shows a downward increasing content of arfvedsonite.

1.00-104.93 m: arfvedsonite lujavrite, in uppermost 10 m containing spheroidal bodies with lighter coloured rims rich in brown aegirine (Fig. 14). There are patches of medium- to coarse-grained lujavrite and xenoliths of naujaite. The arfved-

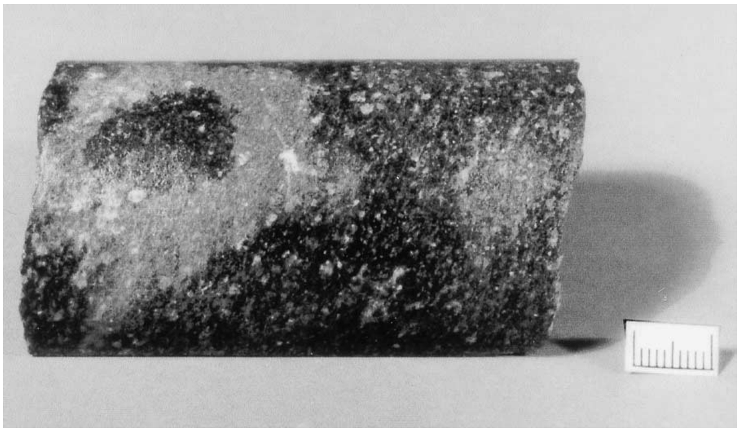

Fig. 14. Sample of drill core III at 7.16 m depth showing a spheroidal body made up of a black core and a light-coloured rim rich in brown aegirine. The rim is about 1 cm wide but appears thicker because it is intersected by the surface of the drill core at an oblique angle. The scale measures 1 cm.

sonite lujavrite is generally fine-grained and laminated but in places coarser-grained and more massive. It is made up of arfvedsonite, microcline, albite, nepheline, altered eudialyte, britholite, monazite and sphalerite in a matrix of analcime. Eudialyte is completely missing in parts of the drill core. The arfvedsonite encloses acicular aegirine and may be intergrown with biotite. Schlieren rich in aggregates of fine-grained biotite penetrate the lujavrite which is infiltrated by biotite adjacent to the schlieren. The biotite is sometimes associated with brown aegirine. Here and there the lujavrite encloses small bodies of felt-like aegirine.

There are pegmatitic veins and patches. Some of these are most probably recrystallized naujaite xenoliths, some may have been formed as a kind of back-veining from remobilized naujaite into the enclosing lujavrite, and some may be true pegmatites and hydrothermal veins. The small size of the samples does not allow a more precise determination of their origin. Most of them have a matrix of analcime in which corroded grains of nepheline, plates of microcline and sometimes albite may be enclosed; some are dominated by large plates of microcline. Arfvedsonite is practically always present and may be concentrated in the contact zones of these rocks. Aegirine and biotite are occasionally present. There are pseudomorphs after eudialyte made up of catapleiite, and there are clusters of small grains of monazite. Sphalerite is almost always present, galena has also been observed and strongly altered grains of steenstrupine have been found in a few of these rocks.

33.95-34.10 m: horizon of aegirine-arfvedsonite lujavrite having microcline, nepheline, arfvedsonite, aegirine, monazite and strongly altered eudialyte in a matrix of analcime.

38.40-39.33 m: arfvedsonite lujavrite containing biotite.

39.40-39.55 m: naujaite, the underlying lujavrite is rich in brown aegirine and with biotite along contact with naujaite.

40.45-42.75 m: strongly brecciated and recrystallized naujaite containing biotite. The underlying arfvedsonite lujavrite is rich in brown aegirine.

45.38-49.00 m: medium- to coarse-grained lujavrite with pegmatitic zones containing analcime, aggregates and schlieren of biotite, altered eudialyte and galena. These rocks are infiltrated by arfvedsonite lujavrite.

49.00-53.70 m: arfvedsonite lujavrite with pegmatitic horizons and locally rich in aegirine. It contains xenoliths of felted aegirine.

53.70-55.00 m: aegirine lujavrite with increasing content of arfvedsonite towards the lower contact.

55.00-57.00 m: arfvedsonite-aegirine lujavrite cut by albite veins with biotite.

66.90-69.20 m: arfvedsonite lujavrite which contains steenstrupine and is enriched in arfvedsonite in contact with the underlying naujaite.

82.50-83.38 m: aegirine-arfvedsonite lujavrite with albite and aegirine in contact zone and with small xenoliths of naujaite.

83.38-84.28 m: albitized naujaite, the underlying lujavrite is rich in pegmatites having arfvedsonite along contacts and analcime in cores. Sphalerite is present.

91.95-92.05m: zone in arfvedsonite lujavrite with about 80% arfvedsonite.

92.05-104.93 m: arfvedsonite lujavrite with pegmatitic zones, one at 95.91 with nepheline, analcime, pseudomorphs after eudialyte, pyrochlore, neptunite, galena, chalcopyrite, monazite, biotite and sphalerite. The lamination is folded around the pegmatites, which appear to infiltrate the lujavrite. From 97.0 downwards decreasing content of arfvedsonite and increasing content of aegirine, but with concentration of arfvedsonite in contact with the underlying aegirine lujavrite.

104.93-162.75 m: aegirine lujavrite with shiny fracture surfaces. The contact against the overlying arfvedsonite lujavrite is marked by a light-coloured rock which appears to replace the lujavrites. The uppermost part contains poikilitic grains of arfvedsonite which are partly altered into brown aegirine. The lujavrite is made up of prismatic grains and aggregates of acicular grains of aegirine, laths of microcline and albite, pseudomorphs after nepheline and eudialyte, analcime and in places ussingite. The arfvedsonite grains are partly poikilitic. They are associated with brown aegirine and biotite. The upper part is rich in pegmatites with arfvedsonite, aegirine, microcline, nepheline, sphalerite, altered eudialyte, analcime and biotite.

111.50-114.70 m and 115.05-120.00 m: the lujavrite is without arfvedsonite and strongly folded.

120.00-120.22 m: albite-analcime rock with aggregates of radiating prismatic arfvedsonite which are transformed into brown aegirine. It is rich in steenstrupine and sphalerite. It may be an altered naujaite xenolith.

151.46-151.50 m: steenstrupine, pyrochlore and sphalerite vein.

159.12-160.75 m: arfvedsonite lujavrite; in contact with the overlying aegirine lujavrite a zone rich in analcime, aegirine and catapleiite and with xenoliths of felted aegirine. At 159.54 m analcime vein with monazite, britholite, pyrochlore, sphalerite, acicular aegirine and aggregates of white mica which may mark the former presence of nepheline. At 160.30 m small xenolith of naujaite with secondary biotite.

162.75-200.00 m: arfvedsonite-aegirine lujavrite with patches of dissolved aegirine lujavrite and small partly dissolved xenoliths of naujaite. The arfvedsonite-rich lujavrite is rather coarse-grained and is made up of arfvedsonite with inclusions of acicular aegirine, and of microcline, eudialyte altered into catapleiite and analcime. Aggregates of white mica in analcime may represent altered nepheline. Biotite is a minor component.

165.93-168.00 m: aegirine lujavrite with scattered small grains of arfvedsonite.

196.20-199.10 m: naujaite with secondary analcime and rich in arfvedsonite and aegirine partially altered into brown aegirine and biotite. It contains pectolite and monazite.

Description of core IV (Fig. 2):

0.0-48.20 m: arfvedsonite lujavrite, weakly laminated and with subhorizontal dip. It shows gradual transition into patches of coarser-grained lujavrite. The arfvedsonite grains have small inclusions of aegirine, some horizons also contain brown aegirine secondary after arfvedsonite. Strongly corroded grains of nepheline, occasional grains of sodalite, laths of microcline and often also of albite are set in a matrix of analcime. The eudialyte grains are practically always altered into catapleiite and also into a rusty pigmentation which appears to contain biotite. Sphalerite and britholite are minor components. Nepheline-rich rocks may be patches or layers in the arfvedsonite lujavrite, though this distinction cannot be made in drill cores having diameters of 3 cm. Downwards there is an increasing transformation of arfvedsonite into brown aegirine and an increasing amount of separate grains of acicular aegirine. Fractures are covered by earthy natrolite.

16.47-17.75 m: naujaite with arfvedsonite altered into biotite.
17.75-32.48 m: many small xenoliths of naujaite.
41.65-41.73 m: small body of altered augite syenite or naujaite.
From 45 m a high content of green and brown aegirine, the latter most probably an alteration product of arfvedsonite.

48.20-98.19 m: laminated aegirine lujavrite with subhorizontal dip and dominated by acicular grains of aegirine. Large parts are without visible arfvedsonite in hand specimens, but some horizons contain varying amounts of arfvedsonite, in part as larger poikilitic grains. The arfvedsonite in most samples is partially altered into brown aegirine. This mineral also overgrows the acicular aegirine. Nepheline occurs as large corroded grains and is often the predominant felsic mineral. There may be laths of both microcline and albite, the matrix is always rich in analcime. The eudialyte crystals are always altered. Sphalerite is an accessory mineral.

63.42-63.56 m and 77.70-78.02 m: analcime veins.
79.00 m: strongly altered naujaite.
97.80 m**:** sharp contact against 3 cm thick horizontal sheet of arfvedsonite lujavrite.
98.10 m: Six cm thick horizontal sheet of arfvedsonite lujavrite.
98.19 m: Contact against underlying arfvedsonite lujavrite. Both lujavrites are rich in nepheline, the aegirine lujavrite contains larger and more corroded grains of this mineral than the arfvedsonite lujavrite and biotite is present on both sides of the contact.

98.19-116.09 m: arfvedsonite lujavrite with horizons of aegirine lujavrite, pegmatitic patches and many xenoliths of naujaite. The lujavrite is dominated by arfvedsonite but also contains acicular aegirine, which may be enclosed in the arfvedsonite. The lujavrite is enriched in nepheline in some parts, in microcline and albite in others, an indication of igneous layering. Eudialyte occurs as unaltered crystals but is generally altered into catapleiite. The matrix is made up of analcime. There are aggregates of fine-grained biotite.

98.19-100.60 m: irregular streaks of aegirine lujavrite in arfvedsonite lujavrite.
100.60-100.62 m: analcime vein.
105.92-106.37 m: naujaite with biotite after arfvedsonite.
106.46-107.25 m: naujaite.
107.25-108.19 m: the arfvedsonite lujavrite has steep, folded lamination, at 107.80 m subhorizontal lamination. Small xenoliths of naujaite have biotite after arfvedsonite and aggregates of monazite crystals.
108.19-108.62 m: naujaite with secondary biotite.
108.62-108.76 m: analcime vein with small amounts of earthy natrolite.
108.76-108.92 m: strongly altered naujaite xenolith consisting of analcime and large grains of arfvedsonite which are altered into biotite along surfaces and fractures. This rock also contains pectolite and aggregates of monazite crystals.
108.92-109.55 m: naujaite with arfvedsonite replaced by brown aegirine in contact zone against lujavrite.
109.79-116.09 m: naujaite.

116.09-136.64 m: arfvedsonite-aegirine lujavrite dominated by arfvedsonite but containing minor amounts of acicular aegirine and brown aegirine secondary after arfvedsonite. Corroded grains of nepheline and microcline occur in a matrix of analcime. Unaltered grains of eudialyte occur, but this mineral is generally altered into catapleiite. There are sheaths of prismatic grains of britholite.

136.64-137.30 m: analcime-natrolite rock with strongly altered eudialyte and prismatic arfvedsonite altered into brown aegirine. There are corroded grains of nepheline and microcline, monazite aggregates, britholite, acicular aegirine and flakes of biotite.

137.30-149.46 m: arfvedsonite lujavrite with horizons of aegirine lujavrite, patches of pegmatitic rocks and naujaite xenoliths.

140.57-141.40 m: naujaite.
141.40-141.55 m: arfvedsonite-aegirine lujavrite.
141.55-141.62 m and 141.86-141.90 m: horizons of aegirine lujavrite. The adjacent arfvedsonite lujavrite contains xenoliths of the green lujavrite.
141.62-141.90 m: arfvedsonite-aegirine lujavrite.
148.44 m: grey nepheline-rich rock.

149.46-200.00 m: aegirine lujavrite, here and there with larger poikilitic grains of arfvedsonite. It consists of acicular aegirine, nepheline, microcline, albite and analcime. The rock is rich in sphalerite. Neptunite and britholite are minor minerals. Large parts of this rock are without arfvedsonite, in other parts arfvedsonite occurs as small scattered grains which may overgrow aegirine. In the lower part of the drill core there are larger grains and areas of arfvedsonite, which may measure several cm across. The large arfvedsonite grains have lath-shaped inclusions of analcime, probably pseudomorphs after feldspars, and of eudialyte pseudomorphs. This is an indication of a late formation of the arfvedsonite. Some of the large arfvedsonite grains are without brown aegirine, others are overgrown by this mineral, a token of late-magmatic reactions. In these cases the brown aegirine also encloses acicular green aegirine.

Description of core V (Fig. 2):

0.0-4.15 m: Medium- to coarse-grained analcime-sodalite-eudialyte-feldspar rock with subordinate rinkite and natrolite and aggregates of arfvedsonite. It appears to be a cumulate of nepheline, sodalite and eudialyte with interstitial grains of microcline, arfvedsonite and occasionally aegirine and with late albite, analcime and natrolite. The arfvedsonite is partially poikilitic but generally occurs as separate prismatic grains which have inclusions of acicular green aegirine and are partially transformed into brown aegirine and sometimes biotite.

4.15-93.68 m: arfvedsonite lujavrite, laminated with shallow dip. The lamination wraps larger crystals of nepheline and sodalite. The lujavrite is layered with thicker layers of homogeneous laminated fine-grained lujavrite alternating with darker and lighter-coloured layers and medium-grained layers (Fig. 15). The medium-grained layers are rich in nepheline crystals, generally constituting 50–80 vol.% of the rocks. The contacts between the light- and dark-coloured layers are sharp (Figs 15, 16). The nepheline-rich layers should be termed urtite and arfvedsonite ijolite. They have been formed by the clustering together of nepheline crystals. There is a gradual transition from nepheline clusters in the laminated lujavrite into layers of nepheline varying in thickness from one crystal layer to several centimetres. The nepheline contains inclusions of arfvedsonite in much smaller grains than in

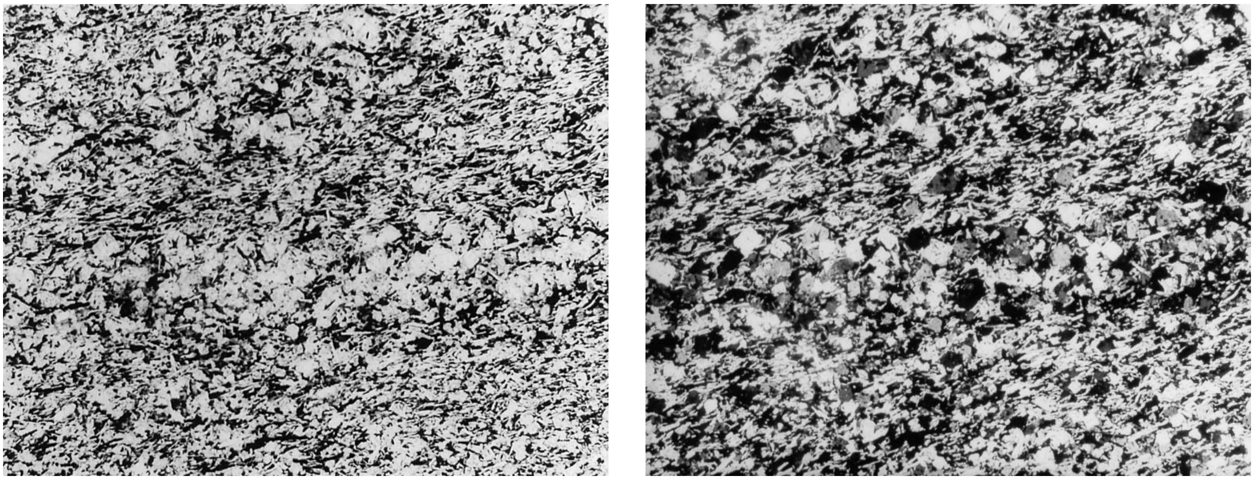

Fig. 15. Microphoto of whole thin section showing alternation of nepheline-rich and feldspar-rich layers without gradation. Bore hole V at 14.47 m. a. plane polarized light, b. crossed polars, horizontal length = 3 cm.

the surrounding rock. The nepheline-rich layers are rich in eudialyte crystals, which may form clusters, and contain sodalite and interstitial feldspar and arfvedsonite in a matrix of analcime and/or natrolite. The eudialyte grains are often associated with grains of green aegirine. The nepheline-rich layers show varying degrees of analcime and natrolite substituting nepheline, brown aegirine substituting arfvedsonite and interstitial grains of a brown isotropic Zr silicate. In the extreme case nepheline and arfvedsonite have disappeared.

At 12.41 m unaltered grains of vitusite occur; pseudomorphs after this mineral have been observed in the uppermost 50 meters of the lujavrite section. Thin sections of rocks from 12 to about 50 m contain grains of a pink and brownish lovozerite which show penetration twinning and irregular rusty-coloured fractures. They grow interstitially between especially crystals of nepheline and eudialyte. There are weakly anisotropic or isotropic brown grains recalling steenstrupine. Other parts of the brown grains are, however, biaxial positive with an axial angle of 40-60°. The rocks in question have up to about 300 ppm U which is most probably located in the brown mineral, a mineral needing a closer examination. In the altered parts of the drill core, these grains are also

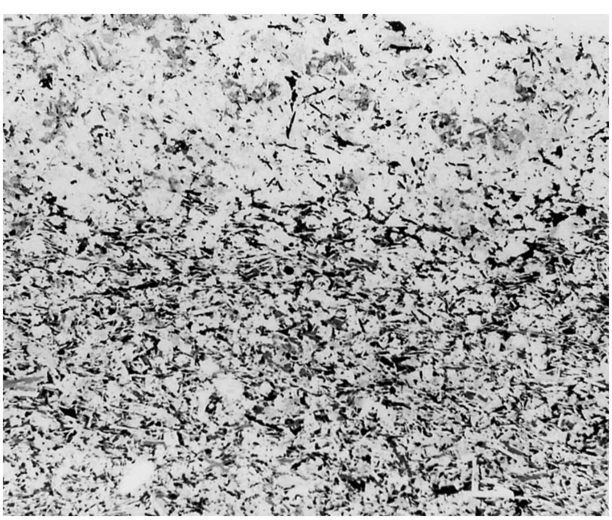

Fig. 16. Microphoto of whole thin section showing sharp contact between arfvedsonite lujavrite at the bottom and nepheline-rich layer at the top. Bore hole V at 28.13 m, plane polarized light, horizontal length = 3 cm.

altered. Some of the altered grains contain a highly birefringent carbonate mineral which may be bastnäsite or another REE carbonate. It is intersected by a network of very fine-grained fibres or scales of a strongly birefringent length-fast mineral. This type of network is also found in the analcime matrix.

Britholite, neptunite, sphalerite, poikilitic plates of a pink mica, poikilitic grains of a deep-red mineral, pectolite and monazite aggregates are accessories. Very small grains of ussingite have been observed.

Analcime, natrolite, brown aegirine and in cases biotite are secondary minerals. Eudialyte occurs as unaltered crystals in the upper part of this lujavrite, but in the lower part is at least partially transformed into catapleiite.

Nepheline-rich horizons have been observed at the depth intervals: 14.47-14.50, 28.09-28.11, 40.97-41.27, 42.37-42.44, 43.62-43.70, 44.33-44.57, 46.20-46.50, 47.23-47.44, 47.82-49.92, 49.96-50.35 m. The regular repetition of these horizons indicates that this section of the lujavrite is made up of a layered sequence of cumulates. Most of the nepheline-rich layers are 1-2 cm thick. This means that the above-mentioned horizons consist of one or several closely spaced nepheline-rich layers.

73.07-79.50 m: eudialyte-rich naujaite xenoliths in arfvedsonite lujavrite.

79.50-80.25 m: medium- to coarse-grained rock consisting of crystals of nepheline, sodalite, microcline and eudialyte with interstitial grains of acicular aegirine and prismatic arfvedsonite, the latter partly transformed into brown aegirine and biotite. Perovskite is an accessory mineral. The matrix consists of natrolite. The eudialyte grains are partly poikilitic and are generally strongly altered into catapleiite, aegirine, natrolite and biotite.

81.04-81.73 m: dense grey sodalite-rich rock with acmite, microcline, strongly altered eudialyte and perovskite in a matrix of natrolite.

93.68-138.97 m: aegirine lujavrite with sharp contact against the overlying lujavrite. It consists of large grains of sodalite and nepheline and altered crystals of eudialyte in a matrix of acicular green aegirine, microcline, albite, and secondary analcime. Parts of it are without visible arfvedsonite, other parts have small grains of that mineral up to a few mm long and in some horizons arranged parallel to the lamination of the rock. The arfvedsonite has inclusions of green acicular aegirine and may poikilitically enclose minerals of the matrix. It is here and there transformed into aggregates of brown aegirine. The aegirine lujavrite is rich in mm-sized cavities in some horizons.

Between 93.62 and 95.97 m there are horizons of arfvedsonite lujavrite which appear to infiltrate the aegirine lujavrite.

130.76-131.06 m: coarse-grained rock with large crystals of nepheline and eudialyte and with small acicular grains of arfvedsonite, sphalerite and secondary biotite in matrix of analcime.

131.06 m: dense analcime-acmite rock.

131.66 m: altered naujaite.

138.15-138.97 m: horizons of aegirine-arfvedsonite lujavrite.

138.97-149.57 m: arfvedsonite lujavrite, in some horizons with blue sodalite and with grains of acicular aegirine close to the contact against the overlying aegirine lujavrite.

140.21-140.35, 142.33-142.87, 143.61-143.84, 143.93-144.94, 145.08-145.67 and 145.67-149.57 m: Coarse-grained generally felsic rocks separated by sheets of arfvedsonite lujavrite which may be intrusions into one large felsic body or may separate several closely spaced xenoliths in the lujavrite. The coarse-grained rock is made up of up to 1 cm large crystals of sodalite, nepheline, microcline and eudialyte in varying proportions and of albite laths and acicular aegirine wrapping the above-mentioned minerals. Some parts of the rock also contain large prismatic grains of green aegirine. Arfvedsonite is locally present as large prismatic grains or as aggregates of small grains. It encloses small grains of green aegirine and is partially transformed into brown aegirine and more rarely into biotite. The nepheline and sodalite grains have inclusions of microcline and aegirine in smaller grains than in the enclosing rock. The large grains of eudialyte are practically always altered into catapleiite, whereas small crystals may be entirely unaltered. There are networks made up of aggregates of monazite crystals appearing to be pseudomorphs after an earlier mineral which occurred as poikilitic grains. The matrix consists of analcime and/or natrolite which in places have completely replaced the original felsic minerals.

149.57-175.31 m: arfvedsonite lujavrite with minor aegirine and with nepheline-rich horizons at 164.02-164.54 and 165.48-165.90 m.

161.90-164.54 and 165.90-175.10 m: Same type of rock as at 140.21-149.57 m, but locally rich in arfvedsonite and in some parts consisting of about 50 % analcime and 50 % eudialyte. Thin horizons contain pectolite, blue fluorite and sphalerite, the last named with rims of biotite. There are aggregates of monazite crystals and rare grains of perovskite. Calcite has been observed as a replacement product of eudialyte and as filling vugs.

175.13-175.24 m: horizon of aegirine lujavrite.

175.31-197.27 m: aegirine-arfvedsonite lujavrite which shows a decreasing content of arfvedsonite towards the bottom of the horizon, but with a concentration of arfvedsonite in contact with the underlying aegirine lujavrite. The arfvedsonite of this rock occurs as separate prismatic grains.

197.27-200.00 m: aegirine lujavrite with poikilitic grains of arfvedsonite up to 1 cm across and locally with sodalite. There are very small xenoliths of coarse-grained rocks resembling the rock found at 167.06-175.10 m.

Description of core VI (Fig. 2):

0.0-4.75 m: arfvedsonite lujavrite, in places layered with white and black layers. It is made up of arfvedsonite, microcline and eudialyte pseudomorphs in a matrix of analcime. The arfvedsonite is partially altered into brown aegirine. Sphalerite and perovskite are accessories and there are veinlets and irregularly-shaped spots of brown aegirine. The lamination dips 45°. Fractures have earthy greenish natrolite. Steenstrupine is found in white veinlets. There is a concentration of arfvedsonite against the underlying aegirine lujavrite.

4.75-10.78 m: aegirine lujavrite , unlaminated, made up of aegirine, microcline plates, eudialyte pseudomorphs, radiating flakes of white mica and grains of pyrite(?) in a matrix of analcime. Some horizons contain parallel needles of arfvedsonite. There is a concentration of aegirine in the upper contact and irregular veinlets of aegirine. At 7.50 m slickensides covered by a brown mineral.

10.78-12.98 m: strongly altered naujaite separated from the lujavrite by a thin zone of felted aegirine. The naujaite is intersected by steep veinlets of felted aegirine and is dominated by analcime and natrolite which enclose corroded grains of nepheline, sodalite and microcline and there are aggregates of small grains of arfvedsonite and aegirine forming a 'network' which most probably represents the former site of poikilitic grains of arfvedsonite. The aegirine felt contains slender prismatic grains of a mineral recalling nacareniobsite.

12.98-14.32 m: At 12.98 m the altered naujaite is in contact with a dense to fine-grained rock characterized by a breccia structure: ellipsoidal black nodules, up to a few cm long, separated by a greyish-white matrix which forms a network between the nodules. The black nodules contain white prismatic phenocrysts of pectolite which are up to 1 cm long. The nodules are characterized by large crystals of nepheline, up to a few mm across, which often form clusters (Fig. 17). They have inclusions of feldspar and arfvedsonite in much smaller grains than in the enclosing rock, but without brown aegirine, in contrast to the enclosing rock. There are also larger inclusions of amphibole and feldspar which have preserved the orientation of these minerals in the enclosing rock. The nepheline grains generally have corroded outlines and have rims of sodalite, analcime and/or natrolite. They are set in an extremely fine-grained rock dominated by laths of albite arranged in a trachytic texture wrapping the larger nepheline grains. There are interstitial grains of arfvedsonite, partially altered into brown aegirine, analcime, natrolite, perovskite, small grains recalling the shape of eudialyte crystals but composed of a pigmentary material, sphalerite, neptunite and white mica. In some nodules analcime and natrolite replace the felsic minerals and brown aegirine replaces the arfvedsonite. The nodular masses are separated by an albititic rock also showing a trachytic texture and with arfvedsonite and aegirine as minor components. The albitite contains enclaves of coarser-grained rocks made up of prismatic grains of brown aegirine which enclose small crystals of an unidentified mineral. The dense rock and the albitite both contain larger prismatic grains of pectolite which in their central parts have tiny inclusions of feldspars and arfvedsonite (Fig. 18). There are also clusters of tiny monazite crystals.

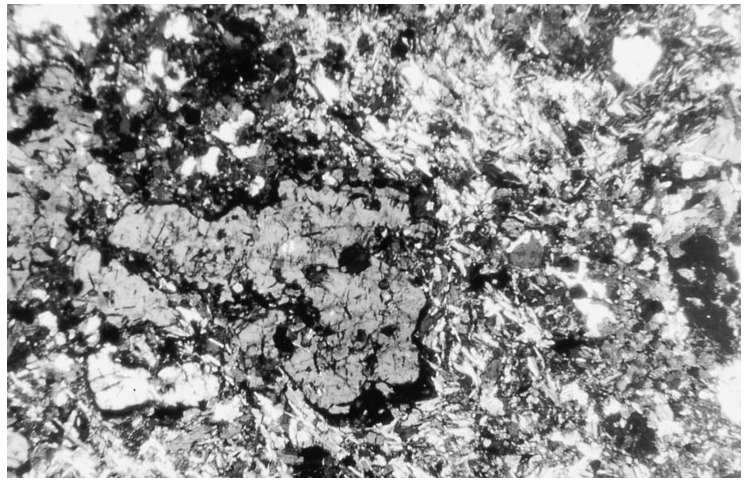

Fig. 17. Corroded grains of nepheline engulfed by a very fine-grained lujavritic rock. Bore hole VI, depth in core 13.08 m. The field of view is 5 mm wide.

14.32-14.67 m: aegirine lujavrite which is separated from the underlying dense black rock by felted green aegirine and a purple zone of microcline, brown aegirine, analcime, natrolite, white mica, neptunite, pigmentary material and sphalerite. This rock may represent a recrystallized shear zone.

14.67-27.27 m: the above-mentioned breccia of nodular masses of dense black or grey rocks. The content of aegirine increases towards the lower contact. From 17.50 m irregular 1-5 mm thick veinlets of brown aegirine, microcline, albite and analcime. The dense black rock is separated from the underlying lujavrite by a zone of analcime, microcline, brown aegirine, and pigmentary material which may represent a recrystallised shear zone.

27.27-122.71 m: arfvedsonite lujavrite with spots, spheroids and veinlets of

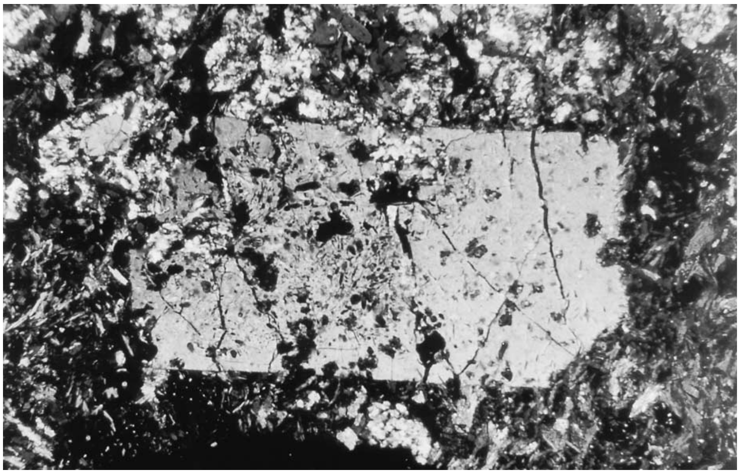

Fig. 18. Phenocryst of pectolite in dense rock in drill core VI at 13.08 m. The central part of the crystal is rich in inclusions of the matrix minerals, but in much smaller grains than in the enclosing rock. The field of view is 5 mm wide.

brown aegirine. The arfvedsonite lujavrite appears to impregnate the brown patches. The dip of the lamination is generally about 45°. The lujavrite consists of arfvedsonite in all stages of transformation into brown aegirine and containing inclusions of acicular green aegirine, corroded nepheline crystals, in places forming clusters, corroded small laths of microcline and albite, aggregates of monazite crystals, white mica, sphalerite, eudialyte pseudomorphs, pectolite and a matrix of analcime and/or natrolite. In the interval 94.75-99.70 m the lujavrite is rich in small red crystals of lovozerite together with grains of vitusite or aggregates of monazite forming pseudomorphs after that mineral. The lovozerite crystals are partly overgrown by arfvedsonite and may be associated with altered grains of eudialyte. These rocks also contain sodalite, britholite, white mica and sphalerite. At 113.80 m the lujavrite contains altered grains of lovozerite associated with aggregates of monazite.

37.06-42.23 m, 47.10 m and 94.75 m: the lujavrite contains masses of the abovementioned dense black rock which appear to be engulfed and partly digested by the arfvedsonite lujavrite. There are analcime veins and 29.98-30.08 m, 96.43-96.68 m and 110.72-111.02 m small xenoliths of naujaite.

122.71-200 m: naujaite locally rich in eudialyte with aegirine partially replaced by biotite and also with white mica. The naujaite is locally natrolitized. There are veins of albite-analcime.

122.71-122.95 m and 126.22-126.45 m: naujaite pegmatites with up to 5 cm long crystals of prismatic arfvedsonite and rich in eudialyte.
125.88-126.22 m: aegirine lujavrite dyke with felted aegirine along contacts.

Description of core VII (Fig. 2):

0-200 m: aegirine lujavrite I. This rock shows a range in variation of structures, grain size, mineralogy and secondary alteration. The major rock-forming minerals are plates of microcline, acicular to slender prismatic grains of aegirine and platy crystals of eudialyte in strongly varying proportions. There are green layers rich in aegirine, red layers rich in eudialyte and felsic layers rich in microcline and more often analcime and natrolite. The orientation of the elongated and platy grains of aegirine, microcline and eudialyte in one plane defines the lamination of the rock which wraps rounded aggregates of small grains of natrolite. These aggregates very rarely contain small remnants of nepheline and therefore are interpreted to be altered grains of nepheline and perhaps also sodalite. Some rocks contain interstitial vein-like material made up of tiny laths of albite. The eudialyte crystals are generally perfectly unaltered, an incipient alteration into catapleiite is seen at deeper levels in the drill core. Natrolite and analcime are interstitial minerals and in some horizons replace all the felsic minerals. Arfvedsonite occurs as interstitial small stout grains or more commonly as poikilitic grains enclosing grains of feldspar and aegirine of much smaller size than in the enclosing rocks but showing the same orientation as in the surrounding rock. The oikocrysts of arfvedsonite may show signs of rotation. Some horizons of the lujavrite are devoid of arfvedsonite, in others poikilitic grains may constitute up to 20-30% of the rocks. In some rocks the poikilitic grains are made up of aggregates of small grains of arfvedsonite. The arfvedsonite may be partially rimmed by brown aegirine. The arfvedsonite-rich horizons are often full of tiny holes after a dissolved unknown mineral. Minor minerals are sphalerite, pectolite and white mica.

The crystals of microcline and aegirine are often bent or broken and the rocks show signs of deformation such as irregular lamination, fracturing and brecciation. The fractures are often occupied by felted aegirine in the form of veins up to about 2 cm thick and in places associated with vugs of aggregates of natrolite crystals. The fine- to medium-grained aegirine lujavrite is in many horizons interwoven or brecciated by dense green rocks which contain fragments of the aegirine lujavrite.

The grain size of the aegirine lujavrite varies throughout the core. At the depth intervals: 14.74-14.77, 88.50-90.78, 94.10-94.50, 102.22-102.42 and 102.64-103.45 and less distictly at 125.90-126.10, 130.20, 135 and 146 m, there are coarse-grained rocks containing plates of microcline, 2-3 cm long, arranged around crystals of eudialyte and rounded aggregates of natrolite which have small remnants of nepheline and are interpreted as altered grains of this mineral. Prismatic and acicular grains of aegirine and arfvedsonite are interstitial to these minerals and natrolite and analcime form the matrix of the rocks. Mineralogically and texturally the coarse-grained rocks resemble kakortokite, but they grade into the adjoining aegirine lujavrite and most probably represent a coarse-grained facies of that rock. It should here be remembered that there is a gradual transition from kakortokite to aegirine lujavrite (Bohse & Andersen 1981).

The aegirine lujavrites also have veins or bands of light-coloured rocks. Some of these cut the lamination of the lujavrites, others are conformable and may be layers or layer-parallel veins. They are generally dominated by analcime and natrolite, but some consist of intergrowths of very fine-grained microcline laths and are commonly associated with aegirine lujavrite enriched in aegirine. This may represent some kind of colour banding. Some of the light-coloured rocks are rich in eudialyte, the contents of aegirine and arfvedsonite vary and are often very small. Arfvedsonite may form larger prismatic crystals. The light-coloured rocks may be separated from the aegirine lujvrite by thin zones of felted aegirine. They have been noted at the depths: 23.70, 24.10-24.53, 24.63, 24.88, 25.22, 26.23, 26.30-28.30, 56.80-58.00, 102.40-103.41, 138.26-138.33, 138.61-138.84, 139.56-139.73, 139.84-139.96, 140.15-141.07, 141.68 m.

The aegirine lujavrite is intersected and penetrated by thin generally conformable veins of very fine-grained arfvedsonite lujavrite which often have a concentration of arfvedsonite in a thin contact zones against aegirine lujavrites and light-coloured rocks. Arfvedsonite lujavrite has been found at the depths: 23.70, 23.97, 28.36-28.66, 49.90, 87.22, 92.04, 93.66-93.68, 93.80-93.84, 94.04-94.15, 94.25, 94.50-95.10, 113.04, 119.58 and 125.02 m. The lamination of these lujavrites is parallel to that of the invaded aegirine lujavrites which form lenticular inclusions in the arfvedsonite lujavrite. In some cases there are also inclusions of felted aegirine which probably are precursors to the injection of lujavrite in fractured aegirine lujavrite. The arfvedsonite lujavrites are dominated by small grains of arfvedsonite and have tiny microcline plates, eudialyte crystals and acicular aegirine which wrap aggregates of small grains of natrolite. These rocks contain rare corroded remnants of nepheline. The eudialyte crystals may be crowded with tiny needles of aegirine and are in some rocks substituted by aggregates of catapleiite. Britholite is an accessory mineral and analcime and natrolite form the matrix of the rocks. The fine-grained arfvedsonite lujavrite may grade into the larger patches of poikilitic arfvedsonite in aegirine lujavrite.

Xenoliths of naujaite in all stages of recrystallization occur at the depths: 32.53, 33.27, 33.57, 36.00, 36.18, 38.76, 44.50, 54.18, 80.37, 103.41, 127.78-128.25, 184.90-185.95, 192.90-193.28 m. Most of them measure a few cm across.

The aegirine lujavrite is brecciated and cut by veins of dense green rocks and of felted aegirine throughout the core at the depths: 16.40, 18.13, 17.80-19.10, 20.20, 21.67-22.00, 23.52, 23.60-24.10, 23.97-24.18, 24.53-24.63, 25.22, 27.13, 27.78, 28.30-28.66, 56.80, 79.25, 86.15, 87.22, 113.02-113.40, 118.34, 125.02, 128.00, 129.65, 144.48. These dense green rocks are dominated by tiny grains of aegirine which form networks of aggregates embedded in natrolite and analcime which often have rectangular shapes, most probably because they are secondary after laths of microcline; they contain remnants of that mineral. The aegirine aggregates my be intersected by veins of fine-grained natrolite and then form "islands" in that mineral. Small grains of eudialyte occur, but this mineral is generally altered into aggregates of catapleiite or into pigmentary material. There are thin zones of felted aegirine which may contain small grains of arfvedsonite. At 129.65 m the aggregates of aegirine contain clusters of a brown mineral, most probably steenstrupine, which is associated with grains of a deep-red isotropic mineral and small crystals of a pink mineral which recall eudialyte but have higher birefringence than that mineral. It is accompanied by britholite, pectolite and sphalerite.

MONOGRAPHS ON GREENLAND

PUBLISHED BY THE DANISH POLAR CENTER

This book describes seven hitherto unpublished drill cores from the Ilímaussaq alkaline complex, South Greenland, the type locality for agpaitic nepheline syenites. It discusses the information the drill cores present on the structure of the complex, on the distribution and evolution of the lujavrites, the most evolved rocks of the complex, and on the distribution of uranium in the lujavrites.

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