Minor intrusions of peralkaline microsyenite in the Ilímaussaq alkaline complex, South Greenland

Contribution to the Mineralogy of Ilímaussaq no. 108

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The agpaitic part of the Ilímaussaq alkaline complex, South Greenland, is made up of a roof zone, an intermediate zone and a floor zone. Dykes and sills of peralkaline microsyenite intersect the rocks of the roof and floor zones, but do not appear to intersect the lujavritic nepheline syenites which make up the intermediate zone. The microsyenites consist of Na-poor microcline, K-poor albite, aegirine and arfvedsonite which are practically identical to those of the agpaitic nepheline syenites of the complex. Neptunite and pectolite are the commonest minor minerals. The microsyenites are silica-saturated, –oversaturated, or, more rarely, undersaturated. The agpaitic part of the Ilímaussaq complex is considered to have been formed in a closed magma chamber; the lujavrites of the intermediate zone representing residual melts left after the consolidation of the roof and floor zones. That the microsyenite intrusions intersect the roof and floor zones but not the youngest lujavrites lying between these zones presents a geometrical problem which is discussed at some length. It is difficult to explain the microsyenites as products of fractionation or contamination of melts within the agpaitic magma chamber. Furthermore, the microsyenites differ mineralogically and chemically from the abundant microsyenitic dykes of the regional Tugtutôq-Ilímaussaq dyke swarm. It is therefore proposed that they originated in the source region which fed the agpaitic melts of the Ilímaussaq complex and that their emplacement in fractures was accompanied by a loss of volatiles and incompatible elements.

Key words: agpaitic, Ilímaussaq, lujavrites, microsyenites.

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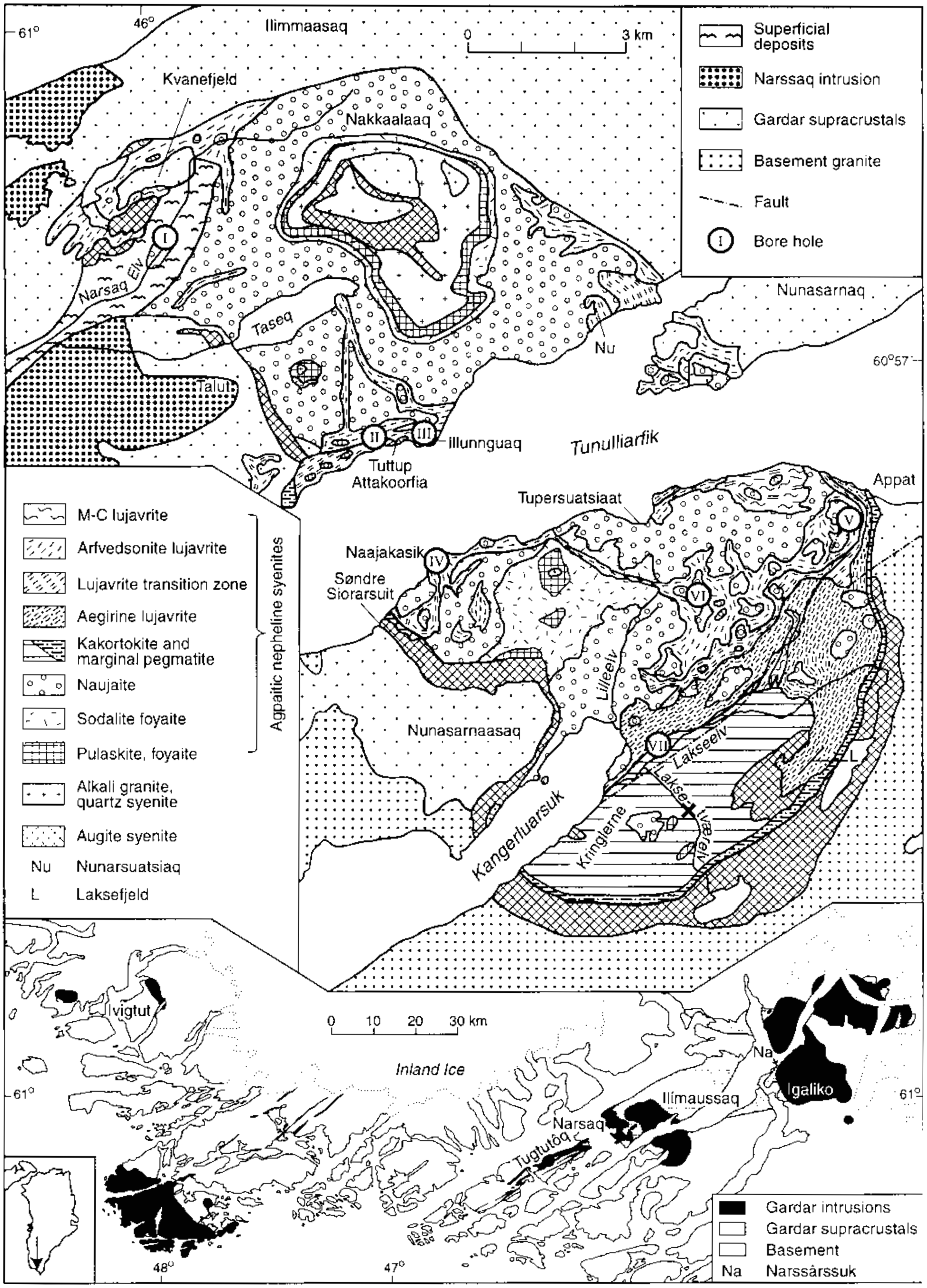
Syenitic rocks are of widespread ocurrence in intrusive complexes and as dykes in the Proterozoic Gardar igneous province, South Greenland (Upton & Emeleus 1987). One of the intrusive complexes, the Ilímaussaq alkaline complex (Fig. 1), the type locality for agpaitic nepheline syenites (Ussing 1912), contains several types of syenite. This complex is made up of three major intrusive phases: (1) augite syenite, (2) alkali granite and quartz syenite, and (3) nepheline syenites. The rocks of phase (1) are now only preserved as a partial shell along the marginal and upper contacts of the complex; phase (2) is found near the roof of the complex and as xenoliths in rocks belonging to phase (3). Phase (3), the major part of the complex, is made up of an upper zone which crystallized from the roof downward in the order pulaskite, foyaite and the agpaitic rocks sodalite foyaite and naujaite, an intermediate zone of agpaitic and hyper-agpaitic lujavrites, and a floor zone made up of a succession of black, red and white layers of the agpaitic cumulate, kakortokite. Naujaite is made up of large crystals of microcline, arfvedsonite, aegirine and eudialyte which poikilitically enclose cm-sized crystals of sodalite. Kakortokite is characterized by a trachytoidal texture and is composed of microcline perthite, nepheline, arfvedsonite and eudialyte in the form of three-layer units composed of a lower black layer rich in arfvedsonite, a red layer rich in eudialyte and an upper white layer rich in feldspar. Lujavrites are fine- to medium-grained meso- to melanocratic rocks composed of separate grains of microcline and albite, nepheline, eudialyte and arfvedsonite in black varieties and aegirine in green varieties. They possess a pronounced igneous lamination. Some medium- to coarse-grain-


61°
46°
Ilimmaasaq
0
3 km
Superficial deposits
Narssaq intrusion
Gardar supracrustals
Basement granite
Fault
Bore hole
Kvanefjeld
Nakkaalaaq
I
Narsaq Elv
Taseq
Talut
Nu
Nunasarnaq
60°57'
II
III
Illunnguaq
Tuttup Attakoorfia
Tunulliarfik
Appat
Tupersuatsiaat
M-C lujavrite
Arfvedsonite lujavrite
Lujavrite transition zone
Aegirine lujavrite
Kakortokite and marginal pegmatite
Naujaite
Sodalite foyaite
Pulaskite, foyaite
Alkali granite, quartz syenite
Augite syenite
Nu Nunarsuatsiaq
L Laksefjeld
Agpaitic nepheline syenites
Naajakasik
IV
Søndre Siorarsuit
V
VI
VII
Lilleelv
Lakseelv
Nunasarnaasaq
Kangerluarsuk
Kringlerne
Lakse-tværelv
L
Ivigtut
0 10 20 30 km
Inland Ice
61°
Na
Igaliko
Ilímaussaq
Narsaq
Tugtutôq
61°
48°
47°
Gardar intrusions
Gardar supracrustals
Basement
Na Narssârssuk

ed varieties show a foyaitic texture. A summary of the geology of the complex is found in Sørensen (in press).

The Ilímaussaq complex is intersected by a number of minor intrusions which do not fit into the abovementioned scheme of three intrusive phases. They fall into two groups, dykes and sills of peralkaline microsyenite and lamprophyric dykes. The latter will not be considered further in the present paper.

The former group has been mentioned by a number of authors but never been thoroughly studied. In connection with the examination of a drill-core, which intersects a sheet of peralkaline microsyenite, the authors undertook a detailed investigation of this microsyenite exposed adjacent to the bore-hole. For comparative reasons, a few additional occurrences of microsyenite were included in the study. The paper presents the results of this study and examines the role of the microsyenites in the evolution of the Ilímaussaq complex and their relation to the regional swarm of syenitic dykes.

Peralkaline microsyenitic intrusions in the Ilímaussaq alkaline complex

Ussing (1912) noted a small number of bostonite-like dykes intersecting the kakortokite in Kringlerne, the southernmost part of the complex. Ferguson (1964) reported on the occurrence of sills of green porphyry connected by dykes and intruded into the kakortokite, and, more sparingly, into the overlying aegirine lujavrite at Laksefjeld (Fig. 1). A 3-6m thick sill occurs below the most prominent layer of red kakortokite, layer +16 red (Bohse, Brooks & Kunzendorf 1971). It is separated from the kakortokite by a pegmatite with radiating aggregates of prismatic aegirine crystals. The microsyenite has phenocrysts of alkali feldspar and crusts of neptunite on fractures. The sill is connected with dykes which are considered to have been its feeders (Bohse et al. 1971). The microsyenitic sill underlying kakortokite layer +16 red and its accompanying pegmatite has been intersected by bore-holes (LeCouteur 1990). The sill is divided into an upper and a lower part by a pegmatitic sheet which is conformable to the contacts of the sill. Microsyenitic sills have also been intersected by bore-holes through units A, B and C of the transitional layered kakortokite at the head of Kangerluarsuk (Bohse & Andersen 1981). At this place, drill core 23 shows six microsyenitic sills at depths 76.45, 99.67, 100.63, 102.75, 110.30 and 113.53 m intruding units A and B and xenoliths of naujaite (LeCouteur 1990). Larsen (1977) studied samples of the feldspar-phyric, peralkaline saturated microsyenite from dykes and sills intruded into the kakortokite consisting mainly of alkali feldspar, aegirine and arfvedsonite. According to the information provided by Lotte Melchior Larsen, the thin microsyenitic dykes in the kakortokite run parallel over some distances, coalesce and intrude into each other, cf. the geological map (Andersen, Bohse & Steenfelt 1988). They branch out from the sill underlying red layer +16. Some aphyric dykes show chill contacts, but chilled contacts are otherwise rare. One of the dykes, 10–50 cm wide, carries 2.5 vol.% aenigmatite phenocrysts (Fig. 2). Further details of the occurrence of microsyenitic dykes and sills in the kakortokite and aegirine lujavrite are shown on the geological maps by Bohse et al. (1971) and Andersen et al. (1988), according to which the dykes have a ENE-NE orientation and are intersected by aegirine pegmatites.

According to the geological map of Ferguson (1964), the naujaite to the north of Tunulliarfik and the overlying alkali granite are intersected by respectively five and three dykes of peralkaline microsyenite. Minor intrusions of microsyenite and alkali syenite are also reported from the Kvanefjeld plateau in the northernmost part of the complex (Sørensen, Hansen & Bondesen 1969; Sørensen, H., Rose-Hansen, Nielsen, Løvborg, Sørensen, E., & Lundgaard 1974). In the eastern part of the plateau, all rocks older than naujaite are cut by dykes of quartz microsyenite, but the time relation between these dykes and the naujaite is not clear due to the lack of contacts between these rocks. A 4 m thick dark grey to green microsyenite dyke occurs in the upper part of the steep slope facing the Narsaq Elv valley. Its dip varies from near horizontal to 40° SSE. A faint layering is seen due to varying contents of feldspar, amphibole and pyroxene. Veins of analcime-sodalite occur along its contacts and intersect the microsyenite. In the western part of the plateau several generations of dykes and sheets of peralkaline silica-undersaturated alkali syenite intersect large masses of augite syenite. They are composed of microcline perthite, albite, arfvedsonite, aegirine, pectolite, neptunite, sodalite, nepheline, analcime, zircon, apatite and murmanite. One

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Fig. 1. Geological map of the Ilímaussaq alkaline complex based on Ferguson (1964) and Andersen et al. (1988). Location of boreholes I to VII are indicated. One sampling locality is near bore-hole I at Narsaq Elv in the north, another marked by a cross at Laksetværelv in the south.

Fig. 2. Aenigmatite-bearing microsyenite dyke intersecting kakortokite (photo: Lotte Melchior Larsen).

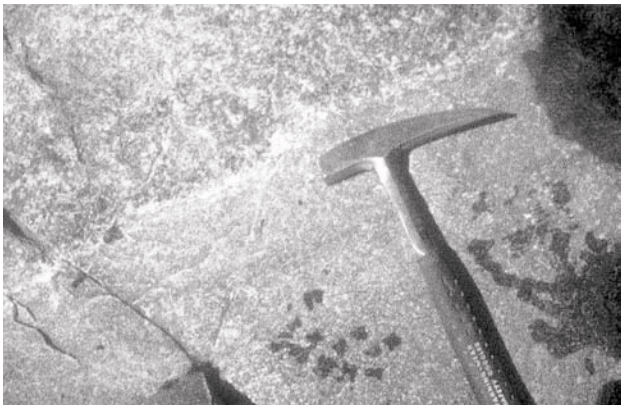

Fig. 3. Contact between naujaite (top) and microsyenite (bottom) with white albitite along the contact. The microsyenite has developed a faint layering parallel to the contacts. The dark patches on the microsyenite are crusts of lichens, Narsaq Elv. Hammer head measures 17.5 cm.

Fig. 4. White rim of albitite between naujaite xenolith and enclosing microsyenite, Narsaq Elv. Hammer head measures 17.5 cm.

Fig. 5A. Pegmatite with radiating groups of arfvedsonite in contact with microsyenite. a. The microsyenite contains a xenolith of naujaite and is light-coloured towards the pegmatite.

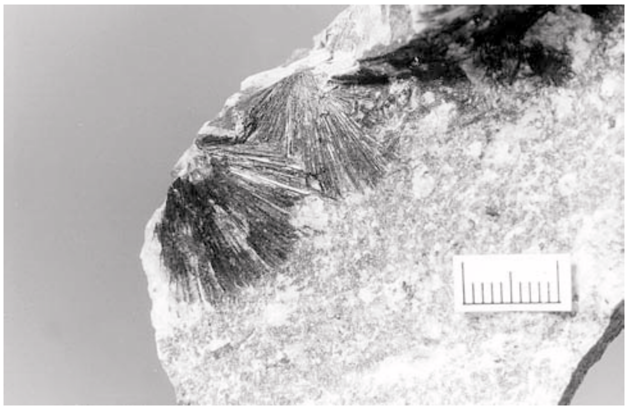

Fig. 5B. Close-up of radiating groups of arfvedsonite growing towards a strongly albitized microsyenite. GI 109309, scale = 1 cm. Photo: Ole Bang Berthelsen.

Fig. 6. White layer in microsyenite, Narsaq Elv. Hammer head measures 17.5 cm.

Fig. 7. Microphoto of whole thin-section showing enclave of coarser-grained albitite in fine-grained microsyenite, Narsaq Elv. GI 88961, crossed polarizers, length of thin section = 3 cm. Photo: Ole Bang Berthelsen.

Fig. 8. Branching pegmatitic veins intersecting the microsyenite sheet. Narsaq Elv. Hammer head measures 17.5 cm.

Fig. 9. Sheet of arfvedsonite lujavrite with white contact zone rich in albite against the underlying microsyenite. Hammer rests on microsyenite. Narsaq Elv. Hammer head measures 17.5 cm.

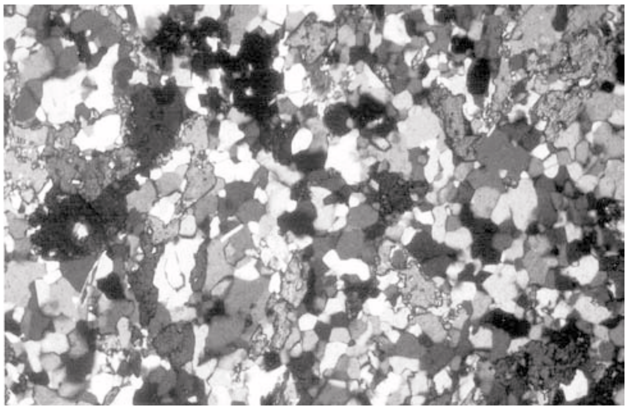

Fig. 10. Microphoto of microsyenite dominated by sugary albite, Narsaq Elv. GI 88961, crossed polarizers, field of view is 2.8 mm wide. (Photo: Ole Bang Berthelsen).

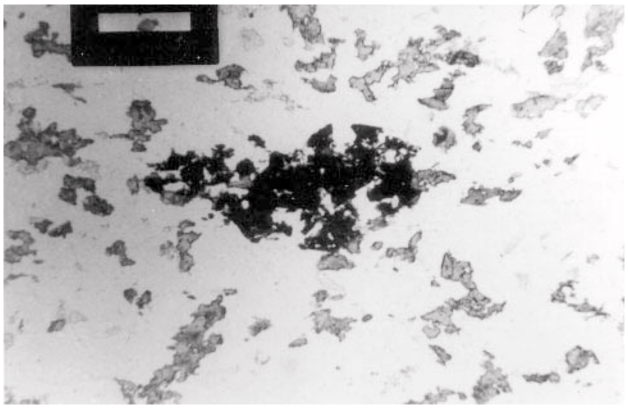

Fig. 11. Microphoto of microsyenite showing oikocryst of neptunite (black) in matrix of feldspar and aegirine, Laksetværelv. GI 109330, plane polarized light, bar measures 0.6 mm.

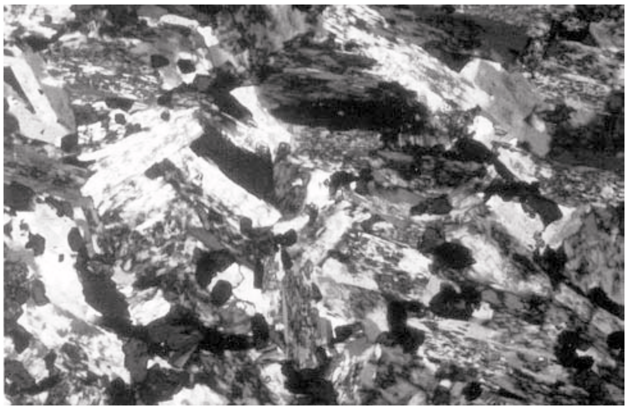

Fig. 12. Microphoto of microsyenite dominated by laths of microcline, Kvanefjeld. GGU 154398, crossed polarizers, field of view is 2.8 mm wide. (Photo: Ole Bang Berthelsen)

analysed sample, GGU 64786, has the agpaitic index 1.10 (Sørensen et al. 1969; Nielsen 1968; Nielsen & Steenfelt 1979). These syenite intrusions are deformed and metasomatised near bodies of medium- to coarse-grained lujavrite. Microsyenitic rocks have been observed in drill-cores 8 (18.00–20.00 m) and 37 (163.30–35 m) from the Kvanefjeld plateau, in both cases intersecting sheared volcanic rocks from the roof of the complex. Also the exposed part of the volcanic roof at Kvanefjeld are intersected by trachytic dykes which are earlier than the agpaitic rocks (Sørensen et al. 1969, 1974; Sørensen, Rose-Hansen & Nielsen 1971).

A dyke of microsyenite intersects naujaite at the altitude 380 m in the bed of the Narsaq Elv (Larsen personal information 2001) and a sheet of microsyenite occurs in the bed of this river at 292.4 m (Fig. 1). This sheet is intersected by bore-hole I (Rose-Hansen, 1969; Rose-Hansen & Sørensen submitted).

The present paper examines samples of the microsyenite sheet from bore-hole I and the Narsaq Elv, microsyenite from the eastern part of the Kvanefjeld plateau and dykes of microsyenite intruding kakortokite in the southern part of the complex.

The microsyenite from bore-hole no. I and from the Narsaq Elv river-bed

This bore-hole is located at tachymetric point 212 at an altitude of 292.4 m in the Narsaq Elv Valley at the foot of the Kvanefjeld mountain (Fig. 1). The surface rock is a naujaite rich in sodalite and nepheline and poor in eudialyte and mafic minerals.

The fine-grained, grey to black peralkaline microsyenite occurs in the river bed about 20 m to the south of the bore-hole which intersects the microsyenite sheet in the depth interval 5.56–21.35 m showing that the sheet is about 15 m thick. The microsyenite can be followed for a few hundred metres downslope from the drilling site. The attitude of the sheet varies from horizontal to gently westward dipping. It is marked as rocks from the Gardar continental series on the geological map (Ferguson 1964).

The microsyenite is more resistant to weathering than the adjacent naujaite and lujavrite and the contact zones against these rocks have generally been eroded. Where exposed, the contact between naujaite and microsyenite is marked by white albititic zones (Fig. 3). The microsyenite has mm-thin greenish aegirine-rich bands parallel to the contact (Fig. 3). No chill zones have been observed. There is often a zone of felted aegirine along the contact zones, a feature interpreted as due to recrystallization along shear zones or joint fillings in the naujaite. These features indicate that the microsyenite was emplaced along a fracture in naujaite. This, and xenoliths of naujaite in the microsyenite (Fig. 4), show that the microsyenite is younger than the naujaite. Pegmatitic zones up to a few cm wide are sporadically developed between the microsyenite and the country rocks (Fig. 5) and contain radiating groups of arfvedsonite crystals and microcline crystals growing on the contact face of the naujaite towards the microsyenite. The pegmatite zones have sheets of arfvedsonite lujavrite and grade via albititic zones into the microsyenite.

The microsyenite sheet shows a weakly developed inch-scale type of layering and also an alternation of greyish-black and white horizontal layers, up to a few metres thick (Fig. 6). There are sharp contacts between these layers which appear to be homogeneous. The microsyenite has scarce small phenocrysts of feldspar, amphibole, clinopyroxene and neptunite and contains scattered cm-large black nodules and xenoliths. There are white patches of albitite which are slightly coarser grained than the microsyenite (Fig. 7).

The microsyenite is intersected by coarse-grained veins (Fig. 8). It is not possible to decide if it is veins of medium- to coarse-grained lujavrites or pegmatites associated with the arfvedsonite lujavrite. In thin sections it is seen that the microsyenite is recrystallized in contact with the pegmatite. Sheets of arfvedsonite lujavrite are separated from the microsyenite by thin rims of albitite which enclose masses of fine-grained aegirine rocks (Fig. 9). The age relation between microsyenite and arfvedsonite lujavrite is difficult to unravel because of the poorly exposed contacts between these rocks. There are no dykes or sheets of arfvedsonite lujavrite intersecting the microsyenite, but the above-mentioned coarse-grained veins of lujavritic composition and the observation that albititic veins intersecting the microsyenite and the adjacent naujaite are cut by veins of arfvedsonite lujavrite lend support to the interpretation that the arfvedsonite lujavrite post-dates the microsyenite. The lujavrite sheet in Figure 9, which most probably corresponds to the sheet of lujavrite in the upper contact of the microsyenite sheet in drill-core I, has most probably been emplaced along the contact between naujaite and microsyenite, see further below in the description of drill-core I.

Description of the relevant part of the drill-core

4.80–5.66 m: Medium- to coarse-grained lujavrite or lujavrite pegmatite with sharp contacts against the overlying naujaite. There are masses of aegirine-rich albitite containing eudialyte, sphalerite, pectolite and monazite and thin zones of felted aegirine along the naujaite contact. The albite occurs as plates and sugary-grained aggregates. There are fragments of earlier albitite rimmed by small crystals of natrolite. The pegmatite has radiating clusters of arfvedsonite crystals and large crystals of microcline growing toward the albitite in the contact on the microsyenite and has interstitial albite with small crystals of eudialyte.

5.66–21.35 m: fine-grained alkali microsyenite with phenocrysts of alkali feldspar, clinopyroxene and neptunite. The upper contact is sharp and marked by a thin white albite zone which passes gradually into the underlying fine-grained rock. The latter shows colour variation from black to white, partly because of almost horizontal m-thick layering, partly because of wavy lighter-coloured albite-rich zones which penetrate the darker-coloured rock.

At 13.33 m there is an intersecting pegmatitic vein (or medium- to coarse-grained lujavrite ?) of ijolitic composition dominated by large crystals of nepheline and with arfvedsonite, sodalite, large and small crystals of eudialyte and with interstitial albite, analcime and natrolite containing flakes of astrophyllite. This recalls the situation in the microsyenite sill underlying kakortokite layer +16 red which, as mentioned above, is divided into upper and lower parts by a pegmatitic zone.

The lowermost part of the microsyenite from 20.0 to 21.35 m is greenish due to its content of aegirine and at 21.20 m it is cut by an albite vein containing steenstrupine.

21.35–21.43 m: coarse-grained albitite containing eudialyte and monazite and with radiating groups of arfvedsonite crystals and microcline crystals growing toward the microsyenite. There are fragments of earlier albitite. The contact against the underlying arfvedsonite lujavrite is sharp.

21.43 to 24.53 m: Arfvedsonite lujavrite with xenoliths of augite syenite and naujaite and patches of albitite with eudialyte, monazite, aegirine and plates of microcline.

24.53–24.92 m: aegirine lujavrite.

24.92-84.25 m: naujaite.

Microsyenite intersecting kakortokite

These microsyenites were examined in samples: GI 109330, green porphyritic aegirine-rich dyke at altitude 375 m to the east of Laksetværelv (Fig. 1), GI 109329, grey aphyric dyke intersecting dyke GI 109330 at altitude 375 m, to the west of Laksetværelv, and GGU 21184, dyke at altitude 355 m in the same river. In addition, Lotte Melchior Larsen, GEUS, has kindly placed a number of chemical analyses of the sill underlying red layer +16 and of dykes intersecting kakortokite at our disposal: GGU 153011 and 153013 composite dyke intersecting xenolith of augite syenite; GGU 53022 coarse-grained central part of sill beneath layer +16; GGU 153023 green part of sill beneath layer +16; GGU 153028 dyke in kakortokite; GGU 153293 chilled dyke; GGU 109261 aenigmatite-bearing dyke in the westernmost part of the kakortokite area.

Petrography

The microsyenite of drill-core I and the Narsaq Elv is fine-grained, the white layers being slightly coarser than the grey to black parts of the sheet. The texture varies from trachytic showing parallel orientation of microcline and albite laths and acicular grains of arfvedsonite and/or aegirine to granular dominated by sugary-grained aggregations of albite (Fig. 10). The proportion of microcline and albite varies from rocks dominated by microcline over rocks having aggregates or scarce plates of microcline in a matrix of albite to albititic rocks. There are phenocrysts of microcline and microcline perthite. The perthite is rimmed by small crystals of arfvedsonite, aegirine and neptunite. The albitites are dominated by sugary-grained aggregates of albite, laths of albite are more scarce. The white layers lack microcline whereas the darker layers contain scattered laths of this mineral. Prismatic or acicular grains of aegirine and arfvedsonite are, in varying proportions, scattered between the feldspar grains. In a few thin sections the aegirine and arfvedsonite grains have brown cores and green or bluish green marginal zones. The arfvedsonite contains inclusions of and forms rims on aegirine but also has rims of that mineral. The arfvedsonite has inclusions of fluorite. The proportion of aegirine and arfvedsonite is practically the same in white and dark layers. Prismatic grains of pectolite and rounded grains of neptunite form single grains or oikocrysts with inclusions of the rock-forming minerals (Fig. 11). There are scarce small crystals of eudialyte which appear to be associated with the albite-rich parts of the rock. Small zircon crystals have been observed in one thin-

Table 1. Representative microprobe analyses of minerals from microsyenitic rocks from the Ilímaussaq alkaline complex (wt.%.)

	Arfvedsonite			Aegirine			
Sample no	154398	156927	109317	154398	156927	109317	109316
SiO_2	50.02	49.52	49.90	51.60	52.06	52.90	49.67
TiO_2	0.52	1.33	0.57	0.68	0.41	0.33	1.28
Al_2O_3	0.14	0.36	0.07	0.20	0.09	0.26	0.32
FeO*	31.74	32.56	32.92	29.68	30.11	30.19	33.93
MnO	0.75	1.05	1.05	0.01	0.23	0.41	0.92
MgO	0.01	0.13	0.01	0.01	0.01	0.01	0.18
CaO	0.26	1.27	0.58	0.23	0.40	0.01	0.56
Na_2O	7.13	6.89	7.33	13.10	12.15	13.10	9.35
K_2O	3.11	2.71	3.00	0.01	0.01	0.01	0.00
Cr_2O_3	0.07	0.07	0.02	0.01	0.02	0.00	0.01
NiO	0.04	0.01	0.01	0.00	0.00	0.02	0.04
Total	93.80	95.90	95.47	95.55	95.52	97.25	96.21
$Fe_2O_3{}^{b}$	0.52	1.30	1.73	31.60	27.33	30.95	20.84
FeO^{b}	31.27	31.39	31.36	1.24	5.52	2.34	15.18
New sum	93.84	96.03	95.63	98.69	98.22	100.33	98.35
Atomic %							
Mg	0.1	1.3	0.1	Mg 0.1	0.0	0.1	0.8
Ca	1.9	9.1	4.2	Fe 3.9	16.9	8.3	42.3
Na	97.9	89.5	95.7	Na 96.0	83.1	91.6	56.8

	Albite			Microcline	
Sample no	154398	109316	109317	156927	154398
SiO_2	68.11	70.33	68.46	64.43	63.51
Al_2O_3	19.95	18.05	18.81	18.91	18.45
CaO	0.00	0.00	0.01	0.00	0.01
Na_2O	11.82	11.43	11.70	0.39	0.39
K_2O	0.06	0.00	0.01	16.21	16.04
Total	99.94	99.81	98.99	99.94	98.40

	Neptunite			
Sample no	154398	156927	109316	109317
SiO_2	53.92	54.53	54.08	52.76
TiO_2	17.60	17.63	16.84	16.49
Al_2O_3	0.10	0.09	0.22	0.14
FeO*	14.91	15.15	16.28	14.81
MnO	1.17	0.34	0.20	0.30
MgO	0.11	0.00	0.00	0.01
CaO	0.00	0.00	0.10	0.01
Na_2O	7.15	6.94	7.11	6.73
K_2O	4.98	5.25	5.17	5.02
Cr_2O_3	0.00	0.02	0.00	0.07
NiO	0.00	0.04	0.00	0.01
Total	99.94	99.99	100.00	96.35

	Aenigmatite		Pectolite	
Sample no	109261+) core	109261+) rim	109261+)	154398
SiO_2	41.8	41.8	53.53	51.91
TiO_2	8.9	8.8	0.00	0.01
Al_2O_3	0.27	0.33	0.06	0.05
$Fe_2O_3{}^{b)}$	1.0	0.6		
$FeO^{b)}$	38.6	38.6	1.43	0.99
MnO	2.06	1.96	1.55	0.04
MgO	0.28	0.27	0.03	0.01
CaO	0.11	0.07	31.64	31.27
Na_2O	7.2	7.2	9.01	9.46
ZrO_2	<0.02	<0.02	0.00	n.a..
Na_2O	n.a.	n.a.	9.01	9.46
K_2O	n.a.	n.a.	0.01	0.01
Cr_2O_3	n.a.	n.a.	n.a.	0.05
Total	100.2	99.7	97.25	95.35
$FeO^{*)}$	39.5	39.2		

*)all iron as FeO; n.a.= not analyzed; b)=calculated
+) from Larsen 1977

Analyses with a JEOL 733 superprobe using the JEOL PACX-M for instrumental control and ZAF correction (Geological Institute, University of Copenhagen) The analyses were performed at 15KV and with a beam current of 15 nA. The standards used were: Na: albite, Al: corundum, K: potash feldspar, Ca: wollastonite, Ti: rutile, Fe: hematite, Mg: olivine, Cr: chromite. Ni: Ni metal, Zr: zircon section but not together with eudialyte. Quartz is generally missing but is a minor mineral in some rocks.

The sugary type of albitite penetrates the microcline-rich microsyenite in an irregular way. This texture, the oikocrysts of pectolite and neptunite and the replacement relationship between aegirine and arfvedsonite may be interpreted as recrystallization textures. The trachytic microcline laths may then represent the primary texture of these rocks.

There are prismatic length-fast grains which resemble the rinkite-nacareniobsite group of minerals (samples GI 109314 and GI 109316 and at the depths 8.15 and 10.38 m in the drill core) and grains of an unidentified mineral showing aggregate extinction (at 5.92, 8.15 and 14.50 m in the drill core).

The samples of microsyenite from Laksetværelv and Kvanefjeld have well-developed trachytic textures (Fig. 12). They are composed of the same minerals as the microsyenite from bore-hole I with the difference that microcline is the predominant groundmass mineral whereas albite occurs as interstitial grains. The Laksetværelv dykes are rich in fluorite.

An aenigmatite-bearing microsyenite from Laksetværelv (GGU 21184) is a green fine-grained rock containing scattered oikocrysts of aenigmatite. It differs from the other samples in having a brecciated texture: coarser-grained microcline-rich rocks are enclosed in a fine-grained matrix of sugary albite, quartz, aegirine and arfvedsonite. The microcline laths of the coarser-grained parts are bent and broken. The aenigmatite oikocrysts enclose laths of microcline but are located in the albite-rich part of the rock. This rock contains small grains of a rinkite-looking mineral.

Mineral chemistry

Chemical analyses of the major rock-forming minerals are listed in Table 1. The feldspars are those typical for agpaitic nepheline syenites, albite with very low contents of K_2O and microcline with very low contents of Na_2O and the characteristic penetration type of twinning (Ussing 1912; Sørensen 1962). The mafic minerals are arfvedsonite and aegirine. Pectolite and neptunite both have compositions closely corresponding to the formulae of these minerals (Table 1). Analyses of aenigmatite and pectolite from a dyke in kakortokite (GGU 109261) are reported by Larsen (1977) and reproduced in Table 1.

Petrochemistry

Four samples of the Narsaq Elv microsyenite representing various proportions of the rock-forming minerals were selected for chemical analyses (Table 2a):

GI 156927 represents the varieties containing aggregates of microcline. It is intersected by white veins and has feldspar and amphibole segregations on fractures.

GI 88961 is dominated by sugary-grained albite with segregations of larger albite grains and scarce plates of microcline. It also contains segregations of larger grains of aegirine which show an increasing green colour towards their margins.

GI 109314 and GI 109316 represent, respectively, the white and the greyish-black layers. The main differences are that the dark variety is finer-grained than the white with a slightly higher proportion of arfvedsonite relative to aegirine and with some microcline whereas the white layers are devoid of microcline. Both varieties are dominated by sugary-grained albite. Lotte Melchior Larsen provided one analysis (GGU 153385) of this microsyenite sheet (Table 2a). She also provided one analysis (GGU 153383) of the microsyenite dyke at 390 m in Narsaq Elv (Table 2b). The dykes and sills in the Kringlerne area were examined in GI 109329 and GI 109330, besides Lotte Melchior Larsen has made a number of analyses of these rocks available (Tables 2a, b).

The samples of the microsyenite sheet from Narsaq Elv (Tables 2a, b) have a strong predominance of Na_2O over K_2O, the Na_2O/K_2O ratio varies from 74.5 to 1.9. In contrast to this, the microsyenite dykes intersecting the kakortokite from Kringlerne, including the aenigmatite-bearing microsyenite have equal contents of Na_2O and K_2O, the Na_2O/K_2O ratio varies from 1 to 1.6.

With the exception of GI 109330, which is slightly undersaturated, the analysed samples of microsyenite are all weakly silica-oversaturated; normative *q* varies from 0.68 to 2.06. The analyzed rocks are strongly peralkaline with the agpaitic indices varying from 1.17 to 1.32; the contents of normative *ns* and *ac* from 0.37 to 2.98 and from 7.71 to 16.13, respectively (Table 2a).

There are very low contents of MgO (< 0.25 wt.%) in common with the most highly-developed agpaitic rocks of the complex. The CaO content is similar to that of the aegirine lujavrite, but much higher than that of the arfvedsonite lujavrites (Table 3, cf. Bailey et al. in press). The variation in the Fe_2O_3/FeO ratio reflects the variation in the proportion of aegirine and arfvedsonite. The contents of Ti and Mn are lower than would be expected from the widespread occurrence of neptunite in these rocks. The potassic rocks have

Table 2a. Chemical analyses of representative samples of microsyenitic rocks from the Ilímaussaq alkaline complex (wt.% and ppm)

	Grey microsyenite Narsaq Elv	Grey microsyenite Narsaq Elv	White microsyenite Narsaq Elv	Grey–black microsyenite Narsaq Elv	Grey microsyenite Narsaq Elv 300 m1)	Grey microsyenite Laksetværelv Kringlerne	Grey microsyenite Laksetværelv Kringlerne	Grey microsyenite Kvanefjeld
	156927	88961	109314	109316	153385	109329	109330	154398
SiO_2	63.02	63.81	64.20	64.24	63.19	64.05	62.39	62.39
TiO_2	0.38	0.39	0.42	0.41	0.41	0.29	0.51	0.35
Al_2O_3	14.71	14.98	15.33	15.35	14.66	15.96	15.03	14.71
Fe_2O_3	3.64	5.49	3.55	3.25	3.55	2.64	5.30	3.13
FeO	2.55	0.52	2.22	2.57	2.33	1.26	0 41	2.96
MnO	0.17	0.13	0.14	0.14	0.19	0.10	0.11	0.22
MgO	0.06	0.09	0.01	0.03	0.02	0.04	0.10	0.12
CaO	1.04	0.79	0.80	0.67	1.07	1.15	1.61	0.90
Na_2O	8.91	11.92	11.68	10.92	8.76	7.56	6.99	6.94
K_2O	3.99	0.16	0.29	1.15	4.51	6.03	6.67	6.52
P_2O_5	0.14	0.08	0.13	0.05	0.11	0.01	0.09	0.13
LOI/H_2O	0.58	0.37	0.32	0.50	0.34	0.31	0.47	1.05
Total	99.19	98.73	99.09	99.28	99.19	99.40	99.68	99.42
q	1.60	0.83	1.19	1.38	2.06	0.68	–	1.21
or	23.67	0.94	1.74	6.88	27.04	35.97	39.79	39.17
ab	53.75	77.53	78.22	73.46	50.67	48.98	38.92	39.49
ne	–	–	–	–	–	–	0.86	–
ns	2.30	1.60	2.34	2.16	2.98	1.59	0.37	2.84
di	3.60	1.60	2.82	2.70	3.70	4.05	0.76	3.06
wo	–	0.64	–	–	–	0.44	2.72	–
hy	3.26	–	2.19	3.00	2.24	–	–	4.15
ac	10.65	16.13	10.40	9.52	10.19	7.71	15.46	9.14
il	0.82	0.74	0.81	0.79	0.76	0.56	0.98	0.61
ap	0.35	0.19	0.31	0.12	0.34	0.02	0.21	0.31
Total	100.00	100.20	100.02	100.01	99.98	100.00	100.00	99.98
Agpaitic index	1.29	1.32	1.27	1.25	1.32	1.19	1.24	1.31
Cs	0.6	0.4	n.a.	n.a.	n.a.	0.5	0.3	3.5
Rb	390	18	7.7	111	401	319	363	748
Li	209	96	225	270	n.a.	124	77	370
Be	15	9	11	11	n.a.	11	9.5	17
B	9	n.a.	n.a.	na.	n.a.	n.a.	n.a.	5
Ba	11	12	7	7	0.8	45	219	32
Pb	53	59	52	85	43	5	9	71
Sr	3.3	16	<0.5	4	2.7	10	32	11
La	354	281	334	354	253	189	158	442
Ce	652	503	712	762	464	412	313	893
Nd	250	204	263	310	193	152	157	328
Sm	33	35	41	52.5	n.a.	23.4	31	46.0
Eu	1.4	1.5	1.4	1.6	n.a.	0.8	2.9	1.8
Tb	4.7	5.8	6.4	8.4	n.a.	3.5	3.9	5.96
Yb	12.8	18.6	16.5	25	n.a.	9.4	8.5	14.1
Lu	1.8	2.5	2.4	3.2	n.a.	1.5	1.2	2.1
Y	165	230	177	226	152	102	95	186
U	13.4	8.7	8.3	11.0	n.a.	8.0	2.2	29.3
Th	44	25.3	23.9	32.5	22	17.8	7.4	78
Zr	1660	3230	2140	2760	1617	1210	924	1710
Hf	32	58	51	67	n.a.	31	19	36
Sn	174	372	177	177	n.a.	25	28	155
Nb	262	341	284	353	208	123	106	436
Ta	12.2	17.2	15	20	n.a.	8.2	4.5	12.5
Zn	322	321	268	393	317	107	81	420

Cont.

Table 2a - *cont.*

	Grey microsyenite Narsaq Elv	Grey microsyenite Narsaq Elv	White microsyenite Narsaq Elv	Grey–black microsyenite Narsaq Elv	Grey microsyenite Narsaq Elv 300 m1)	Grey microsyenite Laksetværelv Kringlerne	Grey microsyenite Laksetværelv Kringlerne	Grey microsyenite Kvanefjeld
Cu	3	49	<1	<1	n.a.	0.5	<1	65
Tl	0.4	<0.5	<0.5	<0.5	n.a.	0.7	1.3	1.8
Ni	0.5	<0.5	<2	2	n.a.	2	3	2.1
Sc	0.5	0.3	0.2	0.2	0.4	1.7	5.4	0.4
V	2.0	2.7	<0.5	<0.5	n.a.	1.2	4.3	<0.5
Cr	<3	<3	6.5	7.4	n.a.	3.5	4.4	0.6
Ga	87	145	143	198	79	68	44	89
F	n.a.	n.a.	780	920	903	680	8000	960
Cl	40	35	200	80	253	90	130	35
S	5	360	80	110	n.a.	40	50	95

Analysts: Major elements: GEUS, Copenhagen; trace elements: John Bailey, Rajmund Gwozdz, Birgit Damgaard, and Haldis Bollingberg, Geological Institute, University of Copenhagen, and Lotte Melchior Larsen, GEUS

1) Personal information Lotte Melchior Larsen, 2001.

n.a.= not analyzed

Table 2b. Chemical analyses of microsyenitic rocks from Narssaq elv and Kringlerne areas Southern Ilímaussaq (provided by Lotte Melchior Larsen) (wt.%)

	Grey microsyenite Narsaq Elv 380 m	Chill of dyke Kringlerne	Aenigmatite bearing dyke Kringlerne	Composite dyke Kringlerne	Green sill Kringlerne	Central part sill Kringlerne	Aphyric dyke Kringlerne	Aphyric dyke Kringlerne
	153383	153293	109261	153011	153023	153022	153013	153028
SiO_2	62.58	61.90	62.05	62.09	62.63	63.21	66.25	67.14
TiO_2	0.41	0.54	0.54	0.40	0.51	0.46	0.26	0.26
Al_2O_3	14.70	14.67	14.99	14.59	14.89	14.91	14.34	14.40
Fe_2O_3	2.48	5.08	2.56	5.44	3.37	2.65	2.51	2.89
FeO	3.11	1.51	3.53	0.34	2.49	2.63	1.61	0.78
MnO	0.20	0.22	0.21	0.14	0.19	0.16	0.13	0.10
MgO	0.01	0.16	0.24	0.20	0.23	0.23	0.04	0.08
CaO	0.80	1.83	1.79	1.57	1.70	1.60	1.01	0.98
Na_2O	7.57	7.29	6.49	7.08	7.92	6.92	6.83	6.82
K_2O	5.98	5.92	6.38	6.93	4.84	6.20	5.45	5.51
P_2O_5	0.22	0.10	0.22	0.04	0.07	0.04	0.01	0.01
H_2O/LOI	0.52	0.26	1.42	0.30	0.38	0.40	0.30	0.22
Total	98.66	99.54	100.42	99.20	99.27	99.51	98.81	99.27
agpaitic index	1.29	1.25	1.17	1.31	1.23	1.21	1.20	1.19

high contents of Rb whereas the sodic varieties are very poor in this element. The sodic varieties have higher contents of LREE (light rare earth elements), Ga, Y, Zr, Hf, Nb, Ta, Pb, Sn, U and Th than the potassic rocks, which are richer in Ba, Sc (and Sr) than the sodic rocks. When compared with the arfvedsonite lujavrites of the Ilímaussaq complex (Table 3), the microsyenites have higher contents of SiO_2, Al_2O_3, CaO and Sc; similar contents of Na_2O, K_2O, TiO_2, MgO and Ga; lower contents of $FeO+Fe_2O_3$, MnO and P_2O_5, and markedly lower contents of most trace elements.

The Kvanefjeld sample (GGU 154398) differs from the other samples in having distinctly higher contents of Cs, Li, Be, Rb, LREE, Th, U, Nb, Zn and Cu which may be ascribed to metasomatic overprinting caused by the nearby, later intrusion of medium- to coarse-grained lujavrite.

Discussion

The small intrusions of peralkaline microsyenite described in the present paper appear to have been emplaced after the formation of naujaite in the roof zone and kakortokite and aegirine lujavrite in the floor zone of the complex, but before the formation of the arfvedsonite lujavrite and the medium- to coarse-grained lujavrite. They are intersected by veins of coarser-grained lujavritic rocks. It is not possible to decide if these are arfvedsonite lujavrite pegmatites or medium- to coarse-grained lujavrite. The microsyenite is recrystallized to a larger grain size in contact with the lujavritic rocks.

The horizontal sheet of microsyenite in Narsaq Elv is richer in sugary albite and is more extensively recrystallized and richer in incompatible elements than the examined dykes which may be explained by its consolidation in a relatively closed space, whereas the consolidation of dykes in fractures facilitated the loss of volatiles. It should, however, be pointed out that the chemical composition of the sill below red layer +16 is very similar to that of the dykes in that area (Table 2b).

The fine grain-size of the microsyenite and its occurrence as dykes and sills show that it was formed by rapid consolidation of melts injected into fractures in the host rocks. Dyke intersections show that there was more than one injection of the microsyenitic melts. As mentioned above, the albitite along the contacts of the microsyenite sheet in Narsaq Elv also contains fragments of earlier albitite. This suggests that there were more than one period of albitization.

Chill zones are developed in dykes characterized by higher contents of SiO_2 than the majority of the microsyenitic intrusions (Table 2b). Some of these dykes intrude earlier microsyenitic dykes (Lotte Melchior Larsen personal information 2001). The general lack of chill zones may be partly explained by emplacement into still hot rocks and partly by recrystallization in connection with the formation of the pegmatite and albitite along the contacts against the host rocks. Guttenberg & LeCouteur (1992) proposed that the pegmatitic zone between kakortokite layer +16 and the underlying microsyenite sill was formed by recrystallization of kakortokite caused by the microsyenite intrusion. At this place, stellar groups of aegirine radiate downward from the upper contact which recalls the earlier-mentioned radiating clusters of arfvedsonite growing downward in the upper and upward in the lower contact of the Narsaq Elv microsyenite (Fig. 5). Another possibility is that the pegmatites and albitites were formed by reactions between the hot host rocks and a fluid phase released from the microsyenitic intrusions. But the most likely explanation of the location of these pegmatite and albitite zones is that they were formed in connection with later injection of fluids through the discontinuities along the contacts between the microsyenites and their host rocks. It should be noted that the albitite penetrates into the microsyenite. Drill core I shows that the emplacement of sheets of arfvedsonite lujavrite in the pegmatitic zones along the contacts between the microsyenite and the underlying naujaite was preceded by the formation of aegirine-albite-rich rocks, felted aegirine and perhaps also aegirine lujavrite.

It is of interest to note that the sill below kakortokite red layer +16 and the sheet in Narsaq Elv are divided into lower and upper parts by a pegmatitic zone. This recalls the situation in many basaltic sills and flows in which such zones are regarded to be segregations of residual melt at the level where the lower and upper crystallization fronts meet (cf. Marsh 1994, 1996). The pegmatites in the microsyenites cannot be formed from residual melts in the consolidating microsyenite since they contain nepheline, eudialyte and other minerals typical for the agpaitic rocks of the complex. These pegmatites are most probably formed from volatile-rich melts introduced into the zone of discontinuity between downward and upward crystallizing parts of the sheets.

Layering in the Narsaq Elv microsyenite

The occurrence of white layers in the greyish black microsyenite of the Narsaq Elv (Fig. 6) presents a special problem. Owing to the fine grain-size, no internal structures such as mineral grading can be observed. The two available thin sections show, as already mentioned, that the darker layers are finer-grained and microcline-bearing, whereas the white layers are coarser and without microcline. The chemical composition of the white and dark layers are almost identical (Table 2a) apart from different contents of Na_2O, K_2O and P_2O_5 and different trace element contents. The dark layers, when compared with the white layers, are enriched in Rb, Li, Pb, REE, Y, U, Th, Zr, Hf, Nb, Ta, Zn, Ga, F and S. This is also reflected in differences in trace element ratios (Table 4) as will be further discussed below.

The regular layering can be followed across the exposure of the about 15 m thick sheet. It is clear that the microsyenite was emplaced in an almost horizontal fracture system in the naujaite, that the layering is conformable to the contacts of the sheet and that contacts between layers are sharp. The available information does not, however, allow a more detailed dis-

Table 3. Chemical analyses of peralkaline microsyenites and lujavrites from the Ilímaussaq alkaline complex (wt.% and ppm)

	microsyenite	aegirine lujavrite	arfvedsonite lujavrite	medium- to coarse-grained lujavrite
SiO_2	62.39–64.24	50.61–54.80	52.25	52.71
TiO_2	0.29–0.51	0.15–0.24	0.23	0.35
Al_2O_3	14.71–15.96	11.45–16.65	12.23	13.29
Fe_2O_3	2.64–5.49	6.15–14.57	6.06	4.04
FeO	0.41–2.96	0.47–2.23	8.72	8.21
MnO	0.10–0.22	0.20–0.58	0.64	0.60
MgO	0.01–0.12	0.07–0.20	0.12	0.12
CaO	0.67–1.61	0.55–1.57	0.27	0.30
Na_2O	6.94–11.92	10.45–13.66	9.25	9.20
K_2O	0.16–6.52	1.01–3.68	3.23	4.69
P_2O_5	0.01–0.14	0.01–0.51	0.34	0.13
Cs	0.3–3.5	5.8–28	4.2–44	57–89
Rb	7.7–390 (748)	183–835	187–850	1230–1370
Li	77–270 (370)	82–630	380–970	865–1000
Be	9–17	27–80	22–81	48–108
Ba	7–45 (219)	60–117	10–112	53–61
Sr	<0.5–32	51–277	30–103	34–46
Pb	5–85	160–603	304–801	391–466
La	158–442	687–4890	1940–3860	1610–3580
Ce	313–893	1160–6750	2100–4700	1990–4180
Nd	152–328	519–1950	523–1840	563–1090
Sm	23.4–52.5	75–275	176	98.8
Eu	0.8–2.9	8.3–20.4	17.3	8.63
Tb	3.5–8.4	12.7–28.7	23.1	10.7
Yb	8.5–18.6	41.1–70.5	40.1	17.3
Lu	1.2–3.2	4.9–8.3	5.32	2.41
Y	95–230	466–955	280–1310	276–753
U	2.2–13.4 (29)	18–233	33–440	140–490
Th	7.4–44 (78)	27–312	41–1290	375–1045
Zr	924–3230	4490–8750	1320–10900	709–12130
Hf	19–67	58–134		12–15
Sn	25–372	180–401	94–5657	2110–645
Nb	106–436	320–736	253–967	448–892
Ta	4.5–20	23–48	39	21.5
Zn	81–420	583–2990	487–3080	2070–3070
Cu	0.5–49 (65)	<1–8	3	<1
Ni	0.5–3	<0.5–3.0	<0.5	1.3
Sc	0.3–5.4	<0.02–0.3	0.01	0.05
V	0.5–7.4	0.5–8.1	4.0	5.4
Cr	3–7.4	3.1–20	11	11
Ga	44–198	71–123	98–132	104–159
F	380–8000	350–1740	1100–1600	1000–2400
Cl	35–253	180–2700	25–2070	15–820
S	5–360	110–650	50–1790	160–1430

Microsyenites from Table 2; ranges in chemical composition of aegirine and arfvedsonite lujavrites and medium– to coarse–grained lujavrite, John C. Bailey personal information 2000; single values from Bailey et al. (in press). Numbers in brackets in the microsyenite column are considered to be due to metasomatic overprinting.

Table 4. Selected trace element ratios based on the microsyenite analyses of Table 2a

	156927	88961	109314	109316	109329	109330	154398
Zr/Nb	6.33	9.47	7.54	7.81	9.84	8.72	3.92
Nb/Ta	21.48	19.83	18.93	17.65	15.00	23.56	34.88
Zr/Hf	51.88	55.69	41.96	41.19	39.03	48.63	47.50
Th/U	3.28	2.91	2.87	2.95	2.22	3.36	2.66
Eu/Eu*	0.14	0.13	0.10	0.10	0.11	0.31	0.14
$(La/Yb)_N$	18.26	9.98	13.37	9.35	13.22	12.26	20.70
Nb/Y	1.59	1.48	1.60	1.56	1.21	1.12	2.34
Zr/Y	10.06	14.04	12.09	12.21	11.86	9.72	9.19
Zr/La	4.69	11.49	6.41	7.80	6.40	5.85	3.87
Nb/La	0.74	1.21	0.85	1.00	0.65	0.67	0.99
La/Ba	32.16	23.41	47.71	50.57	4.20	0.72	13.81
La/Y	2.15	1.22	1.89	1.57	1.85	1.66	2.38
Ba/Sr	3.33	0.75	>14	1.75	4.50	6.84	2.91
Rb/Ba	35.45	1.50	0.90	13.75	7.22	1.68	23.37

cussion of the origin of the layering which must await further sampling and analyses.

Regional relations

The compositions of the microsyenites (Tables 2a, b) resemble those of the syenites presented by Gerasimovsky (1969) and Hamilton (1964), (GGU 77042 and 33506 in Table 5). The available information about the occurrence of these two syenites does not allow a correlation with the microsyenites. The microsyenite analyses of Tables 2a, b are different from that of the alkali syenite of the western part of the Kvanefjeld plateau (Table 5, GGU 64788) which has markedly higher contents of TiO_2, MgO, CaO and P_2O_5 and less SiO_2. This alkali syenite is younger than the augite syenite and older than the deformation which accompanied the formation of the medium- to coarse-grained lujavrite and perhaps also the arfvedsonite lujavrite at Kvanefjeld. Its age relationship to naujaite is unknown due to lack of mutual contacts. Since fragments of quartz syenite of the second intrusive phase of the complex are enclosed in rocks from the roof zone (Steenfelt 1981), they are clearly older than the naujaite and cannot be contemporaneous with the microsyenite. Furthermore, the composition of the quartz syenite (GGU 77027, Table 5) differs from that of the microsyenites (Table 2a, b).

Alkali granites and quartz syenite are prominent members of some of the intrusive complexes of the Gardar province (Upton & Emeleus 1987). Examples are the alkali granite which is the predominant rock of phase 2 of the Ilímaussaq complex; the alkali granite and nordmarkitic quartz syenite of the Dyrnæs-Narssaq complex to the immediate west of the Ilímaussaq complex; and granites, syenites and quartz syenites in the Tugtutôq central complex still further to the west (Allaart 1973; Olsen 1982; Kalsbeek, Larsen & Bondam 1990; Upton, Martin & Stephenson 1990). The occurrence of microsyenitic and comenditic dykes in the ENE–NE oriented Tugtutôq-Ilímaussaq dyke swarm in the country rocks of the Ilímaussaq complex (Upton & Emeleus 1987; Martin 1985) is further evidence of the existence of saturated and oversaturated syenitic melts in the Gardar rift system.

The regional dyke swarm embraces a continuous series from dolerite via trachydolerite to riebeckite microsyenite and riebeckite microgranite (Macdonald 1969). It is characterized by an abundance of trachytic (microsyenitic) rocks (Upton 1974). Microsyenite also occurs as contact facies of the dolerite dykes described under the name 'big feldspar' dykes (Bridgwater & Harry 1968) and silica-oversaturated syenites and quartz syenites occur in the axial part of the younger giant dyke complex (Upton 1987). It is therefore generally accepted that the syenitic rocks of the Tugtutôq-Ilímaussaq dyke swarm are products of fractionation of basaltic melts (Macdonald 1969; Upton 1974; Martin 1985; Upton & Emeleus 1987; Upton et al. 1990).

The rocks of the Dyrnæs-Narsaq complex and the volcanic rocks in the roof of the Ilímaussaq complex are cut by dykes whereas the Ilímaussaq and the Tugtutôq central complexes transect the Tugtutôq-Ilímaussaq dyke swarm. The microsyenitic minor intrusions described in the present paper are, however, younger than than at least parts of the Ilímaussaq complex (cf. Kalsbeek et al. 1990).

Chemical relations

Most of the chemical analyses of microsyenitic dyke rocks reported in the earlier literature (Upton 1964; Watt 1966; Bridgwater & Harry 1968; Macdonald 1969; Martin 1985) differ from the analyses of the microsyenites intersecting the Ilímaussaq complex in not being peralkaline. These rocks contain fayalitic olivine and magnetite, minerals which are absent from the Ilímaussaq microsyenites. The riebeckite microsyenites from the dyke swarm occurring on the island of Tuttutooq to the west of the Ilímaussaq complex are chemically similar to the Ilímaussaq microsyenites, cf. Tables 2a, b and 3, but differ from these rocks in containing opaque ore minerals and in not having normative *ns* (Macdonald 1969). The peralkaline trachyte dyke on Igdlutalik, east of Ilímaussaq, is dominated by albite and aegirine and also contains quartz, riebeckite, micas, zircon, pectolite, apatite, calcite, opaque oxides, narsarsukite, nordite and emeleusite (Upton, Macdonald, Hill, Jefferies & Ford 1976; Upton, Hill, Johnsen & Petersen 1978). Many of the rocks of the dyke swarm are devitrified and could have been *ns*-normative before loss of alkalis.

The rocks of the dyke swarm have lower levels of incompatible elements than the Ilímaussaq microsyenites (Macdonald 1969; Macdonald & Edge 1970; Martin 1985). This is illustrated in Figure 13 which shows the chondrite-normalised REE patterns of arfvedsonite lujavrite and medium- to coarse-grained lujavrite, representative samples of the Ilímaussaq microsyenites and the dyke swarm (based on Upton et al. 1990). All these rocks show pronounced negative europium anomalies. The patterns of the two samples of microsyenite dykes in kakortokite (GI 109329 and 109330) more or less coincide with the zone marking the variation in REE values in the rocks of the dyke swarm, although displaying slightly steeper HREE patterns. The albite-rich microsyenites of Narsaq Elv (GI 156927 and GI 88961) and especially the Kvanefjeld microsyenite (GGU 154398) are enriched in LREE relative to the dyke swarm and the dykes intersecting kakortokite. The flattening out of the curves of the albite-rich rocks (also analyses which are not plotted in Fig. 13) show that these rocks are relatively enriched in HREE when compared with the dyke swarm, and also the medium- to coarse-grained lujavrite (GGU 154399). Flattening out of HREE curves has been described from albitized granites (Bowden & Whitley 1974 and John C. Bailey personal information 2001). The arfvedsonite lujavrite (GGU 154358) is strongly enriched in REE compared to the other examined rocks and shows a steeper REE pattern. The Ilímaussaq microsyenites are also enriched in REE when compared with the syenitic rocks of the Tugtutôq central complex (Fig. 13 in Upton et al. 1990). That there is a difference in chemical composition between the Ilímaussaq microsyenites and the syenites of the Tugtutôq central complex is also apparent from Figure 14 which is based on Upton et al. (1990, fig. 14). The Tugtutôq rocks have higher La/Y ratios than the rocks of the dyke swarm most of which have higher La/Y ratios than the Ilímaussaq microsyenites. This may be explained by the mineralogical differences between the three suites of rocks.

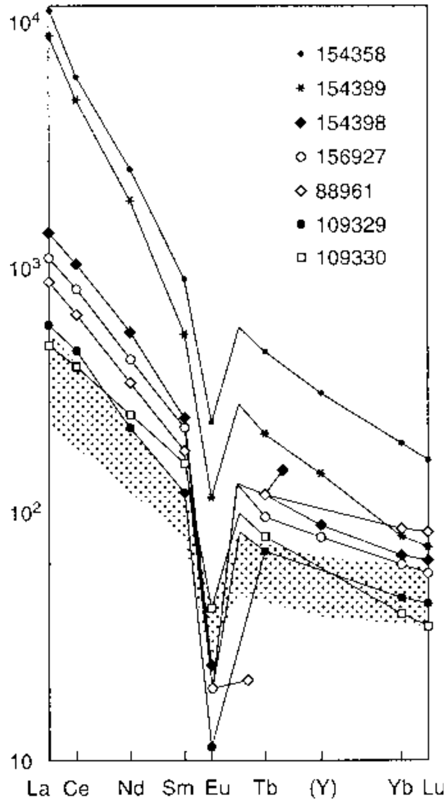

Fig. 13. Chondrite-normalized REE diagram showing curves for arfvedsonite lujavrite and medium- to coarse-grained lujavrite (from Bailey et al. in press), selected samples of microsyenite (from Table 2a) and with dotted ornamentation the variation in REE patterns of the rocks of the Tugtutôq-Ilímaussaq dyke swarm (from Upton et al. 1990). Normalization according to Taylor & Gorton (1977).

The microsyenites described in the present paper are peralkaline, but unlike the agpaitic rocks of the Ilímaussaq complex, most analysed samples are silica-oversaturated. The feldspars and the mafic minerals (Table 1) are, however, practically identical to the albite, microcline, arfvedsonite and aegirine of the lujavrites of the complex. In a few thin sections of the Narsaq Elv microsyenite and of the Laksetværelv dykes, the aegirine and arfvedsonite crystals have brown cores indicating that these minerals did not have the extremely sodic compositions when they

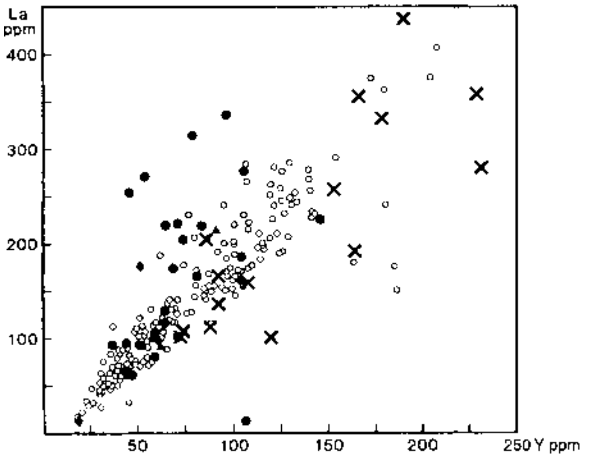

Fig. 14. Y-La diagram showing contents in the Tugtutôq-Ilímaussaq dyke swarm (open circles), the Tugtutôq central complex (closed circles) and the Ilímaussaq microsyenites (crosses). Based on Upton et al. (1990, fig. 14).

began to crystallize. The scarce crystals of eudialyte and the presence of pectolite, neptunite and aenigmatite, and perhaps rinkite-group minerals are features in common with the agpaitic rocks. The albite-rich microsyenites are generally poor in Rb, Ba, Ni, Sc, V and Cr, and rich in Li, Pb, LREE, Y, Th, Zr, Hf, Sn, Nb, Ta, Zn and Ga when compared with the potassic microsyenites (Table 2a). This is partly contradictory to the above-mentioned relations between white and dark layers in the Narsaq Elv sheet, but the dark layer there is very low in K_2O and should in a broader sense be included in the albite-rich microsyenites.

The differences in trace element contents may be primary magmatic or, more probably secondary since the albite-rich microsyenites very likely are products of recrystallization of primary sodic-potassic rocks. The chemical and mineralogical changes may also be explained by reactions with fluids activated during emplacement of microsyenitic melts into still hot host rocks or introduced later along the contacts between microsyenite and host rock. These reactions may have formed the albititic and pegmatitic zones between microsyenite and adjacent naujaite and lujavrite. The elevated contents of most trace elements in the analyzed Kvanefjeld sample (GGU 154398) is most probably a result of metasomatic overprinting since it is well-known that the medium- to coarse-grained lujavrites have metasomatized their country rocks (Sørensen et al. 1969).

The microsyenites were formed from highly evolved melts which, like the agpaitic melts, were very poor in MgO, Ni, Cr, Sc, etc., but, unlike these, only moderately enriched in most trace elements (Table 3).

Selected trace element ratios are presented in Table 4. Even if sample GGU 154398 is disregarded because of metasomatic overprinting, the Table shows a considerable scatter of element ratios. This may be

Table 5. Chemical analyses of syenitic rocks from the Ilímaussaq alkaline complex and from Tuttutooq (wt.%) (from the literature)

	77027	77042	50050	50136	33506	65001	64788
SiO_2	70.96	62.68	62.2	64.2	60.23	63.22	61.48
TiO_2	0.49	0.38	0.76	0.73	0.28	0.36	0.75
Al_2O_3	11.45	16.21	14.30	12.87	13.62	14.33	14.08
Fe_2O_3	4.00	2.40	4.44	3.57	7.47	3.73	3.61
FeO	0.53	2.40	4.96	4.18	4.17	2.22	2.69
MnO	0.12	0.14	0.24	0.19	0.28	0.18	0.20
MgO	tr.	tr.	0.05	0.00	0.28	0.16	0.29
CaO	0.67	1.44	1.68	1.21	0.74	1.37	2.02
Na_2O	6.85	8.11	7.42	4.93	9.65	8.20	8.06
K_2O	4.65	5.58	2.28	6.03	1.76	5.78	5.18
P_2O_5	<0.10	0.14	0.09	0.06	0.13	0.13	0.23
H_2O/LOI	0.40	0.89	0.48	0.59	0.90	–	0.84
Total	100.22	100.37	98.90	98.56	99.59	99.68	99.43
agpaitic index	1.43	1.20	1.04	1.14	1.30	1.38	1.34

GGU 77027: quartz syenite from the Ilímaussaq complex (Gerasimovsky 1969).
GGU 77042: syenite from the Ilímaussaq complex (Gerasimovsky 1969).
GGU 50050: riebeckite microsyenite dyke, Tuttutooq (Macdonald 1969); also contains 0.23% F.
GGU 50136: riebeckite microsyenite dyke, Tuttutooq (Upton 1964; Macdonald 1969); also contains 0.11 % F, 1.14 % CO_2.
GGU 33506: soda syenite, green porcellaneous spherulitic dyke, Ilímaussaq complex (Hamilton 1964).
GGU 65001: fine-grained microsyenite from Kvanefjeld (Sørensen et al. 1969).
GGU 64788: alkali syenite from Kvanefjeld (Sørensen et al. 1969).
The agpaitic indeces are calculated by the authors.

explained by loss of volatile components during emplacement and by recrystallization processes which have resulted in redistribution of elements. Samples GI 109314 and 109316 represent adjacent white and grey layers of the Narsaq Elv microsyenite sheet. Zr, Nb, Hf, Y, Th and U show comparable ratios in the two layers, whereas La, Sr, Rb and Ba show markedly different ratios. This may indicate that the high-field-strength element ratios were not affected by the above-mentioned layer-forming processes, whereas ratios involving LREE, Ba, Sr and Rb were changed. Samples GI 156927 and GI 88961, from the same microsyenite sheet as GI 109314 and 109316, are rich in albite and show element ratios differing from the just mentioned ratios with the exception of Th/U and Nb/Y. The dykes GI 109329 and 109330 have preserved their trachytic texture and appear not to have been albitized. The dyke intersection shows that these dykes represent two pulses of magma injection. The marked differences in trace element ratios between these two samples may, however, be best explained by a loss of volatiles during emplacement. Thus, Table 4 shows that trace element ratios are of little use in determining the mutual relations and the origin of the melts which formed the microsyenites.

The formation of the microsyenitic magmas

The lujavritic magma chamber is estimated to have been only 200–400 m high and it was most probably divided into 'sub-chambers' separated by downward protuding masses of the overlying naujaite (Andersen et al. 1981; Larsen & Sørensen 1987; Sørensen et al. submitted). The lujavritic melts represented residual liquids from the crystallization of the roof and floor zones of the complex. It has been demonstrated that there was a gradual transition from the kakortokite sequence of the floor zone to the aegirine lujavrite and arfvedsonite lujavrite in the lower part of the lujavrite zone (Bohse & Andersen 1981) and that this evolution took place in a closed magma system. The arfvedsonite lujavrite of the upper part of the lujavrite zone intrudes the overlying roof zone rocks and encloses rafts of these which resulted in the formation of a breccia zone between the naujaite of the roof zone and the lujavrite (Ussing 1912). The microsyenitic dykes and sills intersect the kakortokite, aegirine lujavrite and naujaite but not the arfvedsonite lujavrite lying between the aegirine lujavrite and the naujaite. There is no observation of microsyenitic dykes intersecting the contacts of the Ilímaussaq complex, cf. maps by Allaart (1969, 1973) and Andersen et al. (1988), but Larsen & Steenfelt (1974) have described a phonolite dyke intruding the marginal augite syenite of the complex, cf. the geological map of Ferguson (1964). According to Allaart (1969), phonolitic dykes are among the youngest members of the dyke swarm located to the north-east of the Ilímaussaq complex. The microsyenitic dykes within the complex are oriented ENE-NE as are the dykes in the Tugtutôq-Ilímaussaq dyke swarm.

The fact the the microsyenitic dykes do not intersect the contacts of the complex but intrude rocks lying beneath and above the magma chamber of the arfvedsonite lujavrite presents a geometrical problem. It is hard to imagine how pulses of microsyenitic melts could simultaneously or successively intrude into fractures in rocks lying above and beneath a magma chamber without leaving traces of their penetration of the rocks being formed in the chamber. There are four ways of explaining this discrepancy:

(1) It may be argued that the microsynite is younger than the arfvedsonite lujavrite since the age relations between these rocks are not very clear. There are no known examples of direct intersections of these rocks. The microsyenite sills and dykes in the kakortokites are located more than 200 m below the arfvedsonite lujavrite which excludes mutual contacts. The microsyenite of Narsaq Elv is intersected by veins of coarse-grained rocks of lujavritic affinity and arfvedsonite lujavrite appears to have intruded the contact zones between the microsynite sheet and the over- and underlying naujaite. At Kvanefjeld, the microsyenite is definitely older than the medium- to coarse-grained lujavrite. These observations are in best agreement with a younger age of the arfvedsonite lujavrite.

(2) The emplacement of the microsyenite melts took place at a stage in which the floor and roof zones were completely consolidated but the arfvedsonite lujavritic only partly consolidated. There was certainly a large temperature interval between the liquidus and solidus temperatures for the lujavrites, from ca. 900 to 450°C at 1 kbar (Piotrowsky & Edgar 1970). At a considerable temperature range above the solidus, where varying portions of melts were present in the crystalline interstices, one may envisage that the lujavrite would have behaved as a mechanically coherent rock. If this was the case melts could have migrated upward through crystal-liquid mush, or along intercrystal boundaries as well as, towards or below the solidus, via fractures without leaving traces. In this connection reference should be made to the findings of Marsh (1994, 1996), that at a degree of consolidation of ca. 55%, mafic magmas change from a viscous fluid suspension and mush to an elastic crystalline network of some strength and containing interstitial residual liquid. This behaviour of basaltic melts was also demonstrated in the experiments of

Philpotts, Shi & Brustman 1998; Philpotts, Brustman, Shi, Carlson & Denison 1999; Philpotts & Dickson 2000) according to which plagioclase formed a continuous three-dimensional network of chains when the melts were no more than 25% crystallized. This network was so strong that is prevented compaction of the crystallizing basalt. The network was permeated by interconnected channels through which the interstitial liquid could travel easily.

The application of these results on the arfvedsonite lujavrites is made difficult by the fine grain-size and pronounced igneous lamination of these rocks, indications of a rather rapid consolidation and compaction. This leaves doubt that the crystallizing lujavrite was coherent enough to allow the passage of the microsyenitic melts. The proposed mechanism is also contradicted by field evidence of lujavrite pegmatites cutting the microsyenite sheet in Narsaq Elv.

(3) The arfvedsonite lujavrite of the upper part of the lujavrite zone represents an independent intrusive phase, that is, the magma chamber was not closed during the formation of the agpaitic part of the complex. In support of this view it may be argued that also the medium- to coarse-grained lujavrite may have been a late independent intrusive phase. However, the generally accepted view is that the petrographical and geochemical data indicate a continuous evolution in a closed magma chamber. It should in this connection be emphasized that the upper part of the floor zone crystallized later than the lowermost part of the roof zone according to the the mineral chemical data (Larsen 1976). This indicates that there was a hiatus between the formation of these rocks which supports the view of the presence of a sandwich horizon of residual melt in a closed magma chamber. The medium- to coarse-grained lujavrite is generally considered to have been formed from a highly evolved residual magma in the uppermost part of the lujavrite zone.

(4) When the idea of an evolution in a closed magma chamber is upheld, the above-mentioned geometrical problem may be solved if it is assumed that the microsyenitic intrusions in the floor and roof zones were formed by pulses of magma from separate magma sources or that their melts were able to migrate upwards through fractures in rock lying between residual sub-chambers at a late stage in the consolidation of the arfvedsonite lujavrite. Guttenberg & LeCouteur (1992) (see also the geological map by Andersen et al. 1988) have demonstrated that the lujavrites at the head of Kangerluarsuk thin out in a way indicating that the base of the overlying naujaite was an undulatory, rather than a planar surface so that 'roof pendants' of naujaite may have subdivided the lujavritic melt into sub-chambers.

The observation that the microsyenitic dykes do not transgress the contacts of the agpaitic rocks points to a derivation of their melts within the complex. The melts ranged from silica-saturated to -oversaturated whereas the agpaitic melts were undersaturated. The microsyenites have 61–64 wt.% SiO_2, whereas the lujavrites have about 53% (Table 3). Transition from silica-undersaturated to silica-oversaturated conditions could be explained by fractionation of arfvedsonite, aegirine and nepheline or sodalite. Some lujavrites have thin layers of these minerals, but the layers are clearly formed by continuous crystal fractionation in a closed system as it will be discussed in a separate paper. There are no traces of oversaturated differentiation products in the main lujavrite zone. It is difficult to imagine that oversaturated redidual melts could be separated without leaving traces.

The idea that microsyenitic melts could originate in one of the lujavritic sub-chambers is implausible considering that microsyenite intersects the rocks not only above but also beneath the lujavrites; there are no cases of lujavrite intruding the kakortokites below the sandwich horizon of lujavrites.

The possibility that the transition from under-saturated to over-saturated compositions is a result of assimilation of granitic or quartzitic country rocks in agpaitic melts is also hard to prove. It is well-known that large blocks of quartzite have sunk into the augite syenite at the early stages of formation of the complex. These blocks reacted with the augite syenitic magma to form alkali granite (Ussing 1912; Ferguson 1964; Hamilton 1964). The objection that microsyenite intrudes rocks above and beneath the lujavritic magma chambers also rules out the possibility that the microsyenite originated in one or more lujavritic magma sub-chambers contaminated by country rocks. A formation of oversaturated melts by contamination must therefore, in spite of the lack of dykes traversing the contacts of the agpaitic rocks, be referred to sources outside the agpaitic magma chamber, perhaps to the source region of the agpaitic melts. It is possible that some of the melts formed in the source region have reacted with the granitic basement or with stoped blocks of sandstone and granite and achieved oversaturated compositions, but this cannot be proved or disproved since the composition of the primary melts is not known and the microsyenites during and after intrusion have been subject to chemical and mineralogical changes.

In conclusion, the melts forming the microsyenite cannot be derived by fractionation processes from the agpaitic melts which formed the rocks of phase 3 of the complex. Instead, an external origin is proposed. The regional Tugtutôq-Ilímaussaq dyke swarm does not contain peralkaline microsyenitic dykes with agpaitic mineralogy. This difference could be explained if microsyenites of the regional swarm during emplacement in fractures in the agpaitic rocks of the complex reacted with sodium-rich fluids and were recrystallized. The remnants of brown clinopyroxene and amphibole in a few thin sections may support this view. But the lack of dykes intersecting the contacts of the Ilímaussaq complex and the fact that the most primitive Ilímaussaq microsyenites have an agpaitic mineralogy are hard to reconcile with this view. It may therefore be proposed that the melts originated in the source region which fed the agpaitic part of the complex. This interpretation is in accordance with the view that the syenitic and granitic rocks of the Tugtutôq central complex have been formed from a succession of increasingly fractionated magma batches arisen from a differentiating basaltic parent magma body near the base of the crust (Upton et al. 1990).

The peralkaline melts, which were emplaced in fractures in the form of dykes and sills, underwent a loss of a vapour phase as pointed out by Macdonald (1969) and Macdonald & Edge (1970) and consolidated as peralkaline microsyenitic rocks poor in REE, Th, U, Nb and Ta. This must have happened in connection with opening of fractures. By contrast the agpaitic rocks of the Ilímaussaq complex formed in closed magma chambers, which explains their elevated contents of rare and volatile elements (cf. Larsen & Sørensen 1987).

The emplacement of the microsyenitic dykes and sills apparently took place in the interval between the formation of the roof and floor zone rocks (naujaite and kakortokite-aegirine lujavrite) and the formation of the arfvedsonite lujavrite. This time interval was also marked by formation of the breccia zone in which large fragments of naujaite enclosed in, and intruded by, lujavrite in the lower part of the roof zone resulted from subsidence of the central part of the complex (Ussing 1912).

Conclusions

Minor intrusions of microsyenite are abundant in the Tugtutôq-Ilímaussaq dyke swarm and also form dykes and sills which intrude rocks of the roof and floor zones of the Ilímaussaq complex. The microsyenites appear to be older than the arfvedsonite lujavrite and medium- to coarse-grained lujavrite, the youngest rocks of the complex.

It is highly unlikely that the silica-oversaturated microsyenitic rocks have been derived by crystal fractionation from the silica-undersaturated melts which consolidated to form the agpaitic rocks of the Ilímaussaq complex. The melts which formed the microsyenitic minor intrusions must therefore be of external origin. The microsyenites within the Ilímaussaq complex are more strongly peralkaline and have more evolved trace element contents than the microsyenites of the dyke swarm outside the complex. This could indicate an origin of the melts in the source region of the agpaitic melts. Unlike the agpaitic melts which consolidated in closed magma chambers, the microsyenitic melts consolidated in fractures which resulted in a loss of volatiles and residual elements.

The existence of dykes and sills traversing some of the rocks of the Ilímaussaq complex indicates that the consolidation of the agpaitic magma chamber was not a continuous process. The emplacement of the microsyenitic minor intrusions separates the consolidation of the floor zone kakortokites and aegirine lujavrites and the naujaite of the roof zone from the consolidation of the arfvedsonite lujavrite and the medium- to coarse-grained lujavrite.

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Dansk sammendrag

Ilímaussaq-komplekset ved Narsaq i Sydgrønland er en sammensat intrusion, som opbygges af tre intrusive faser. Den tredje fase, som udgør hovedparten af komplekset, består af agpaitiske nefelinsyenitter, dvs. peralkaline nefelinsyenitter, som er karakteriseret af tilstedeværelsen af sjældne, komplekst sammensatte mineraler som f.eks. eudialyt. Den tredje intrusive fase opbygges af en øvre del, en mellemste del og en nedre del. Den mellemste del består af lujavritiske nefelinsyenitter. Bjergarterne i den øvre og nedre del skæres af peralkaline mikrosyenitiske dykes og sills. Disse skærer også de nederste lujavritter fra den mellemste del, men de synes at blive skåret af de senest dannede lujavritter. Den herskende opfattelse er, at de agpaitiske bjergarter fra tredje fase blev dannet i et lukket magmakammer. Lujavritterne blev dannet af restsmelter efterladt efter dannelsen af de øverste og nederste dele af komplekset. De skærende små intrusioner af mikrosyenit viser, at bjergarterne fra de øvre og nedre dele af komplekset var størknet før dannelsen af de yngste lujavritter, dvs. at størkningen af de agpaitiske magmaer ikke var en ubrudt proces.

De mikrosyenitiske dykes og sills er overmættede og kan næppe være afledet af de undermættede smelter, som dannede de agpaitiske bjergarter. De adskiller sig kemisk og mineralogisk fra mikrosyenitiske bjergarter, som findes i den dykesværm, der gennemsætter fjeldgrunden omkring Ilímaussaq-komplekset. Det foreslås derfor, at de mikrosyenitiske smelter ikke er direkte led af den regionale dykesværm. Deres magmaer må være blevet dannet uden for Ilímaussaqs magmakammmer, måske i kildeområdet for de smelter, som dannede de agpaitiske bjergarter i Ilímaussaq-komplekset.

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