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The origin and mode of emplacement of lujavrites in the Ilímaussaq alkaline complex, South Greenland ☆

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Abstract

Lujavrites are rare meso- to melanocratic agpaitic nepheline syenites that are characterized by elevated contents of elements such as Li, Be, Zr, REE, Nb, Th and U. They are the most evolved members of the three large composite agpaitic complexes – Lovozero, Kola Peninsula, Russia; Pilansberg, South Africa; and Ilímaussaq, South Greenland – and are inferred to stem from the same deep fractionating magma sources that fed the earlier members of the complexes. The composition of the melts that evolved into lujavrites is, however, not well known. The agpaitic part of the Ilímaussaq complex is divided into a roof series, a floor series of cumulates and an intermediate series of lujavrites sandwiched between the two. In the traditional view, the lujavrites formed from residual melts left between the downward crystallizing roof series and the floor cumulates. New field observations and geochemical data suggest that the floor cumulates and the main mass of lujavrites constituted a separate intrusive phase which was emplaced into the already consolidated roof series rocks largely by piecemeal stoping. Studies of the contact facies of the floor cumulates indicate that the initial magma of the floor cumulate–lujavrite sequence was peralkaline nepheline syenitic with enhanced contents of Zr, Hf, HREE, Y, Nb, Ta, F, Ba and Sr. Subsequent crystallization in a closed system resulted in the formation of the floor cumulates and lujavrites. Chemical analyses of dykes within and outside the complex represent stages in the magmatic evolution of the agpaitic rocks.

Keywords: Agpaitic; Greenland; Ilímaussaq; Lujavrite; Piecemeal stoping

1. Introduction

Lujavrites are meso- to melanocratic agpaitic nepheline syenites which are rich in eudialyte, arfvedsonite and/or aegirine. A pronounced igneous lamination is characteristic. The agpaitic index (molecular ($Na_2O+K_2O):Al_2O_3$) commonly exceeds 1.5. Lujavrites are exceptionally enriched in elements such as Li, Be, REE, Y, Zr, Hf, Nb, Ta, Th and U, of which they may be a future source (Sørensen, 1992).

Lujavrites are major components and the most evolved members of the Lovozero complex, Kola Peninsula, Russia (Ramsay, 1890; Ramsay and Hackman, 1894), the Ilímaussaq complex, South Greenland (Ussing, 1894, 1912) and Pilansberg, South Africa (Brouwer, 1909, 1910) and they are minor components of a few other intrusions. The general lack of chilled

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margins and the fact that most lujavrites are cumulates impede the study of the composition and origin of their parental melts but it has been inferred that the melts stem from the same magma reservoirs that fed the earlier parts of the complexes (e.g. Gerasimovsky et al., 1966/1968; Larsen and Sørensen, 1987; Kramm and Kogarko, 1994; Markl et al., 2001; Marks et al., 2004).

The Lovozero and Ilímaussaq lujavrites have been studied intensively. In Lovozero, lujavrite occurs as layers in one intrusive phase and is the major component of two intrusive phases (Bussen and Sakharov, 1967, 1972; Pekov, 2000). In Ilímaussaq, lujavrites occupy the middle part of the exposed volume of agpaitic rocks (Ferguson, 1964).

The mode of emplacement of the Ilímaussaq lujavrites and melt compositions have until now been treated in a generalised way. New field observations and laboratory data allow us to refine the model for the emplacement and the evolution of the Ilímaussaq lujavrites and to reconsider their status in the complex thereby throwing some new light on the occurrence and origin of this group of rare rocks.

2. The Ilímaussaq lujavrites

The Ilímaussaq complex is one of the intrusions of the mid-Proterozoic Gardar igneous province, South Greenland (Upton et al., 2003). The complex is generally considered to be made up of three intrusive phases: (1) Augite syenite, remnants of which are now found along the margins of the complex and as xenoliths in rocks of the third phase. (2) Alkali granite, remnants of which occur near the roof of the complex. (3) Nepheline syenites which occupy the largest part of the exposed volume and are divided into a roof series, a floor series and an intermediate series sandwiched between the two (Larsen and Sørensen, 1987; Markl et al., 2001). The roof of the magma chamber, consisting of Gardar supracrustal rocks, and the uppermost ca. 1500 m of the complex are well exposed. The floor series and the lowermost part of the intermediate series are exposed south of the major fault through the Lakseelv valley and Kangerluarsuk fjord in the southern part of the complex (Fig. 1). The block north of the fault has been down-thrown relative to the south side (Bohse et al., 1971) and comprises the uppermost part of the floor series, the intermediate series and the roof series.

The roof series crystallized from the roof downwards in the order pulaskite, foyaite, sodalite foyaite and naujaite. Naujaite is a poikilitic sodalite-rich agpaitic nepheline syenite/sodalitolite. The floor series consists of cumulates of rocks which are similar to some lujavrites from the Lovozero complex (the type locality of lujavrites) and strictly speaking are lujavrites. Ussing (1912), however, emphasized the different appearances of the floor and intermediate series rocks by naming them respectively kakortokite and lujavrite, a practice accepted by his successors. These two rocks consist of the same major minerals – alkali feldspar, nepheline, arfvedsonite, aegirine and eudialyte – but kakortokites have perthite, whereas lujavrites have separate microcline and albite, and partly have different minor and accessory minerals. Kakortokite is characterized by alternating units, several metres thick, consisting of a lower black layer rich in arfvedsonite, a red layer rich in eudialyte and an upper white layer rich in alkali feldspar. They are medium- to coarse-grained; the black and white layers are laminated, the red layers granular. The lujavrites are generally fine-grained, laminated and occasionally layered with individual layers a few cm thick (Bailey et al., this volume).

The lujavrite series is at least 500 m thick and saucer-shaped; the lamination is steep along the marginal contacts and nearly horizontal away from the contacts. Its lower part is rich in aegirine, the upper part rich in arfvedsonite; the rocks are accordingly called aegirine lujavrites and arfvedsonite lujavrites (Ussing, 1912). Naujaite rafts are enclosed in the lujavrites (Fig. 2a). The detailed lujavrite stratigraphy was established in the Laksefjeld–Lakseelv area in the southern part of the complex (Figs. 1 and 2b), where kakortokite grades into the overlying aegirine lujavrite. The aegirine lujavrite is divided into a lower aegirine lujavrite I and an upper aegirine lujavrite II and is succeeded upwards – via a transition zone of alternating layers of aegirine lujavrite and arfvedsonite lujavrite – by the main unit of arfvedsonite lujavrite which is divided into a number of varieties (Andersen et al., 1981a; Bohse and Andersen, 1981).

A separation in time between the formation of aegirine lujavrite I–II and arfvedsonite lujavrite is marked by peralkaline, silica-oversaturated microsyenitic sheets and dykes which intrude aegirine lujavrite and are intersected by arfvedsonite lujavrite (Rose-Hansen and Sørensen, 2001).

Aegirine lujavrite also occurs at higher levels in the complex. Transitional stages between aegirine lujavrite and arfvedsonite lujavrite are represented by aegirine arfvedsonite lujavrites in which early aegirine is overgrown and replaced by arfvedsonite. Alternating layers of aegirine lujavrite and arfvedsonite lujavrite are common (Ferguson, 1964; Rose-Hansen and Sørensen, 2002), as are enclaves and patches of aegirine lujavrite

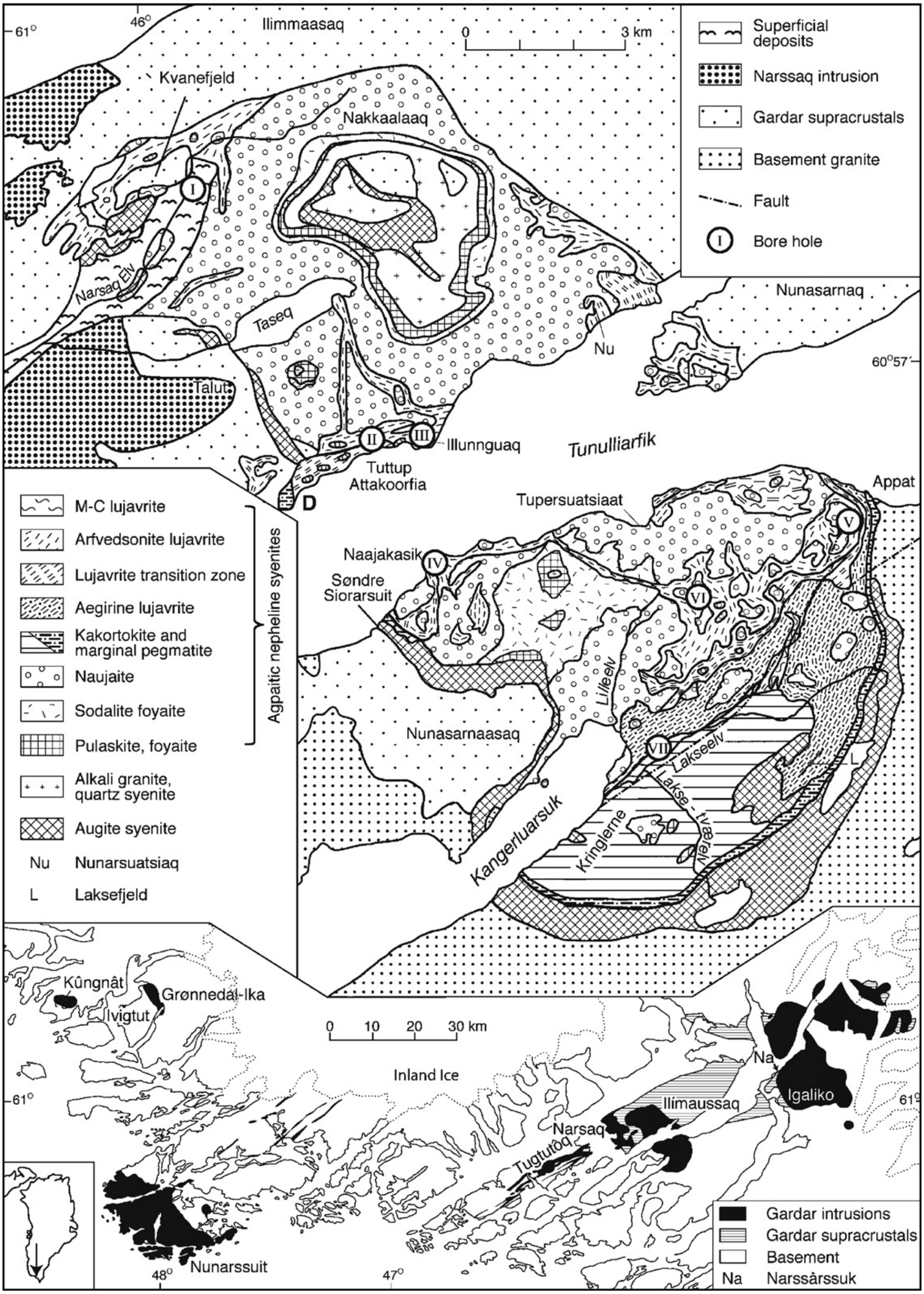


Fig. 1. Geological map of the Ilímaussaq complex and the Gardar igneous province, South Greenland, with location of boreholes. Based on Ferguson (1964), Andersen et al. (1988) and new observations. D: location of dyke 109322.

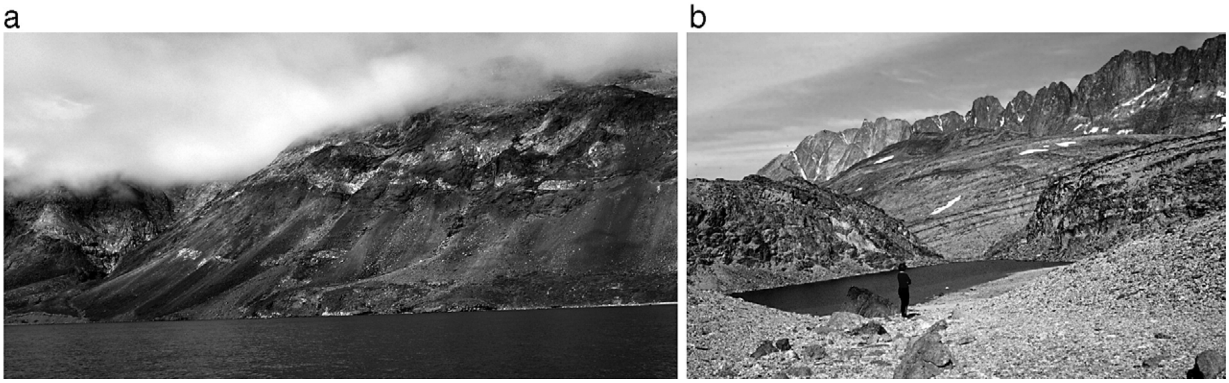


Fig. 2. (a) The north coast of Tunulliarfik. The mountain wall consists of lujavrites (dark colour) with parallel horizons of naujaite rafts (light colour). The boundary against the overlying roof series is concealed by clouds but it is seen in the gulley at the left-hand side of the photo, which coincides with a depression in the boundary. Tuttup Attakoorfia is the small black coastal cliff in centre. Note that the uppermost naujaite rafts, which occur in the boundary between lujavrite and overlying naujaite, have been tilted. Borehole II is located in the gulley on the left side of the photo. (b) In middle ground centre, Laksefjeld (680 m) showing the distinctly layered kakortokites (light-coloured with black layers) overlain by lujavrite (dark colour) at the summit. The white patches are snow drifts. In the foreground, crumbling material derived from a naujaite xenolith enclosed in layered kakortokite which is seen on the sides of lake 287 m. The mountain ridge (1216 m) in the background is the Proterozoic basement granite.

in arfvedsonite lujavrite. Lujavrite dykes and sheets intrude the enclosed naujaite rafts and the overlying naujaite and sodalite foyaite.

Intersecting lujavrite intrusions have not been observed below the kakortokite–lujavrite boundary in the well-exposed Laksefjeld profile (Fig. 2b) and are extremely rare in aegirine lujavrites I and II. Three examples are: (1) Thin sheets of aphanitic arfvedsonite lujavrite intersect aegirine lujavrite I in drill core VII from the Lakseelv area (Fig. 1). The sheets range from a few to more than 20 cm thick and consist of arfvedsonite, microcline, eudialyte and acicular aegirine (Rose-Hansen and Sørensen, 2002). (2) A sheet of M–C lujavrite intrudes aegirine lujavrite I in the Lakseelv valley (Fig. 1; Andersen et al., 1988). M–C lujavrites are medium- to coarse-grained lujavrites which occur as minor intrusions at Kvanefjeld (Sørensen et al., 1969) in the northern, and at Appat (Bohse and Andersen, 1981) in the south-eastern part of the complex. (3) On the north coast of Tunulliarfik, arfvedsonite lujavrite dykes intersect aegirine lujavrite which will be further described in Section 4.1.

3. The marginal pegmatite

The kakortokite of the floor series is rimmed by an up to 100 m wide contact zone which is termed the marginal pegmatite (Bohse et al., 1971; Andersen et al., 1988; Sørensen, in press). This zone passes gradually into the main mass of layered kakortokite and consists of a matrix of agpaitic nepheline syenite which is penetrated by short pegmatite veins. At some contacts the matrix is homogeneous, displays foyaitic texture and is without layering and igneous lamination, which indicates in situ crystallization of the magma. The marginal pegmatite is in its uppermost part intruded by aegirine lujavrites I and II. Locally, masses of naujaite, which occur at least 500 m below the main naujaite horizon, are enclosed in the marginal pegmatite.

4. A section through the lujavrites

The north coast of Tunulliarfik presents an instructive section through the major part of the lujavrite series. On this coast, marginal pegmatite occurs in the east and west contacts of the complex. In the east contact at Nunasarnaq (Fig. 1), it is intruded by aegirine lujavrite which, after a transition zone of alternating layers of aegirine lujavrite and arfvedsonite lujavrite, is succeeded by arfvedsonite lujavrite, i.e. the same lujavrite succession as in the southern part of the complex. In the west contact, the marginal pegmatite is intruded by aegirine lujavrite which, immediately inside the contact, is sheared and faulted and contains xenoliths of basalt, augite syenite and naujaite. These disruptions and poor exposures prevent the establishment of the lujavrite stratigraphy in this contact zone. However, upwards in the lujavrite series and inwards in the complex, arfvedsonite lujavrite becomes predominant, but with layers, xenoliths and patches of aegirine lujavrite. An instructive example is seen at the site of borehole II (Fig. 1), about 1 km east of the west contact, where closely packed pillow-shaped aegirine lujavrite xenoliths (Fig. 3) are enclosed in and intruded by arfvedsonite lujavrite

Fig. 3. Pillows of green lujavrite in black lujavrite, north coast of Tunulliarfik in the gorge on the left side of Fig. 2. Hammer shaft is 50 cm long.

(Sørensen, 1958, 1962). The vertical 200 m deep borehole intersects seven of these pillow horizons which are up to 2 m thick (Rose-Hansen and Sørensen, 2002). This borehole and also borehole VI in the south-eastern part of the complex (Fig. 1) terminate in naujaite which in both holes is more than 80 m thick, i.e. much thicker than the 10–20 m thick horizons of naujaite rafts enclosed in lujavrites.

The boundary between the arfvedsonite lujavrite and the overlying naujaite displays an irregular form which is seen in the north wall of Tunulliarfik: lujavritic 'wave crests' ('domed' areas) adjacent to the west contact and above the point Tuttup Attakoorfia are separated by an intervening 'wave trough' (Figs. 1 and 2a). Away from the contacts, the lamination of the lujavrite and planar structures in the enclosed naujaite rafts are parallel and nearly horizontal. This leaves the impression that the exposed lujavrite sequence constitutes one large body with conformable horizons of naujaite rafts.

4.1. Arfvedsonite lujavrite dykes intersecting aegirine lujavrite

About 300 m from the west contact (D in Fig. 1), the aegirine lujavrite exposed on the north coast of Tunulliarfik is intruded by thin arfvedsonite lujavrite dykes, from a few centimetres to 1 m wide (Fig. 4a). They are slightly discordant to the vertical lamination of the aegirine lujavrite. Thin apophyses branch out from the dykes and intersect the aegirine lujavrite (Fig. 4b).

In hand specimen, the lujavrite of the most prominent dyke (GI 109322) is black, fine-grained, homogeneous and laminated, with spots of brown aegirine. In thin section, it displays a distinct lamination parallel to the contacts of the dyke. The lamination is defined by parallel chains of tiny prismatic crystals of arfvedsonite alternating with chains of albite laths and of lath-shaped analcime of the same size and orientation as the albite. The albite-rich parts 'enclose' the analcime-rich parts (Fig. 5). The lateral contacts between analcime-rich and albite-rich parts are sharp, but the layers interfinger along strike, leaving the impression that the lath-shaped analcime has replaced albite. The albite-rich and the analcime-rich parts contain microcline tablets which are smaller than the albite laths. Both parts also contain scattered corroded grains of nepheline and pseudomorphs after eudialyte made up of brown pigmentary material. Brown aegirine replaces arfvedsonite and this is especially common in the border zones between albite-rich and analcime-rich parts. Interstitial minerals include analcime, natrolite and white mica. There are scattered centimetre-size sodalite grains wrapped by albite and arfvedsonite.

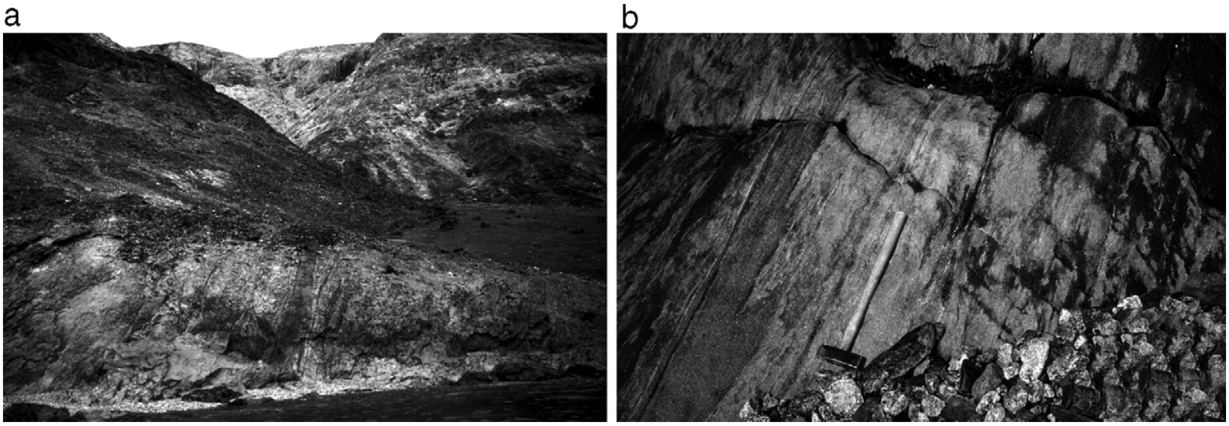


Fig. 4. (a) Arfvedsonite lujavrite dykes intruding vertically laminated aegirine lujavrite, north coast of Tunulliarfik (D in Fig. 1). The thickest dyke is about 1 m wide. (b) Detail of arfvedsonite lujavrite dyke with a short apophysis into the host aegirine lujavrite.

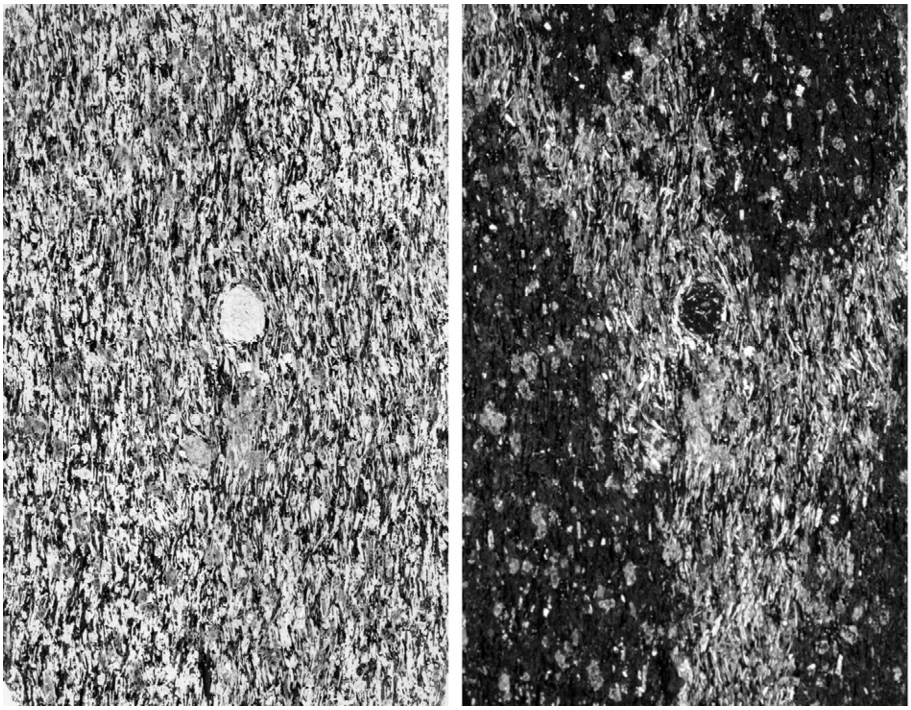


Fig. 5. Microphoto of whole thin section of the widest dyke of Fig. 4a: (a) plane-polarized light; (b) crossed polarizers. Note the textural homogeneity with parallel laths of respectively albite and analcime (black in panel b) and the sodalite crystal in centre (109322, the thin section measures 3 × 2 cm^2).

The mineralogy and texture of the lujavrite of these dykes recall an albite-rich variety of arfvedsonite lujavrite containing spheroidal bodies (see Section 6.1).

5. Whole-rock chemistry

Analyses have been carried out by the methods described by Kystol and Larsen (1999) and Bailey et al. (this volume).

The analysis of dyke 109322 is compared with the average analysis of the 'background arfvedsonite lujavrite', i.e. the average of seven samples of lujavrites from this part of the complex which are homogeneous and without macroscopic features such as layering or spheroids (Table 1). The composition of the dyke differs from the background analysis in higher contents of SiO_2, total Fe and F, relatively high Na/K and lower CaO, K_2O, H_2O and most trace elements. This is consistent with elevated contents of albite and low contents of microcline and eudialyte.

The chemical composition of the dyke is similar to that of the above-mentioned spheroidal arfvedsonite lujavrite (see Table 1 and Section 6.1). In hand specimen, the dyke rock looks homogeneous and it is impossible to separate the albite-rich and the analcime-rich parts for chemical analysis. The analysis of the dyke is therefore of the bulk of the rock, whereas the analysis of the spheroidal lujavrite is of the host rock only and excludes the spheroids.

Most of the lujavrites of the complex are cumulates and their analyses are not representative of melt compositions. But dyke rocks such as the above-mentioned 109322, which consolidated rapidly in a narrow fissure, may proxy melt compositions. Five additional dyke analyses are listed in Table 1: 66433, an aphanitic aegirine lujavrite intersecting naujaite at the head of Kangerluarsuk; and dykes intersecting the country rocks of the Gardar intrusive complexes: tephriphonolite (153099, Larsen, 1979) and agpaitic phonolites (325907, Pearce, 1988; 153200 and 42475, Larsen, 1979). Table 1 also contains analyses of the matrix of the marginal pegmatite (104361A), which is inferred to be close to the composition of the initial kakortokitic magma, and of the chill zone of Ilímaussaq augite syenite (153394) representing the composition of the initial augite syenitic magma. These analyses will be discussed in Section 6.3.

6. Discussion

The lujavrite stratigraphy established south of Tunulliarfik appears to be valid also north of this

Table 1
Chemical analyses of lujavrites, augite syenite and marginal pegmatite from the Ilímaussaq complex, tephriphonolite and agpaitic phonolite dykes from the country rocks

	Arfvedsonite lujavrite dyke 109322	Spheroidal lujavrite 154372	Arfvedsonite lujavrite (average of 7)	Aegirine lujavrite dyke 66143	Agpaitic dyke, 325907	Augite syenite, chill 153394	Tephriphonolite dyke 153099	Agpaitic phonolite dyke 153200	Marginal pegmatite 104361A	Agpaitic phonolite dyke 42475
SiO_2	54.02	54.79	52.01	52.53	50.55	53.24	56.71	52.98	54.60	51.83
TiO_2	0.30	0.23	0.17	0.23	0.33	2.44	0.86	0.47	0.20	0.55
ZrO_2	0.15	0.35	0.83	1.18	0.85	0.04	0.14	0.35	0.75	0.58
Al_2O_3	11.01	11.18	13.80	13.11	14.00	14.79	15.81	16.55	14.53	14.57
Fe_2O_3	6.90	6.14	4.85	9.83	10.02	2.64	2.42	5.00	8.50	7.56
FeO	10.87	9.97	7.17	3.86	1.65	8.66	7.12	4.27	2.40	4.61
MnO	0.60	0.60	0.53	0.30	0.49	0.24	0.31	0.44	0.24	0.48
MgO	0.01	0.16	0.12	0.09	0.34	1.60	0.42	0.35	0.16	0.14
CaO	0.23	0.27	0.42	1.41	2.35	4.94	2.46	1.89	2.78	2.54
Na_2O	10.31	9.94	10.59	10.63	11.27	4.68	7.15	9.65	7.16	8.81
K_2O	2.30	2.13	3.06	3.05	2.35	4.26	5.25	5.24	5.27	4.87
S	n.a.	0.01	0.12	0.02	0.14	0.15	n.a.	n.a.	n.a.	0.12
Cl	0.06	0.02	0.03	0.18	0.70	0.03	0.09	0.46	0.03	0.33
F	0.30	0.15	0.14	0.14	1.04	0.10	0.19	0.70	0.88	0.84
P_2O_5	0.31	0.35	0.41	0.02	0.19	0.74	0.42	0.23	0.05	0.08
H_2O	1.61	2.09	4.04	2.73	2.70	0.29	0.60	1.42	2.51	2.03
	98.98	98.38	98.29	99.31	98.97	98.84	99.95	100.00	100.06	99.94
–O	0.14	0.07	0.13	0.11	0.67	0.12	0.10	0.40	0.38	0.49
Total	98.84	98.31	98.16	99.20	98.30	98.72	99.85	99.60	99.68	98.45
A.I.	1.77	1.67	1.50	1.58	1.63	0.83	1.10	1.3	1.20	1.36
Cs	5.8	6.4	12	5.8	15	0.4	2.3	6.35	10.0	7.0
Rb	297	213	644	435	330	69	164	308	517	360
Ba	17	14	38	110	145	3230	137	136	365	36
Pb	279	453	534	312	136	12	27	61	56	71
Sr	31	37	71	58	32	410	36	111	166	50
La	1660	2350	3260	654	595	67	147	341	403	483
Ce	2370	3020	4770	1160	1140	141	312	628	770	845
Nd	503	824	1630	566	415	66	129	202	295	298
Sm	35.4	92	190	105	73	11.7	21.5	38.0	59	39
Eu	2.8	7.3	19	10.9	8.0	4.7	2.1	3.0	5.8	3.4
Tb	3.3	9.6	28	20.6	11.1	1.9	2.6	4.4	10.0	7.6
Yb	7.8	17.9	53	67.3	47.5	3.8	9.1	14.9	36.3	34.2
Lu	1.5	2.4	7.1	8.3	3.4	0.6	n.a.	n.a.	5.0	n.a.
Y	107	290	912	679	428	51	105	173	322	330
U	n.a.	34	201	48	31	1.3	5	25	12	29
Th	77	44	287	41	189	3.4	17	59	31	63
Zr	1100	2560	6144	8720	6290	284	1014	2623	5549	4231
Hf	16.7	28	69	181	128	6.6	20.4	48	128	90
Nb	351	378	628	785	1350	80	219	737	528	867
Ta	8.4	16	41	52	54	4.6	n.a.	n.a.	34.0	n.a.
Zn	1210	920	1980	728	660	164	n.a.	n.a.	227	n.a.
Ga	113	113	127	77	58	30	n.a.	n.a.	71	n.a.
Na/K	3.8	5.4	3.1	3.1	4.2	1.0	1.2	1.6	1.2	1.6
La/Yb	212.8	131.2	61.5	9.7	12.5	17.6	16.1	22.9	11.1	14.1
Zr/Nb	3.1	6.8	9.8	11.1	4.7	3.6	4.6	3.6	10.5	4.9

Major elements in wt.%, trace elements as ppm.

Analysts: J.C. Bailey, R. Gwozdz, B. Damgaard and J. Kystol.

n.a. = not analysed, A.I = agpaitic index $(Na_2O+K_2O)/Al_2O_3$ mol. 109322: Arfvedsonite lujavrite dyke (new analysis). 154372: Spheroidal lujavrite (Sørensen et al., 2003). Average of seven analyses is average composition of arfvedsonite lujavrites in Tunulliarfik area. 66143: Dyke of aegirine lujavrite (new analysis). 325907: Dyke from Igaliku peninula (Pearce, 1988, new analysis). 153394: Augite syenite chill, Ilímaussaq. N.V. Ussing's sample U-106 (new analysis). 153099 and 153200: Tephriphonolite and agpaitic phonolite dykes from Igaliku peninsula (Larsen, 1979). 104361A: Matrix of marginal pegmatite, north coast of Kangerluarsuk (new analysis). 42475: Agpaitic dyke south of the Ilímaussaq complex (Larsen, 1979).

fjord, at least for the part near the east contact and, in consideration of the regular structure of the complex, perhaps for the whole northern part.

Aegirine lujavrites I and II are definitely the lowermost lujavrites. From the association of rocks and textural features, the lujavrite in the contact zones on the north coast of Tunulliarfik has been identified as aegirine lujavrite II. Thus, the arfvedsonite lujavrite dykes (109322) occur at a low stratigraphical level in the complex. Intersecting arfvedsonite lujavrite has not been observed at this level in the Laksefjeld–Lakseelv area (Fig. 2b), with the exception of the thin sheets of arfvedsonite lujavrite intruding aegirine lujavrite I observed in borehole VII and the sheet of M–C lujavrite intersecting aegirine lujavrite I in the Lakseelv valley (see Section 2). The occurrence of arfvedsonite lujavrite at this low level in the lujavrite series is not consistent with the regular lujavrite stratigraphy of the sandwich model. This invites reconsideration of the status of the lujavrites of the Ilímaussaq complex. In the following section we consider three main aspects of this: (1) the status of the arfvedsonite lujavrite dykes on the north coast of Tunulliarfik, (2) the status of the lujavrites of the Ilímaussaq complex, and (3) the magmatic evolution of the complex.

6.1. The status of the arfvedsonite lujavrite dykes on the north coast of Tunulliarfik

The mineralogical and chemical compositions (Table 1) of the analysed dyke (109322) are very similar to those of the albite-rich variety of arfvedsonite lujavrite which is the host for spheroidal bodies (Sørensen et al., 2003). The contents of major elements are practically identical but the dyke has lower contents of most trace elements and different La/Yb and Zr/Nb ratios.

The spheroids consist of a core of arfvedsonite and analcime and in most cases a rim of analcime, brown aegirine and secondary K-feldspar. In the cores and rims of the spheroids, albite is substituted by analcime with preservation of the texture of the host lujavrite. With regard to texture and modal composition, the analcime-rich parts of the dyke are similar to the spheroid cores. The brown aegirine-rich rims of the spheroids are lacking in 109322 but enrichment in brown aegirine along the borders between the albite-rich and the analcime-rich parts of the dyke recalls the rims of the spheroids. The analcime-rich parts may be interpreted as incompletely developed spheroids. The lack of fully developed spheroidal bodies may be explained by the relatively rapid consolidation of a small batch of magma in a fissure.

Spheroidal lujavrite is of widespread occurrence in the complex as a local development in arfvedsonite lujavrite. Its occurrence seems unrelated to any particular geological setting which suggests that it is a response to differentiation processes within the arfvedsonite lujavrite. Spheroids are restricted to a distinct facies of arfvedsonite lujavrite characterized by high SiO_2, Na_2O, Na/K, agpaitic index, total Fe and Li, and low CaO, K_2O, H_2O, Rb, Ba, Sr, Zr, Nb, REE and Y, i.e. lujavrites rich in albite and arfvedsonite and poor in K-feldspar and eudialyte. The spheroids are considered to have been formed by liquid immiscibility in a late stage of consolidation of the lujavrite (Sørensen et al., 2003). This magma type was formed at intervals in space and perhaps in time. The dykes of the north coast of Tunulliarfik prove the existence of an independent magma of this lujavrite type at a low stratigraphical level in the lujavrite series.

6.2. The status of the lujavrites of the Ilímaussaq complex

It is generally agreed that the roof series was formed by downward crystallization of a single batch of syenitic magma (Larsen and Sørensen, 1987). Sodalite contents up to 75 vol.% in the about 600 m thick naujaite horizon, which constitutes the lowermost part of the series, required sodalite crystallization in a considerable magma volume. Fluid inclusions in some naujaitic sodalite crystals were trapped at pressures of 3.5 kbar corresponding to a depth of 10 km below the surface, whereas the exposed Ilímaussaq complex was formed at pressures of ±1 kbar corresponding to depths of 2–3 km (Markl et al., 2001). This suggests that crystallization began deep in the crust and that the naujaite formed in a system that was open downwards and sealed at the roof (Fig. 6).

The occurrence of naujaite in the marginal pegmatite at a low level in the complex, the thick naujaite masses below lujavrite in boreholes II and VI and naujaite rafts in lujavrites and kakortokites indicate an originally thicker naujaite horizon.

In the sandwich model for the evolution of the agpaitic part of the complex (Sørensen, 1958; Ferguson, 1964; Gerasimovsky, 1969), the lujavrites are considered to be formed from volatile- and rare element-rich residual melts left after the simultaneous crystallization of the roof series and the floor series in a closed magma chamber. Steenfelt and Bohse (1975) presented evidence that at least parts of the roof series are older than the floor series and that some of the enclosed naujaite rafts are thoroughly altered which indicates contact with the volatile-rich magma during extended periods. This made

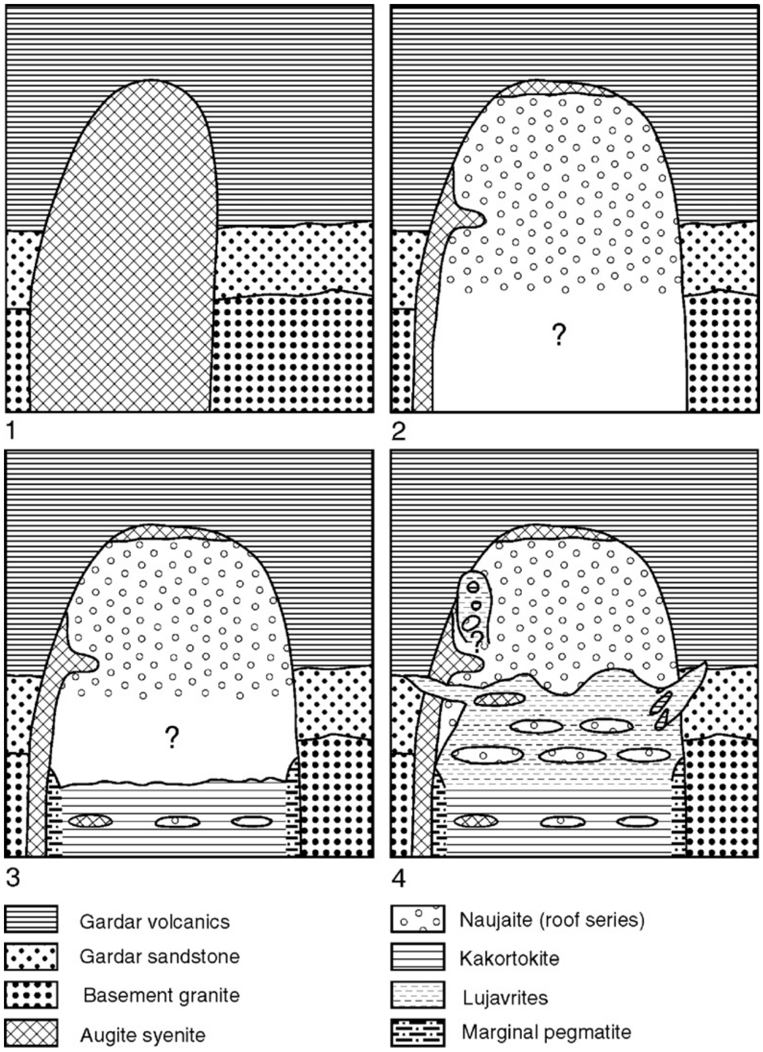
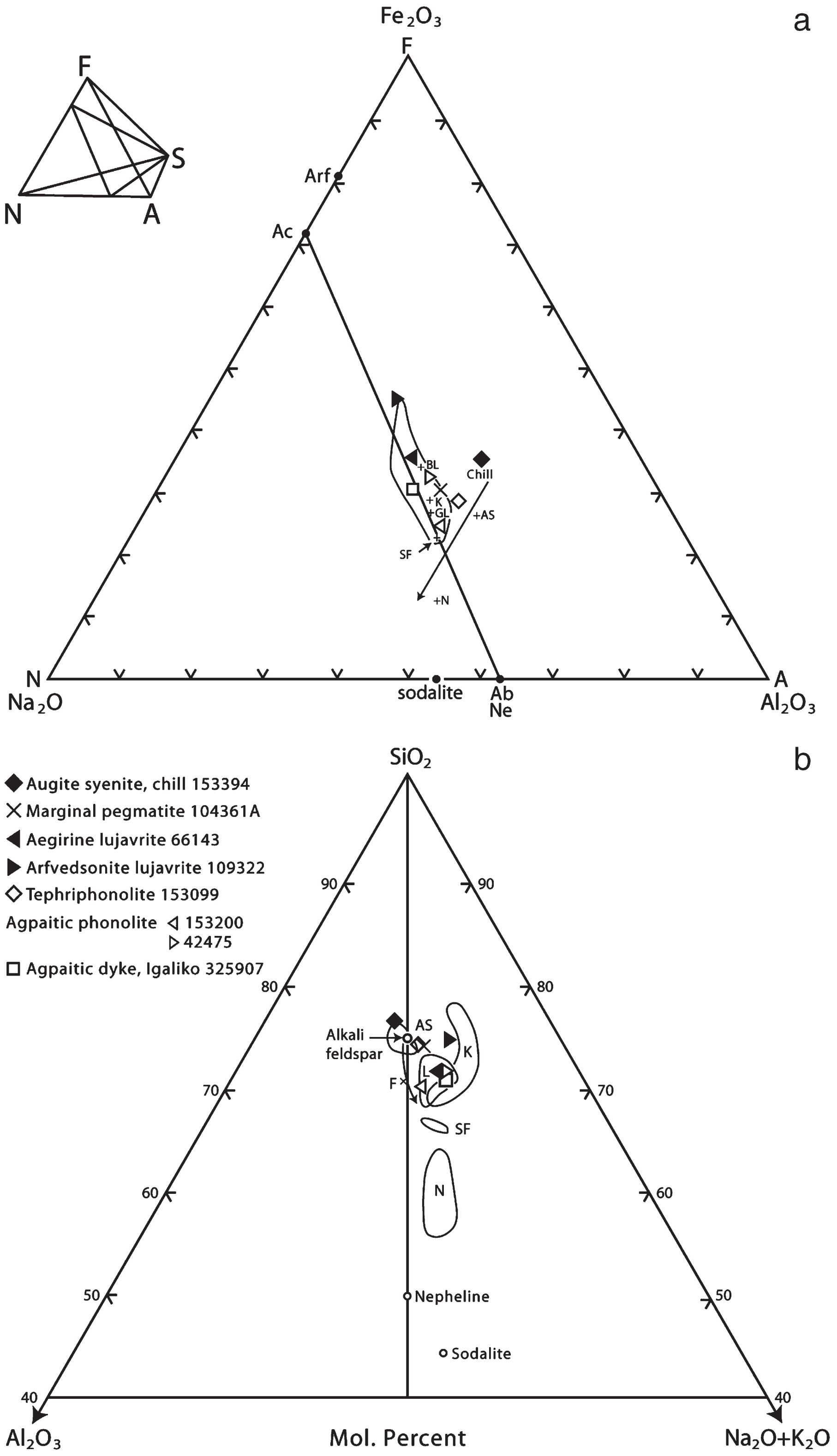


Fig. 6. Cartoon showing inferred stages in the evolution of the Ilímaussaq complex. The alkali granite stage is omitted and the height–width proportion is not correct. 1: Augite syenite intrudes the sequence of basement granite, sandstone and volcanics. 2: The roof series stage and formation of naujaite in a downward open (?) magma system. The inferred hidden floor series is not shown. 3: The marginal pegmatite–kakortokite stage passing into 4. 4: The lujavrite stage. Note that augite syenite xenoliths only occur in kakortokite–lujavrite. The source of the upper-left lujavrite (corresponding to the Kvanefjeld occurrence) is unknown.

Larsen and Sørensen (1987) conclude that the formation of the roof series by downward crystallization of successively more differentiated and more volatile-rich melts was accompanied by a build-up of volatiles beneath the crystallization front. The temperature–composition–density gradients, which were established in the underlying magma, brought the liquidus temperature of the uppermost part of the magma below the actual magma temperature and arrested crystallization of the roof series. Crystallization shifted to the floor of the magma chamber where kakortokite cumulates formed. Subsequently the lujavrites originated in a disc-shaped, few hundreds of metres thick magma chamber in the middle part of the complex.

Fig. 7. Geochemical diagrams. (a) The system N–F–A–S (Na_2O–Fe_2O_3–Al_2O_3–SiO_2), simplified from Engell (1973, Fig. 3). N (lower left corner of diagram) = total alkalis as Na_2O, F = total Fe as Fe_2O_3. Chill = chilled augite syenite, AS = augite syenite, SF = sodalite foyaite, N = naujaite, K = kakortokite, GL = aegirine lujavrite, BL = arfvedsonite lujavrite. The trend from AS chill to N and the kakortokite–lujavrite field are marked. (b) The system Na_2O+K_2O–Al_2O_3–SiO_2 (simplified from Macdonald, 1974, Fig. 8). AS, SF, N and K as panel a, F = foyaite, L = lujavrite. The arrow shows the trend from augite syenite to foyaite in the Tugtutôq Older Giant Dyke (Upton, 1964).


a
Fe₂O₃
F
F
S
N
A
Arf
Ac
+BL
Chill
+K
+GL
+AS
SF
+N
N
Na₂O
sodalite
Ab
Ne
A
Al₂O₃
b
SiO₂
◆ Augite syenite, chill 153394
× Marginal pegmatite 104361A
◀ Aegirine lujavrite 66143
▶ Arfvedsonite lujavrite 109322
◇ Tephriphonolite 153099
Agpaitic phonolite ◁ 153200
▷ 42475
□ Agpaitic dyke, Igaliko 325907
90
90
80
80
Alkali feldspar
AS
K
L
F
70
70
SF
60
60
N
50
50
Nepheline
Sodalite
40
40
Al₂O₃
Mol. Percent
Na₂O+K₂O

A number of features suggest that the main kakortokite–lujavrite sequence consolidated from the floor upwards under calm conditions: (1) The gradual transition from kakortokite to lujavrite; (2) the nearly horizontal orientation of the kakortokite layers and the lujavrite lamination and the undisturbed continuity of individual rafts in the horizons of naujaite rafts; (3) the regular geochemical trends through the main sequence of kakortokite–lujavrite (Andersen et al., 1981b); (4) the scarcity of internal intrusive contacts, of graded layering and of structures which can be related to current activity within the lujavrite sequence. Naujaite rafts and xenoliths detached from the roof of the magma chamber were successively enclosed by kakortokite and lujavrite, i.e. the lower part of the main zone of naujaite was replaced by kakortokite–lujavrite. This intrusion process may be termed *piecemeal stoping* (Fig. 6).

Patches of aegirine lujavrite in contact zones of arfvedsonite lujavrite against naujaite indicate that aegirine lujavrite crystallized first but was later assimilated by arfvedsonite lujavrite. Apart from this, there is no lujavrite contact facies against the naujaite roof, most probably because of the high content of volatiles in the magma. The naujaite of the contact zone is, however, strongly altered and recrystallized and various types of coarse-grained rocks have been formed by reaction between naujaite and the lujavritic magma (Sørensen, 1962). The aegirine lujavrite 'pillows' in arfvedsonite lujavrite in drill core II, and the microsyenite sheets which intrude aegirine lujavrite and are intruded by arfvedsonite lujavrite, indicate temporary fluctuations and interruptions of the crystallization process.

Ussing (1912) pointed out that the densities of naujaite and of the Fe-rich arfvedsonite lujavritic magma were both close to 2.5 g/cm^3. Therefore, the naujaite rafts detached by the intruding lujavrite magma did not sink but remained more or less in position. This explains the continuity of structures and the conformity of the naujaite raft horizons in lujavrite.

The irregularly shaped boundary between lujavrite and the naujaite roof may indicate that locally the conditions permitted the lujavrite magma to rise to higher levels than in neighbouring areas or, alternatively, that the 'wave troughs' in this boundary surface may have been formed by foundering of large masses of naujaite. Thus, the thick naujaite mass in borehole II is located below a depression in the boundary surface (Fig. 2a). The above-mentioned density relations and the buoyancy effect may have prevented the thin rafts from sinking, whereas the big masses subsided in the magma.

At the 'wave crest' above Tuttup Attakoorfia (Fig. 2a), i.e. at the contact between the lujavrite sequence and the roof series, lujavrite intruded fractures in the overlying naujaite. Naujaite fragments were partially detached from the roof. These fragments are not conformable with the generally nearly horizontal lamination of the lujavrite but appear to be stacked or tilted. This may be referred to increasing viscosity of the lujavrite magma in the waning stage of consolidation which prevented the fragments from settling as conformable rafts.

The kakortokite layers span the whole width of the Ilímaussaq complex. The gradual transition from kakortokite to aegirine lujavrite makes it most likely that the lujavrites also span the complex though large variations in the shape of the roof disturbed the lateral continuity. It appears that the consolidating lujavrite magma preserved the overall horizontal primary structure. The limited lateral extent of spheroidal lujavrite, layered lujavrites and other lujavrite varieties indicates that their consolidation took place in discrete domains or facies.

The lujavrites are largely confined to the sandwich unit in the middle part of the complex, but transgress its west and east contacts on the north coast of Tunulliarfik, and intrude the roof series and the volcanic rocks at the roof of the complex at Kvanefjeld and between Kvanefjeld and the foothill of Ilimmaasaq mountain in the northern part of the complex (Fig. 1). The sheets of arfvedsonite lujavrite and M–C lujavrite intruding aegirine lujavrites I and II provide evidence for the existence of independent pools of lujavritic magma below the main mass of lujavrites. Such pools do not fit into the regular structure of the sandwich model. In passing, we note that the thick naujaite masses which underlie lujavrites in boreholes II and VI also fail to fit the sandwich model.

In the systems Na_2O–Al_2O_3–Fe_2O_3–SiO_2 (Fig. 7a; Engell, 1973), SiO_2–Al_2O_3–(Na_2O+K_2O) (Fig. 7b; Macdonald, 1974), U in eudialyte (Bohse et al., 1974) and U–Zr (Andersen et al., 1981b), the kakortokite–lujavrite trend diverges from the roof series trend. Steenfelt and Bohse (1975), Larsen (1976) and Bailey et al. (2001) have demonstrated mineralogical and chemical discontinuities between naujaite and kakortokite. Further, the ε_{Nd} values of -1.0, -1.1 for naujaite and sodalite foyaite and -1.4, -1.5, -1.8 for lujavrite and kakortokite (Marks et al., 2004) suggest that these rocks fall into two groups. Altogether, the discontinuities between the roof series and the floor series do not support direct derivation of the kakortokites–lujavrites from the residual melts remaining after crystallization of the roof series, but rather formation from a separate batch of magma as proposed by Larsen (1976) and Bailey et al. (1981).

Interestingly, the emplacement model outlined for the Ilímaussaq complex in the present paper appears to have its parallel in the Lovozero complex (Bussen and Sakharov, 1967, 1972; Pekov, 2000) where the first phase of syenites, nepheline syenites, etc., is only preserved as xenoliths. This first phase corresponds to the Ilímaussaq augite syenite. The poikilitic sodalite- and nosean-rich rocks, which constitute the second phase, occur only as large xenoliths, especially in the upper part of the complex. They are very similar to the Ilímaussaq naujaite. The third phase forms the lowest exposed part of the complex and consists of a thick layered series of urtite–foyaite–lujavrite which recalls the kakortokites of Ilímaussaq. The fourth phase is made up of eudialyte lujavrites which intrude and overlie the layered series. The fifth phase consists of small bodies of highly evolved lujavrites that intrude the phase three and four rocks. The xenoliths of poikilitic sodalite-rich rocks indicate that the Lovozero complex may have had a roof series as in Ilímaussaq but this was partly digested by the third and fourth phases. In contrast to Ilímaussaq, it seems that the layered series did not grade into lujavrites. It was intruded by two major lujavrite pulses, whereas in Ilímaussaq the kakortokites were not intruded by lujavrites and only a few minor separate lujavrite pulses have been recognised within the lujavrite series.

6.3. The magmatic evolution of the complex

The melts which formed the rocks of the Ilímaussaq complex are thought to stem from a fractionating alkali basaltic magma chamber in the deep crust (Larsen and Sørensen, 1987; Markl et al., 2001; Marks et al., 2004). Consecutive magma pulses formed augite syenite, alkali granite, the roof series rocks and the kakortokite–lujavrite sequence. The relationship between gabbro, syenite and nepheline syenite is seen in the composite Older Giant Dyke of Tugtutôq, west of the Ilímaussaq complex (Fig. 1). It consists of a gabbroic margin and a syenitic core which displays the transition from augite syenite to foyaite (Fig. 7b) (Upton, 1964; Upton et al., 2003).

The chilled contact of the Ilímaussaq augite syenite (153394) has high TiO_2, MgO, CaO, FeO*, P_2O_5, Ba and Sr, an agpaitic index below 1.0, a low Na/K ratio, low alkalis and low contents of most trace elements. Fractional crystallization of augite syenitic melts in a closed system can yield highly reduced, strongly silica-undersaturated alkaline melts (Marks and Markl, 2001). Such features have not been observed at the present exposure level, but dyke 153099 may be an example of an evolved augite syenite and bridges the gap between the augite syenite and the agpaitic rocks of the complex (Table 1; Fig. 7a, b). It displays higher contents of TiO_2, MgO, FeO*, P_2O_5, Ba and Sr and lower contents of Na and residual elements such as REE, U, Th, Zr and Nb than the agpaitic rocks.

Pulaskite, the first rock to form in the roof series, is cumulitic and has furthermore reacted with the granite of the second intrusive phase. Thus its chemical composition is not representative of the magma composition and it is not included in Table 1. Pulaskite grades downwards into foyaite and further to sodalite foyaite and naujaite, i.e. the evolution of the roof series is well constrained by field observations and mineralogical and chemical data (Larsen, 1976, 1977; Larsen and Sørensen, 1987; Markl et al., 2001). Some of the dykes of the region, such as the agpaitic phonolite dykes 153200 and 42475, appear to represent stages in the formation of agpaitic melts and prove the existence of such melts. These melts may stem from the Ilímaussaq complex or may have an independent origin (Allaart, 1969; Larsen and Steenfelt, 1974; Larsen, 1979).

The matrix of the marginal pegmatite was the first rock to form in the exposed part of the kakortokite–lujavrite sequence. With regard to major elements and agpaitic index, the matrix rock is rather similar to the tephriphonolite dyke (153099), but it is low in TiO_2 and P_2O_5 and surprisingly rich in the eudialyte components Zr, CaO, Ba, Sr, HREE, Y, Hf, Nb and Ta. This could indicate a cumulus origin of the rock. However, samples of massive-textured marginal pegmatite matrices from other localities (not included in Table 1) and the two aegirine-rich dykes, 66143 and 325907 (Table 1), which most likely represent rapid crystallization of lujavritic melts, also have relatively elevated contents of these elements. Furthermore, the kakortokites and the lower lujavrites have high contents of cumulus eudialyte which reflects that the initial magma of the kakortokite–lujavrite suite had elevated contents of Zr, Y, Nb, etc. The elevated Ba and Sr contents in these rocks are in marked contrast to low Ba and Sr contents in the roof series rocks (Ferguson, 1970; Bailey et al., 2001). The agpaitic phonolite 153200 represents an intermediate stage between 153099 and the marginal pegmatite 104361A (Fig. 7a). According to Fig. 7a, the marginal pegmatite melt could be derived from the chill augite syenite composition via the tephriphonolite (153099) and phonolite (153200) compositions, i.e. a trend deviating from the augite syenite to naujaite trend of Fig. 7a. The agpaitic phonolite (42475) appears to correspond to the foyaite–sodalite foyaite stage of Ilímaussaq (Marks and Markl, 2003) which is in agreement with its high CaO and low Ba and Sr. However, the parameters used in Figs. 7a and b suggest that this rock plots in the kakortokite–lujavrite field.

The evolution from kakortokite through aegirine lujavrite to the highly evolved arfvedsonite lujavrite took place in a sealed magma chamber. The copious crystallization of eudialyte in kakortokites and aegirine lujavrites I and II deprived the magma in its eudialyte components. Accordingly, the background arfvedsonite lujavrite of the Tunulliarfik area and the spheroidal lujavrite have reduced contents of these components. The arfvedsonite lujavrites of Table 1, with the exception of dyke 109322, are cumulates. Their analyses nevertheless reveal different lines of evolution which produced local facies characterized by different agpaitic indices, Na/K ratios and residual element contents.

7. Conclusions

1. The arfvedsonite lujavrite of the dykes intruding aegirine lujavrite on the north coast of Tunulliarfik is so similar to the arfvedsonite lujavrite hosting the spheroidal bodies that it most probably formed from the same magma type. The dykes indicate that such magmas existed and represent an early stage in the formation of the spheroidal lujavrite.
2. In the original sandwich model for the evolution of the Ilímaussaq complex, the lujavrites were thought to crystallize from the residual melts left between the downward growing roof series and the floor series of cumulates. However, the presence of arfvedsonite lujavrite dykes intersecting aegirine lujavrite II on the north coast of Tunulliarfik and other minor lujavrite occurrences, and the occurrence of large naujaite masses beneath the main body of lujavrite indicate that the general structure of the agpaitic part of the Ilímaussaq complex is more complicated than hitherto believed and that pools of lujavritic magmas existed below the sandwich zone of lujavrite.
3. Mineralogically and chemically, the kakortokites are lujavritic rocks. Geochemical data and trends, the general structure and the rarity of cross-cutting relations suggest that the main kakortokite–lujavrite sequence formed a separate intrusion which was emplaced by piecemeal stoping of overlying naujaite. It consolidated from the floor upwards incorporating horizons of naujaite rafts.
4. The recognition that the matrix of the marginal pegmatite is the contact facies of the kakortokite gives information about the initial composition of the magma which formed the kakortokitic–lujavritic sequence and the first information about the composition of an initial lujavrite magma. Dykes such as nos. 109322, 66143 and 325907 (Table 1) prove the existence of lujavritic melts and illustrate their remarkable chemical composition.

Acknowledgements

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