Naujakasite from the Ilímaussaq alkaline complex, South Greenland, and the Lovozero alkaline complex, Kola Peninsula, Russia: a comparison

Alexander P. Khomyakov, Henning Sørensen, Ole V. Petersen and John C. Bailey

Naujakasite, $Na_6(Fe,Mn)Al_4Si_8O_{26}$, long known from the Ilímaussaq alkaline complex, South Greenland, was not reported until 1999 from other occurrences of alkaline rocks in spite of the fact that the mineral is composed of common elements. In 1999, a variety of naujakasite rich in Mn was found in the Lovozero alkaline complex in the Kola Peninsula, Russia. This variety has been approved by the IMA as a new mineral, manganonaujakasite, $Na_6(Mn_{0.53}Fe^{2+}_{0.47})Al_4Si_8O_{26}$. At Ilímaussaq naujakasite is a rock-forming mineral in the highly evolved rock naujakasite lujavrite in which it may make up more than 75 vol.%; at Lovozero manganonaujakasite is a very rare constituent in mineralised lovozerite–lomonosovite lujavrite. Naujakasite appears to take the place of nepheline in hyper-agpaitic nepheline syenites characterised by exceptionally high Na/K ratios. The nepheline syenites at Ilímaussaq have an average Na/K (atomic) ratio of 3.08, and the naujakasite lujavrites have the extreme ratio 4.56. The nepheline syenites of the Khibina and Lovozero complexes are characterised by lower Na/K ratios, 1.27 for Khibina and 1.67 for Lovozero, and thus nepheline is stable in the hyper-agpaitic rocks and naujakasite occurs only in pegmatites.

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Keywords: agpaite, hyper-agpaite, Ilímaussaq, Lovozero, lujavrite, manganonaujakasite, naujakasite, nepheline syenite

The Ilímaussaq alkaline complex is the type locality for naujakasite, $Na_6(Fe,Mn)Al_4Si_8O_{26}$. For half a century, the only known specimen of this mineral was a boulder weighing 350 gram, collected in 1897 by the Swedish mineralogist G. Flink at the small peninsula Naajakasik (then Naujakasik) on the south coast of the Tunulliarfik fjord, well within the complex (see Sørensen 2001, this volume for a map of the localities mentioned in the text and a brief description of the complex). Flink's original label tentatively identified the silvery white mica-like mineral that constituted 75% of the boulder as 'chlorite?'. Bøggild (1933) established this phase as a new mineral and named it after the place where it was found, and Gossner & Krauss (1933) presented the first set of unit cell parameters. Naujakasite was first found in outcrop in 1955 (Danø & Sørensen 1959). Based on the new material a complete redescription, including a redetermination of the unit cell parameters, was given by Petersen (1967), and the structure was worked out by Basso *et al.* (1975).

Naujakasite is now known to be of widespread occurrence in the Ilímaussaq alkaline complex in the rock called naujakasite lujavrite (see further below) and may constitute more than 75 vol.% of that rock. Because naujakasite is composed of the common elements Na, Fe, Mn, Al and Si, it is surprising that for 100 years naujakasite was a single locality mineral. In 1998, the first discovery of the mineral outside Ilímaus-

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

Rock type	Texture	Essential minerals*	Minor minerals
Augite syenite	hypidiomorphic to xenomorphic granular, massive or layered, medium to coarse	alkali feldspar, hedenbergite, titanomagnetite, ferropargasite, olivine, biotite	ternary feldspar, apatite, pyrrhotite, nepheline
Pulaskite and foyaite	massive, medium to coarse, platy feldspars	alkali feldspar, nepheline, hedenbergite, fayalite, aegirine-augite to aegirine, katophorite	titanomagnetite, apatite, aenigmatite, biotite, fluorite, eudialyte
Sodalite foyaite	foyaitic, coarse	alkali feldspar, nepheline, sodalite, aegirine-augite to aegirine, katophorite, arfvedsonite	fayalite, hedenbergite, apatite, aenigmatite, titanomagnetite, eudialyte, rinkite, fluorite, biotite
Naujaite	poikilitic, coarse to pegmatitic	sodalite, alkali feldspar, nepheline, aegirine, arfvedsonite, eudialyte	aenigmatite, hedenbergite, aegirine-augite, fayalite, apatite, katophorite, rinkite, polylithionite, biotite, sphalerite, pectolite, villiaumite, fluorite, titanomagnetite
Kakortokite	laminated, layered, medium to coarse	alkali feldspar, nepheline, aegirine, arfvedsonite, eudialyte	sodalite, aenigmatite, magnetite, rinkite, fluorite, löllingite, sphalerite, galena
Lujavrite†	laminated, fine-grained; sometimes layered or massive, medium to coarse	microcline, albite, nepheline, sodalite, analcime, naujakasite, aegirine, arfvedsonite,eudialyte,	monazite, britholite, villiaumite, sphalerite, pectolite, steenstrupine, lovozerite, vitusite, polylithionite, ussingite, lueshite, neptunite
Alkali granite, quartz syenite	hypidiomorphic granular, medium to coarse	alkali feldspar, quartz, aegirine, arfvedsonite	aenigmatite, elpidite, zircon, ilmenite, pyrochlore, neptunite, fluorite, sphalerite

* Analcime and natrolite are secondary minerals in most rocks.
† There are several types of lujavrites. Three major groups may be distinguished: *aegirine or green lujavrite* with aegirine being the dominant mafic mineral; *arfvedsonite or black lujavrite*, fine grained, often laminated with arfvedsonite as the dominant mafic mineral; *medium- to coarse-grained lujavrite (M-C lujavrite)* with arfvedsonite as the dominant mafic mineral and generally showing foyaitic textures. *Naujakasite lujavrite* is a variety of arfvedsonite lujavrite containing naujakasite instead of nepheline and with steenstrupine instead of eudialyte.

saq was made by one of the authors (A.P.K.) in the Lovozero alkaline complex, Kola Peninsula, Russia.

The present paper describes the mineralogy and occurrence of naujakasite in the two complexes and discusses the stability relations of the mineral.

Mineralogy

The mineralogical properties of naujakasite from the Ilímaussaq alkaline complex and naujakasite from the Lovozero alkaline complex are compared in Table 1.

X-ray powder diffraction patterns of naujakasites from Ilímaussaq and Lovozero obtained under identical conditions show practically identical sets of lines and relative intensities. The unit cell parameters of naujakasite from Lovozero are almost identical to the parameters determined by Basso *et al.* (1975) for Ilímaussaq (Table 1); see also Khalilov *et al.* 1977).

The chemical analyses of the Ilímaussaq naujakasite published by Bøggild (1933), Petersen (1967) and Semenov (1969) show that it has a very high Fe/Mn ratio: around $Fe_{0.90}Mn_{0.10}$ in the structural formula. The Lovozero mineral, on the other hand, is dominated by Mn. Recalculated on the basis of 26 oxygen atoms, the empirical formula of the naujakasite from Lovozero has $Fe_{0.49}Mn_{0.53}$ (Table 2). The Lovozero mineral is thus the Mn-dominant analogue of the Ilímaussaq

Table 1 (*continued*)

Mineral	Formula	Reference
Cuprite	Cu_2O	López-Soler *et al.* (1975)
Cuprostibite	$Cu_2(Sb,Tl)$	Sørensen *et al.* (1969)
Dahllite, *see* carbonate-hydroxylapatite		
Diaspore	$AlO(OH)$	Ussing (1894)
Digenite	$Cu_{1.8}S$	López-Soler *et al.* (1975)
Djerfisherite	$K_6(Na,Li)(Fe,Cu,Ni)_{24}S_{26}Cl$	Karup-Møller (1978b)
Djurleite *	$Cu_{1.96}S$	Karup-Møller *et al.* (1978)
Dorfmanite	$Na_2(PO_3OH)\cdot 2H_2O$	Petersen *et al.* (1993)
Dyscrasite	Ag_3Sb	López-Soler *et al.* (1975)
Elpidite	$Na_2ZrSi_6O_{15}\cdot 3H_2O$	Ussing (1912)
Ephesite	$NaLiAl_2(Si_2Al_2)O_{10}(OH)_2$	Semenov (2001)
Epididymite	$NaBeSi_3O_7(OH)$	Hamilton (1964)
Epidote	$Ca_2FeAl_2(Si_2O_7)(SiO_4)(O,OH)_2$	Flink (1898)
Epistolite	$Na_5TiNb_2(Si_2O_7)_2(O,F)_4\cdot 5H_2O$	Bøggild (1899)
Erikite ‡		Bøggild (1903), Pekov *et al.* (1997a)
Eudialyte	$Na_{15}Ca_6Fe_3Zr_3Si(Si_{25}O_{73})(O,OH,H_2O)_3(Cl,OH)_2$	Stromeyer (1819)
Eudidymite	$Na_2Be_2Si_6O_{15}\cdot H_2O$	Semenov & Sørensen (1966)
Evenkite * †	$C_{24}H_5$	
Famatinite	Cu_3SbS_4	Karup-Møller (1974)
Fayalite	Fe_2SiO_4	Ussing (1912)
Ferrosalite	$Ca_3Fe_2Mg(Si_2O_6)_3$	Larsen (1976)
Ferropargasite	$NaCa_2(Fe,Mg,Al)_5(Si_6Al_2)O_{22}(OH)_2$	Larsen (1976)
Fersmite	$(Ca,Ce,Na)(Nb,Ta,Ti)_2(O,OH,F)_6$	Petersen *et al.* (1998)
Fluorite	CaF_2	1809 (Giesecke)‡‡
Galena	PbS	1809 (Giesecke)‡‡
Garnet (group)		Flink (1898)
Gelbertrandite * ‡		Semenov (1969)
Genthelvite	$Be_3Zn_4(SiO_4)_3S$	Bollingberg & Petersen (1967)
Gerasimovskite	$(Mn,Ca)(Nb,Ti)_5O_{12}\cdot 9H_2O(?)$	Semenov *et al.* (1967a)
Gmelinite	$Na_4(Al_4Si_8)O_{24}\cdot 11H_2O$	Karup-Møller (1976)
Goethite (limonite)	$FeO(OH)$	1806 (Giesecke)‡‡
Gold	Au	Davison (1989), Bohse & Frederiksen

* Recalculated to 100% assuming all iron present as FeO, and disregarding the results of the thermogravimetric analysis.

† From Petersen (1967).

‡ Analyst: G.N. Nechelyustov. Electron microbe analysis, Superprobe 733.

Empirical formulae

Ilímaussaq:
$(Na_{5.72}K_{0.10})_{\Sigma 5.82}(Fe_{0.74}Mn_{0.15}Ca_{0.05})_{\Sigma 0.94}(Al_{3.91}Si_{8.13})_{\Sigma 12.04}O_{26}$

Lovozero: $Na_{5.96}(Mn_{0.53}Fe_{0.49}Ca_{0.01})_{\Sigma 1.03}Al_{3.95}Si_{8.03})_{\Sigma 11.98}O_{26}$

naujakasite, and manganonaujakasite has been approved as a new mineral by the Commission of New Minerals and Mineral Names of the International Mineralogical Association (Khomyakov *et al.* 2000).

The occurrence of naujakasite in the Ilímaussaq alkaline complex

The first outcrop of naujakasite-bearing rocks was found by one of the authors (H.S.) in the bay of Tupersuatsiaat and described by Danø & Sørensen (1959). Shiny rhomb-shaped flakes of naujakasite, up to 0.2 cm across, are scattered throughout a thin dyke of fine-grained arfvedsonite lujavrite intersecting a lenticular body of naujaite.

Bondam & Sørensen (1958) and Buchwald & Sørensen (1961) described an occurrence of naujakasite lujavrite from an altitude of 400 m in the mountains south of Tupersuatsiaat. Ferguson (1964) reported that naujakasite lujavrite is quite common on Kvanefjeld where it forms minor horizons rarely wider than 50 m and usually only 5–10 m wide. Petersen (1967) presented the first detailed mineralogical description of naujakasite from Tupersuatsiaat and Kvanefjeld.

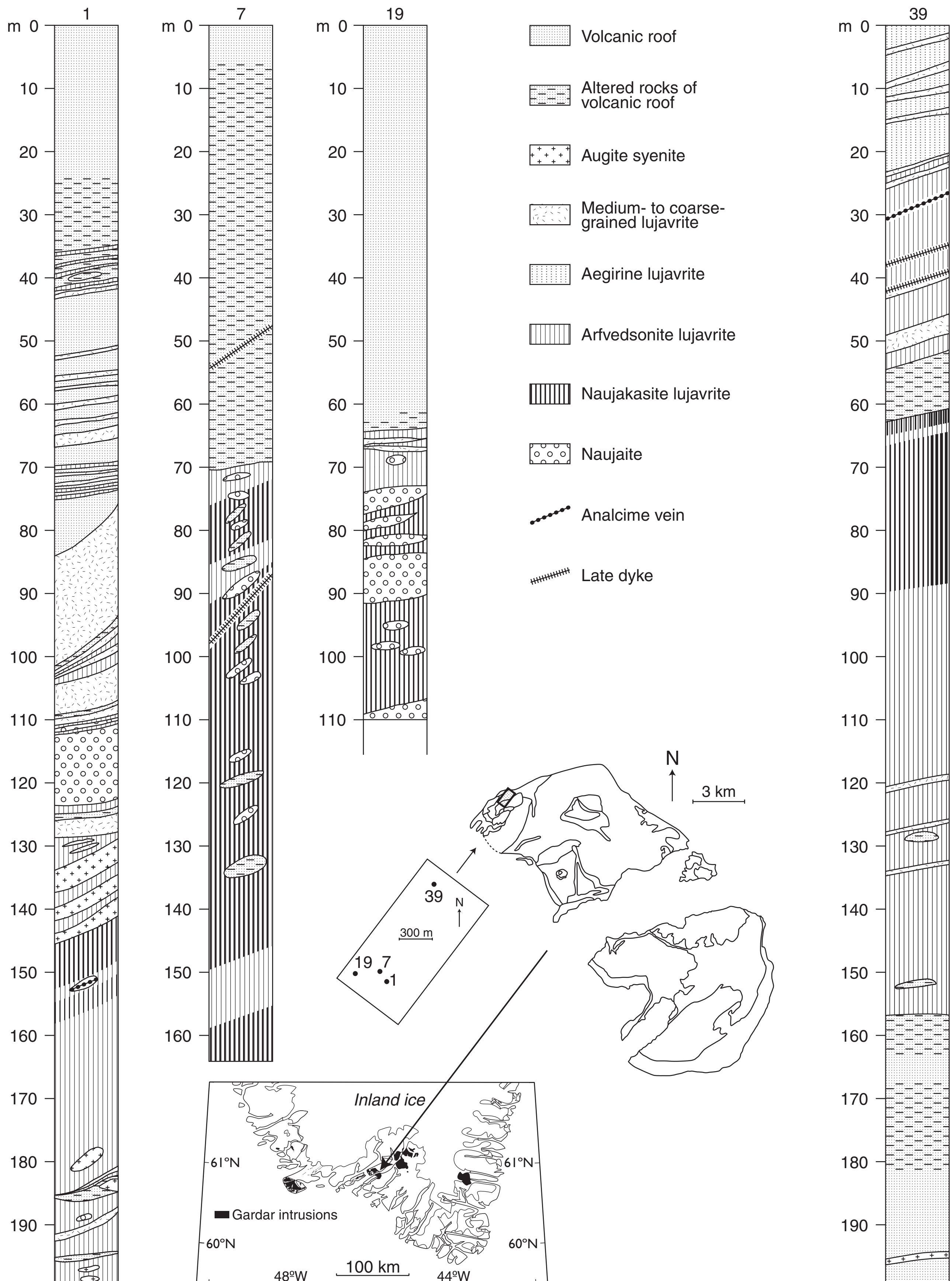
Sørensen *et al.* (1969, 1971, 1974) described the geology of the Kvanefjeld area based on surface mapping and the examination of 42 drill cores from drilling programmes in 1958 and 1969. Several varieties of lujavrites are distinguished (Fig. 1). Naujakasite-bearing lujavrite outcrops in the northernmost part of the Kvanefjeld plateau and at its southern edge in the upper part of the slope facing the Narsaq Elv valley. In the first-named area, there is a succession of lujavrites which form zones running parallel to the contact against the volcanic country rocks to the north. Naujakasite lujavrite occurs as a zone of crumbling, brownish-black lujavrite which is separated from a fine-grained, fissile arfvedsonite lujavrite to the north by a mixed zone made up of alternating bands of these two rock types. The naujakasite lujavrite is ten or more metres wide and can be followed for over a hundred metres. It is intersected by rare veins of green medium- to coarse-grained lujavrite and contains xenoliths of augite syenite, foyaite, naujaite and contact metasomatised volcanic rocks from the roof of the complex. The naujakasite lujavrite in the southern part of the Kvanefjeld plateau occurs mainly as thin sheets intruding naujaite and augite syenite with sharp, but not chilled contacts.

At Tupersuatsiaat and the Taseq slope in the Narsaq Elv valley, naujakasite lujavrite forms minor intrusions in naujaite (Engell 1973).

Petersen & Andersen (1975) described an occurrence of naujakasite located about 1 km south-east of Tupersuatsiaat. They distinguish three modes of occurrence: (1) as an accessory mineral in arfvedsonite lujavrite, that is naujakasite-arfvedsonite lujavrite; (2) as a naujakasite-rich contact facies of lujavrite against a large xenolith of naujaite, containing plates of naujakasite up to 2 cm in size and constituting up to about 75 vol.% of the rock; (3) composite flakes of naujakasite in recrystallised naujaite enclosed in naujakasite lujavrite. The last-named type of naujakasite contains inclusions of nepheline which are arranged in a hexagonal pattern.

The only observation of naujakasite in a hydrothermal vein is reported by Metcalf-Johansen (1977) who found the mineral in an albitite vein in the roof basalt to the east of Kvanefjeld. The vein consists of albite, microcline, aegirine, arfvedsonite, analcime, natrolite, apatite, chkalovite, sphalerite, hemimorphite, willemite, monazite, neptunite and Li-mica. Rhomb-shaped crystals of naujakasite occur in miarolitic cavities in the albitite. These crystals measure 2 × 3 × 0.4 mm.

Nyegaard (1979), Makovicky *et al.* (1980) and Kunzendorf *et al.* (1982) report results of mineralogical and chemical studies of naujakasite lujavrite in cores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Volcanic roof
Altered rocks of volcanic roof
Augite syenite
Medium- to coarse-grained lujavrite
Aegirine lujavrite
Arfvedsonite lujavrite
Naujakasite lujavrite
Naujaite
Analcime vein
Late dyke
N
3 km
39
N
300 m
19 7
1
Inland ice
61°N
60°N
Gardar intrusions
100 km
48ºW
44ºW

from a drilling programme in 1977 in the northernmost part of the Kvanefjeld area.

A re-examination of the drill core logs presented by Sørensen *et al.* (1971) and Nyegaard (1979) shows that naujakasite lujavrite is of widespread occurrence on the Kvanefjeld plateau where lujavrites are in contact with the volcanic roof of the complex (Fig. 1). Almost half of the drill cores contain horizons of naujakasite lujavrite which vary in thickness from a few centimetres to more than 30 m. It is not possible to correlate from core to core as is evident from fig. 8 in Sørensen *et al.* (1974). Naujakasite lujavrite occurs especially in the uppermost part of sheets of arfvedsonite lujavrite, often in contact with overlying naujaite xenoliths and rafts of augite syenite and volcanic rocks from the roof (Fig. 1, cores 1, 39) and may dominate the lujavrite sheets (Fig. 1, core 7). In addition, it forms sheets intersecting xenoliths of naujaite and augite syenite (Fig. 1, core 9). Sheets of naujakasite lujavrite have been observed to depths of 345 m below the present surface.

The Kvanefjeld adit (Nyegaard 1980) intersects large masses of naujakasite lujavrite. The 960 m long adit is nearly horizontal, its opening on the slope facing the Narsaq Elv valley is located at 470 m and its innermost wall at 512 m above sea level, that is 100–150 m below the surface of the Kvanefjeld plateau. According to Nyegaard (1980) the adit intersects naujakasite lujavrite at the intervals 220–450 m, 585–650 m, 690–730 m and 755–880 m, measured from the opening of the adit. A 50 m long side branch at 230 m also intersects naujakasite lujavrite. The naujakasite lujavrite in the adit contains disseminated villiaumite. It also contains xenoliths of naujaite, sodalite foyaite, alkali syenite, augite syenite and sheared and metasomatised lava and gabbro from the volcanic roof, i.e. the same xenolith association as in the surface exposures. The naujakasite lujavrite is seen to intrude into augite syenite, naujaite and large masses of volcanic rocks from the roof, and it is intersected by sheets of medium- to coarse-grained lujavrite.

Whereas the drill cores from the Kvanefjeld plateau are rich in villiaumite and naujakasite lujavrite, six drill cores through lujavrites in the southern part of the complex are without villaumite and naujakasite lujavrite (J. Rose-Hansen & H. Sørensen, unpublished data 2000). Naujakasite lujavrite has, however, as mentioned above, been observed in surface outcrops at Tupersuatsiaat and on the Taseq slope in the Narsaq Elv valley. It therefore appears that in general naujakasite lujavrite occurs in the upper part of the lujavritic sequence of the complex (Sørensen 2001, this volume).

Fig. 1. Logs of selected drill cores from the Kvanefjeld plateau in the northern part of the Ilímaussaq complex (slightly modified from Sørensen *et al.* 1971). The cores illustrate the mode of occurrence of naujakasite lujavrite. **1**: Drill core 1. Development of naujakasite lujavrite at *c.* 145–160 m in the uppermost *c.* 15 m of a thick sheet of arfvedsonite lujavrite which contains xenoliths of augite syenite and altered volcanic rocks from the roof of the complex and is cut by dykes of medium- to coarse-grained lujavrite. Naujaite and augite syenite immediately above the naujakasite lujavrite are cut by arfvedsonite lujavrite without naujakasite. **7**: Drill core 7. Thick sheet of arfvedsonite lujavrite under roof of volcanic rocks contains naujakasite over more than 95 m (below *c.* 75 m depth). There are xenoliths of naujaite and volcanic rocks. **19**: Drill core 19. Sheets of naujakasite lujavrite at *c.* 75–110 m, intersecting naujaite and with xenoliths of that rock. In this core, the arfvedsonite lujavrite in direct contact with the volcanic roof is without naujakasite. **39**: Drill core 39. Thick sheet of arfvedsonite lujavrite in volcanic rocks with naujakasite in the uppermost *c.* 27 m (at *c.* 63–90 m depth) and with xenoliths of volcanic rocks and intersecting veins of medium- to coarse-grained lujavrite. The arfvedsonite lujavrite in the upper part of the drill core is without naujakasite. The cartoon of the intrusion indicates the positions of the drill cores used in the illustration.

Petrography of naujakasite lujavrite from the Ilímaussaq alkaline complex

The unaltered naujakasite lujavrite may be described as a variety of fine- to medium-grained arfvedsonite lujavrite that contains naujakasite and steenstrupine and is poor in or without nepheline and eudialyte. The rock contains separate laths of microcline and albite and acicular grains of arfvedsonite and more rarely aegirine in parallel orientation, resulting in a more or less pronounced igneous lamination. Nepheline, when present, occurs as corroded grains, often in larger grains than the feldspars and mafic minerals and wrapped by these forming a sub-porphyritic texture.

The content of naujakasite varies from a few to more than 75 vol.%. When present as a minor component, the plates of naujakasite are interstitial to the feldspars and arfvedsonite and generally show irregular outlines in thin section (Fig. 2a, b). When present at 10–50 vol.% the plates of naujakasite normally occur as perfectly developed lozenges with well-defined margins. They are of larger size than the other minerals, forming a sub-porphyritic texture recalling the above-mentioned setting of nepheline (Fig. 2c, d). The

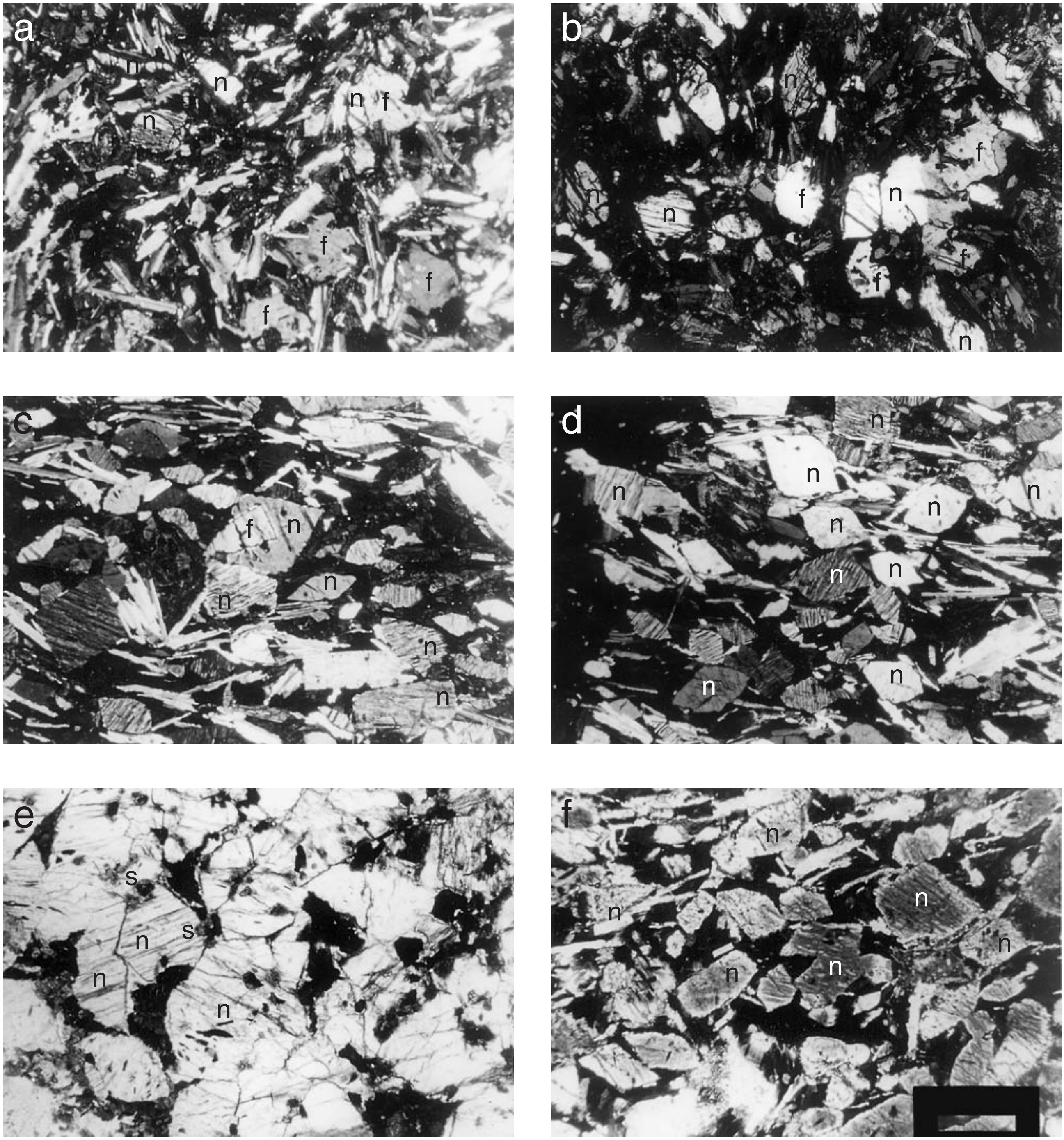

Fig. 2. Photomicrographs showing stages in the formation of naujakasite in arfvedsonite lujavrite; **n**: naujakasite, **f**: nepheline, **s**: steenstrupine. All with crossed polars and scale bar in **f** 0.6 mm. **a**: Small irregularly shaped grains of naujakasite (upper left) in arfvedsonite lujavrite with corroded crystals of nepheline (especially lower right). Drill core 11, Kvanefjeld, at 167.05 m. **b**: Corroded grains of nepheline (centre and centre right) and irregularly shaped grains of naujakasite in matrix of feldspar, arfvedsonite and analcime. Centre right: naujakasite growing on nepheline. Drill core 7, Kvanefjeld, at 112.20 m. **c**: Well-shaped crystals of naujakasite in matrix of dark arfvedsonite and light albite and microcline. Naujakasite crystal in centre overgrows nepheline. Drill core 7, Kvanefjeld, at 110.90 m. **d**: Naujakasite lujavrite with crystals of naujakasite in matrix of dark arfvedsonite, and light albite and minor analcime. Drill core 11, Kvanefjeld, at 130.22 m. **e**: Aggregate of naujakasite crystals with interstitial dark arfvedsonite. The naujakasite encloses tiny grains of arfvedsonite and small crystals of steenstrupine, the latter especially in the marginal parts of the grains. Sample GGU 154364, naujakasite-rich lujavrite in contact with naujaite xenolith, Tupersuatsiaat. **f**: Naujakasite-rich rock in which naujakasite is partially altered into stripes of black pigmentation and analcime. Drill core 7, Kvanefjeld, at 149.95 m.

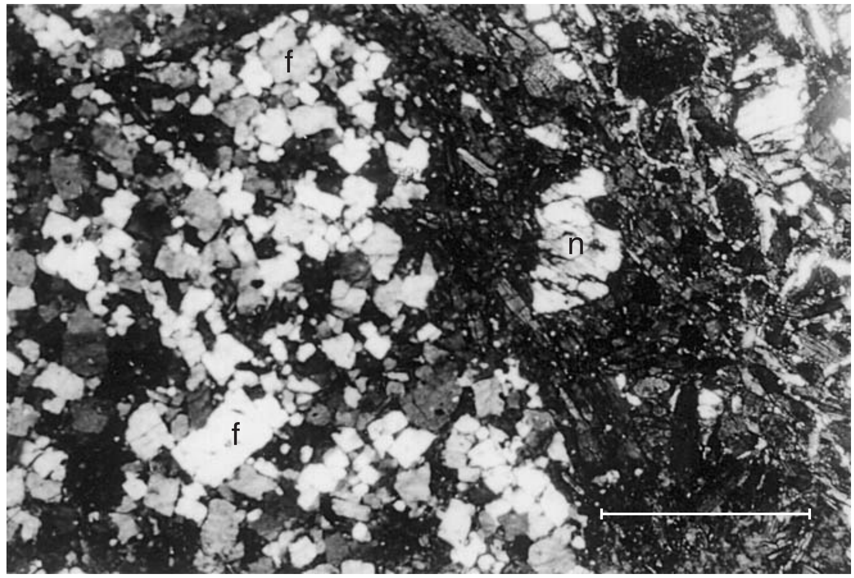

Fig. 3. Fine-grained cumulate of nepheline crystals (**f**) in naujakasite lujavrite with large grains of naujakasite (**n**) in matrix of arfvedsonite, feldspar and analcime. Drill core 11, Kvanefjeld, at 130.22 m. Crossed polars and scale bar 0.6 mm.

naujakasite-rich lujavrites have the appearance of cumulates made up of closely packed plates of naujakasite with interstitial feldspars and arfvedsonite.

The naujakasite plates may have inclusions of arfvedsonite and zoned small crystals of steenstrupine (Fig. 2e), sometimes also of feldspars and aegirine, generally in smaller grains than in the enclosing rock. The steenstrupine crystals are found particularly in the marginal parts of the naujakasite plates (Fig. 2e).

In some drill cores, the naujakasite lujavrite includes cumulate clusters made up of small crystals of nepheline (Fig. 3). The 3 cm diameter of the drill core makes it impossible to decide whether these cumulates form layers or xenoliths in the lujavrite.

The lack of nepheline in the naujakasite lujavrite examined by Danø & Sørensen (1959) and Engell (1973) and the above-mentioned textural similarity between nepheline and naujakasite made these authors propose that naujakasite may have taken the place of nepheline in the naujakasite lujavrite. Early-formed crystals of eudialyte are very rarely seen in the naujakasite-bearing lujavrite, but eudialyte is generally represented by grains which have preserved the outlines of the eudialyte crystals but are made up of ill-defined pigmentary material. In the rocks with pseudomorphs after eudialyte there are small crystals of steenstrupine which, as discussed further below, appear to occur instead of eudialyte. The steenstrupine crystals show concentric yellow and brown zones and may constitute up to 10 vol.% of the rocks. The steenstrupine in some rocks is altered into dark brown or dusted grains. These rocks generally have more than 300 ppm U and are a part of the Kvanefjeld uranium deposit.

Makovicky *et al.* (1980, table 7) list the mineral associations of many lujavritic rocks from the northernmost part of Kvanefjeld examined by them with special emphasis on the steenstrupine in these rocks. In a number of cases, nepheline, naujakasite, eudialyte and steenstrupine are reported to co-exist. There are, however, no descriptions of the textural relationship between these minerals.

Sørensen (1997) examined thin sections of naujakasite lujavrite from the 1958 drill cores. He found that some of these contain strongly corroded grains of nepheline which may be overgrown by naujakasite. Some plates of naujakasite have inclusions of nepheline. The naujakasite is shown to belong to the hyper-agpaitic stage of formation of the Ilímaussaq complex, as is steenstrupine. This is supported by the observation that ussingite in some of the naujakasite lujavrites replaces microcline and that villiaumite, lovozerite and vitusite are minor minerals in some of the rocks. Other accessories are sodalite, sphalerite, pectolite, Li-mica, monazite and neptunite.

The naujakasite lujavrite is generally altered – arfvedsonite is replaced by brown aegirine (acmite in the earlier literature), the feldspars by analcime and perhaps natrolite, and naujakasite by analcime and very fine-grained black pigmentation (Fig. 2f). The end product is a crumbling brown aegirine-rich rock devoid of naujakasite but with textural ghosts of analcime with lines of black pigmentation indicating the former presence of naujakasite.

Table 3. Analyses of rocks representing Ilímaussaq liquids

	1 augite syenite, chilled margin	2 evolved augite syenite, av. of 3	3 Cl-poor sodalite foyaite, av. of 3	4 Fe-rich phonolite dyke	5 Fe-rich phonolite dyke	6 aegirine lujavrite av. of 3	7 arfvedsonite lujavrite av. of 2	8 medium- to coarse-grained lujavrite weighted av.
SiO_2 (wt%)	53.24	62.33	51.01	51.83	52.27	52.38	52.25	52.71
TiO_2	2.44	0.50	0.34	0.55	0.46	0.22	0.23	0.35
ZrO_2	0.04	0.11	0.36	0.55	0.78	0.95	0.25	0.13
Al_2O_3	14.79	15.65	17.38	14.57	14.09	13.20	12.23	13.29
Fe_2O_3	2.64	2.12	4.73	7.56	11.03	10.90	6.06	4.04
FeO	8.66	3.54	4.62	4.61	1.15	1.96	8.72	8.21
MnO	0.24	0.16	0.25	0.48	0.30	0.37	0.64	0.60
MgO	1.60	0.31	0.13	0.14	0.07	0.10	0.12	0.12
CaO	4.94	1.69	1.97	2.54	2.06	1.20	0.27	0.30
Na_2O	4.68	6.74	10.08	8.81	9.27	10.72	9.25	9.20
K_2O	4.26	5.53	3.93	4.87	4.12	2.82	3.23	4.69
P_2O_5	0.74	0.08	0.05	0.08	0.09	0.18	0.54	0.41
H_2O^+	0.29†	0.68	4.19	1.56†	1.18†	3.44	3.65	3.70
H_2O^-	0.19	0.20	0.16	0.47	0.36	0.28	0.24	0.13
CO_2		0.23	0.07			0.09	0.19	0.07
S	0.15	0.00	0.02	0.12	0.03	0.06	0.06	0.14
Cl	0.03	0.01	0.09	0.33	0.08	0.05	0.03	0.05
F	0.10	0.15	0.41	0.84	1.80	0.08	0.14	0.16
others	0.46	0.08	0.31	0.42	0.71	0.89	1.64	1.47
	98.99	100.11	100.10	100.33	99.85	99.89	99.74	99.77
- O	0.12	0.07	0.20	0.49	0.79	0.07	0.10	0.15
	98.87	100.04	99.90	99.84	99.06	99.82	99.64	99.62
A.I.	0.83	1.09	1.20	1.36	1.40	1.57	1.53	1.52
FeO*	11.04	5.45	8.88	11.41	11.08	11.77	14.17	11.85
Zr (ppm)	284	836	2690	4040	5740	7010	1860	939

Analysts: J. Kystol, J.C. Bailey and R. Fuge.

† Loss on ignition corrected for other volatiles where known.

A.I.: Agpaitic index, $(Na_2O+K_2O)/Al_2O_3$ mol.

FeO*: Total Fe as FeO.

1: GGU 153394 (new analysis of sample U-106 from Ussing's collection in the Geological Museum, Copenhagen).
2: Average of GGU 152122, 152130, 154378.
3: Average of GGU 57070, 154303, 154347.
4: Sample GGU 42475 (Larsen & Steenfelt 1974), new analysis.
5: Sample ARM 62/8010 (Martin 1985). New analysis.
6: Average of GGU 152128, 154302, 66143.
7: Average of GGU 152127, 154363.
8: 1:1 average of (a) 3 large surface samples (GGU 154397, 154399, 154724) and (b) 21 smaller samples from drill cores.
GGU prefixed to sample numbers: samples in the collections of the Geological Survey of Denmark and Greenland.

Petrochemistry

Chemical analyses of naujakasite lujavrite have been reported by Gerasimovsky (1969), Engell (1973), Kunzendorf *et al.* (1982) and Sørensen (1997). Some new analyses are presented in Table 3. The rock is characterised by very high contents of Na_2O, up to 15 wt% and even higher in villiaumite-bearing naujakasite lujavrite (Kunzendorf *et al.* 1982). This gives normative values of *ne* 10–20% and of *ac c.* 10%, but as much as 28% in the altered rocks rich in brown aegirine. Normative *ns* is *c.* 10%, but *c.* 14% in villiaumite-bearing rocks and as low as 3% in the altered rocks in which naujakasite is replaced by analcime.

Gerasimovsky (1969), Andersen *et al.* (1981) and Kunzendorf *et al.* (1982) reported trace element analyses of naujakasite lujavrite. Additional data are presented in Table 3. Naujakasite lujavrite shares the highly fractionated character of trace element patterns found in all lujavrites at Ilímaussaq: high contents of Cs, Rb, Pb, REE (especially LREE), Th, U, Li, Zn, Ga, Be, Sn and Sb, and low contents of Sr, Co and Sc (cf. Bailey *et al.* 2001, this volume). Other elements which have been extensively removed at earlier agpaitic stages of the Ilímaussaq evolution by fractionation of sodalite (Cl) and eudialyte (Zr, Hf, Nb and Ta) only occur in moderate concentrations in naujakasite lujavrite. The naujakasite lujavrites differ from the arfvedsonite lujavrites in higher contents of Na, Mn, Fe, Th, U, Zn and P, and in lower contents of K, Sr, Zr, Hf and Nb. There appears to be a continuous transition from agpaitic to hyper-agpaitic rocks without any sharp change in physico-chemical conditions.

Naujakasite lujavrite and medium- to coarse-grained lujavrite are the two latest and most evolved types of lujavrite (see Sørensen 2001, this volume). Their hyper-agpaitic character is seen geochemically in (1) the high agpaitic index (1.5–2.0), (2) the replacement of eudialyte indicators (high Ca, Sr, Zr and Hf) by steenstrupine indicators (high P, REE, Y, Th and U) and (3) the medium- to coarse-grained lujavrite, when compared with the naujakasite lujavrite, shows higher contents of K, Cs, Rb, Li, Be, Ti and Nb and lower contents of Na, Mn, REE, Y, Zr, Hf, Th, U and Pb (unpublished data). The ratio LREE/HREE is markedly lower in the naujakasite lujavrite. Naujakasite lujavrite seems more evolved in its lower Zr/U and Zr/Y ratios (Andersen *et al.* 1981), whereas medium- to coarse-grained lujavrite seems more evolved in its lower K/Rb and Y/U ratios. This difference in behaviour of trace elements in the two most evolved types of lujavrite most probably reflects a difference in composition of the volatile phase in strongly sodic and potassic-sodic systems.

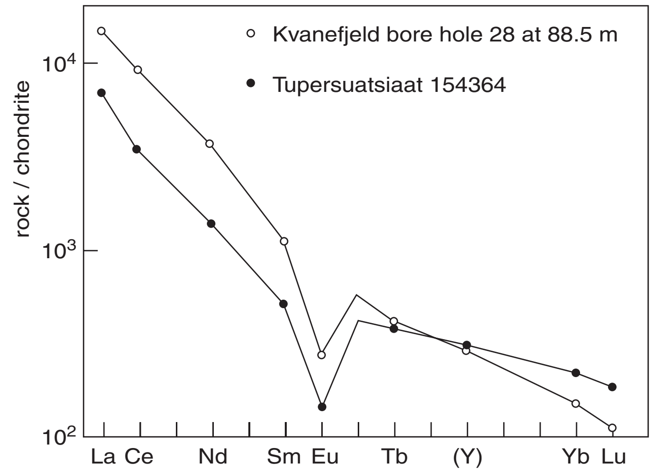

Fig. 4. Chondrite-normalised (Masuda *et al.* 1973) REE diagram of the new analyses of naujakasite lujavrite. The pronounced Eu anomaly is common to all agpaitic rocks of the Ilímaussaq complex.

Naujakasite lujavrite from both Tupersuatsiaat and Kvanefjeld is most readily distinguished from all other lujavrites at Ilímaussaq by the high levels of Na, Na/K, Fe^T (total iron) and Mn, i.e. features which can be attributed to the chemistry of naujakasite itself. Compared to the naujakasite lujavrite from Tupersuatsiaat, those from Kvanefjeld have a more evolved geochemistry with higher levels of P, Cs, Rb, REE, Y and La/Lu but lower levels of Mg, Zr, Hf, Ta, Co and K/Rb. It is worth noticing that Th, U, Nb, Li and Be contents are comparable at the two localities. At Tupersuatsiaat, the REE pattern shows a considerable change in slope between the steep LREE and the less steep HREE (Fig. 4). At Kvanefjeld, the slope is steep throughout the pattern. At Tupersuatsiaat, slightly higher levels of Mn and Mn/Fe^T and lower K and K/Na probably reflect the greater abundance of naujakasite in the two analysed samples from this locality.

Zeolitized samples of naujakasite lujavrite from Kvanefjeld are distinguished by a fall in the agpaitic index but a rise in levels of volatiles, K/Na, Fe^{3+}/Fe^{2+}, Cs, Th/U and Th/P.

A comparison of Ca–Na–K relations (atomic) in various lujavrites at Ilímaussaq is seen in Fig. 5. The low Ca proportions of the arfvedsonite lujavrite and the medium- to coarse-grained and naujakasite lujavrites are due to extensive fractionation of eudialyte. The more or less steady advance of Na/K ratios through-

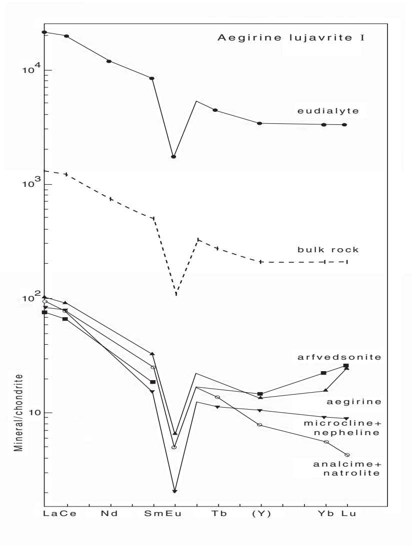

Fig. 5. Na–K–Ca (atomic) diagram showing plots of the various types of lujavrite from the Ilímaussaq alkaline complex and average values for the nepheline syenites of the Ilímaussaq (**I**), Khibina (**K**) and Lovozero (**L**) complexes (authors' compilation). The dashed curve with arrows is the liquid line of descent for the Ilímaussaq complex (based on data in Bailey *et al.* 2001, this volume).

out the Ilímaussaq liquids, which reflects prolonged extraction of microcline, comes to an end in the lujavrites where the arfvedsonite lujavrites and aegirine lujavrites have approximately similar Na/K ratios. The naujakasite lujavrites typically plot between arfvedsonite lujavrite and the composition of naujakasite in Fig. 5. Some scatter of analyses reflects (1) varying amounts of naujakasite, (2) variable proportions of albite and microcline in the matrix and (3) subsequent alteration to analcime. The final agpaitic rock type at Ilímaussaq, the microcline-rich medium- to coarse-grained lujavrite, is characterised by a sharp decrease in Na/K ratios.

Naujakasite lujavrite marks the culmination of Mn contents (av. 0.70 wt%) and Mn/Fe^T ratios (0.08) at Ilímaussaq. These features can be attributed to the high level of Mn (0.85 wt%) and Mn/Fe^T (0.17) in naujakasite and constitute a subdued reflection of the manganiferous naujakasite at Lovozero.

The new occurrence of naujakasite in the Lovozero alkaline complex

Naujakasite was found by one of the authors (A.P.K.) on Mount Alluaiv in the Lovozero complex in a *c.* 1 m thick zone of intensely mineralised medium-grained lovozerite-lomonosovite lujavrite, which occurs in the eudialyte lujavrite of intrusive phase III of the complex (cf. Gerasimovsky *et al.* 1974). These rocks were encountered in a drill core sample recovered from a depth of about 250 m below the surface. Although the rocks contain readily hydrolysable and water-soluble minerals and the core boxes have been stored in the open air for more than ten years, the cores are still well preserved, although covered by a crust of white opal-like material up to 2 mm thick. Freshly fractured lovozerite-lomonosovite lujavrite consists of vuggy, irregularly shaped aggregates with an irregular lamellar structure, composed mainly of alkali feldspar laths. Interstices between the feldspar laths contain smaller segregations of partially dissolved villiaumite and grains of sodalite, nepheline, analcime, aegirine (fibrous and acicular), lovozerite, and a whole series of other less common minerals, such as tisinalite, lamprophyllite, manaksite, nordite, umbozerite, sphalerite, and molybdenite. Lomonosovite occurs as oikocrysts up to 1 cm across which poikilitically enclose the aforementioned minerals.

The naujakasite is scattered among the interstitial minerals as irregularly shaped grains 0.5 to 1 mm in size, occasionally with a well-defined pinacoid {001}. Less commonly, it occurs as oikocrysts up to 5 mm across pierced by alkali feldspar laths and aegirine needles. It also contains inclusions of euhedral tabular vuonnemite crystals. Against the light grey background of the rocks, naujakasite stands out markedly owing to its bright blue colour and its typical mirror-like or pearly lustre along the plane of perfect mica-like cleavage (001).

Discussion

The new data on the Lovozero naujakasite and published and new data on the Ilímaussaq naujakasite indicate that many minerals associated with naujakasite in the two complexes are characteristic of the special type of alkaline rock distinguished as hyper-agpaitic (Khomyakov 1990, 1995, 2001, this volume; Sørensen 1997; Sørensen & Larsen 2001, this volume). Eudialyte, which is a typical mineral of moderately alkaline agpaitic rocks, has not been found in association with the Lovozero naujakasite and is rarely present in the naujakasite lujavrite of Ilímaussaq. Under conditions of ultra-high alkalinity, eudialyte becomes unstable and is substituted by zirconium minerals with higher contents of alkali metals such as zirsinalite or by steenstrupine. Zirsinalite is substituted by lovozerite with decreasing alkalinity and hydration (Khomyakov 1990, 1995). In view of this, naujakasite may, as proposed by Sørensen (1997), be regarded as one of the most characteristic minerals of hyper-agpaitic rocks.

The agpaitic index of naujakasite (Na/Al = 1.5) is only slightly lower than that of the most agpaitic sodium aluminosilicate ussingite (Na/Al = 2). Naujakasite accumulations tend to occur in rocks of the main intrusive phases, whereas ussingite is largely confined to post-magmatic and hydrothermal rocks and to late stages of formation of the naujakasite lujavrite. An examination of primary gas–liquid inclusions in minerals of hyper-agpaitic pegmatites in the Lovozero complex indicates that ussingite crystallised over the temperature range 305–165°C (Shchegoleva *et al.* 1988).

Nepheline–naujakasite relations

The relationship between nepheline and naujakasite presents a special problem. At Ilímaussaq, nepheline is evidently unstable under the hyper-agpaitic conditions reigning during the formation of the naujakasite lujavrite. The occurrence in some naujakasite lujavrite samples of corroded grains of nepheline and platy crystals of naujakasite, and the co-occurrence of pseudomorphs after eudialyte and crystals of steenstrupine, indicate that hyper-agpaitic conditions developed gradually during the consolidation of the rock and that there was a short period of co-existence of nepheline and naujakasite but with nepheline rapidly becoming unstable and naujakasite taking over. The subsequent replacement of naujakasite by analcime shows declining hyper-agpaitic conditions. This rise and fall in alkalinity is a characteristic feature of hyper-agpaitic rocks (Khomyakov 1995).

The nepheline grains in the naujakasite lujavrite are sometimes overgrown by naujakasite or may be enclosed in naujakasite plates (Fig. 2c). Petersen & Andersen (1975) have, for instance, shown that plates of naujakasite in a naujaite xenolith enclosed in naujakasite lujavrite have inclusions of nepheline arranged in such a way that the original hexagonal shape of the nepheline grains may be traced. This last observation made A. Finch suggest (personal communication 2000) that there is a topotactic relationship between nepheline and naujakasite, the latter being formed by adaptation of the structure of the former as a result of exchange of elements via a fluid phase. Finch furthermore points out that the crystal structure of naujakasite determined by Basso *et al.* (1975) may be derived from the crystal structure of nepheline: "In the *a-c* plane, the nepheline structure consists of rings of six tetrahedra with apices pointing up and down alternately, a feature common to the same plane in naujakasite. However, in nepheline, the rings are interconnected on all sides to other hexagonal rings forming a flat sheet of rings perpendicular to (0001). In naujakasite, the hexagonal layers are joined to each other by bridging rings of four tetrahedra, forming a chain rather than a sheet. The structure of naujakasite may be derived from that of nepheline by considering the structure first perpendicular to (0001) for the hexagonal rings, and then perpendicular to (1000) for the four-membered rings. The structure of naujakasite therefore represents a zig-zag slice through that of nepheline. The planes, along which disconnection of the 'naujakasite' part of the structure must take place, are parallel to the directions {0001} and {1122}. These are interestingly the two possible cleavages in the nepheline structure, and indicate that metasomatic 'fracturing' of the nepheline structure would provide a naujakasite-type 'framework'" (A. Finch, written communication 2000). A topotactic relationship between nepheline and naujakasite is a possible background for the above-mentioned observation of inclusions of nepheline in naujakasite in metasomatically altered naujaite in contact with naujakasite lujavrite, as will be discussed further below. But the overgrowths of naujakasite on nepheline described by Sørensen (1997) and reported in the present paper (Fig. 2b, c) would rather indicate a reconstructive type of relationship between naujakasite and nepheline, i.e. formation of a new crystal structure.

The role of potassium

The fact that naujakasite is an important rock-forming mineral in the Ilímaussaq complex and very rare or non-existent in the Lovozero and Khibina complexes cannot be ascribed solely to differences in alkalinity during the formation of the three complexes. In Lovozero and Khibina, there are rocks that formed at similar or even more hyper-agpaitic conditions than the Ilímaussaq naujakasite lujavrites, but without naujakasite. Some Khibina rocks, e.g. the rischorrites (nepheline syenites in which nepheline is poikilitically enclosed in microcline perthite and with biotite, aegirine augite and opaque minerals) contain natisite, Na_2TiSiO_5. The synthetic analogue of this mineral crystallises only from melts with a NaOH concentration of 38 to 100%, i.e. under extremely high alkalinity. These same rocks contain delhayelite, $Na_2K_3Ca_2AlSiO_{19}(F,Cl)_2$, and altisite, $Na_3K_6Ti_2Al_2Si_8O_{26}Cl_3$, with agpaitic indices, respectively, of 5 and 4.5, and other highly alkaline minerals, but naujakasite is absent.

The Khibina–Lovozero rocks contain a whole series of peralkaline minerals that are absent in Ilímaussaq. Such an endemic mineral, which is virtually unknown outside Khibina, is fenaksite, $NaKFeSi_4O_{10}$. This mineral is of interest in that its hypothetical Na analogue, $Na_2FeSi_4O_{10}$, is a key component which, when combined with the nepheline composition, would yield naujakasite:

$$Na_2FeSi_4O_{10} + 4NaAlSiO_4 = Na_6FeAl_4Si_8O_{26}$$

A reaction between the hypothetical pure Na manaksite, $Na_2MnSi_4O_{10}$ and the nepheline composition would yield manganonaujakasite, $Na_6MnAl_4Si_8O_{26}$. Fenaksite and manaksite may accordingly be regarded as the 'antipodes' of naujakasite and managanonaujakasite. All these four minerals are indicators of hyperagpaitic conditions.

A fundamental difference between the hyper-agpaitic rocks of Ilímaussaq and Khibina is that the former are predominantly sodic and the latter are sodic-potassic. The importance of a high content of Na for the formation of naujakasite is corroborated by the extreme Na/K (atomic) ratio of 3.08 for the average composition of the nepheline syenites of Ilímaussaq, whereas the Na/K ratio for 136 bodies of nepheline syenites generally varies between 0.3 and 2.5 (authors' compilation). Averages for Khibina (1.27) and Lovozero (1.67) fall within this range. The average Na/K ratio of the naujakasite lujavrite is 4.56. K-deficient conditions seem to be favourable for the formation of naujakasite, whereas under K-rich conditions, Fe is bound in $NaKFeSi_4O_{10}$ preventing the formation of naujakasite. Lovozero represents an intermediate case which may explain the co-existence of manganonaujakasite and manaksite in the same rock. Potassium appears to be an inhibitor not only for the formation of naujakasite but also for ussingite which is almost entirely absent in the hyper-agpaitic rocks of Khibina.

Nepheline, which is stable in hyper-agpaitic rocks of Na-K composition in Khibina and Lovozero, is unstable in a hyper-sodic environment. This fact, coupled with the aforementioned relationships, explains why nepheline is readily substituted by naujakasite in large volumes of rocks, and why naujakasite is endemic to Ilímaussaq.

Metasomatic relations

The preceding discussion has only considered naujakasite as a rock-forming mineral formed during crystallisation of hyper-agpaitic lujavritic melts. It should, however, be pointed out that naujakasite has also been observed as a metasomatically formed mineral in naujaite xenoliths in naujakasite lujavrite (Petersen & Andersen 1975), where it appears to replace nepheline in a topotactic way, and as a hydrothermally formed mineral in albitite veins in the roof of the Ilímaussaq complex (Metcalf-Johansen 1977). This most probably reflects that there is a gradual transition from magmatic to hydrothermal conditions in hyper-agpaitic systems.

Petrology

There appears to be a gradual transition from arfvedsonite lujavrite to naujakasite lujavrite. Small flakes of naujakasite with irregular outlines begin to appear in arfvedsonite lujavrite containing corroded grains of nepheline and almost unaltered crystals of eudialyte. With increasing contents, naujakasite may overgrow the nepheline grains. At this stage, eudialyte is altered into brown to black pigmentary material, and zoned steenstrupine crystals become an important constituent. With still further evolution nepheline disappears and well-developed crystals of naujakasite become the dominant mineral. At the most evolved stage, the rocks are made up of densely packed crystals of naujakasite in a cumulate-like manner. It thus appears that naujakasite may be formed partly by a continuous process during which nepheline is dissolved and naujakasite is formed interstitially, and partly as a liquidus phase in highly evolved lujavritic melts when contents of Na and Fe have reached levels which inhibit crystallisation of nepheline and favour the formation of naujakasite.

The fact that the naujakasite lujavrite occurs in the uppermost part of the lujavrite sequence of the complex and is concentrated in the upper part of thick sheets of nepheline-rich arfvedsonite lujavrite below larger masses of naujaite, augite syenite and volcanic rocks is indicative of upwards migration in the magma of volatiles rich in Na, Th, U, etc. and a concentration of volatiles in the uppermost part of the magma beneath the impermeable roof. This results in conditions favouring the crystallisation of naujakasite as a liquidus mineral. In view of the very evolved character of the melts it may be imagined that naujakasite is formed at relatively low temperatures (cf. Sørensen & Larsen 2001, this volume). Fe^{2+} and Mn^{2+} are important components of the naujakasite structure suggesting that redox conditions may also be of significance for the formation of naujakasite.

The rare occurrence of naujakasite in metasomatically altered naujaite and in albitite veins indicates that naujakasite is also stable in high-temperature hydrothermal fluids which have escaped from the Na-rich lujavrite magma.

Conclusions

Naujakasite is an important rock-forming mineral in a type of lujavrite in the Ilímaussaq alkaline complex, the so-called naujakasite lujavrite which may contain more than 75 vol.% of this mineral. Naujakasite has not been found in the intensively studied Khibina complex and is a very rare mineral in the Lovozero complex where the variety manganonaujakasite has been found. The reason for the practical non-existence of naujakasite in the two Kola complexes and the abundance in the Ilímaussaq complex may be the extremely sodic composition of the hyper-agpaitic rocks of Ilímaussaq, whereas the Kola hyper-agpaitic rocks are sodic-potassic. K-deficient conditions are favourable for the formation of naujakasite, whereas under K-rich conditions surplus Fe is bound in fenaksite, $NaKFeSi_4O_{10}$. The Na analogue of fenaksite, $Na_2FeSi_4O_{10}$, combined with the nepheline composition yields the composition of naujakasite.

The frequent occurrence of naujakasite lujavrite in the upper parts of arfvedsonite lujavrite sheets, where these are overlain by impermeable xenoliths of naujaite, augite syenite and volcanic rocks from the roof, indicates that volatile transfer processes may have played an important role in concentrating Na, Fe, Mn, Th, U, P, etc. in the uppermost parts of the magma masses, thus creating the hyper-agpaitic conditions favouring the formation of naujakasite and steenstrupine. There appears to be a gradual transition from nepheline-bearing arfvedsonite lujavrite to nepheline-free naujakasite lujavrite, an indication of a continuous process of building-up hyper-agpaitic conditions of crystallisation.

In conclusion, the reason for the virtual restriction of naujakasite, a mineral composed of common elements, to the Ilímaussaq alkaline complex is the attainment at late stages of agpaitic crystallisation of hyper-agpaitic conditions characterised by exceptionally high Na/K ratios and high contents of Fe and Mn which make naujakasite stable at the expense of nepheline. Naujakasite has a narrow field of stability and is substituted by analcime with declining alkalinity and temperature.

Acknowledgements

The authors are grateful to I.I. Kudryashov, Chief Geologist of the Lovozero Geological Prospecting Expedition, for the opportunity to sample drill cores for mineralogical investigations, to G.N. Nechelyustov, All-Russia Institute of Mineral Resources, Moscow, for the chemical analysis of manganonaujakasite, and to A. Finch, University of St. Andrews, UK, for information about his ideas on naujakasite formation. The project was supported by The International Association for the Promotion of Co-operation with Scientists from the Independent States of the Former Soviet Union (INTAS 93-1474).

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