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Distribution of characteristic elements in the radioactive rocks of the northern part of Kvanefjeld, Ilímaussaq intrusion, South Greenland

by

Helmar Kunzendorf, Per Nyegaard and Bjarne Leth Nielsen

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Abstract

About 600 one-metre drill core sections from lujavrites and country rock xenoliths of northern Kvanefjeld were analysed for Li, Be, F, Na, K, Ca, Ti, Mn, Fe, Cu, Zn, Y, Zr, Nb, Pb, Th and U. The samples were taken from 7 of the 23 drill cores of the 1977 drilling operations.

The analysed rocks were divided into seven rock groups: (1) naujakasite lujavrite, (2) naujakasite lujavrite with visible villiaumite, (3) arfvedsonite lujavrite, (4) arfvedsonite lujavrite with visible villiaumite, (5) volcanic rocks (lava and gabbro), (6) sheared volcanic rocks, and (7) sheared volcanic rocks with visible Nb minerals.

Naujakasite lujavrite (both groups) has high concentrations of Th, U and Y at relatively low Zr contents. Arfvedsonite lujavrite (both groups) has high Zr contents but lower contents of Th, U and Y than naujakasite lujavrite. Thorium, U and Y generally accumulate at upper levels of lujavrites, mostly at the contact to xenoliths. This is thought to be caused by temperature gradients at the contacts. Zirconium enrichment occurs at lower levels of mainly arfvedsonite lujavrites expressing gravity settling of eudialyte during crystallisation.

Naujakasite lujavrite is regarded as the youngest and most differentiated lujavrite.

Microscopic and chemical investigations of two transition zones of lava and gabbro at contacts with lujavrites revealed typical features of metasomatic action, i.e. formation of aegirine, arfvedsonite, albite, microcline, pectolite and other minerals. A general increase of sodium from the unaffected volcanic rocks towards the lujavrite contact is accompanied by a depletion of silicon and other elements. Niobium mineralisation is confined to sheared marginal zones of country rock xenoliths.

Resource evaluation for Zr, Nb, Zn, Be, F, Li and rare earth elements of the rocks of northern Kvanefjeld suggest Nb and rare earth elements as potential by-products of a possible uranium extraction process of the Kvanefjeld ore, while F should be extracted for mainly environmental reasons.

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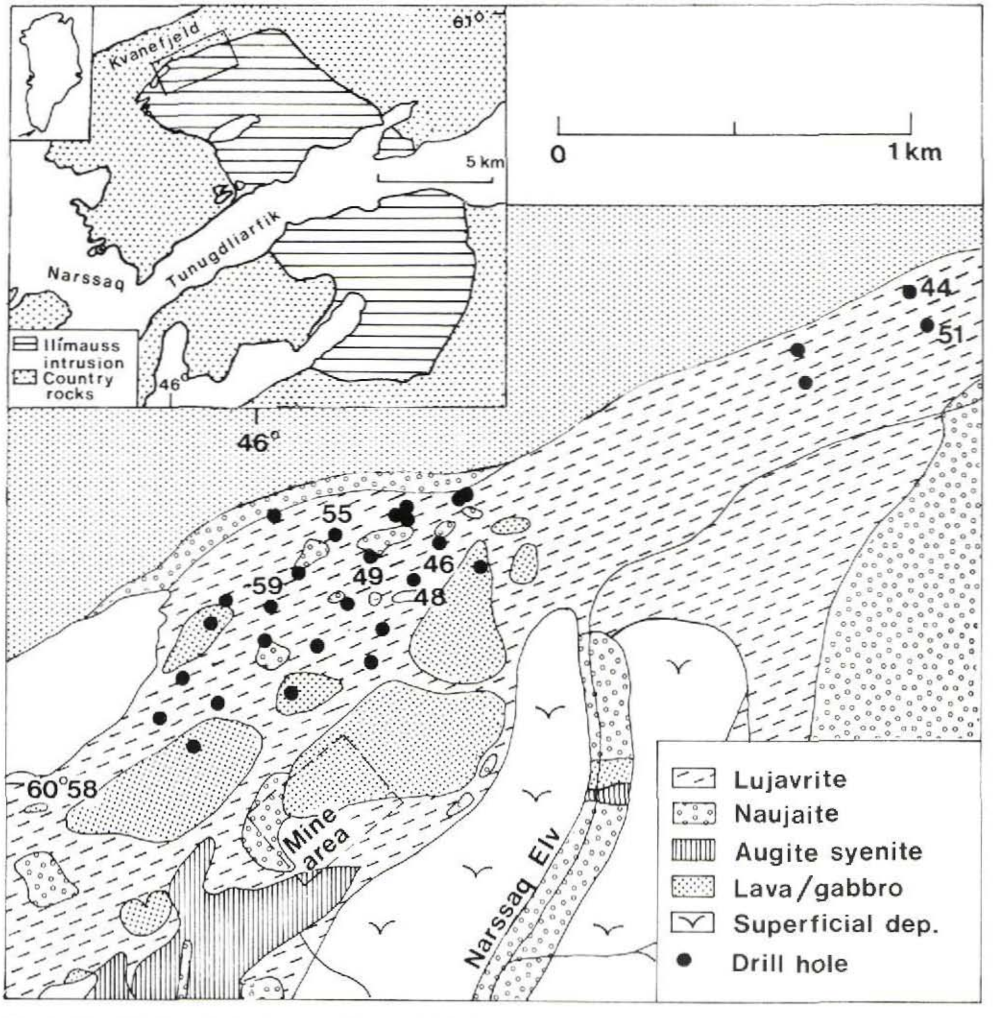


Fig. 1. Simplified geological map of Kvanefjeld, Ilímaussaq intrusion, South Greenland. Black circles with numbers indicate the drill holes investigated.

INTRODUCTION

Previous drilling at the Kvanefjeld uranium prospect, South Greenland, proved some 6000 metric tons of uranium in reasonably assured resources with an average grade of about 0.03 per cent U in lujavrites (nepheline syenites) in the central part (mine area) of the mineralised area (Sørensen *et al.*, 1969, 1974). In the latter publication, an attempt was made to evaluate the potential of other metals of possible economic value which are associated with the radioactive rocks. These metals include Li, Be, Zn and Nb. Because of the occurrence of villiaumite (NaF) in the lujavrites, a discussion on the amounts of fluorine present in the rocks, and released by natural leaching processes into the nearby environment, was also given by these authors.

Further drilling in 1977 in the northern and northeastern part of Kvanefjeld added significant amounts to the known tonnage of uranium. The total figures for the deposit are at present 27 000 metric tons uranium as reasonably assured resources and 16 000 metric tons uranium as estimated additional resources, calculated on the basis of a cut-off grade of 250 ppm U (Nyegaard, 1979; Løvborg *et al.*, 1980). The average grade of the ore is 340 ppm U.

Because of the large increase in the resource figures an estimate of other elements in the ore is of importance for the overall judgement of the deposit, for the development of the extraction methods, and for environmental considerations. Seven of the drill cores from the latest drilling at Kvanefjeld were therefore chosen for systematic geochemical investigation. Their location is shown in fig. 1. We report here on the analysis of Li, Be, F, Na, K, Ca, Ti, Mn, Fe, Cu, Zn, Y, Zr, Nb, Pb, Th and U in about 600 samples from drill core sections and discuss their distribution in lujavrites and country rock xenoliths. A few lujavrites were investigated mineralogically and these results are also discussed. An estimate of the total amounts of Be, Li, F, Zn, Y (including rare earth elements), Zr, and Nb present in the Kvanefjeld area using a similar tonnage calculation method to that outlined by Nyegaard (1979) is included.

GEOLOGICAL SETTING

The Kvanefjeld area, 3 km^2 in size, belongs to the Ilímaussaq alkaline complex which comprises a series of alkaline and peralkaline syenites, and granites (Ussing, 1912; Sørensen, 1958; Ferguson, 1964). It is situated at the northern margin of the intrusion close to the contact against continental lavas and sandstones of the Eriksfjord Formation (Poulsen, 1964; Larsen, 1977). Table 1 outlines the various rocks types present at Kvanefjeld and includes remarks on their texture and mineralogy.

The latest rocks to be formed during the differentiation of the Ilímaussaq magma were agpaitic nepheline syenites ($Na+K>Al$) termed lujavrites. The lujavrite magma intruded overlying syenites and country rocks, and in the Kvanefjeld area numerous xenoliths of the

Table 1. Description of rock types from the Kvanefjeld area

Rock type	Short characterisation	Mineral assemblage: Essential	Mineral assemblage: Accessory
Anorthosite	massive, coarse-grained rock	plagioclase $An_{50\text{-}60}$, pyroxene	iron oxide, apatite
Augite syenite	massive, medium- to coarse-grained rock	Alkali feldspar, ferro-salite, titanomagnetite, olivine	biotite, apatite
Alkali syenite	massive, fine- to coarse-grained rock	microcline, albite, arf-vedsonite, aegirine	neptunite, pectolite
Pulaskite	massive, coarse rock	alkali feldspar, alkali pyroxene, alkali amphibole, nepheline	apatite, fayalite, mag-netite, sodalite, heden-bergite
Sodalite fayaite	massive, coarse-grained rock	alkali feldspar, nephe-line, sodalite, alkali pyroxene, alkali amphibole	eudialyte, apatite, fayalite, magnetite, hedenbergite
Naujaite	poikilitic, coarse-grained rock	sodalite, nepheline, alkali feldspar, alkali pyroxene, alkali amphibole, eudialyte	rinkite, villiaumite, apatite, fayalite, mag-netite, hedenbergite
Lujavrite	laminated, fine-grained rock	microcline, albite, nepheline, arfvedsoni-te, aegirine, analcime, naujakasite	eudialyte, monazite, lovozerite, steenstru-pine, sphalerite, Li-mi-ca, villiaumite
Lujavritic pegmatite	massive, medium- to coarse-grained rock	microcline, albite, nepheline, arfvedsoni-te, aegirine, analcime	steenstrupine, monazite, sphalerite

Table 2. Important minerals of the Kvanefjeld area that carry elements of economic interest

Mineral	Formula	Li	Be	F	Zr	Nb	REE	Th	U	Zn
Aegirine	$NaFe^{3+}Si_2O_6$				+					
Arfvedsonite	$Na_{2\text{-}3}(Fe,Mg,Al)_5Si_8O_{22}$	+			+					
Astrophyllite	$(K,Na)_3(Fe,Mn)_7Ti_2Si_8O_{24}(O,OH)_7$				+	+				
Britholite	$(Ca,Ce)_5(SiO_4,PO_4)_3(OH,F)$						+	+		
Chkalovite	$Na_2BeSi_2O_6$		+							
Epistolite	$Na_2(Nb,Ti)_2Si_2O_9 \cdot nH_2O$					+				
Eudialyte	$Na_4(Ca,Fe,Ce,Mn)_2ZrSi_6O_{17}(OH,Cl)_2$				+	+	+			
Lepidolite	$K(Li,Al)_3(Si,Al)_4O_{10}(F,OH)_2$	+								
Lueshite	$NaNbO_3$					+				
Monazite	$(Ce,La,Y,Th)PO_4$						+	+	+	
Murmanite	$Na_2(Ti,Nb)_2Si_2O_9 \cdot H_2O$					+				
Neptunite	$(Na,K)_2(Fe^{2+},Mn,Ti)Si_4O_{12}$	+				+				
Niobophyllite	$(K,Na)_3(Fe,Mn)_7(Nb,Ti)_2Si_8(O,OH,F)_{31}$					+				
Pyrochlore	$(Na,Ca,U)_2(Nb,Ta,Ti)_2O_6(OH,F)$					+		+	+	
Rinkite	$(Na,Ca,Ce)_3Ti(SiO_4)_2F$			+		+	+		+	
Sorensenite	$Na_4SnBe_2Si_6O_{16}(OH)_4$		+							
Sphalerite	ZnS									+
Steenstrupine*	$Na_{12\text{-}x}H_xCa(La,Ce,Nd)_6(Mn,Fe,Th,Zr,U)_5(Si_6O_8)_2[(P,Si)O_4](OH,Cl) \cdot nH_2O$		+				+	+	+	
Thorite	$ThSiO_4$							+	+	
Tugtupite	$Na_4BeAlSi_4O_{12}Cl$		+							
Villiaumite	NaF			+						

*A modified formula was given by Makovicky *et al.* (1981).
The chemical formulas are those of Roberts *et al.* (1974).

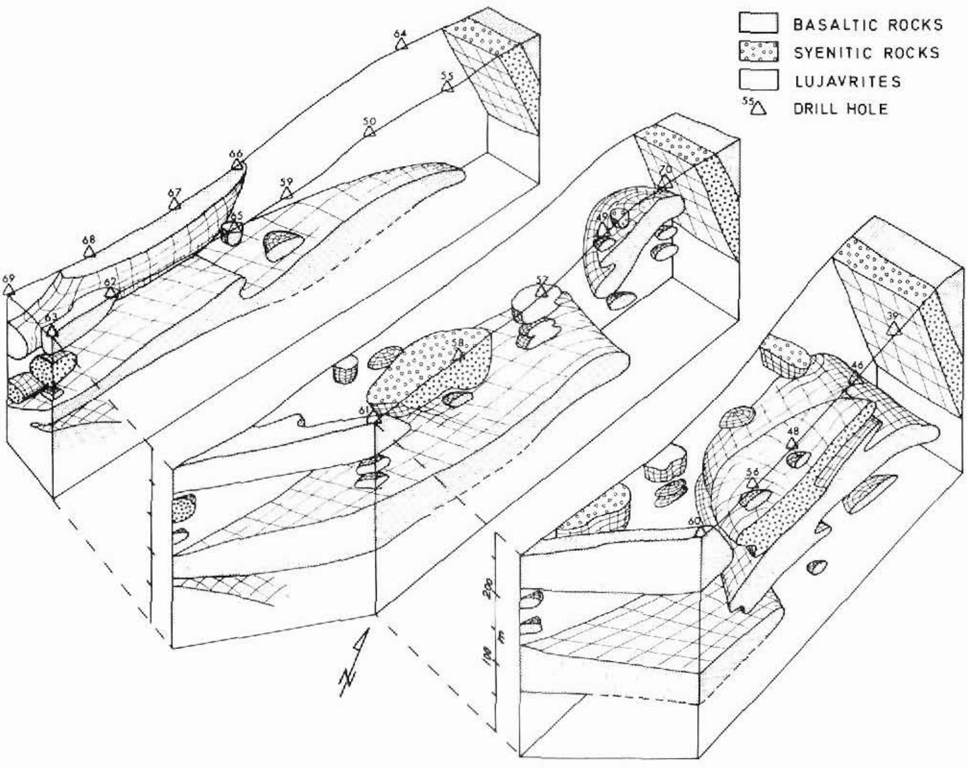


Fig. 2. Model of large flat lying xenolithic rafts of lava and gabbro in lujavrites of northern Kvanefjeld. Syenitic rocks are mainly naujaite and pulaskite.

older rocks subsided into the lujavrite magma. The present erosional surface gives the impression of an extensive intrusive breccia with matrix lujavrite constituting about 50 per cent of the area. Nielsen & Steenfelt (1978) discussed the intrusive mechanism and advocated permissive intrusion accompanied by subsidence of large xenoliths from the roof to maintain their orientation during their subsidence in the lujavrite magma. The general geology and the petrography of the exposed rocks were described by Sørensen *et al.* (1969).

It is generally believed that the lujavrites at Kvanefjeld intruded in a number of separate pulses giving rise to several major rock types: (1) black arfvedsonite lujavrite, (2) arfvedsonite lujavrite with up to 50 per cent naujakasite (naujakasite lujavrite), (3) medium- to coarse-grained lujavrite (M-C lujavrite) and (4) green aegirine lujavrite. All types of lujavrite, except the aegirine-bearing which is not common at Kvanefjeld, may or may not contain the water-soluble mineral villiaumite (NaF).

The lujavrite magma was enriched in rare elements as expressed by the large number of unusual accessory minerals (Table 2).

The drill cores studied belong to the northern part of Kvanefjeld and to the Steenstrup Fjeld area. The latter area is situated approximately 2 km to the east of Kvanefjeld and forms the continuation of a lujavrite zone (fig. 1). In both areas the exposed rocks are mainly lujavrites in which are embedded xenoliths of gabbro and lava (roof rocks) as well as xenoliths of naujaite and pulaskite (Table 1). The simplified map in fig. 1 does not show all the xenoliths.

The drilling programme in 1977 (Nyegaard *et al.*, 1977; Nyegaard, 1979) revealed a number of large flat-lying xenolithic rafts of gabbro and lava in the lujavrites of the northern Kvanefjeld area below the present level of erosion (fig. 2). These rafts may have subsided more than 300 m into the lujavrite magma (Nielsen & Steenfelt, 1978). The sections in fig. 2 illustrate the relatively high proportion of naujaite xenoliths. The same types of xenoliths are also found in the drill cores from the Steenstrup Fjeld area. Oblique drill holes in this area show that the contact between lujavrites and the supracrustal rocks dips 60 to 70° to the north. The size of the xenoliths varies from a few centimetres to several hundred metres across. Their shape in the exposed area may be rounded to angular or elongated.

Typical plastic deformation occurs along the borders of some of the xenoliths (Sørensen *et al.*, 1969; Nielsen & Steenfelt, 1978). The deformed marginal zones may extend to over 10 m in width and it is noted that deformation is almost exclusively confined to blocks of supracrustal rocks. The deformation zone typically contains Nb mineralisation (Hansen, 1968). There is no similar mineralisation in the border zones between lujavrites and earlier consanguineous nepheline syenites. The deformation zone may represent pre-intrusive regional shear zones, which during the following magmatic history were accentuated, acting as conductive zones for heat exchange through the roof (Nielsen & Steenfelt, 1978). During the final collapse of the roof, zones of weakness probably also controlled shape and size of blocks subsiding into the lujavrite magma. The mineralisation of the deformation zone is believed to have taken place mainly after subsidence because no similar Nb mineralisation was found in shear zones or joint zones outside the intrusive complex.

RESULTS AND DISCUSSION

Several analytical methods were used to determine Li, Be, F, Na, K, Ca, Ti, Mn, Fe, Cu, Zn, Y, Zr, Nb, and Pb in split and powdered 1 m drill core sections. Thorium and U data are those obtained by gamma-ray spectrometry (Nyegaard, 1979). A compilation of the analytical methods is given in Table 3. Every second metre of the lujavrite drill core sections was usually sampled, the analytical result being the average elemental content of the 1 m section. However, for some drill cores, especially around transition zones of lujavrites and volcanic rocks, every metre of drill core was used for analysis. Out of 23 drill cores the following were sampled for systematic analysis: drill cores 44, 46, 48, 49, 51, 55, and 59.

The rocks analysed were arfvedsonite lujavrite and naujakasite lujavrite, and country rock xenoliths. They were divided into the following groups:

(1) naujakasite lujavrite (without visible villiaumite),
(2) naujakasite lujavrite with visible villiaumite,
(3) arfvedsonite lujavrite (without visible villiaumite),
(4) arfvedsonite lujavrite with visible villiaumite,
(5) volcanic rocks (lava & gabbro, unaffected),
(6) sheared volcanic rocks (lava & gabbro), and
(7) sheared volcanic rocks with visible Nb minerals.

Table 3. Analytical methods employed

Analytical method	Elements	Remarks
X-ray fluorescence (XRF)[1]	Y, Zr, Nb	Other elements determined: Ga, Zn, Rb, Sr, Pb, Th
Energy-dispersive X-ray fluorescence (EDX)[2]	Nb Cu, Zn, Pb, K, Ca, Ti, Mn, Fe	Other elements determined: Rb, Sr, Y, Zr, U, Th
Instrumental neutron activation (INAA)[3]	Na	33 other elements determined
Optical emission spectrography (OS)[4]	Li, Be	
Fluorimetry[5]	F	Cold-extractable F by ion-sensitive electrode

[1,3,4] Institute for Petrology, Copenhagen University, J.C.Bailey, R.Gwozdz, and H.Bollingberg, respectively.
[2] Risø National Laboratory, H.Kunzendorf.
[5] The Geological Survey of Greenland, P.Jensen.

Table 4. Description of rock types investigated in drill cores from the northern part of Kvanefjeld

Rock type	Class	Characterisation
Lujavrites		
Naujakasite lujavrite	without NaF	Fine-grained laminated rock with a similar appearence than arfvedsonite lujavrite; the rock is rich in acmite and has significant quantities of naujakasite.
	with NaF	Similar to the barren type but villiaumite occurs.
Arfvedsonite lujavrite	without NaF	Black, fine-grained rock with magmatic lamination and/or folding, the rock may have a flamed appearence due to the alteration to acmite; the rock may have spots of nepheline and is quite often porous (leaching of villiamite?); spots and crack fillings of filted aegirine are common; minerals include arfvedsonite, aegirine, acmite, microcline, albite, steenstrupine, eudialyte, monazite and sphalerite.
	with NaF	Similar to the barren type but villiamite occurs in the rock.
Volcanic rocks		
Lava		Fine-grained greyish rock with or without porphyroblasts; major minerals include plagioclase, pyroxene, ozides, and altered olivine.
	sheared	The degree of shearing determines the type of sheared lava: a. Fine-grained greyish to greyish green rock with or without feldspar and star-shaped albite; spots of filted aegirine visible; in more strongly sheared rocks the porphyroblasts are spread out to schlieren. b. Fine- to medium-grained greyish or dark green layered or cauliflower-like rock; star-shaped albite aggregates occur; the rock may be folded. Minerals frequently observed include plagioclase, alkali feldspar, augite, arfvedsonite, nepheline, aegirine, sphalerite, villiaumite, neptunite and astrophyllite.
	sheared with Nb	Similar to sheared lava but Nb minerals occur.
Gabbro		Medium- to fine-grained olive green rock with plagioclase, pyroxene, oxides and altered olivine.
	sheared	Medium- to fine-grained dark green rock with aggregates of star-shaped albite; the mineral assemblage is essentially the same than for sheared lava; the rock has a mottled appearence and in strongly sheared varieties lamination and/or folding occurs.
	sheared with Nb	Similar to sheared lava but with Nb minerals.

Table 5. Average content and standard deviation of Na, K, Ca, Ti, Mn and Fe in rocks of the northern part of Kvanefjeld

Rock type	Number of samples	Na(%)	K(%)	Ca(%)	Ti(%)	Mn(%)	Fe(%)
Lujavrites							
Naujakas.lujav.	21	8.35±1.03(27)	2.72±0.39	0.91±0.18	0.33±0.06	6114±1129	11.66±1.23
with NaF	30	11.81±1.62(35)	2.87±0.33	0.59±0.10	0.30±0.03	4967±1044	11.60±1.34
Arfvedson.lujav.	139	7.36±0.87(77)	2.72±0.59	0.62±0.21	0.31±0.06	4401± 723	12.36±2.29
with NaF	162	9.05±1.24(107)	2.74±0.51	0.62±0.12	0.27±0.04	3948± 701	11.40±2.11
Volcanic rocks							
Lava/gabbro	42	5.52±1.56(33)	3.71±1.05	2.95±1.51	0.79±0.48	1710± 667	7.73±2.43
sheared	33	5.79±2.26(25)	2.91±0.94	2.99±1.53	0.68±0.25	2462± 919	8.38±1.82
with Nb	64	7.39±1.03(39)	3.10±0.95	2.79±1.10	0.78±0.29	2742±1195	7.32±2.01

The data for Na are based on the number of samples given in parentheses.

The petrography and the mineralogy of these rock types is outlined in Table 4.

The different lujavrite types considered in the investigated area extend to depths of about 200 m below surface. Over these lengths numerous xenoliths of nepheline syenites or volcanic rocks occur. The systematic analytical data therefore give information about chemical variations with depth for the different rock types and at the contacts between lujavrites and xenoliths.

Systematic reviews on the geochemical behaviour of the studied elements in alkaline rocks can be found in the literature (e.g. Gerasimovsky, 1969, 1974; Vlasov, 1966; Wollenberg *et al.*, 1978). Little geochemical work has been carried out on drill core material from Kvanefjeld, though a general account on the geochemistry and geology of the Ilímaussaq intrusion was given by Ferguson (1964, 1970), Hamilton (1964), and Bailey *et al.* (1981 a–d). Previous geochemical studies on rocks from Kvanefjeld dealt either with uranium resource evaluation following drilling operations (Sørensen *et al.*, 1969, 1974; Nyegaard 1979) or with specific metals in the mineralised rocks within a certain rock suite (e.g. Hansen, 1968; Kunzendorf, 1973).

Sodium, potassium, calcium, titanium, manganese, and iron

Average contents of Na, K, Ca, Ti, Mn and Fe in the various groups of lujavrites and volcanic rocks are listed in Table 5.

Compared to common nepheline syenites (Le Maitre, 1976) the lujavrites may be described geochemically as low-Ca, low-Ti rocks enriched in Na, Mn and Fe. The analyses reveal differences in sodium contents of two lujavrite groups without visible NaF: naujakasite lujavrite has about 15 per cent more Na than arfvedsonite lujavrite. Villiaumite-bearing lujavrites are expectedly enriched in Na. The enrichment is about 41 per cent in naujakasite lujavrite (with NaF) and about 23 per cent in arfvedsonite lujavrite (with NaF) as compared to the respective lujavrites without villiaumite. Within the four groups of lujavrites there is no significant variation in K, Ti, and Fe contents. Naujakasite lujavrite without villiaumite has higher Ca and Mn values than the other lujavrites.

Average major element contents of volcanic rocks are accompanied by large standard deviations (Table 5). This observation is explained by the fact that the gabbro and the lava

Table 6. Analytical data for Li, Be and F in rocks of the northern part of Kvanefjeld

Rock type	Li(ppm)	Be(ppm)	F(%)
Lujavrites			
Naujakasite lujavrite	1421±513	69±55	0.06±0.16
	(8)	(10)	(19)
with NaF	1944±610	53±18	0.67±0.52
	(9)	(9)	(37)
Arfvedsonite lujavrite	1914±454	73±29	0.09±0.28
	(24)	(31)	(97)
with NaF	2147±629	64±28	0.98±0.70
	(44)	(47)	(278)
Volcanic rocks			
Lava/gabbro			0.01
			(2)
sheared			0.07±0.07
			(15)
with Nb			0.06±0.11
			(15)

The number of analyses given in parentheses.

drill core sections were treated as one rock group. The high Na content in the sheared volcanic rocks with Nb mineralisation expresses strong metasomatic action caused by the agpaitic magma because the sheared rocks almost exclusively occur at the contact to the agpaites. An indication of contact metasomatism is also the slightly lower K contents of sheared volcanic rocks. A similar explanation may possibly be used for the enrichment of Mn in these rocks.

Lithium, beryllium, and fluorine

Analytical data for Li, Be, and F are compiled in Table 6. Lithium analyses are regarded as semiquantitative and the results given here are about 2 to 3 times higher than those found by other chemical methods (J. C. Bailey, personal communication).

Li and Be do not vary very much in the lujavrites. Naujakasite lujavrites have possibly lower Li contents than other lujavrites, but too few analyses exist to prove this observation. Bailey *et al.* (1981 b) recently presented a more detailed investigation on Li contents, mainly devoted to rocks outside Kvanefjeld.

Lithium and beryllium occur usually dispersed in the minerals arfvedsonite (Li), and in nepheline and feldspars (Be) in alkaline rocks (Vlasov, 1966; Wedepohl, 1969), but they also form independent minerals in their pegmatite and hydrothermal stages. Li is therefore probably also present in lepidolite and arfvedsonite in the fine-grained lujavrites at Kvanefjeld. The enrichment of Be and Li in the pegmatitic rocks and hydrothermal veins at Ilímaussaq resulted in the formation of the Be minerals sorensenite, tugtupite, eudidymite, chkalovite, the Li mineral lepidolite and others (Sørensen *et al.,* 1974). The radioactive mineral steenstrupine may have 100 ppm BeO (unpublished results), but higher amounts BeO were found, thereby significantly contributing to the observed Be content in the lujavrites investigated. Lujavrites from northern Kvanefjeld have higher Li and Be contents than comparable rocks from the alkaline massifs of the Kola peninsula (Lovozero, Khibina; Vlasov, 1966).

The number of F analyses was extended to samples from nearly all drill cores of the northern part of Kvanefjeld, and therefore results of over 350 arfvedsonite lujavrites are compiled in Table 6. A maximum of 3.2 per cent F was found in arfvedsonite lujavrite with visible villiaumite, the average content of 0.98 per cent F being about 40 per cent higher than for the villiaumite-bearing naujakasite lujavrite. Only a few samples of volcanic rocks were analysed for F. The sheared rocks have F contents comparable to the barren lujavrites (without NaF), i.e. below 0.1 per cent.

Fluorine is present in lujavrites in several rock-forming and accessory minerals like arfvedsonite, eudialyte, villiaumite, rinkite, and pyrochlore, of which villiaumite is the most important F-bearing mineral. It is widespread in lujavrites from northern Kvanefjeld. According to Kogarko (1974), the high capacity of an alkaline melt to dissolve water and volatile elements like F and Cl explains the presence of these elements in the rock-forming minerals. Furthermore, complexes of rare metals and volatile components are not stable in highly alkaline melts and the rare elements are believed to form complexes with oxygen. As the alumino-fluoride complex AlF^{3-} is not stable in high-alkali low-Si melts, F alternatively forms bonds with Na. This explains the formation of villiaumite instead of, for instance, cryolite in the lujavrites. A small number of locally very fluorite-rich alkaline veins and breccias (Hansen, 1968; Nielsen, 1981) in the neighbouring Eriksfjord Formation were believed to be genetically connected with the Ilímaussaq intrusion. However, the explosive character of the breccia rocks does not support this idea because of the limited availability of a fluid phase in the magma at late stages. Fluorite is also found regionally in breccias, and the source of this fluorite is not believed to be the Ca-poor Ilímaussaq magma (see chapter on contact phenomena).

Yttrium, zirconium, niobium, thorium, and uranium

Average contents of Y, Zr, Nb, Th, and U in lujavrites and the volcanic rocks are compiled in Table 7 and the distribution of these elements is given in fig. 3.

It appears from the table that in all lujavrites the Nb contents are relatively constant, about 200 to 300 ppm. Naujakasite lujavrites have high U, Th, and Y contents compared to arfvedsonite lujavrites. The Zr contents are lower in naujakasite lujavrites than in arfvedsonite lujavrites. Thorium is generally low (average 380 ppm) in arfvedsonite lujavrite without NaF, the Th/U ratio being at or below 1.5. A few high Th values were observed in lujavrites at the contact with volcanic rocks or in lujavrites from areas with large numbers of xenoliths. In contrast to arfvedsonite lujavrites the naujakasite lujavrites have Th/U ratios greater than 1.5. The differing behaviour of Y, Zr, Th, and U in the four lujavrite groups may also be visualised from the frequency distributions in fig. 3. However, the distributions of these elements within naujakasite lujavrite groups and within arfvedsonite lujavrite groups are rather similar.

Although Zr occurs in numerous mafic minerals in alkaline rocks the principal mineral is eudialyte (Vlasov, 1966). Niobium occurs in Na-titanosilicates, e.g. murmanite, or may

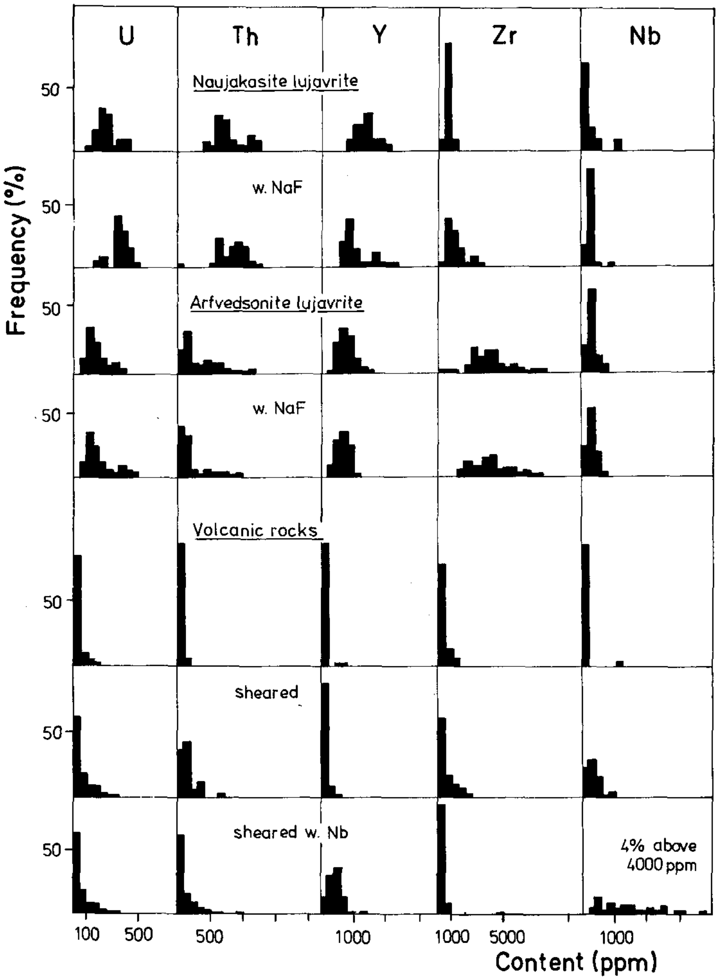


Fig. 3. Distribution of U, Th, Y, Zr and Nb in lujavrites and volcanic rocks of selected drill cores from northern Kvanefjeld. The histograms are based on about 600 samples.

substitute for Zr and Ti in other minerals. Eudialyte is only found in arfvedsonite lujavrites (Table 11). Naujakasite lujavrites have unusually low Zr contents (~ 1000 ppm) and only in the section of drill core 48, below 150 m, does Zr reach about 3000 ppm. In contrast to this, relatively high Zr values (> 2000 ppm), increasing with depth (see chapter on depth variations), are found for all arfvedsonite lujavrites. Zr and Nb data suggest that these elements are mainly confined to the mineral eudialyte in arfvedsonite lujavrite but not in naujakasite lujavrite if a Zr/Nb ratio of 9 to 12 (Vlasov, 1966; Bailey *et al.*, 1981 c) is assumed for eudialyte; both elements possibly also occur dispersed in mafic minerals in all lujavrites. The lack of eudialyte in naujakasite lujavrite and the higher contents of Th, U, and Y compared with arfvedsonite lujavrite strongly supports the idea that the naujakasite lujavrite is the youngest intrusion of fine-grained lujavrites at Kvanefjeld as suggested by Sørensen *et al.* (1969) on field and petrological evidence.

Table 7. Average content and standard deviation of U, Th, Y, Zr, Nb, Cu, Zn and Pb in rocks of the northern part of Kvanefjeld

Rock type	U(ppm)	Th(ppm)	Y(ppm)	Zr(ppm)	Nb(ppm)	Cu(ppm)	Zn(ppm)	Pb(ppm)
Lujavrites								
Naujakas.lujav.	259± 80 (25)	810±232 (25)	1421±294 (24)	790± 182 (24)	262± 288 (24)	71± 6 (21)	2061±314 (21)	183±35 (21)
with NaF	338± 68 (35)	753±214 (35)	1104±440 (35)	1275± 701 (35)	289± 150 (35)	59± 8 (30)	1694±284 (30)	154±17 (30)
Arfvedson.lujav.	214± 93 (152)	380±365 (152)	791±254 (157)	3883±1511 (157)	319± 203 (157)	66±12 (139)	1809±569 (139)	219±57 (139)
with NaF	195±102 (165)	239±264 (165)	681±322 (160)	4239±1730 (160)	304± 165 (160)	66±16 (162)	1693±536 (162)	193±45 (162)
Volcanic rocks								
Lava/gabbro	6± 13 (40)	16±119 (40)	83±119 (43)	375± 264 (43)	97± 242 (43)	45±10 (42)	372±351 (42)	57±41 (42)
sheared	49± 42 (33)	155±135 (33)	134± 94 (33)	645± 543 (35)	317± 217 (35)	83±71 (33)	1061±818 (33)	96±98 (33)
with Nb	57± 58 (57)	144±176 (57)	432±229 (49)	393± 714 (49)	1697±1150 (49)	45±15 (64)	970±489 (64)	61±20 (64)

The number of samples is given in parentheses.

Uranium and thorium occur mainly in rare earth minerals like steenstrupine. As regards the radioactive minerals identified, steenstrupine was detected in nearly all of the lujavrite thin sections investigated (see appendix and Table 11). The type and alteration state of this mineral varies considerably. By microprobe analyses, Makovicky *et al.* (1981) and Hansen (1977), discovered additional mineral phases rich in Y-Zr-U and Nb-U. These minerals were termed pigmentary material by previous authors. They are most likely alteration products formed during decomposition of eudialyte and/or steenstrupine. The relative surplus of Nb in naujakasite lujavrite may then be accounted for by the presence of this Nb-U mineral in addition to steenstrupine.

Volcanic rocks have, as expected, very low contents of radioactive elements (Table 7). A number of samples with relatively high U and/or Th is nevertheless observed in the sheared volcanic rocks (fig. 3) contributing about 10 per cent to the U tonnage in the Kvanefjeld area (Løvborg *et al.,* 1980). Yttrium follows this trend indicating the possible presence of radioactive rare earth minerals. Metasomatic processes at the border zones between lujavrite and sheared volcanic rocks have resulted in a significantly increased Zr content in the sheared lavas and gabbros. This Zr enrichment is, however, only found in sheared rocks with low Nb (Table 7 and fig. 3). Quite often the metasomatically altered lava and gabbro is enriched in the Nb mineral murmanite and these rocks do not have anomalous Zr values. The average Nb content of mineralised sheared rocks is 0.17 per cent but 4 per cent of the analyses of sheared volcanic rocks with visible murmanite give Nb values greater than 0.4 per cent.

Zinc, lead, and copper

Lujavrites from Kvanefjeld have relatively high average Zn and Pb contents (Table 7). There is no significant variation in the average contents for the various lujavrite groups but arfvedsonite lujavrites have a large range of Zn and Pb contents (fig. 4). Occasionally, more

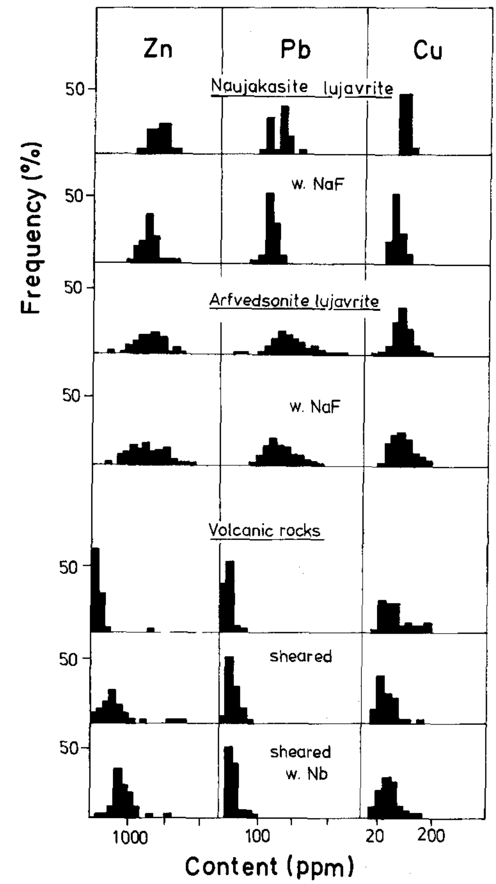


Fig. 4. Distribution of Zn, Pb and Cu in lujavrites and volcanic rocks of selected drill cores from northern Kvanefjeld.

than 3000 ppm Zn and more than 300 ppm Pb were found in arfvedsonite lujavrites. The lujavrites have Cu contents of about 60 ppm. These values are in agreement with the copper values obtained during U extraction of the rocks (E. Sørensen, personal communication) but are in contrast to Cu contents, generally less than 1 ppm, found for other lujavrites of the Ilímaussaq intrusion. The lujavrites have also slightly higher Cu contents than the volcanic rocks.

Ilímaussaq rocks have relatively high Zn and Pb contents compared with similar rock types (Gerasimovsky, 1969) and the same is true for the Kvanefjeld lujavrites. However, the amount of sulphide minerals in these rocks is limited (Karup-Møller, 1978). The retention of volatiles in the agpaitic melt and a low sulphur fugacity resulted in the fixation of metals like Zn and Pb in silicate minerals like arfvedsonite. Nonetheless, sphalerite is common in hydrothermal veins in the upper levels of the lujavrites and this hydrothermal enrichment may also account for a slight increase of Zn values in the upper lujavrite sections. Sphalerite may also occur disseminated in the lujavrites. A portion of the lead disseminated in the lujavrites may be of radiogenic origin though some Pb is also present as galena.

Geochemical correlations

Correlation coefficients at the 95 per cent confidence level for selected element combinations in the various rock groups are given in Table 8.

Naujakasite lujavrites have only a few significant element correlations compared to arfvedsonite lujavrites. Both naujakasite lujavrite groups show good correlation (correlation coefficient *r* between 0.6 and 0.8) between Th and U and between Th and Pb supporting a partly radiogenic origin for Pb. Zr-Pb, Zr-Th and Zr-U show good correlation in naujakasite lujavrite without visible villiaumite, but the respective correlations are not significant or absent in the villiaumite-bearing group. A possible explanation for this is the different depth-variation behaviour of Zr in naujakasite lujavrites (see chapter on depth variations). Rather high correlation coefficients ($r>0.8$) were found for Mn-Fe and Th-U in both arfvedsonite lujavrite groups expressing the presence of the minerals arfvedsonite and steenstrupine, respectively. A good correlation exists between Y and Nb in arfvedsonite lujavrite with villiaumite, whereas Y shows good correlation with Th and U in arfvedsonite lujavrite without villiaumite.

A rather high correlation coefficient, greater than 0.8, is found for the element combination Th-U in all volcanic rocks, which for the sheared rock groups suggests that the radioactive elements are found in probably one mineral (steenstrupine). In unaffected volcanic rocks the element combination Zn-Pb has a high correlation coefficient but is significantly lower or absent in the sheared groups. Also, the good correlation between Zr-Y and Zn-Y in unaffected volcanic rocks is not observed in the sheared rocks. In contrast the Nb-Y correla-

Table 8. Selected correlation coefficients (r) *for volcanic rocks and lujavrites of the northern part of Kvanefjeld*

Correlation	Naujakasite lujav.		Arfvedson. lujav.		Volcanic rocks		
	barren	with NaF	barren	with NaF	unaffected	sheared	sh/w. Nb
K-Ca	-	-	0.20	0.46	-0.33	-	-
Mn-Fe	0.46	-	0.87	0.84	0.48	0.35	0.78
Fe-Ti	-	-0.38	-0.14	-	0.58	0.63	-
Cu-Mn	-	-	0.29	-	0.40	-	-
Cu-Fe	-	0.42	0.28	0.19	0.48	0.44	0.33
Zn-Fe	-	-	-0.25	-0.36	-	0.43	-
Zn-Y	-	-	0.15	-0.15	0.67	-	-
Zn-Pb	0.46	-	0.42	0.42	0.96	0.48	-
Zn-U	-	-	0.15	-	-	0.64	-
Y-Pb	-	-	0.32	-	0.41	-	0.54
Y-U	-	-	0.69	0.36	0.35	-	0.47
Zr-Y	-	-0.53	-	-	0.75	-	-
Zr-Nb	-	-	0.33*	0.45*	-	-	-
Zr-Pb	0.72	-	0.38	0.22	0.51	-	0.37
Zr-Th	0.75	-0.44	-0.46	-0.52	-	-0.42	-
Zr-U	0.73	-	-0.24	-0.42	-	-0.40	-
Nb-Y	-	-	0.17	0.63	0.40	0.71	0.64
Nb-Th	-	-	-0.14	-0.32	0.47	-	-
Nb-U	-	-	-0.12	-0.25	0.53	-	0.28
Pb-Fe	-	-	-0.21	-0.37	-	0.37	0.56
Th-Zn	-	-	0.19	-	0.44	0.40	-
Th-Y	-	-	0.69	0.24	0.57	-	0.31
Th-Pb	0.74	0.60	0.17	-0.10	-	0.39	0.75
Th-U	0.72	0.70	0.82	0.91	0.87	0.83	0.87

*Different correlation coefficients for different drill cores. Only coefficients at the 95 per cent level were tabulated.

tion is significantly higher in the sheared than in the unaffected volcanic rocks. Some of the sheared groups of volcanic rocks show characteristic good element correlations: Mn-Fe in sheared volcanic rocks with visible Nb mineralisation and Zn-U in sheared volcanic rocks without Nb. The correlations in the sheared rocks therefore clearly reflect the action of the lujavrite magma on the volcanic rocks.

Element variations with depth

Uranium, Th, Zr, and Nb for all investigated drill core sections are plotted against depth in fig. 5.

In most lujavrite sections Zr increases with depth; the rate of increase is, however, significant only below depths of about 100 m. An exception is the Zr trend of drill core 51 where Zr increase starts already at about 30 m. The Zr increase with depth in arfvedsonite lujavrite sections possibly reflects gravity settling of eudialyte in a lujavrite magma of low viscosity. Lujavrites of drill cores 46, 48 and 49 (mostly naujakasite lujavrite) have relatively low Zr contents, at or below 2000 ppm, compared to typical lujavrite contents with 3000 to 4000 ppm. Nb follows the distribution trend for Zr with depth in lujavrites of drill cores 44, 51, and 59. In other lujavrite sections the Nb contents are relatively constant, between 200 and 300 ppm. A characteristic feature of the lujavrites of drill cores 44, 49, 55, and 59 is the Zr/Nb ratio (not plotted in the figures) in excess of about 10, the approximate value for eudialyte. For example, arfvedsonite lujavrite with villiaumite of drill core 59 exhibits at depths below 100 m two distinct Zr/Nb maxima with values above 25. Zr is most likely not only confined to eudialyte in these sections. Makovicky *et al.* (1981) reported on uranium-rich Y-Zr silicates in arfvedsonite lujavrite from drill core 49 (depth: 140 m) and the excess Zr observed in our study probably resides in such mineral phases. Large parts in other drill cores have, however, Zr/Nb ratios characteristic for eudialyte. In contrast, extremely low Zr/Nb was found in naujakasite lujavrite of drill core 48, increasing continuously from a value of 2 to about 15 towards the contact to a volcanic xenolith. The Zr accumulation pattern is similar to that found in the arfvedsonite lujavrite sections, but no eudialyte is visible.

Uranium concentrations above 300 ppm were found in the low-Zr sections of drill cores 46, 48, and 49, whereas high-Zr lujavrites at similar depths (drill cores 44, 51, 55, and 59) have relatively low U contents, frequently below 200 ppm. The latter sections also have low Th contents, Th/U ratios being below or at 2. Yttrium (not plotted) follows closely U and Th in the lujavrite sections with depth: low and relatively constant concentrations are observed in lujavrites of drill cores 55 and 59, but high Y values occur in naujakasite lujavrites of drill cores 48 and 49. Generally, within the surface lujavrite sections, between 10 and 70 m depth, U, Th and Th/U decrease with depth. The decrease is most distinct for Th and Th/U. Lower-level lujavrite sections (at greater depths) have more constant U, Th and Th/U values. Such depth variations of some characteristic elements were previously reported by Sørensen *et al.*, (1974) who observed a decrease of uranium and of the Th/U ratio with depth in M-C lujavrite from the central Kvanefjeld area. A possible explanation for the accumulation of radioactive elements in the upper-level fine-grained lujavrites of the northern part of Kvanefjeld may be the presence of temperature gradients between xenolithic rafts and the cooling lujavrite magma, favouring the crystallisation of steenstrupine at the contact.

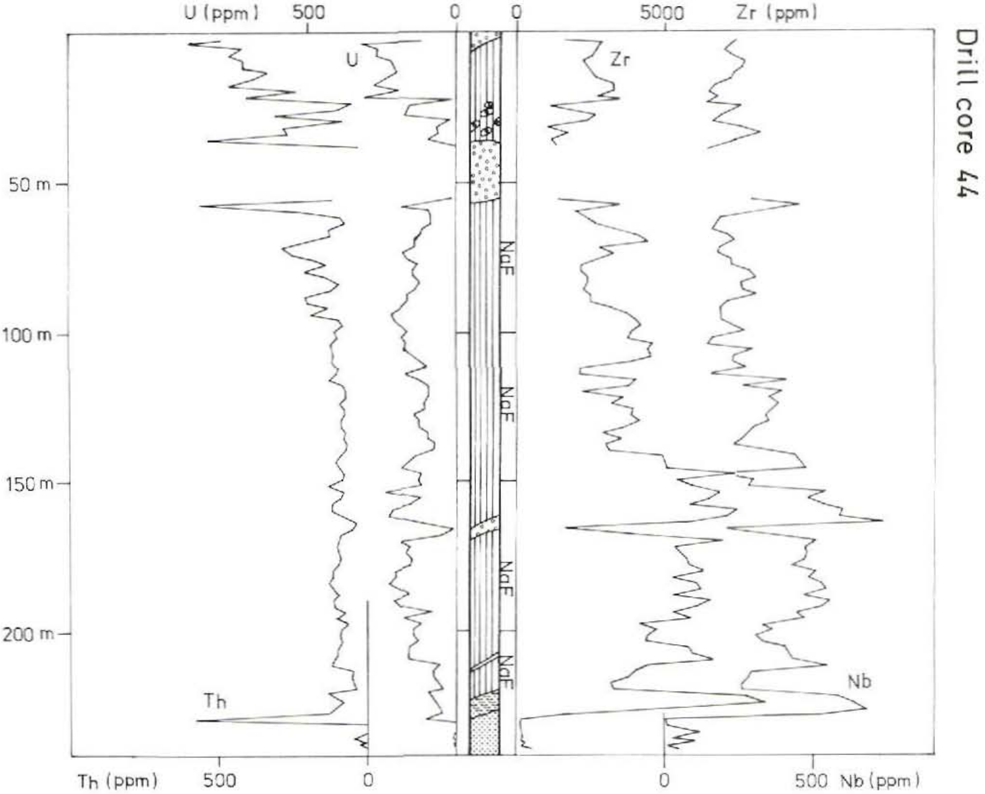
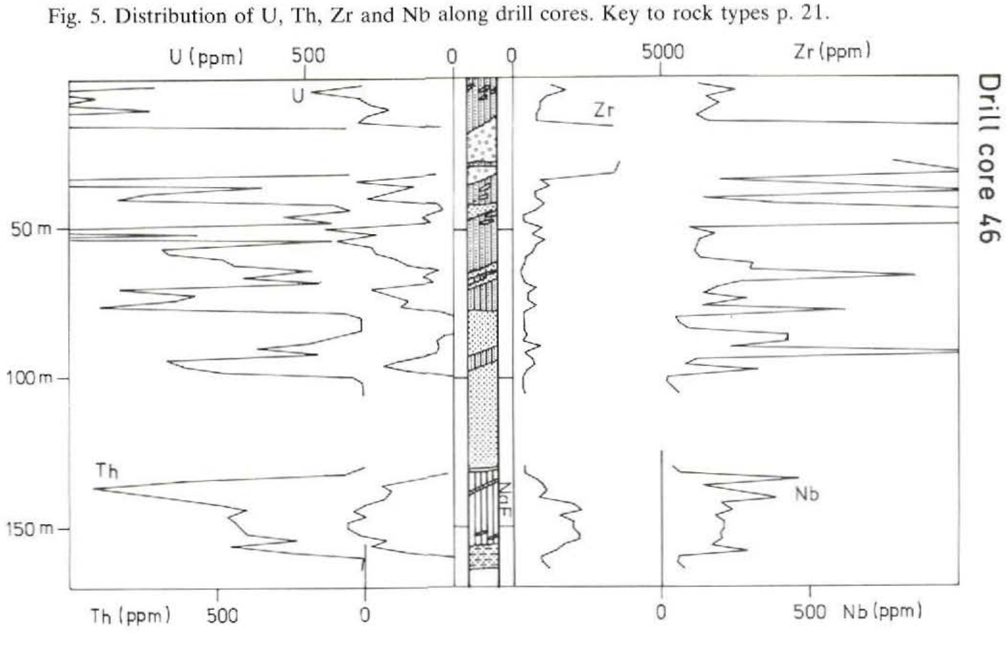
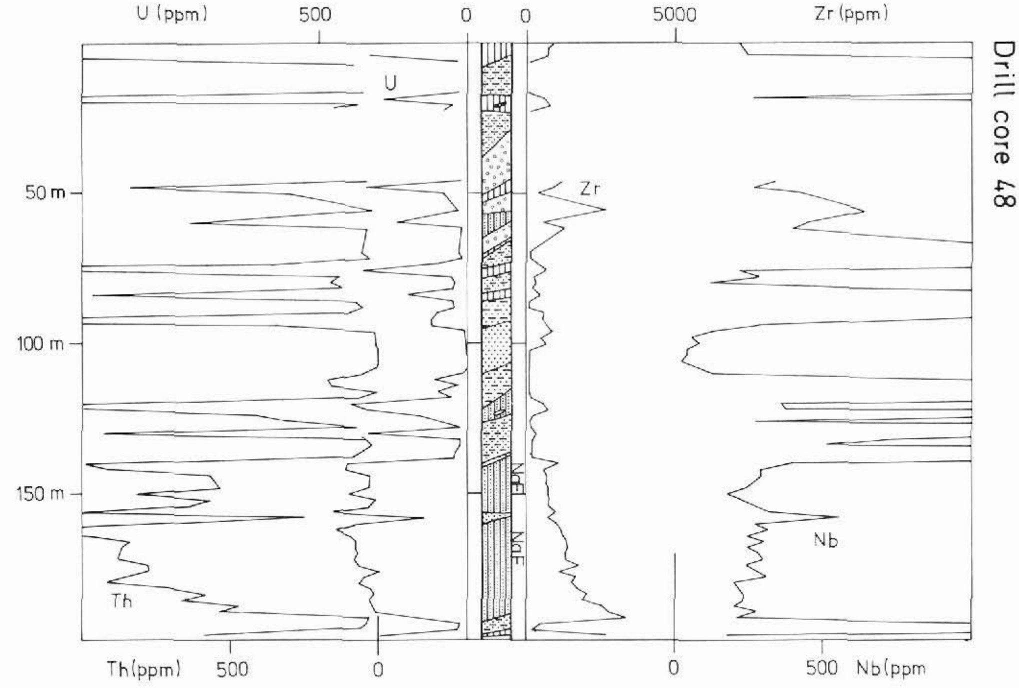


Fig. 5. Distribution of U, Th, Zr and Nb along drill cores. Key to rock types p. 21.




U (ppm)
500
0
0
5000
Zr (ppm)
Drill core 48
U
Zr
50 m
100 m
150 m
NaF
NaF
Nb
Th
Th(ppm)
500
0
0
500
Nb(ppm

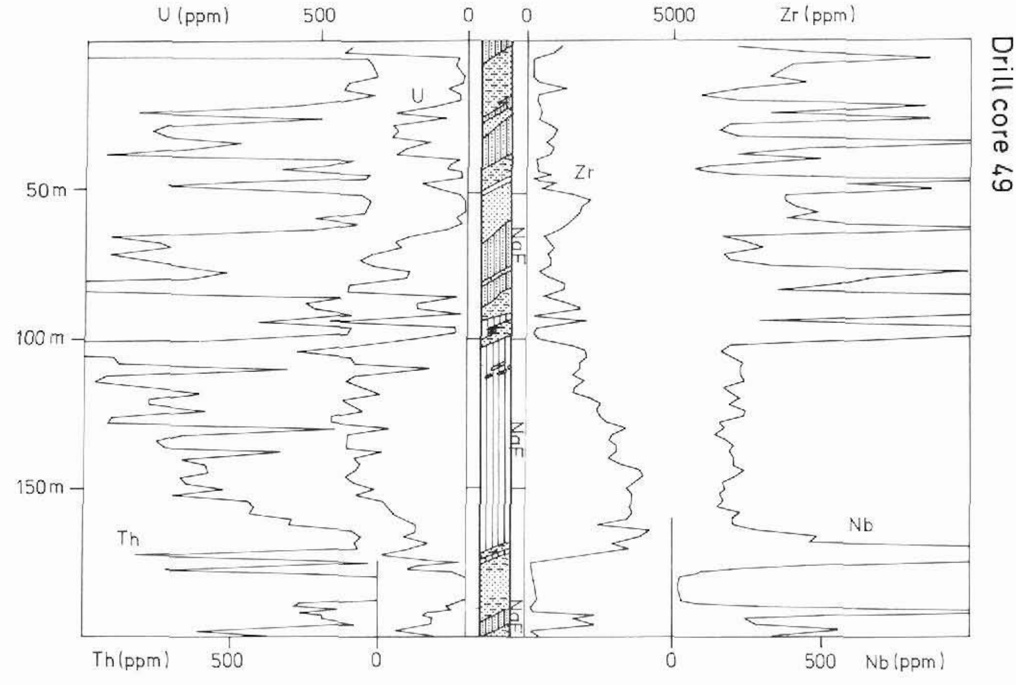
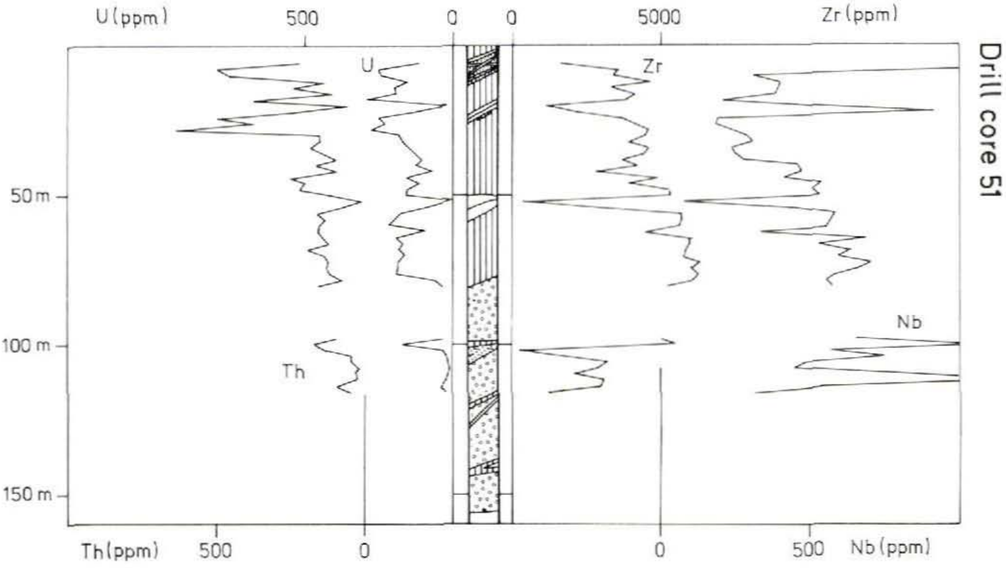

U (ppm)
500
0
0
5000
Zr (ppm)
Drill core 49
U
Zr
50 m
100 m
150 m
NaF
NaF
NaF
Nb
Th
Th(ppm)
500
0
0
500
Nb (ppm)

Fig. 5 cont.


U (ppm)
500
0
0
5000
Zr (ppm)
Drill core 51
U
Zr
50 m
100 m
150 m
Th
Nb
Th (ppm)
500
0
0
500
Nb (ppm)

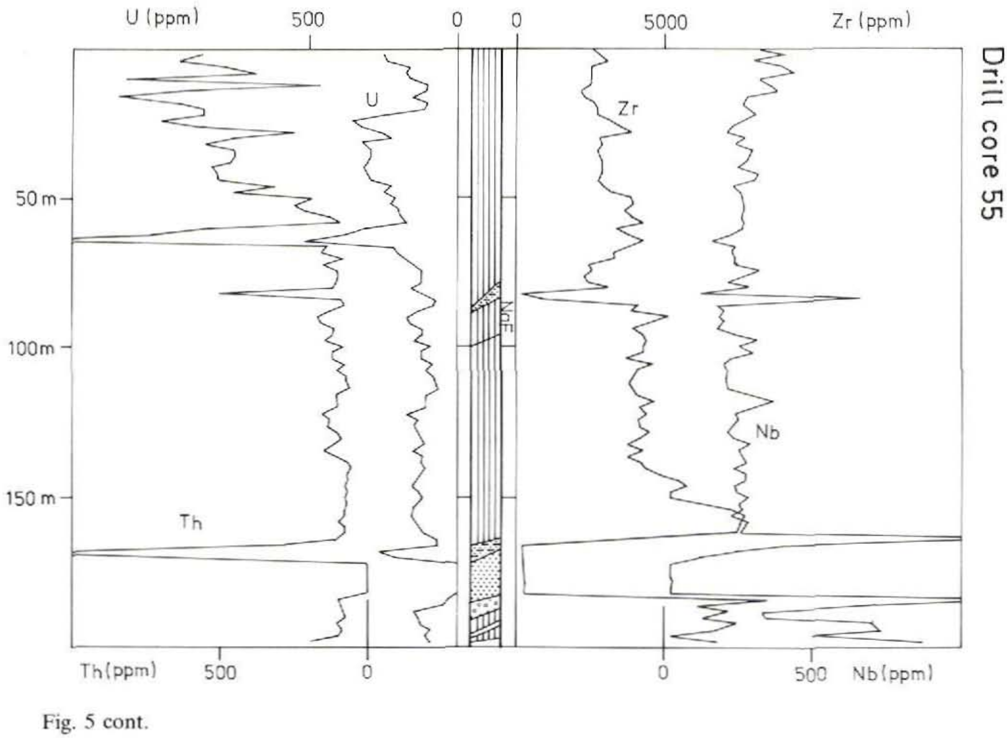

U (ppm)
500
0
0
5000
Zr (ppm)
Drill core 55
U
Zr
50 m
100 m
150 m
Th
Nb
Th (ppm)
500
0
0
500
Nb (ppm)

Fig. 5 cont.

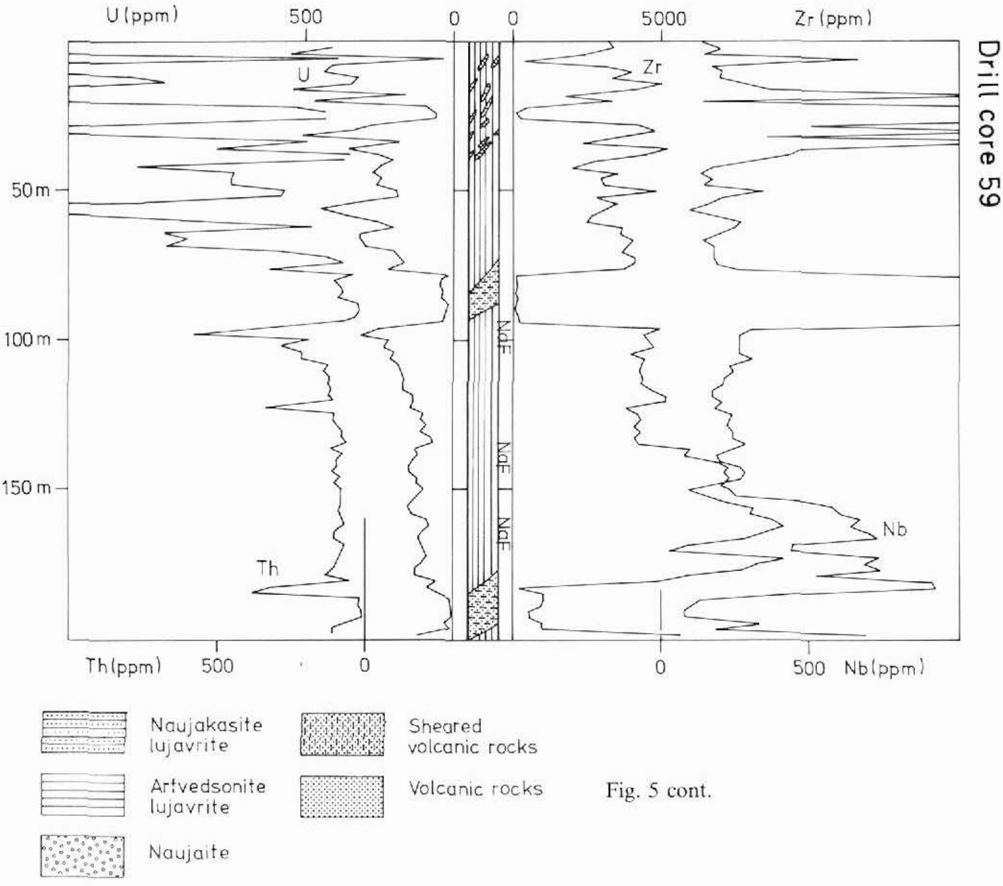


Fig. 5 cont.

Zinc and lead do not vary much with depth in lujavrites and rarely exceed 2500 and 300 ppm, respectively. There is, however, a slight tendency for Zn enrichment in the upper levels of lujavrites. Zn/Pb ratios of 5 to 10 are characteristic along the lujavrite sections.

Contact phenomena in country rock xenoliths

At the contact between lujavrites and the country rock xenoliths sheared and variously metasomatically altered rocks are found. The xenoliths are particularly numerous in drill cores 46, 48, and 49. The contact between country rock xenoliths and lujavrite is normally sharp, although it may be difficult to visually distinguish the bordering rock types.

According to Nielsen & Steenfelt (1978), the ultimate shearing took place during the collapse of the roof and subsidence into the lujavrite magma. The simultaneous metasomatic action on the xenoliths is expressed as a recrystallisation of lava and gabbro into a new rock type which in the ultimate stage is mineralogically similar to bordering lujavrite. Such processes are described by Borodin & Pavlenko (1974). The microscopic study (see appendix) revealed features of the metasomatic action with formation of minerals like aegirine,

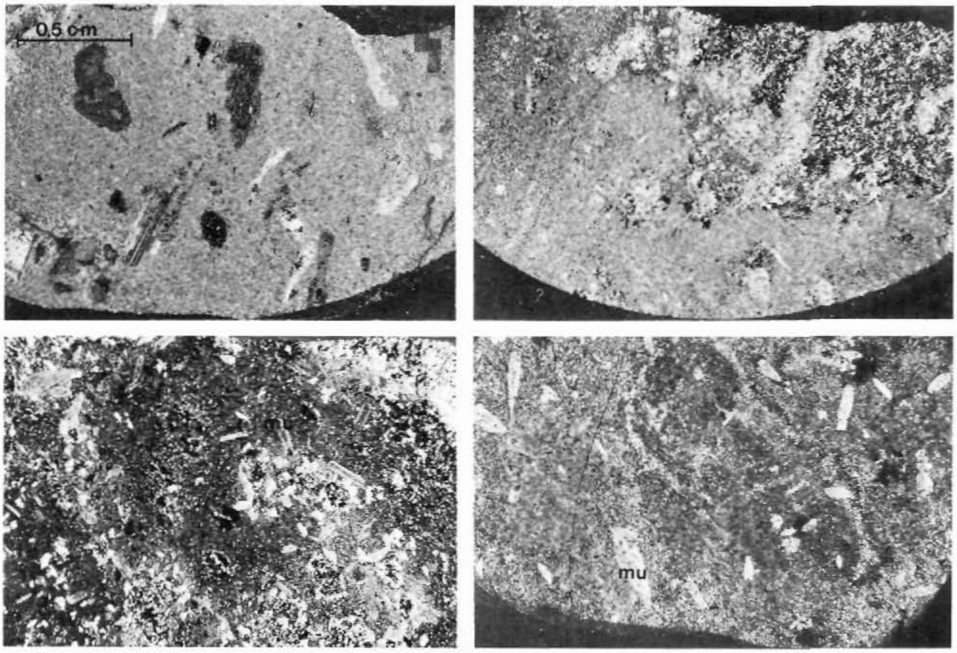


Fig. 6. Shearing, fenitisation and recrystallisation of porphyritic lava. Upper left: unaffected lava. Upper right: partly recrystallised lava, phenocrysts absent. Lower left: sheared, completely recrystallised lava, scattered tablets of murmanite. Lower right: niobium-mineralised fenitised lava, completely recrystallised, poikiloblasts of murmanite. Thin sections are from drill core 49, 186 to 192 m. Same scale for all sections, crossed nicols.

arfvedsonite, albite, microcline, pectolite, neptunite, steenstrupine, and water-bearing silicates like analcime and natrolite. The change in mineralogy from unaffected lava to strongly sheared lava in contact with naujakasite lujavrite containing villiaumite (drill core 49, 186 to 192 m), and from unaffected gabbro to strongly sheared recrystallised gabbro in contact with naujakasite lujavrite (drill core 48, 108 to 118 m) are presented in the appendix.

Niobium mineralisation is confined to sheared marginal zones of country rock xenoliths. Megascopically, the deformation is seen as a stretching of feldspar phenocrysts along which the succeding recrystallisation took place (fig. 6). The Nb minerals are frequently discordant to the foliation planes indicating that the niobium mineralisation followed the deformation. Microscopically, the Nb mineral murmanite is found as porphyroblasts with numerous inclusions of pectolite and arfvedsonite supporting a late origin of the mineralisation (fig. 7). Besides murmanite the following Nb minerals occur: niobophyllite, pyrochlore and an unknown Nb mineral probably belonging to the epistolite group. The present geochemical situation is complicated by the fact that a hydrothermal mineralisation is superimposed on the metasomatic alteration of the rocks. The poikilitic character of the murmanite crystals as well as their discordance with the foliation planes of the sheared xenoliths suggests that this mineralisation is later than the main phase of metasomatism, and it is believed that Nb-rich fluids were derived from the lujavrite magma at a very late stage of differentiation and

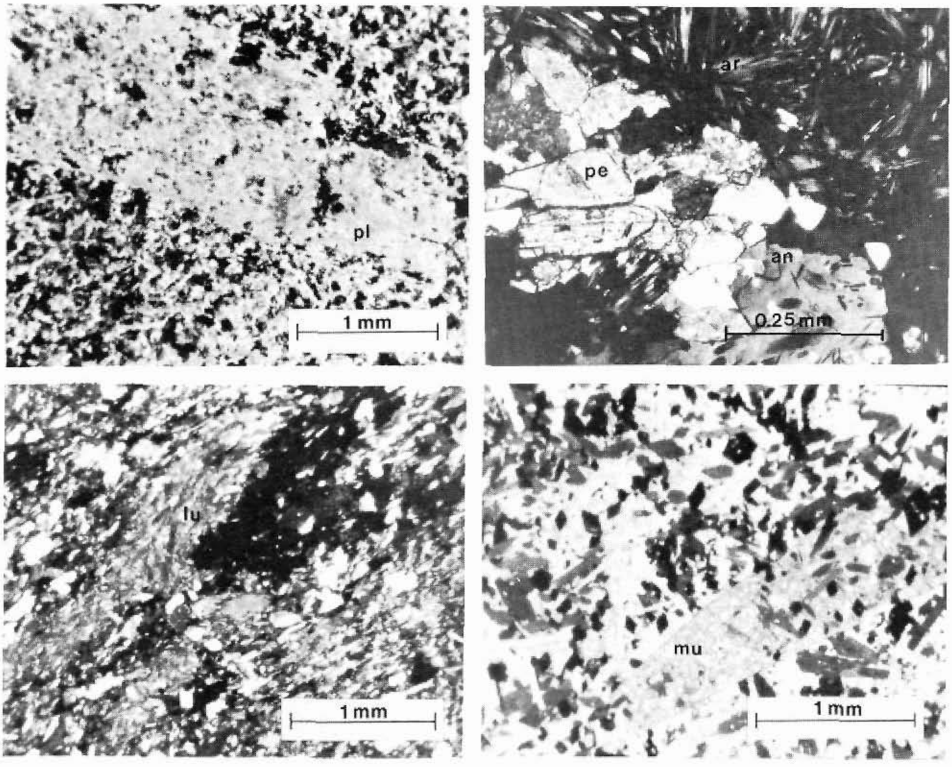


Fig 7. Photomicrographs of xenoliths variously sheared, metasomatised and recrystallised. Upper left: unaffected lava with plagioclase phenocryst. Upper right: recrystallised gabbro with arfvedsonite, pectolite and analcite. Lower left: sheared recrystallised gabbro with lens-shaped aggregates of an unknown Nb mineral in a matrix of sodalite, pectolite and arfvedsonite. Lower right: porphyroblast of murmanite with numerous inclusions of pectolite and arfvedsonite in niobium-mineralised recrystallised lava. The thin sections are from drill cores 49/186 m, 48/112 m, 48/116 m and 49/192 m, respectively. Sections 48/112 m and 48/116 m with crossed nicols.

Table 9. Major element contents in gabbro (drill core 48) and lava (drill core 49) at contact to lujavrite

	Drill core 48					Contact →		Drill core 49					Contact →	
	106 m	108 m	110 m	112 m	114 m	116 m	118 m	186 m	187 m	188 m	189 m	190 m	191 m	192 m
SiO_2	42.92	42.42	42.53	49.68	48.39	48.69	49.34	51.13	52.79	47.83	45.53	47.14	51.42	49.60
TiO_2	1.97	2.05	1.75	1.32	1.34	1.10	1.02	2.01	1.95	2.54	3.11	2.78	1.89	1.59
Al_2O_3	12.97	13.15	11.96	10.15	11.50	10.24	10.73	16.43	15.82	13.98	11.91	11.72	10.32	9.83
Fe_2O_3	1.41	1.50	1.37	3.87	3.93	4.60	4.89	4.27	1.15	0.66	1.64	2.67	2.93	3.55
FeO	12.97	12.72	11.30	5.25	4.76	5.60	5.69	5.58	7.94	9.92	10.17	8.30	6.92	7.57
MnO	0.16	0.15	0.15	0.23	0.34	0.47	0.52	0.15	0.10	0.15	0.16	0.24	0.50	0.51
MgO	10.43	10.30	9.01	6.00	5.05	5.22	4.58	1.86	1.39	1.66	1.57	1.37	1.03	1.60
CaO	6.12	5.77	5.84	3.53	4.22	3.67	3.14	5.88	5.34	7.68	8.70	6.96	5.45	4.33
Na_2O	4.47	4.44	6.08	11.71	10.67	12.97	11.84	5.55	6.79	8.43	10.89	11.85	12.32	12.29
K_2O	2.34	3.15	4.43	1.91	2.26	2.06	2.67	4.56	3.96	3.64	2.47	2.49	1.84	1.99
volat.	2.66	2.98	3.26	3.27	2.59	2.25	2.44	0.86	1.24	1.35	1.45	1.98	2.39	2.94
P_2O_5	0.75	0.79	0.64	0.49	0.51	0.43	0.37	0.94	0.91	1.23	1.51	1.33	1.24	1.21
	99.17	99.42	98.32	97.41	95.56	97.30	97.23	99.22	99.38	99.07	99.11	98.83	98.25	97.01
Sr	418	415	404	359	348	186	65	314	281	284	181	174	131	175

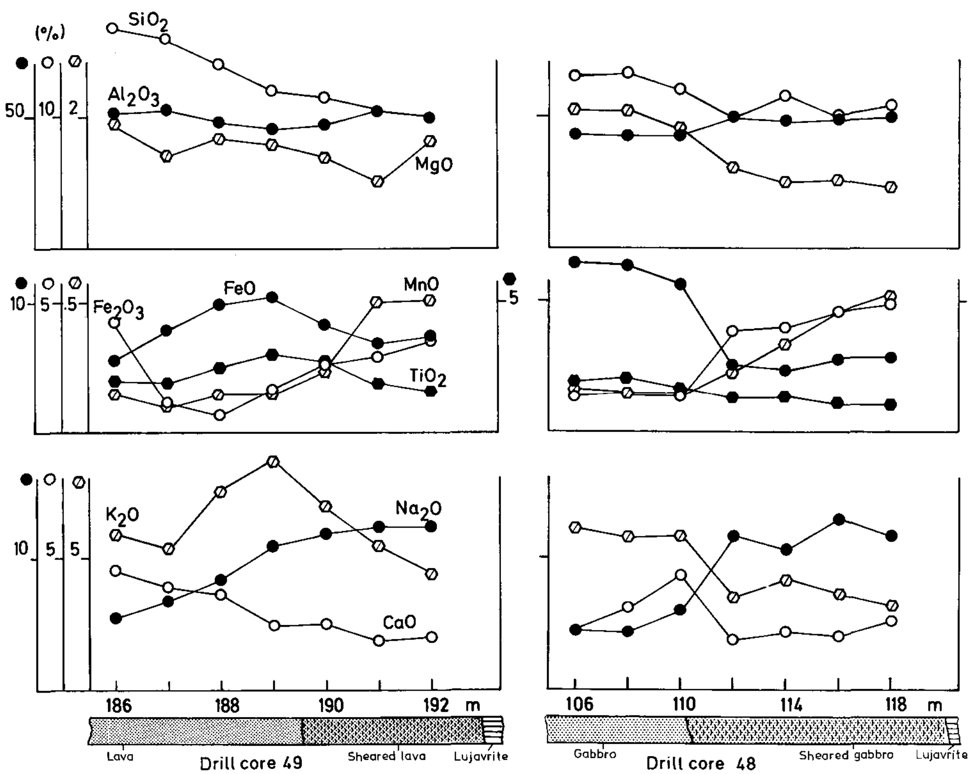


Fig. 8. Distribution of major elements in lava (drill core 49) and gabbro (drill core 48) at contact to lujavrite.

emplaced into the deformation zones along the xenolith contacts. The mineralisation may be classified as a hydrothermal impregnation type. Supporting this is the presence of Nb minerals in naujaite xenoliths (drill core 51, 194, 202 m) as well as in hydrothermal veins at the upper intrusive levels. The Nb mineralised naujaite shows no sign of metasomatic alteration.

Chemical changes of major elements in country rock xenoliths of drill cores 48 and 49 in contact to the lujavrites are shown in fig. 8 and Table 9. Metasomatic processes as outlined by the gradual increase of Na_2O from the unaffected rock towards the contact to lujavrite are accompanied by a depletion of SiO_2, MgO, TiO_2, K_2O and FeO. MnO closely follows Na_2O.

In general, the distribution pattern of selected elements in transition zones is complicated. Sodium metasomatism took place in 2 to 6 m wide zones along contacts of most volcanic xenoliths with the lujavrites. Sometimes, additional maxima of Na are observed within the volcanic rocks and these Na enrichments are followed by Zn-Pb and Th-U accumulations (fig. 9 a, b).

In contrast to the general mineralogy of the lujavrites at Kvanefjeld, aegirine is frequently found in lujavrites bordering lava and gabbro. The width of the aegirine-bearing zones may reach 2–3 m and often a 1–20 cm wide zone of pure felted aegirine is developed at the contact to the xenolith. Typically, steenstrupine crystals are concentrated in the

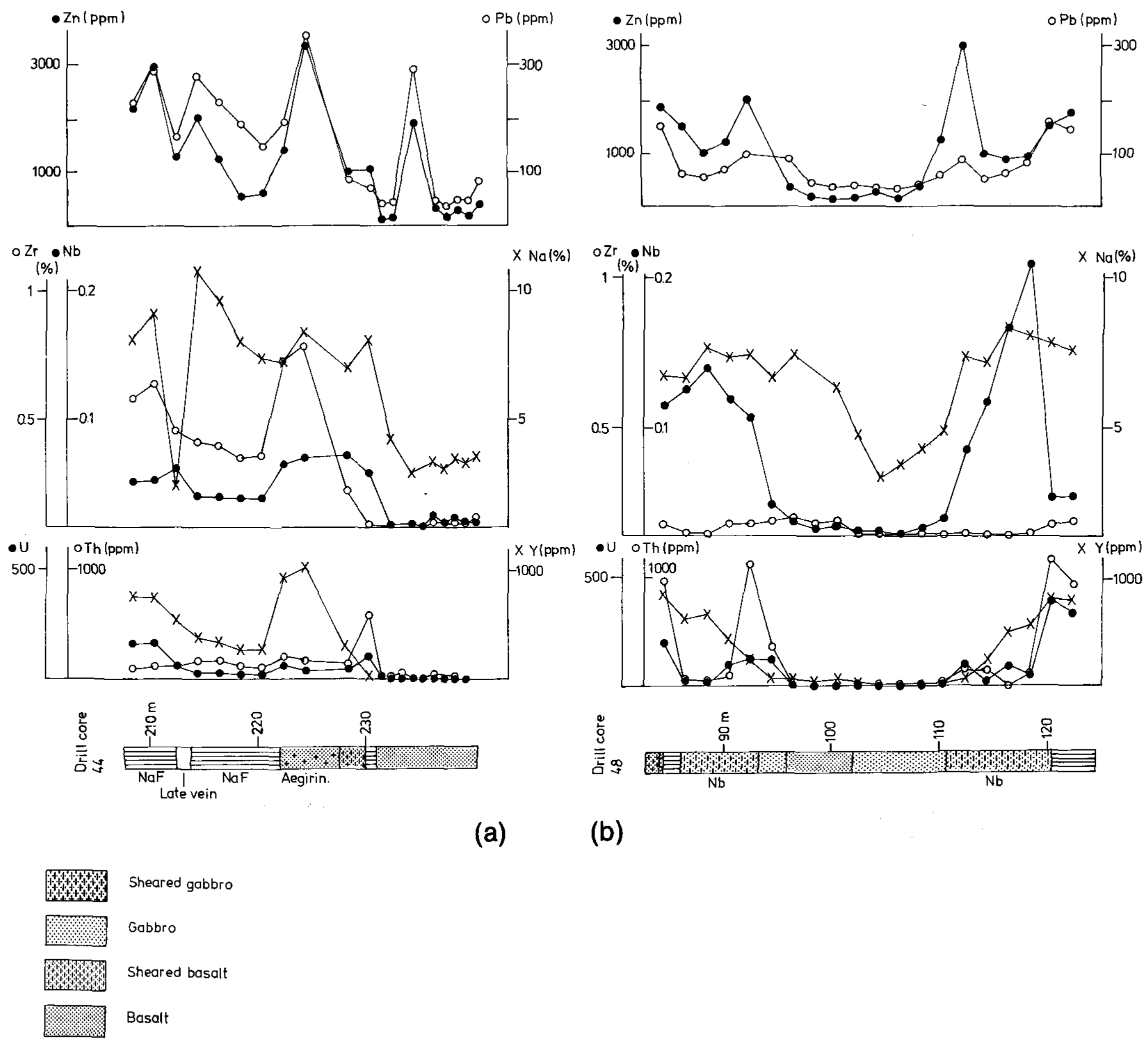
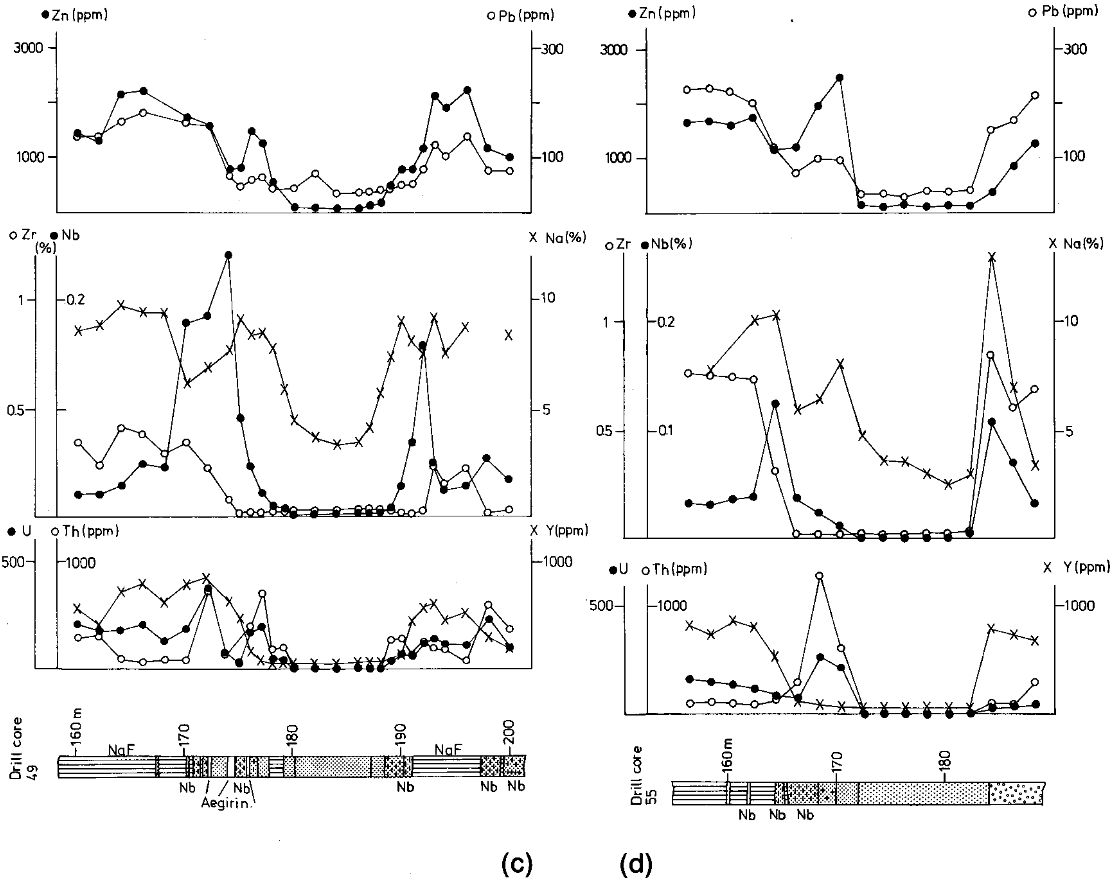


Fig. 9a–e. Distribution of Zn, Pb, Na, Zr, Nb, Y, U and Th in the transition zone of drill cores 44, 48, 49, 55 and 59.



● Zn (ppm)
○ Pb (ppm)
3000
1000
300
100
○ Zr ● Nb
(%)
X Na (%)
1
0.5
0.2
0.1
10
5
● U ○ Th (ppm)
X Y (ppm)
500
1000
Drill core 49
160 m
170
180
190
200
NaF
Nb
Aegirin.
Drill core 55
160 m
170
180
Nb
(c)
(d)

Fig. 9c–d cont.

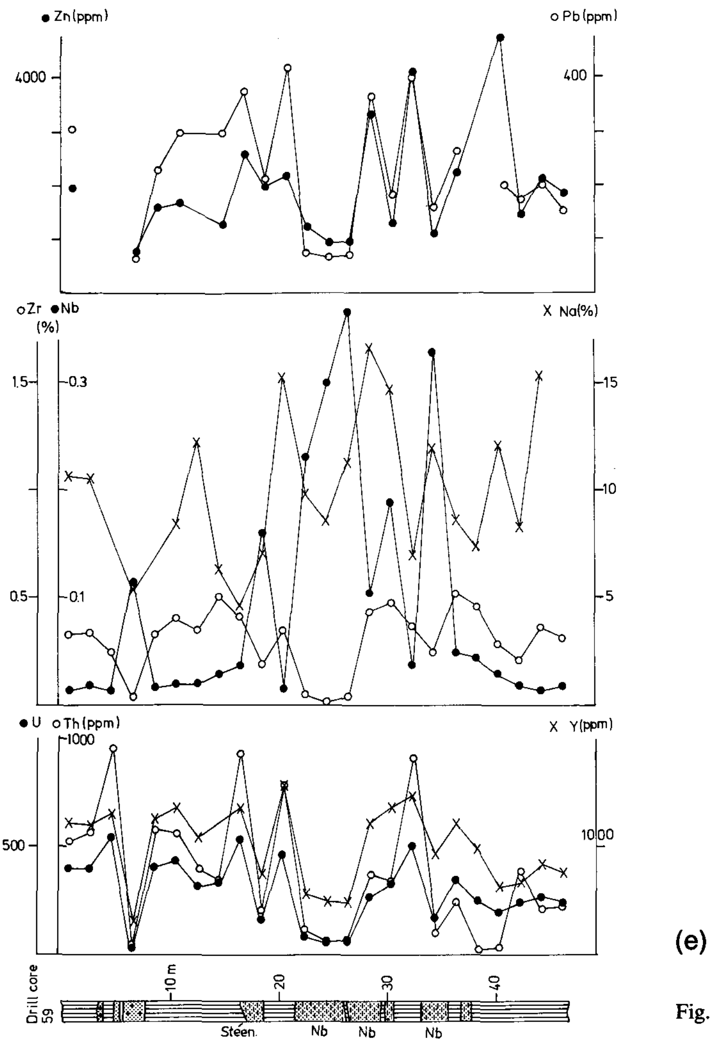


Fig. 9e cont.

contact zones of the lujavrite, up to 1 m away from the contact. This accumulation of steenstrupine is expressed and followed by anomalously high contents of Zn, Y, Zr, Nb, Pb, Th, and U (fig. 9).

In the section on fluorine it was mentioned that only a limited amount of volatiles and water were left for pneumatolytic-hydrothermal activity because these components, to a high degree, were dissolved in the peralkaline lujavrite magma. This explains the lack of pneumatolytic contact alteration of rocks bordering the Ilímaussaq complex as well as the relatively small number og hydrothermal veins with Nb, Li, and Be minerals and the predominance of these veins in the Ilímaussaq rocks of upper intrusive levels. Thus, Nb mineralisation has not been found in the bordering lavas, except at one locality north of Kvanefjeld where murmanite has been identified in a lava 2 m from the contact with the lujavrite.

RESOURCE EVALUATION

Other elements in addition to uranium may be of importance in connection with a possible exploitation of the Kvanefjeld uranium deposit, either as by-products or for considerations of waste disposal.

A discussion on occurrences of Zr, Nb, Zn, Be, F, Li, and the rare earth elements in radioactive rocks from Kvanefjeld was given by Sørensen *et al.* (1974). Data from the central part of Kvanefjeld covered by these authors are presented in Table 10 together with new resource calculations for the northern part of Kvanefjeld. The same tonnage calculation model was used as that by Nyegaard (1979). Though detailed tonnage calculations for especially Zr, Zn, Be, Li and the rare earth elements for the central part of Kvanefjeld are not known, it is assumed that the greater part of the Zr, Nb and F tonnages resides in the rocks of the northern Kvanefjeld area.

Low grades of Zr, Be, and Zn in the Kvanefjeld rocks are unlikely to be of any economic importance as by-products during a possible uranium extraction process of the Kvanefjeld ore. However, relatively large quantities of Nb, rare earth elements and F should be considered in a cost-benefit calculation of the Kvanefjeld project.

According to the Mining Annual Review 1980, niobium mining is in excess of the industrial needs and very sensitive to fluctuations in the steel industry. Most of the Nb is mined from pyrochlore deposits in Brazil and Canada, though some Nb comes as a by-product of tin operations. In spite of the relatively large tonnages of Nb in the rocks of Kvanefjeld (about three times the current annual world Nb_2O_5 consumption) the Nb grade of the

Table 10. Resource estimates for Zr, Nb, Zn, Be, F, Li, Y and REE in metric tons for the Kvanefjeld area

Element	Central part, Sørensen *et al.* (1974)	Northern part, this investigation		Present total estimate
Zr	No tonnage estimate	379,000 (0.37) 19,000 (0.08)	arfv. lujav. nauj. lujav.	398,000 (0.36)
Nb	1,100 (0.02) M-C lujav. 5,000 (0.1) shear. volc. rocks	34,000 (0.03) 17,000 (0.15)	arfv. lujav. shear. vol. rocks	51,000 (0.07)
Zn	No tonnage estimate (0.2) in M-C lujav.	213,000 (0.17) 12,000 (0.04)	arfv. lujav. shear. vol. rocks	225,000 (0.16)
Be	No tonnage estimate	7,300 (0.006)*	arfv. lujav.	7,300 (0.006)
F	10,000 (>0.5)	460,000 (0.96)	arfv. lujav. w. NaF	470,000 (0.96)
Li	No tonnage estimate	232,000 (0.19)*	arfv. lujav.	235,000 (0.19)
REE	No estimate	840,000 (0.82) 260,000 (1.1) 30,000 (0.23)	arfv. lujav. nauj. lujav. volc. rocks	1,130,000 (0.8)
Y	No tonnage estimate	74,000 (0.07) 26,000 (0.12) 5,000 (0.04)	arfv. lujav. nauj. lujav. shear. vol. rocks	105,000 (0.08)

*Sampling every 4th metre.
The average grade is given in parenthesis, the value for the total tonnage is the weighted mean of all rocks considered. Tonnage in metric tons, grade in weight per cent.

sheared rocks of Kvanefjeld is relatively low, about 0.15 per cent by weight, and although Nb consumption may rise at some future time, Nb is possibly of limited economic interest.

Very large tonnages of rare earth elements occur in the rocks of the northern Kvanefjeld area. World production (1979) in the form of rare earth element concentrates produced from mainly bastnäesite deposits in the USA, and mineral sand operations in Australia, India, and Brazil is less than 40 000 metric tons per year. Because growing demand is for more specialised rare earth compounds requiring special rare earth element separation installations, rare earth element production from Kvanefjeld is therefore possibly also doubtful.

Large tonnages of fluorine (Table 10) are found in the rocks of Kvanefjeld which can hardly be neglected in the ore processing. The fluorine-bearing mineral villiaumite is water soluble. Thus, fluorine is discharged into the main drainage channels leading to Narssaq Elv. It is estimated (Sørensen *et al.*, 1974) that about 80 tons F per year are discharged into this river which is near the settlement Narssaq (population: about 2000). For environmental reasons, a fluorine benefication scheme should be added to the uranium extraction process to reduce fluorine discharge into the drainage system.

CONCLUSIONS

About 600 crushed one-metre drill core sections systematically taken at every second metre were analysed for 17 major and trace elements by different analytical methods. The rocks were divided into naujakasite lujavrite (two subgroups), arfvedsonite lujavrite (two subgroups) and volcanic rocks (three subgroups). The following conclusions can be made from the geochemical and microscopic investigations.

The two lujavrite types of the northern Kvanefjeld area differ geochemically: the arfvedsonite lujavrite (both groups) has generally high Zr contents whereas the naujakasite lujavrite (both groups) is characterised by high radioactive elements and Y at relatively low Zr contents. In both lujavrites, these elements vary with depth. Accumulation of Th, U and Y occurs at upper levels of lujavrite sections, mostly at contacts to xenoliths, whereas Zr enrichment generally is found at lower levels, expressing temperature gradients at contacts and gravity settling of eudialyte during crystallisation, respectively. There is no significant difference in average contents of other minor elements in the different lujavrites. Except for elevated Ca and Mn contents in naujakasite lujavrite without villiaumite, the average concentrations of major elements (Na, K, Ti and Fe) are rather constant in the lujavrites. The grouping into lujavrites without and with visible villiaumite yielded no particular geochemical differences except for Na and F.

Eudialyte is generally not found in naujakasite lujavrite (both groups). The two lujavrite types are therefore regarded as two different stages in the consolidation of the lujavrite magma, naujakasite lujavrite being younger and more differentiated than arfvedsonite lujavrite. Disseminated villiaumite is found in both lujavrites together with rare earth and uranium-thorium bearing minerals like steenstrupine.

Niobium mineralisation is found in sheared xenoliths of lava and gabbro, and in some veins rich in U, Th, Be, and Li. These occurrences represent a late water and volatile-rich magma or hydrothermal solutions crystallising near the roof of the intrusion or were emplaced along sheared xenolith contacts.

From an economic point of view, niobium, rare earth elements, and fluorine constitute potential by-products during any future uranium mining operation. Most of the drill holes are about 200 m deep and they often terminate in lujavrites of the types described in this paper. The uranium mineralisation may continue to greater depths, thereby considerably increasing the present resource figures.

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APPENDIX

Microscopic investigations

Thin sections from about 80 lujavrite samples were investigated microscopically in order to review the mineralogy, the alteration and the structure of various types of lujavrites in the drill cores. A similar study on lujavrite in drill cores from the entire Kvanefjeld area, with special amphasis on steenstrupine, is presented by Makovicky *et al.* (1981).

Two transition series from undisturbed lava and gabbro into strongly sheared, Nb-bearing, metasomatically altered rocks were also examined in the microscope. A description of the findings is given below.

Lujavrite

Characteristic mineralogical observations from lujavrites are presented in Table 11. The majority of thin sections are from arfvedsonite lujavrite (52) and only six are from naujakasite lujavrite. According to Makovicky *et al.* (1981) the degree of alteration is reflected by the replacement of primary felsic minerals like nepheline, microcline and sodalite with water-bearing silicates analcime and natrolite. Albite, ferromagnesian and accessory minerals are less influenced by this 'hydration' process. It is seen from the table that there are no major differences between the main types of lujavrites based on the rock-forming minerals

Table 11. Mineralogical observations from 58 lujavrite thin sections of northern Kvanefjeld

Rock type	Number of thin sections	Rock forming minerals Felsic or secondary	Mafic	Accessory minerals
Arfvedsonite lujavrite	23	albite (18) microcline (17) nepheline (21) analcime (16) natrolite (8) sodalite (10)	arfved. (22) acmite (13)	natrolite (1) analcime (1) steenstr. (15) neptun. (2) eudial. (8) astroph. (2) lepidol. (7) chlorite (1)
Arfvedsonite lujav. with villiaumite	29	albite (24) microcline (21) nepheline (24) analcime (22) natrolite (13) sodalite (17)	arfved. (29) acmite (20)	natrolite (3) steenstr. (24) neptun. (6) eudial. (17) astroph. (7) lepidol. (10) chlorite (2) pectolo. (4)
Naujakasite lujav. with villiaumite	6	naujakas. (3) microcline (4) analcime (6) nepheline (3) natrolite (1) sodalite (2) albite (2)	arfved. (6) acmite (3)	steenstr. (6) lepidol. (3) astroph. (3)

The number of observations is given in parentheses.

except for the presence of naujakasite. However, naujakasite lujavrite contains only a small number of accessory minerals compared with arfvedsonite lujavrite. It is particularly noted that eudialyte is not present in naujakasite lujavrite.

The pronounced variation in lamination and alteration is believed to have only slight geochemical control on the rock. It does however reflect a complex emplacement history for the lujavrites.

Lava

The transition from unaffected lava to strongly sheared lava in contact with lujavrite is described for drill core 49, 187 to 192 m.

The unaffected lava is porphyritic having partly altered alkali feldspar and plagioclase phenocrysts in a strongly altered matrix of plagioclase and ferromagnesian minerals. Apatite and opaque minerals are accessory.

In the least metasomatised lava, 4 to 7 m from the contact to the lujavrite, neptunite, pectolite and biotite are formed, irregularly distributed in the rock; apatite and opaque minerals are absent. About 3 m from the contact the lava is sheared with poikilitic murmanite crystals. A few grains of pyrochlore were observed. At a distance of 2 m from the contact to the lujavrite the deformed rock has recrystallised completely into a heterogeneous matrix of sodalite, pectolite, arfvedsonite and albite with 5 to 10 mm large murmanite poikiloblasts. In one sample, about 1.5 m from the contact, the altered lava contains no murmanite but porphyroblasts of niobophyllite and microcline occur. The amount of neptunite is highest about 3–4 m from the lujavrite contact.

Gabbro

The transition from unaffected gabbro to strongly sheared and recrystallised gabbro was studied in drill core 48, 108 to 118 m.

The metasomatically unaltered gabbro consists of plagioclase, chlorite/sericite and opaque minerals. By shearing and metasomatism the gabbro recrystallises into a strongly foliated rock composed of arfvedsonite, pectolite and sodalite/analcime/natrolite. At the contact to the lujavrite, sodalite constitutes about 50 per cent by volume of the altered gabbro. The Nb mineralisation is expressed by the presence of scaly aggregates of an unknown Nb silicate, probably belonging to the epistolite-murmanite group.

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