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PART IX.

THE MINERALOGY OF THE KANGERDLUGSSUAQ
ALKALINE INTRUSION, EAST GREENLAND

BY

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WITH 24 FIGURES AND 28 TABLES IN THE TEXT
AND 5 PLATES

KØBENHAVN

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Abstract

The constituent minerals of the Kangerdlugssuaq alkaline intrusion are systematically described, with 28 full analyses and additional partial and X-ray analyses.

The main mineral of the intrusion, alkali feldspar, is a low-albite-orthoclase or low-albite-microcline microperthite, of composition ranging from Or₃₈ in the nordmarkites, Or₃₆ in the transitional pulaskite, and Or₄₁ in the main pulaskite to Or₅₅ in the foyaite. The nordmarkites and transitional pulaskite contain phenocrysts of low-albite-orthoclase microperthite (Or₂₉₋₂₈). Microperthite phenocrysts, composition Or₁₈, and rich in calcium (up to An₁₂), are also present in the basalt xenoliths. Six full analyses of feldspars are given, together with 13 partial analyses and X-ray compositions from 74 homogenized specimens. The sodic plagioclase rimming the perthites is an albite (An₄).

Both types of perthitic alkali feldspar are considered to be derived by unmixing from single feldspars of the anorthoclase-sanidine series. There is reasonable agreement between the structural state of the phenocrysts, seen as progressive (Al,Si) ordering, and the concept of centripetal cooling of the intrusion. In the case of the groundmass feldspars, of which the obliquities have been determined, there is less good correlation. The application of ВАРТН's geothermometer to the coexisting alkali and plagioclase feldspars indicates temperatures of crystallization of 970° C in the nordmarkites, falling gradually by some 200° to 760° in the foyaite.

Three full analyses of nephelines are presented, together with a further 12 compositions from X-ray analysis. The geothermometric temperatures of crystallization of the nephelines are in agreement with those of the feldspars.

The pyroxenes of the intrusion are aegirines and aegirine-augites; seven full analyses are given. The former are present mainly in the pulaskites (\simeq Ac₈₀) but are also common in the veins cutting both nordmarkites and pulaskites (\simeq Ac₉₀). In the foyaite the pyroxene is a strongly core-and-rim zoned aegirine-augite (\simeq Ac₃₀) and it is also present in veins in the foyaite. The two varieties of pyroxene both contain appreciable ZrO₂ and V₂O₅, and are rich in MnO. There is textural evidence that in the pulaskites many of the pyroxenes derive, with biotite, from the breakdown of alkali amphibole.

Alkali amphibole is present in the nordmarkites (katophorite) and pulaskites (magnesoarfvedsonite), whilst the veins of both groups contain arfvedsonite. Full analyses of five amphiboles are given; like the pyroxenes they are rich in MnO, and contain lesser amounts of ZrO₂. Li₂O is also present.

The Si/Al^{IV} ratios in both the pyroxenes and amphiboles show a progressive decrease in passing from the outer to the inner units of the intrusion, whilst the iron oxidation ratio rises from the nordmarkites to the pulaskites. In the foyaite, where amphibole is present in negligible amounts, the oxidation ratio decreases markedly in the pyroxene as aegirine is replaced by aegirine-augite, and is accompanied by the crystallization of melanite.

Two full analyses of biotite are given. This mineral is found mainly in the pulaskites and is also rich in MnO. It is the only mineral in the intrusion in which cesium has been detected.

The accessory minerals: quartz; sodalite (present as primary crystals with secondary overgrowths); melanite garnet (analysed); iron oxides (limenite in the early-formed rocks, magnetite in the later ones, with some hematite in the pulaskites); sphene; apatite; zircon; perovskite; astrophyllite (analysed); l avenite (analysed); eudialyte-eucolite (analysed); catapleiite (analysed); hiortdahlite; chevkinite; fluorite and analcite are described. The rare zirconium-rich accessory minerals are found mainly in the veins of the pulaskites.

The trace element contents of the analysed minerals and some of the analysed rocks are presented. In addition, five important element ratios have been determined for the various mineral groups, some of which (K/Rb; Ba/Sr; Rb/Sr) show a tendency to converge in the foyaite, suggesting equilibration. In some cases, however, they show marked breaks in the transitional pulaskite. The evidence from the element distribution in coexisting minerals in the pulaskites suggests crystallization at equilibrium, under constant external (P,T) conditions.

I. PREFACE

This contribution to the study of the Kangerdlugssuaq alkaline intrusion is based on the material collected by L. R. WAGER and W. A. DEER during the British East Greenland Expedition, 1935–36, leader L. R. WAGER, and by the members of the East Greenland Geological Expedition, 1953, leaders L. R. WAGER and W. A. DEER. A preliminary account of the intrusion was given by WAGER (1965), and was followed by a more detailed investigation of the petrology by KEMPE, DEER and WAGER (1970).

The laboratory work associated with this account of the mineralogy, except that relating to the accessory minerals, was undertaken by the first named author, but both authors have collaborated over the discussion and presentation of the results.

General acknowledgements, particularly in relation to the financial assistance in connection with the expeditions, during the course of which the mapping of the intrusion was carried out, have already been given in the earlier paper on the petrology of the intrusion.

The study of the main rock forming minerals of the intrusion by the first named author was carried out at the suggestion of and under the supervision and with the guidance of the late Professor WAGER, and that author wishes to record his indebtedness to Professor WAGER, and to Professors G. M. BROWN and J. ZUSSMAN for their valuable help and advice. Professor W. S. MACKENZIE and Dr. D. L. HAMILTON are thanked for their advice and assistance over the work relating to the alkali feldspars, as are many members of the Department of Geology and Mineralogy, Oxford, and the Department of Mineralogy, British Museum (Natural History), London, for discussion and help on various aspects of the work. He further acknowledges a N.E.R.C. Research Studentship, during the tenure of which most of the work was accomplished.

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II. ALKALI FELDSPARS

Perthitic alkali feldspars are by far the most abundant minerals in the Kangerdlugssuaq intrusion, forming, on average, up to 90 per cent of the earlier-formed rocks and 60 per cent of the foyaite. Two main types of alkali feldspars are present: a coarse low-albite-orthoclase or low-albite-microcline microperthite, varying in composition from $Or_{33}(Ab + An)_{67}$ to $Or_{59}(Ab + An)_{41}$, and a fine low-albite-orthoclase microperthite, with a composition range of $Or_{24}(Ab + An)_{76}$ to $Or_{32}(Ab + An)_{68}$. The first group constitutes the 'groundmass' feldspar and is present in each of the rock units of the intrusion: the second is porphyritic in habit and is only present in the nordmarkites and transitional pulaskite. Large fine microperthites are also present in the modified basalt inclusions which occur in the nordmarkites and occasionally in the transitional pulaskite, and which were originally described by WAGER (1965) as porphyroblastic cryptoperthites, but are now considered to be phenocrysts in respect to the syenite magma. They have a compositional range $Or_{17}(Ab + An)_{83}$ to $Or_{30}(Ab + An)_{70}$.

Laths of albite are abundant in the veins and pegmatitic segregations, where they form felty aggregates flowing round large crystals of perthite or feldspathoid. These have not been investigated in detail but a composition close to albite is indicated by their refractive indices. Plagioclase is present as irregular rims, occasionally 'swapped', of a sodic plagioclase, usually surrounding the coarse microperthites. Plagioclase also occurs as discrete, subhedral crystals interstitial to the microperthite. Its anorthite content was determined by measurement of the α' index on cleavage flakes and is An_4 in the nordmarkites and pulaskites whilst in the foyaite the composition ranges from An_4 to An_{13} although the less calcic varieties are the more common. This increase in anorthite content is related to higher calcium contents in the host rocks, whilst the presence of some calcium in the plagioclase of all the rocks results from the operation of the plagioclase effect (BOWEN, 1945).

In the early rocks the coarse microperthites forming the groundmass are subhedral to euhedral in habit; in the later rocks — main pulaskite and foyaite — they have a pronounced tabular shape, parallel to $\{010\}$, and show multiple Carlsbad twinning. This tabular habit has been noted

by TILLEY (1956, 1960) in microclines of certain undersaturated rocks from South Africa, and by MACKENZIE and SMITH (1961) in microcline microperthites from nepheline syenites. MACKENZIE and SMITH noted that this habit, which is characteristic of sanidine, is common in feldspars which have crystallized from nepheline syenite magmas, and have suggested that it may be due to the metastable crystallization of sanidine (-cryptoperthite) at low temperatures, and the subsequent preservation of the sanidine habit.

The unmixing into two phases which has taken place in all the coarse microperthites varies from a patchy development of plates and lamellae to well developed lamellae of the potassium phase (Plate 1). The lamellae are best developed in the alkali feldspars of those rocks, especially the main pulaskite, in which the feldspars have a well developed tabular habit, and is possibly related to the fluxing effect of the higher volatile content (vapour pressure) under which the later rocks crystallized. In the patchy perthites especially, albite twinning is locally developed in the sodic (host) phase, but the cross-hatched twinning of microcline (albite and pericline laws) is generally absent, although in a vein in the transitional pulaskite well developed cross-hatched twinning in the microperthites has been observed. Zoning is rare in the coarse microperthites but a crystal showing an oscillatory zoned rim was found in one foyaite specimen.

Of the large scale twinning laws, Carlsbad twinning (see Plate 1) is by far the most commonly developed. Simple twinning of two individuals is ubiquitous in all the rocks, but in the tabular feldspars, especially in the main pulaskite, multiple development of up to six individuals is common. In Carlsbad twins in perthites from the Pilanesberg complex RETIEF (1962) has reported that the pole of the composition plane coincides with the $Z(\gamma)$ axis of both components and has suggested that, since the potassium phase is at least in part triclinic, this coincidence implies that the composition plane is parallel to (010) in the original monoclinic crystal from which the separate phases developed. In the Kangerdlugssuaq feldspars, although γ is close to the pole of the composition plane, it is separated from it by about 2° . In cases of multiple twinning, γ is common to all individuals whilst α and β of alternate individuals are separated by about 4° . Examples of interpenetrant Carlsbad twinning have also been noted. The next most common simple twinning observed is the Manebach type and the herring-bone structure resulting from this type of twinning in perthites is frequently present (Plate 1). Baveno twinning in the feldspar was positively identified in only a small number of rocks.

In all the feldspars examined on the universal stage, it was observed that the angle between the $\{001\}$ cleavage and the planes of the perthite

lamellae is 72° to 73° ; this is in agreement with the observations of several workers (see SMITH, 1961, and DEER, HOWIE and ZUSSMAN (1963b, p. 20).

Some microperthites contain exsolved acicular needles and plates of aegirine; where these were examined on the universal stage it was found that they were usually orientated parallel to $\{001\}$, so that their poles coincided with those of the $\{001\}$ cleavages and, in Manebach twins, the pole of the composition plane. Occasionally, they were found to be parallel to $\{010\}$.

The dark grey or grey-blue phenocrysts in both nordmarkite and transitional pulaskite, and in the basalt inclusions, are subhedral, but the zoning in many cases indicates the potential shape of the crystals. Unmixing shows locally as a patchy development of the potassium phase, while other parts of the same crystal may be optically homogeneous. Albite twinning is developed locally in the sodic phase forming the host but examples of fine cross-hatched twinning (albite and pericline) characteristic of anorthoclase have not been observed. The phenocrysts in the basalt xenoliths contain many small inclusions of ferromagnesian minerals but in other respects the two types of phenocryst are optically similar. Both show a sodic core (Plate 2) zoned outwards with progressive increase in potassium so that the outer edges sometimes appear to merge into the coarse groundmass microperthite. The outer, more potassic rims show a similar development of exsolution lamellae of the potassium phase. In general, being larger, the phenocrysts in the basalt xenoliths are more clearly defined both in hand specimen and microscopically; the concentric zoning is marked by rings of exsolved iron-rich material and indicates more clearly the crystal morphology. The zoning in both types is sometimes oscillatory but does not show any particular pattern, and is considered to result from minor fluctuations in the Na/K ratio of the magma during crystal growth.

Systematic measurement of the refractive indices of the alkali feldspars was not undertaken in view of the coarse perthitic nature of most of the crystals. Some measurements, however, were made in order to test for the possible presence of iron-rich feldspars but no abnormally high values were found.

The extinction angles of both exsolved phases, in sections parallel to (010), were measured in some groundmass samples; those of the potassium phases showed a general decrease from 9° in the nordmarkite to 6° in the foyaite feldspars, while the sodium phases varied from 14° in the nordmarkites to 20° in the foyaite. Both sets of values are consistent with the changing composition of the individual phases to more nearly pure potassium and sodium feldspars respectively during the transition from nordmarkite to foyaite.

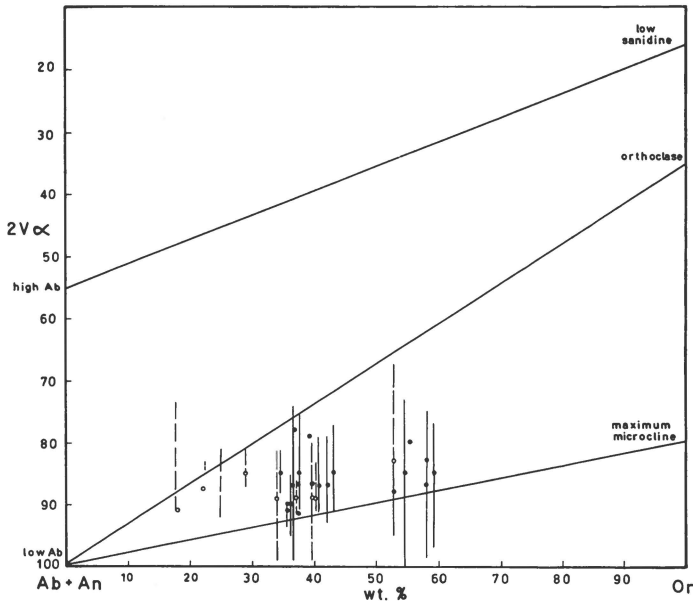


Fig. 1. Plot of optical axial angles in alkali feldspars (diagram modified from TUTTLE (1952) and others). Lines: ranges. Circles: mean or most representative values. Heavy lines, solid circles: groundmass feldspars. Broken lines, open circles: phenocrysts.

The 2Vs of over thirty specimens were determined by the orthoscopic method on the universal stage and are plotted in Fig. 1. Broken lines indicate the ranges of values in phenocrysts and solid lines the ranges in the groundmass microperthites; open circles (phenocrysts) and solid circles (groundmass) indicate measurements which are considered the most typical, or are the means of several determinations in one section. The 2Vs are the average figures for the bulk feldspars, since individual measurement of the two phases is impracticable; as noted by PARSONS (1965), the range increases with the broadening of the perthite lamellae. In these low-temperature feldspars, the optic axial plane is normal to (010).

The 2Vs of the groundmass crystals show a spread typical of feldspars intermediate between orthoclase and maximum microcline, and are consistent with the X-ray data; the change in composition compensates for the generally higher obliquity in the feldspars of the later units of the intrusion. A comparison with Fig. 5 in PARSONS (1965) shows an almost identical coverage and his comments on the limitations of 2V measurements in perthitic feldspars apply to the present suite. In the case of the phenocrysts, comparison is more interesting since the Kangerdlugssuaq feldspars tend to have higher 2Vs than Loch Ailsh feldspars of similar bulk composition. This is considered to be a direct consequence of their

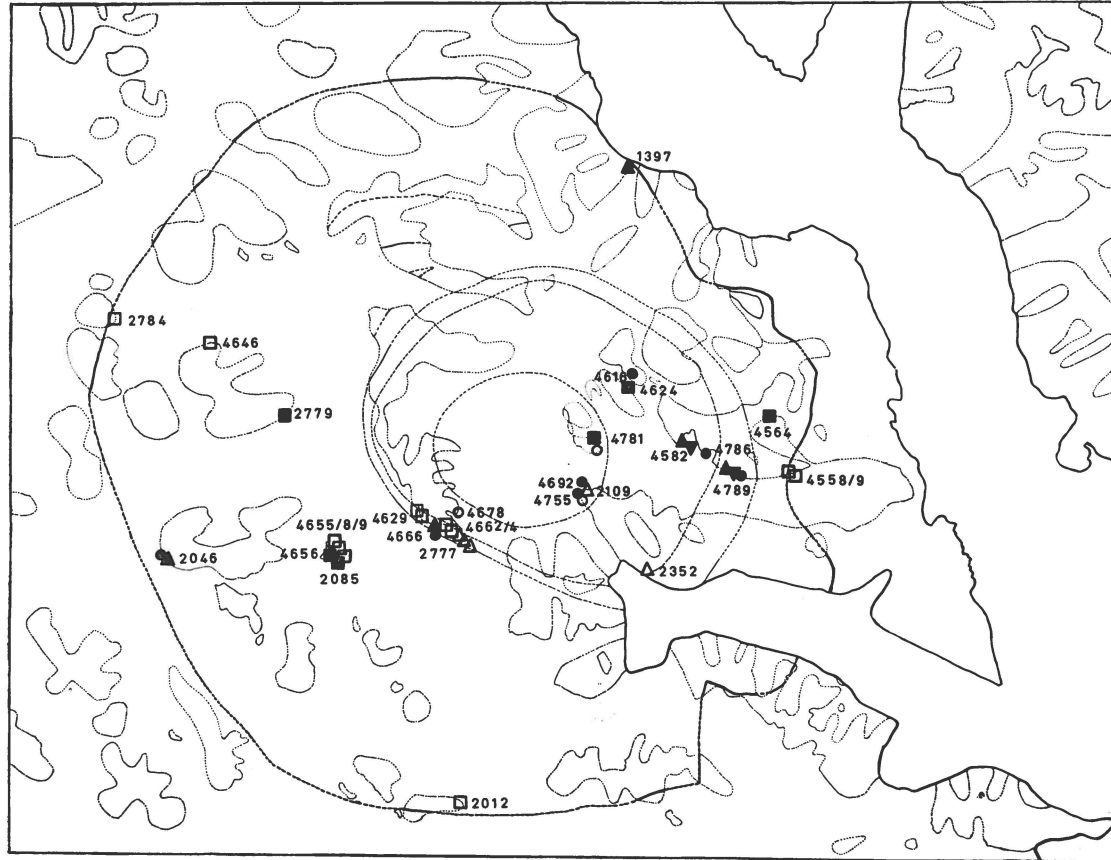


Fig. 2. Locality map of analysed minerals. Solid squares: feldspar full analyses. Open squares: feldspar partial analyses. Open circles: nephelines. Solid circles: pyroxenes. Solid triangles: amphiboles. Solid inverted triangles: biotites. Open triangles: other minerals.

higher calcium content which increases the optic axial angle when it is present in quantities greater than the equivalent of 3 to 4 per cent An (DEER *et al.*, 1963b).

a) Chemistry

Analyses of three phenocrysts from modified basaltic inclusions and three coarse groundmass microperthites are given in Table I; the structural formulae are shown in Table II. In addition, the alkalis and, in some cases, lime, were determined in a further eleven phenocrysts, of which four are from modified inclusions and seven from normal syenites, and on two groundmass microperthites (see Fig. 2). These, together with the relevant parts of the full analyses, are set out in Table III. The estimated compositions of all these feldspars from the $\bar{2}01$ X-ray method (using Table I of TUTTLE and BOWEN, 1958) are also included in this table. The trace elements of four of the feldspars, together with the Sr and Ba values for a phenocryst from the transitional pulaskite, are given in Table IV: they are discussed later in the section on trace element chemistry.

The compositions of the coarse microperthites are very similar, except for a slightly high SiO_2 and low Al_2O_3 content, to those of other microcline microperthites (DEER *et al.*, 1963b). The somewhat high values for Fe_2O_3 suggest partial substitution of Fe^{+3} for Al, a substitution that is not uncommon in both natural and synthetic feldspars (FAUST, 1936). BAILEY and SCHAIRER (1966) have recently discussed the important role of this substitution in the petrogenesis of alkaline rocks, and their views will be discussed in a later paper. The other minor elements are considered to proxy for major elements in the usual way: thus, Ti (and Zr and Ga) substitute for Al; Fe^{+2} , Mn, Mg, and Sr for Ca, and Ba and Rb for K. The barium and strontium contents of the feldspars are small, the former decreasing slightly and the latter rising to the equivalent of 0.02 per cent in the foyaite. The percentages of the celsian and strontium molecules present in the feldspars are therefore small and are of little significance.

The proportion of anorthite is slightly higher than is common in microcline microperthites and averages slightly over 3 per cent. In Table II, three methods have been used to calculate the proportions of the feldspar end-members. The molecular percentage values are considered to be the most valid, but the end-member compositions calculated directly from the three oxides, Na_2O , K_2O and CaO , are also included, since this method is used to estimate compositions from the partial analyses; the values obtained by these two methods are in good agreement. The results of the normative calculation show a greater difference, since in this calculation the ferromagnesian oxides are allocated to pyroxenes and olivines; this method has the advantage, however, of indicating the maximum

Table I. *Alkali Feldspars – Chemical Analyses*

	Phenocrysts from basalt inclusions			Groundmass microperthites		
	1	2	3	4	5	6
Distance from centre	.677	.677	.668	.681	.311	.185
SiO ₂	62.70	63.57	63.84	66.16	66.44	65.54
TiO ₂	0.35	0.32	0.40	0.06	0.03	0.03
Al ₂ O ₃	20.30	19.60	19.94	18.32	18.81	18.44
Fe ₂ O ₃	0.50	0.75	0.91	0.73	0.47	0.14
FeO.....	0.92	0.87	0.87	0.02	0.02	nil
MnO.....	0.07	0.11	0.12	0.02	0.01	tr.
MgO.....	0.87	0.34	0.28	0.06	0.05	0.04
CaO.....	2.38	1.70	1.51	0.69	0.67	0.54
Na ₂ O.....	8.42	8.01	7.42	7.19	6.84	4.96
K ₂ O.....	2.97	3.75	4.28	6.22	6.63	9.38
H ₂ O ⁺	0.20	0.49	0.21	0.21	0.14	0.20
H ₂ O ⁻	0.06	0.15	0.12	0.06	0.06	0.13
P ₂ O ₅	n.d.	0.14	0.18	n.d.	n.d.	n.d.
SrO.....	0.16	n.d.	n.d.	tr.	tr.	0.02
BaO.....	0.27	n.d.	n.d.	0.03	0.02	0.02
Rb ₂ O.....	0.01	n.d.	n.d.	0.01	0.01	0.02
Total.....	100.22	99.80	100.08	99.78	100.20	99.46

1. Phenocryst, basalt inclusion, nordmarkite, E.G. 4656, small nunatak southeast of Fangetårnet.
Anal. D. R. C. KEMPE (H₂O⁺ estimated value; total includes ZrO, 0.03; Li₂O, 0.01).
2. Phenocryst, basalt inclusion, nordmarkite, E.G. 2085, small nunatak southeast of Fangetårnet.
Anal. W. A. DEER.
3. Phenocryst, basalt inclusion, nordmarkite, E.G. 2779, east point of Fangetårnet.
Anal. W. A. DEER.
4. Groundmass microperthite, nordmarkite, E.G. 4564, mountain south of Nordre Syenitgletscher.
Anal. D. R. C. KEMPE.
5. Groundmass microperthite, pulaskite, E.G. 4624, nunatak southeast of Kælv-gletscheren.
Anal. D. R. C. KEMPE.
6. Groundmass microperthite, foyaite, E.G. 4781, nunatak at the head of Søndre Syenitgletscher.
Anal. D. R. C. KEMPE (H₂O⁺ estimated value).

Table II. *Alkali Feldspars**Numbers of ions on the basis of 32 oxygens and end member compositions*

	Phenocrysts from basalt inclusions			Groundmass micropertthites				
	1	2	3	4	5	6		
Distance from centre . . . . .	.677	.677	.668	.681	.311	.185	
Si	11.315	11.535	11.525	11.931	11.917	11.961		
Al	4.319	4.184	4.235	3.895	3.977	3.967		
Ti	0.048	0.044	0.054	0.008	0.004	0.004		
Fe ⁺³	0.068	0.102	0.123	0.099	0.063	0.019		
Fe ⁺²	0.139	0.132	0.131	0.003	0.003	—		
Mn	0.011	0.017	0.017	0.003	0.002	—		
Mg	0.234	0.093	0.076	0.016	0.013	0.011		
Ca	0.460	0.331	0.292	0.133	0.129	0.106		
Sr	0.017	—	—	—	—	0.002		
Ba	0.019	—	—	0.002	0.001	0.001		
Na	2.946	2.813	2.593	2.514	2.379	1.755		
K	0.684	0.869	0.986	1.431	1.517	2.184		
Z	15.75	15.87	15.94	15.93	15.96	15.95		
X	4.13	4.01	3.87	4.08	4.03	4.05		
Mol. %	{	Or	17.0	21.7	25.5	35.1	37.7	54.0
		Ab	71.4	70.1	67.0	61.7	59.1	43.4
		An	11.6	8.2	7.5	3.2	3.2	2.6
Oxides (recalc. to 100%)	{	Or	17.5	22.6	26.5	36.4	39.1	55.4
		Ab	70.8	68.9	65.7	60.2	57.6	41.9
		An	11.7	8.5	7.8	3.4	3.3	2.7
Norm (recalc. to 100%)	{	Or	19.5	23.5	26.8	38.2	39.9	56.7
		Ab	70.5	69.7	66.6	61.8	59.0	42.9
		An	10.0	6.8	6.7	—	1.1	0.4
Original norm total		90.0	94.4	94.4	96.3	98.1	97.8	
<i>Other normative constituents</i>								
qz	—	—	1.0	—	0.2	0.1		
ne	4.2	1.1	—	tr.	—	—		
ac	—	—	—	1.1	—	—		
di + wo + hy + ol	4.3	1.6	1.1	1.6	1.1	1.1		
mt + il	1.4	1.7	2.1	0.1	0.1	—		
hm	—	—	—	0.4	0.5	0.1		

Note: Rb₂O is not included in the calculated structural formulae of nos. 1, 4, 5 and 6.

Table III. *Alkali Feldspars*

<i>Phenocrysts from basalt inclusions</i>							
	4646-QN	4559-N	4655-N	4656-N	4658-N	2085-N	2779-N
Distance from centre .....	.813	.693	.677	.677	.677	.677	.668
Na ₂ O	8.73	7.61	8.27	8.42	8.43	8.01	7.42
K ₂ O	3.12	4.96	3.19	2.97	3.24	3.75	4.28
CaO	—	1.07	—	2.38	—	1.70	1.51
Calc. from oxides Or	18.5	29.6	18.9	17.5	19.2	22.6	26.5
(recalc. to 100 %) Ab	73.8	65.0	69.9	70.8	71.2	68.9	65.7
An	7.7	5.4	11.2	11.7	9.6	8.5	7.8
Original total	—	99.0	—	100.6	—	98.3	95.5
Or wt. per cent (201 X-ray method)	22.2	27.0	14.5	10.0	13.0	18.0	—

For localities of feldspars, see Fig. 2.

Anal. (except nos. 2085 and 2779) D. R. C. KEMPE.

Anal. (nos. 2085 and 2779) W. A. DEER.

amount of impurities (in terms of the CIPW normative minerals) which may be present in the feldspars.

In addition to the chemical analyses, the compositions of 74 homogenised feldspars (see Table V) have been determined by the 201 X-ray method (BOWEN and TUTTLE, 1950). The average compositions of the groundmass alkali feldspars obtained from all methods of analysis are compared below with the compositions estimated by drawing tie-lines in the system nepheline-kalsilite-quartz, from quartz or nepheline through the normative plots of the averages of the rock analyses.

	Composition from analysis	Composition estimated by tie-line construction
All nordmarkites	Or _{35.4}	Or _{37.5}
Transitional pulaskite	Or _{36.2}	Or _{31.3}
Main pulaskite	Or _{40.9}	Or _{41.1}
Foyaite	Or _{34.7}	—

The analyses of the phenocrysts from basaltic inclusions present a number of difficulties. Despite repeated centrifuging in heavy liquid it was not possible to remove the minute inclusions of biotite, amphibole and pyroxene, and in consequence the normative impurities are high, and the low silica content of these feldspars is probably due to the same cause. They are richer in aluminium than the groundmass microperthites

- Partial Analyses

<i>Normal phenocrysts</i>							<i>Groundmass micropertthites</i>				
2012- QN	4651- QN	4558- N	4659- N	4629- TP	4662- TP	4664- TP	2784- QN	4564- N	4629- TP	4624- P	4781- F
.992	.887	.693	.677	.517	.485	.485	.996	.681	.517	.311	.185
7.84	7.83	8.05	7.66	7.89	7.35	7.75	6.55	7.19	7.14	6.84	4.96
4.19	4.98	5.13	5.32	4.71	4.58	4.79	6.72	6.22	6.07	6.63	9.38
1.91	—	—	—	—	1.38	—	0.76	0.69	0.93	0.67	0.54
24.7	29.5	30.3	31.5	27.8	28.2	28.4	40.2	36.4	35.6	39.1	55.4
65.9	66.2	68.0	64.7	66.7	64.7	65.5	56.0	60.2	59.8	57.6	41.9
9.4	4.3	1.7	3.8	5.5	7.1	6.1	3.8	3.4	4.6	3.3	2.7
100.5	—	—	—	—	96.1	—	98.9	101.0	100.9	100.4	100.1
21.8	19.3	27.8	28.0	25.0	27.0	25.0	40.3	35.0	35.0	40.6	53.3

and the high content of this atom shows that little or no substitution of Al by Fe^{+3} is present. The main compositional differences between the phenocrysts in the basalt and the groundmass perthites are in their alkalis and lime contents, the former being much poorer in K_2O and richer in Na_2O and CaO , as shown in Tables II and III in which the Or content of the basalt phenocrysts is seen to vary from Or_{17} to Or_{30} . These low values result in a correspondingly high value of both the albite and especially the anorthite components. The effect of the high anorthite content on the X-ray diffraction pattern is discussed in the next section. The anorthite content, which in some of the phenocrysts in the basalt amounts to nearly 12 per cent, is considerably higher than in the normal phenocrysts, but is comparable with other feldspars from similar parageneses such as the Oslo larvikites, some of which contain as much as 14 per cent of the anorthite component (MUIR and SMITH, 1956), and in feldspars from the Kûngnât syenite (UPTON, 1960), which contain up to 11 per cent anorthite. The content of most of the minor elements is higher than in the groundmass micropertthite and their high values are probably attributable to the inclusions, as in the case of the SrO , 0.16 per cent, and BaO , 0.27 per cent, in a basalt phenocryst in the nordmarkite (Table I). The SrO content can be related to the lime-rich environment in which the feldspars developed and the BaO is probably derived from the biotite inclusions in the feldspars.

Partial analyses of the normal phenocrysts (Table III) show that the compositions range from Or_{24} to Or_{32} and span the gap between the compositions of the phenocrysts in the basalt inclusions and those of the

Table IV. *Alkali Feldspars – Trace Elements* (p. p. m.)

	Sensitivity p.p.m.	Ionic radius (Å)	1	2	4	5	6
Distance from centre			.667	.485	.681	.311	.185
Ga ³⁺	3	0.62	22	n.d.	24	20	18
Li ¹⁺	0.5	0.68	50	n.d.	2	0.5	1
Cu ²⁺	0.5	0.72	6	n.d.	3	—	—
V ³⁺	5	0.74	20	n.d.	10	10	10
Zr ⁴⁺	10	0.79	320	n.d.	44	37	37
Yb ³⁺	10	0.86	1*	n.d.	—	—	—
Y ³⁺	10	0.92	5*	n.d.	—	—	—
Sr ²⁺	5	1.12	1380	555	19	30	200
La ³⁺	10	1.14	63	n.d.	27	—	—
Ba ²⁺	5	1.34	2400	2500	264	185	212
Rb ¹⁺	1	1.47	53	n.d.	96	109	252

2. Phenocryst in transitional pulaskite, E.G. 4662. Numbers 1 and 4–6, see Table I and Fig. 2.

Anal. D. R. C. KEMPE.

* Approximate value.

groundmass; the anorthite content, averaging 5.5 per cent, is also intermediate between the other two groups. To verify the common origin of the two types of phenocryst, the strontium and barium in a phenocryst from 4662-TP were determined. These values, together with those of four other feldspars given in Table IV, show a much closer agreement with the basalt phenocryst from 4656-N than with the groundmass feldspars.

For comparison with the values in the tables, the average compositions of the phenocrysts, based on all determinative methods, are:

Nordmarkites	Or _{29.1}
Basalt inclusions in nordmarkite	Or _{18.4}
Transitional pulaskite	Or _{28.1}

A semi-quantitative determination of the total Fe, Ca and K in the zoned basaltic phenocryst from 4656-N was made by electron microprobe analysis. A profile of half the phenocryst is shown in Fig. 3 and illustrates diagrammatically the local fluctuations of each element in the different regions of the crystal; variations due to inclusions of ferromagnesian minerals have been ignored. The sodic and calcic core, relatively poor in total iron, is clearly shown in the profile, and is separated from the rim, which is optically perthitic and merges with the groundmass microperthite, by a dark intermediate zone, midway in composition, containing concentric rings of iron-rich impurities. This diagram, although it does

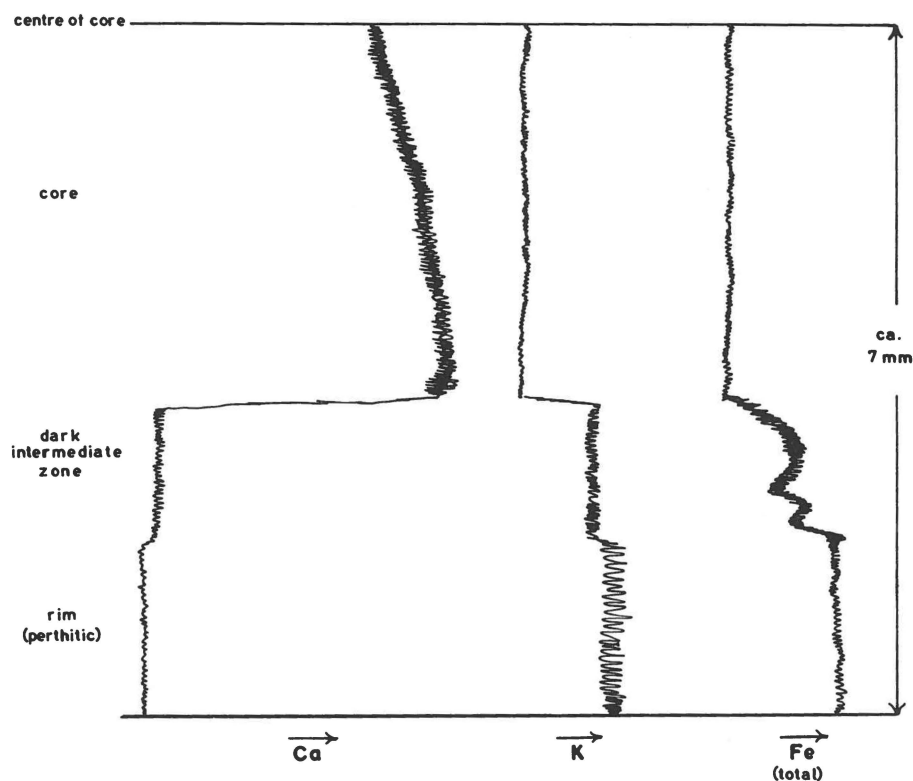


Fig. 3. Electron microprobe profile (Ca, K, total Fe) from core to margin of a feldspar phenocryst from a basalt inclusion.

not show the oscillatory zoning, illustrates the general compositional pattern which is common to both types of phenocryst, i.e. a Na- and Ca-rich core, becoming progressively more potassic and richer in iron from core to margin.

The essential compositional relationships between the basalt phenocrysts, normal phenocrysts, and groundmass alkali feldspar, can thus be summarized as a general decrease in Na and Ca and an increase in K, the changes being greater between the normal phenocrysts and groundmass feldspar than between the two types of phenocryst. The notably high Ca content of the basaltic phenocrysts is related to their growth in a Ca-rich environment, whilst introduction from the syenitic magma of Na and, especially, K, increases as the basalts are progressively more severely modified.

The compositions of the feldspars in the veins were determined only by the $\bar{2}01$ X-ray method. They are shown as solid triangles in Fig. 4, in which all the measured feldspar compositions are plotted. The veins contain more potassium-rich feldspars than those of the host rocks and,

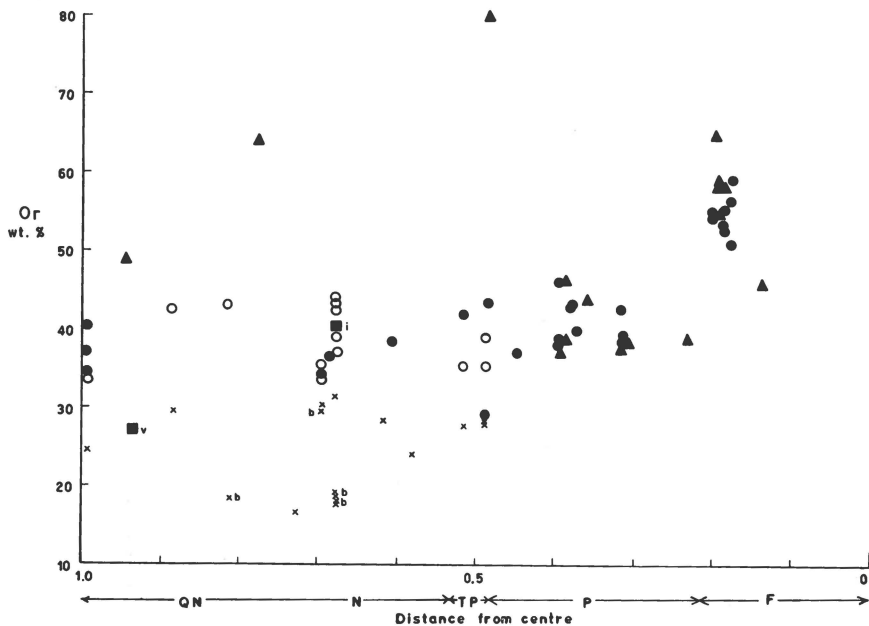


Fig. 4. Alkali feldspar compositions. Solid circles: groundmass feldspars of aphyric rocks. Open circles: groundmass feldspars of rocks containing phenocrysts. Crosses: phenocrysts, b: indicating those from basalt inclusions. Solid triangles: veins. Squares: i: the microsyenitic perthite in a modified basalt inclusion and v: the feldspar from a vug in a basalt inclusion.

in the case of one vein in the nordmarkite (2338-V), and one in the transitional pulaskite (4666-V), they are very much richer in potassium. This enrichment in potassium of the late-stage feldspars is accompanied by a more general enrichment in sodium which enters into albite and pyroxene and, in some of the more alkaline rocks, the feldspathoids.

b) X-ray Investigations of Composition and Structural State

Over 70 alkali feldspars were separated and examined by X-ray diffraction (see Fig. 5). These samples were also homogenized by dry heating at 1025° C for an average period of seven days, this temperature and heating period being found to give the best results, with a minimum of residual peaks or partial fusing. For the homogenized feldspars, quartz was used as an internal standard, since interference from potassium-rich feldspars does not occur within the compositional range studied.

The diffractometer traces of the unheated phenocrysts of both types — those modified by growth in basalt inclusions and those which crystallized in the normal syenites — showed no systematic differences. Both

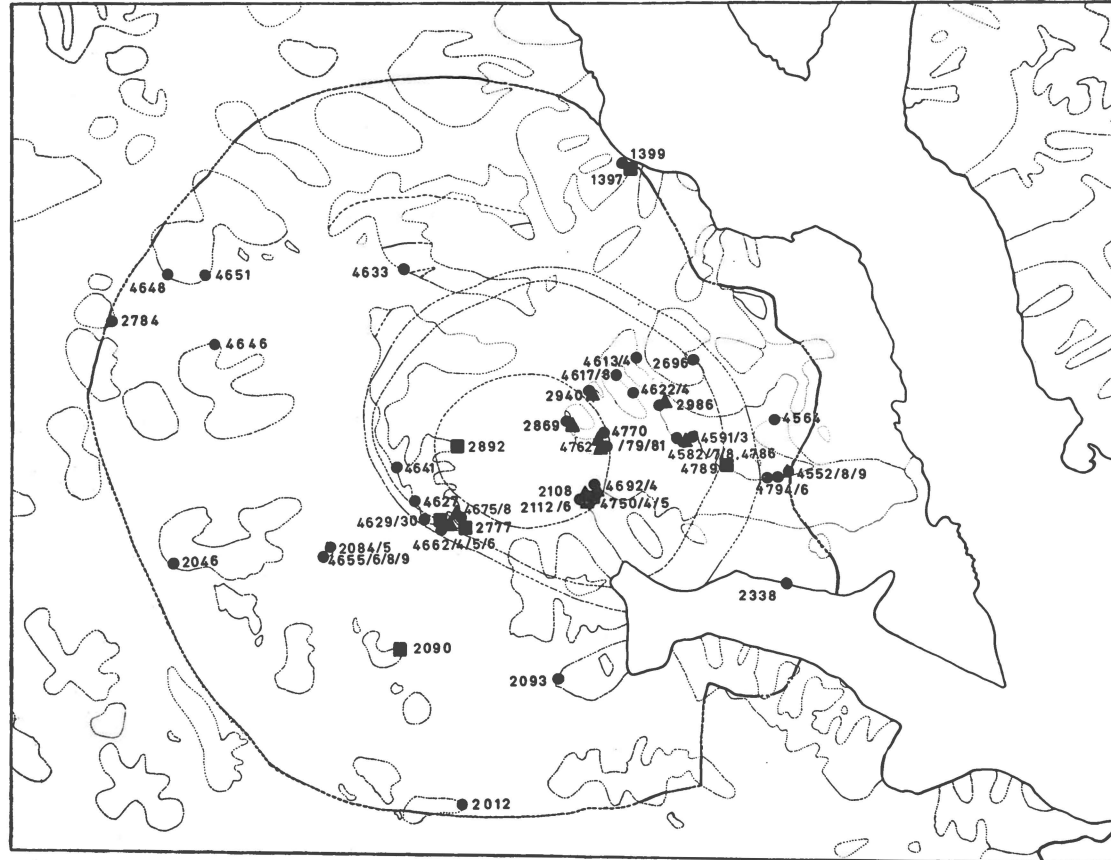


Fig. 5. Locality map of minerals studied by X-ray methods. Circles: feldspars. Triangles: nephelines. Squares: other minerals.

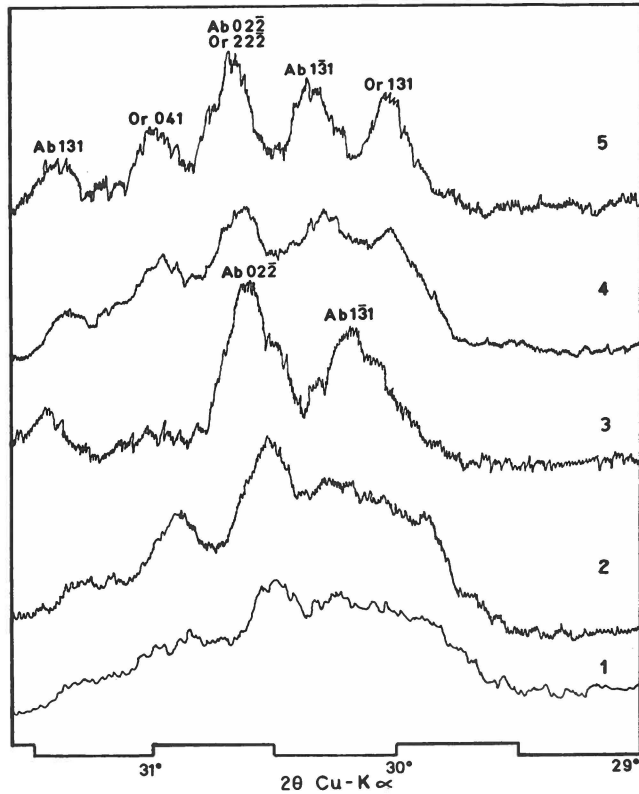


Fig. 6. Typical X-ray diffractometer traces: alkali feldspar phenocrysts.

are low-albite-orthoclase microperthites, in which unmixing is visible under the microscope and thus precludes use of the name cryptoperthite, and it is this similarity between the two types, together with their compositional resemblance, that forms the basis for the conclusion that both types are phenocrystal in origin. If the phenocrysts in the basalts were in fact porphyroblasts, it is probable that their structural state would be different from the normal phenocrysts which, if derived from metasomatised gneiss inclusions from the basement complex, as suggested earlier by WAGER (1965), might be expected to have a structural state closer to maximum microcline.

Peak types shown by the phenocrysts from quartz-nordmarkite (no. 1); nordmarkites (nos. 2 and 4); a phenocryst in a modified basalt inclusion in the nordmarkite (no. 3); and a transitional pulaskite (no. 5), are given in Fig. 6. These peak types are representative of all those observed and show a serial development from a relatively high structural state, represented by a nearly homogeneous anorthoclase type, to a low structural state, in which the sodic and potassic phases are clearly un-

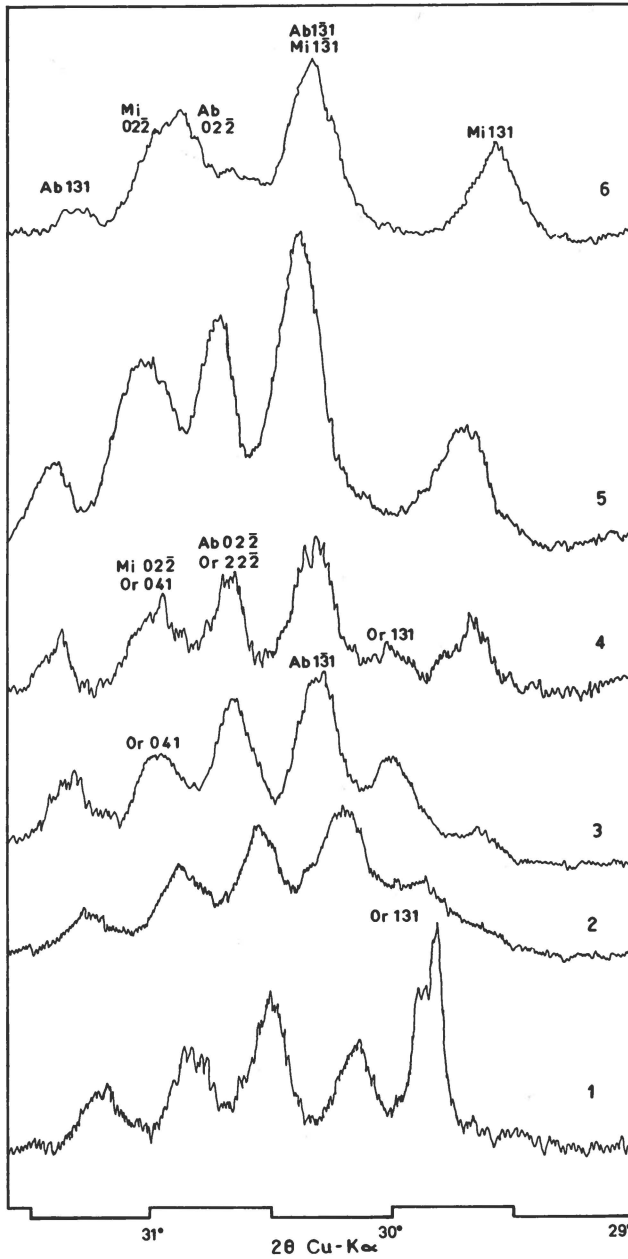


Fig. 7. Typical X-ray diffractometer traces: groundmass feldspars.

mixed into low-albite and orthoclase. This development takes place inwards from the outer quartz-nordmarkite to the transitional pulaskite, the stage at which phenocrysts cease to be present, and is further evidence of the inward centripetal cooling of the intrusion. The phenocryst in the

basalt inclusion, except for its higher albite content, demonstrated by the size of the albite $1\bar{3}1$ and $02\bar{2}$ peaks, is otherwise comparable with the phenocrysts in the nordmarkites.

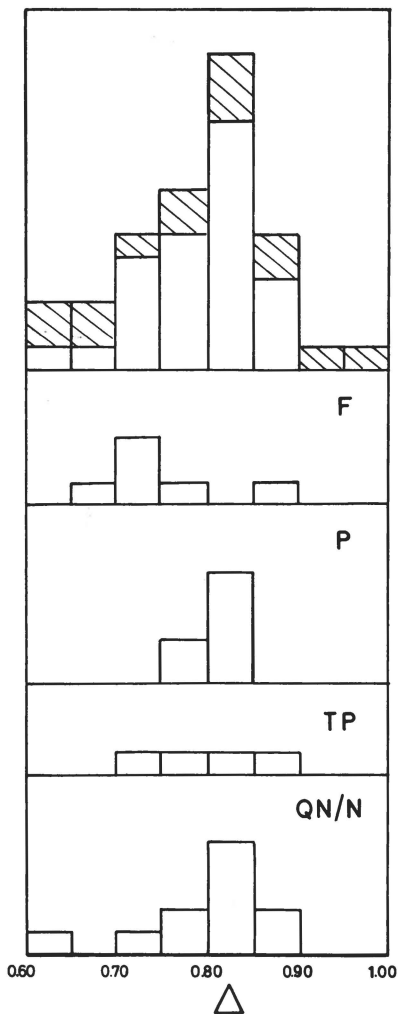


Fig. 8. Histogram of obliquities of groundmass alkali feldspars. Shaded areas: veins. Remainder of top figure: all main rocks.

Representative groundmass microperthite peak types are shown in Fig. 7 and include both low-albite-orthoclase and low-albite-microcline types. These are not arranged according to the position of the host rock relative to the centre of the intrusion: numbers 1, 3 and 4 are from main pulaskites, number 2 from a quartz-nordmarkite and numbers 5 and 6 from veins in the quartz-nordmarkites. Thus no systematic ordering of

the feldspars occurs in passing from the outer quartz-nordmarkite inwards to the foyaite. Nevertheless the most ordered peak types, consistent with their low-temperature paragenesis, are obtained from the vein feldspars. This lack of systematic ordering is further illustrated by the histogram showing the obliquities of the coarse microperthites (Fig. 8), in which the high value maxima are found in the feldspars of the main pulaskite and nordmarkites. The veins show a wide range of values but include those nearest to maximum microcline. In addition to the general concept of order-disorder, based on the (Al, Si) distribution, and its relation to the low-high structural state of the feldspar, MACKENZIE (1954) has suggested that the obliquity is influenced by the amount of sodium in solid solution, the obliquity increasing as the sodium content decreases. This is an additional factor which should lead to an increase in obliquity of the feldspars in the foyaite, the most potassic rock of the intrusion. A possible reason for the anomaly shown by the rocks of the main units may be related to the time each rock type took to cool. If this explanation is correct then the larger, outer ring of nordmarkite had the longest cooling period during which greater ordering was possible, whilst the relatively large pulaskite unit cooled less rapidly than either the smaller bodies of transitional pulaskite and foyaite, in which units ordering may have thus been partially inhibited. This is supported by the relatively large number of feldspars from the pulaskites and foyaites which retain an Or 131 peak (Table V).

Obliquity was measured from the separation of the microcline $\bar{1}\bar{3}1$ and 131 peaks (GOLDSMITH and LAVES, 1954) but in a few cases an attempt was made to use the method of MACKENZIE (1954) based on the $\bar{1}\bar{3}0$ and 130 peak separation (2θ region 23° to 25°). The latter were found to be too heavily masked by albite peaks to be of much value but, where measurement was possible, they give rather higher, but otherwise consistent, values than those obtained from the $\bar{1}\bar{3}1$ and 131 reflections. Masking of the $\bar{1}\bar{3}1$ and 131 peaks by albite is also liable to render this method ineffective, and a new technique, based on the position of the single, resolved 131 reflection, relative to the $02\bar{2}$ reflection of low-albite, has been developed by PARSONS (1965). Checks, on some of the current $\bar{1}\bar{3}1$ and 131 values, were made using PARSONS' method, but showed only slight differences compared with the results obtained using the method of GOLDSMITH and LAVES.

Excluding the veins, the average obliquity of the feldspars in the main units is 0.79; in the various types the average obliquity is: quartz-nordmarkite and nordmarkite, 0.80; transitional pulaskite, 0.81; pulaskite, 0.80; foyaite, 0.75.

The $\bar{2}01$ reflection lies at 2θ angles of between 20.5° and 22.5° and unmixing is immediately apparent from examination of the diffraction

Table V. *Alkali Feldspar X-ray Powder Data*

E.G. No.	Distance from centre	Composit. from $\bar{2}01$ method ¹	Chemical or corrected compos. ²	Obliquity of triclinic phase	Monoclinic (Orthoclase) 131 peak
Basalt phenocrysts					
4646-QN .....	.813	22.2	18.5	0	not distinguishable
4559-N .....	.693	27.0	29.6	0	trace
4655-N .....	.677	14.5	18.9	0	not distinguishable
4656-N .....	.677	10.0	17.5	0	not distinguishable
4658-N .....	.677	13.0	19.2	0	not distinguishable
2085-N .....	.677	18.0 ³	22.6	n.d.	not distinguishable
Normal phenocrysts					
2012-QN .....	.992	21.8	24.7	0	not distinguishable
4651-QN .....	.887	19.3	29.5	0	not distinguishable
4558-N .....	.693	27.8	30.3	0	present
4659-N .....	.677	28.0	31.5	0	trace
4796-N .....	.618	26.0	28.3	0	trace
4794-N .....	.580	20.0	24.0	0	present
4629-TP .....	.517	25.0	27.8	0	present
4622-TP .....	.485	27.0	28.2	0	present
4664-TP .....	.485	25.0	28.4	0	present
Groundmass micropertithes					
1399-QN .....	.996	34.0 ³	n.d.	n.d.	n.d.
2784-QN .....	.996	40.3 (37.0 ³)	40.2	.83	absent
2012-QN .....	.992	31.4	33.4	0	trace
4651-QN .....	.887	40.6	42.6	.81	absent
4646-QN .....	.813	41.0	43.0	.83	absent
4558-N .....	.693	32.0	34.0	.63	absent
4559-N .....	.693	33.7	35.7	0	present
4552-N .....	.691	32.0	34.0	.77	absent
4564-N .....	.681	35.0	36.4	.74	absent
2084-N .....	.677	37.0 ³	n.d.	n.d.	n.d.
4655-N .....	.677	40.0	42.0	.89	absent
4656-N .....	.677	37.0	39.0	.79	absent
4656 modified inclusion .....	.677	37.4	39.4	0	not distinguishable
4658-N .....	.677	41.8	43.8	.84	trace
4659-N .....	.677	41.5	43.5	.84	absent
4633-N .....	.607	36.2	38.2	.86	absent

¹) Compositions derived from Table I in TUTTLE and BOWEN (1958).²) Compositions derived from chemical analysis, or $\bar{2}01$ method adjusted to best value.³) Determinations by Prof. O. F. TUTTLE (1954, unpublished). Feldspar localities shown in Fig. 5.

(continued)

Table V (continued)

E.G. No.	Distance from centre	Composit. from 201 method ¹	Chemical or corrected compos. ²	Obliquity of triclinic phase	Monoclinic (Orthoclase) 131 peak
4629-TP .....	.517	35.0	35.6	.83	trace
4630-TP .....	.517	40.0	42.0	.78	present
2696-TP .....	.485	29.0 ³	n.d.	n.d.	n.d.
4662-TP .....	.485	33.3	35.3	.74	trace
4664-TP .....	.485	37.0	39.0	.86	absent
4627-P.....	.483	41.3	43.3	.81	trace
4641-P.....	.447	35.0	37.0	0	present
4582-P.....	.391	36.0	38.0	.77	trace
4587-P.....	.391	36.7	38.7	.78	absent
4588-P.....	.391	44.0	46.0	.84	absent
4613-P.....	.378	41.3	43.3	.81	trace
4614-P.....	.378	41.3	43.3	.81	present
2986-P.....	.370	40.0 ³	n.d.	n.d.	n.d.
4617-P.....	.315	36.6	38.6	.81	present
4618-P.....	.315	40.6	42.6	0	present
4624-P.....	.311	40.6	39.1	0	present
4762-F.....	.200	52.6	54.6	.71	absent
4770-F.....	.200	53.3	55.3	0	trace
2108-F.....	.187	53.0 ³	n.d.	n.d.	n.d.
4779-F.....	.185	50.7	52.7	.86	present
4781-F.....	.185	53.3	55.4	.71	absent
2112-F.....	.177	54.3	56.3	.74	absent
2116-F.....	.177	49.0	51.0	.76	present
4755-F.....	.172	57.3	59.3	.69	present
Veins and pegmatites					
2046-V.....	.947	n.d.	48.7	.82	absent
4648 (vug in basalt in QN)....	.937	24.5	27.0	.72	absent
2338-V.....	.777	62.0	64.0	.94	absent
2093-V.....	.727	11.0	16.8	0	not distinguishable
4666-V.....	.483	78.0	80.0	.67	present
4587-V.....	.391	44.0	46.0	.61	trace
4591-V.....	.391	35.0	37.0	.82	absent
4593-V.....	.391	36.7	38.7	.86	trace
4675-V.....	.357	42.0	44.0	.76	trace
4678-V.....	.317	35.5	37.5	.97	present
4622-V.....	.313	36.3	38.3	0	present
2940-V.....	.231	36.9	38.9	.87	trace
4692-V.....	.198	53.1	55.1	.80	present
4694-V.....	.198	62.7	64.7	0	present
4750-V.....	.191	56.8	58.8	.79	present
4754-V.....	.191	56.0	58.0	0	present
4781-V.....	.185	56.0	58.0	.60	absent
2869-V.....	.139	43.7	45.7	.66	absent

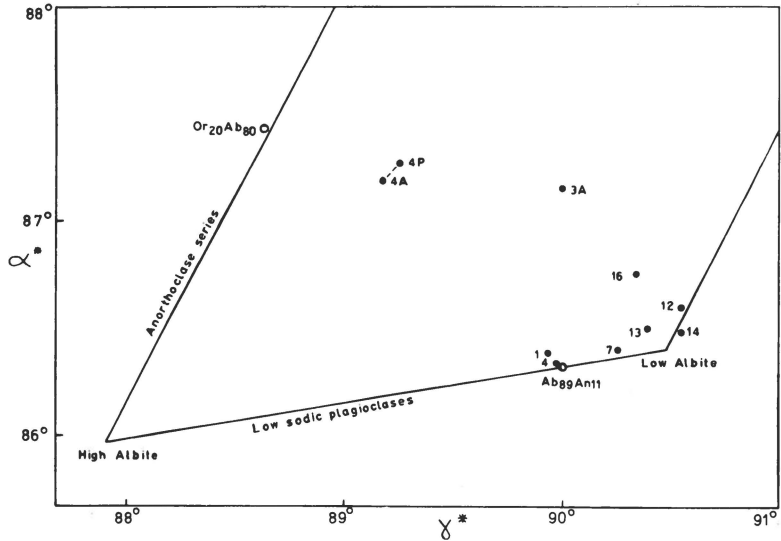


Fig. 9. Reciprocal lattice angles α^* and γ^* of alkali feldspars (from KEMPE, 1966, after MACKENZIE and SMITH, 1962). No. 1: 4656-N. 3: 4655-N. 4: 4658-N. 7: 4662-TP. 12: 4629-TP. 13: 4564-N. 14: 4624-P. 16: 4781-F. The first four feldspars are phenocrysts, the second four are groundmass. A and P indicate homogenized feldspars of which α^* and γ^* have been measured by albite and pericline twinning, respectively.

traces. All the unheated Kangerdlugssuaq feldspars show the presence of a sodic phase at a 2θ angle of about 22° and a potassic phase at about 2θ 21° . The separation of the two peaks was measured, mid points being taken at approximately two-thirds peak height, and averaged 1.03° for the phenocrysts and 1.05° for the microperthites of the groundmass and veins. This is additional evidence of the greater degree of ordering and unmixing that has taken place in the groundmass feldspars, since the amount of albite that can be retained in solid solution in the potassic phase decreases with falling thermal state and increasing (Al,Si) ordering (see Fig. 9). MACKENZIE and SMITH (1955) have discussed the possibility of using the $\bar{2}01$ spacing of the sodium- and potassium-rich phases to determine their compositions. These authors and LAVES (1952) both found that anomalous results are often obtained, for which LAVES (1952) and SMITH (1961) have offered explanations based on the distortion of the feldspar lattices consequent on unmixing. An attempt was nevertheless made to measure the compositions of the two phases of five samples, from Table I of TUTTLE and BOWEN (1958), using the 101 reflection of KBrO_3 at $2\theta = 20.205^\circ$ as an internal standard, from which the position of the $10\bar{1}0$ reflection of quartz could be calculated. In the case of the sodium phases, anomalous results were obtained and were at variance with the compositions of the sodic phases as indicated by single-crystal X-ray

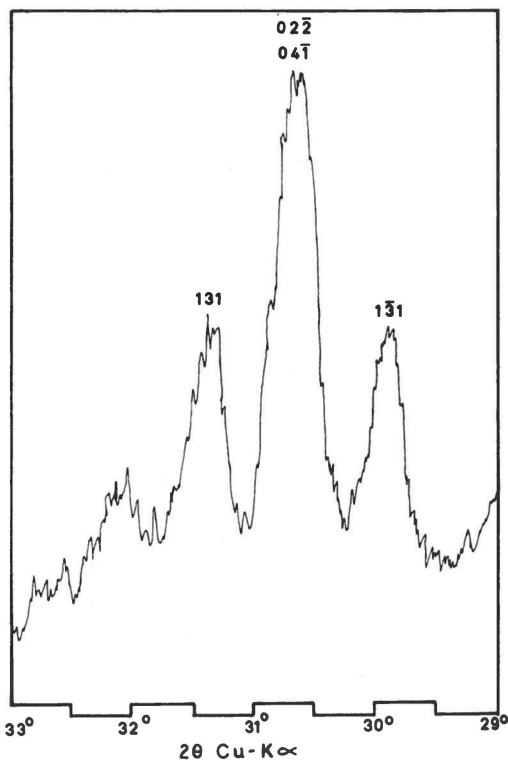


Fig. 10. Typical X-ray diffractometer trace: homogenized alkali feldspar phenocryst.

measurements of the reciprocal lattice angles (see Fig. 9). One of the potassium phases (4664-TP groundmass) gave a doubtful value, but the compositions obtained for the other four are not incompatible with the single-crystal data. Two phenocrysts (4558/9-N) gave compositions of $\text{Or}_{91.7}$; while two groundmass samples, 4633-N and 4588-P, gave $\text{Or}_{96.8}$ and $\text{Or}_{94.6}$ respectively. These compositions, representing some 8 per cent Ab in the potassic phase (orthoclase) of the phenocrysts, and an average of about 4.5 per cent of Ab in the predominantly triclinic potassium phases of the groundmass, are in agreement with the data of GOLDSMITH and LAVES (1961) who found up to 10 per cent of Ab in orthoclase and as much as 5 per cent in microcline.

In the heated feldspars, the positions of the single $\bar{2}01$ reflections were used to obtain the estimates of the compositions given in Table V. The method of BOWEN and TUTTLE (1950) was used, the values of 2θ ($\bar{2}01$, feldspar)- 2θ ($10\bar{1}0$, quartz) being converted into orthoclase content from Table I in TUTTLE and BOWEN (1958). To ensure that homogenization was complete, various checks were made. Thus, samples that showed residual peaks, in addition to the single reflection indicating a homogeneous feldspar, were subjected to further heat treatment. The foyaitite feld-

spars were more difficult to homogenize than those of the other units of the intrusion, probably due in part to the fact that the highest solvus temperature occurs in the region of their composition (ca. Or₅₅). The 2θ range 29° to 31.5° was examined, and in all cases the traces showed a single broad $\bar{1}\bar{3}1$ peak compatible with the presence of one triclinic feldspar. A typical trace is given in Fig. 10, using different diffractometer and chart speeds and settings from those employed for the unheated feldspars.

In order to test the reliability of the method, a pilot curve was constructed from some of the partial analyses given in Table III. It was found that, provided allowance (ca. 2 per cent Or) is made for the fact that the high-temperature (synthetic) curve gives slightly low Or percentages for homogenized natural alkali feldspars (see ORVILLE, 1958; KORITNIG, 1961; and PARSONS, 1965), good agreement with the values of TUTTLE and BOWEN (1958) was obtained for the groundmass feldspars. In the case of the phenocrysts and especially those from the modified basalt inclusions, it was found that the values of Or (wt. per cent) derived from the $\bar{2}01$ method were abnormally low, and it is suggested that this may result from distortion of the lattice due to the high calcium content of the phenocrysts (KEMPE, 1966; but see PARSONS, 1968; and HAMILTON and EDGAR, 1969). The compositions given in Table V have been corrected by reference to the pilot curve.

In order to obtain further information on the structure of the feldspars, single-crystal oscillation photographs (Cu- $K\alpha$ radiation) were taken of seven unheated feldspars, using the technique of SMITH and MACKENZIE (1955). The crystals were mounted along the y -axis and oscillated through 15° , the X-ray beam being parallel to (001) at the centre of the oscillations. In each case, the sodium phase was found to be albite-twinned, low-temperature sodic plagioclase, near to low-albite. The potassium phases are monoclinic in the phenocrysts (fine micropertthites) and mainly triclinic, though with some monoclinic reflections, in the groundmass feldspars (coarse micropertthites). The values of the reciprocal lattice angles α^* and γ^* of the sodium phases were calculated from the albite twinning and are plotted in Fig. 9.

Single-crystal photographs were taken of three of the homogenized phenocrysts; the material from heated groundmass micropertthites was found unsuitable for this purpose. The positions of two of the three heated feldspars are plotted in Fig. 9; the third feldspar (4656-N, no. 1), gave a very poor photograph, showing single spots only. Although chemical homogenization has taken place, and single, triclinic feldspars with albite and, in some cases, pericline twinning, have been produced, they have not progressed far towards the high-albite-orthoclase join and are located in a lower central part of the parallelogram, in which the only natural feldspars reported are those of MUKHERJEE (1961).

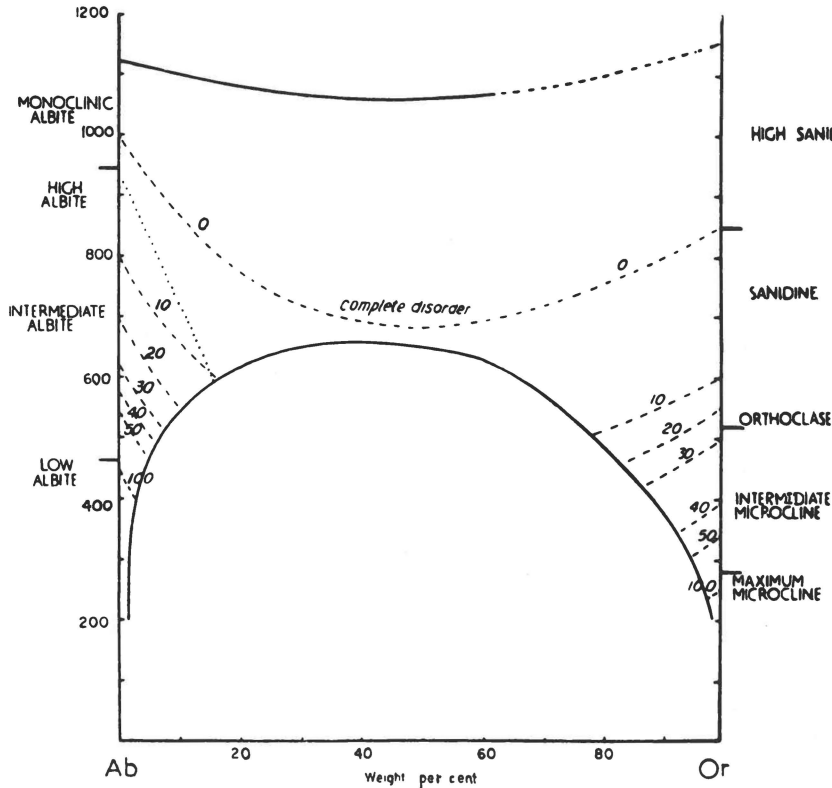


Fig. 11. The alkali feldspar phase diagram. The dashed numbered curves indicate percentage of (Al,Si) ordering (from MacKENZIE and SMITH, 1961).

c) Conclusions

The alkali feldspars of the Kangerdlugssuaq intrusion form a mineral series in which the varying compositions are related to the changing chemistry of the fractionating syenite magma. The products of the earlier crystallization of this magma gave rise to a series of porphyritic nordmarkites, followed later by the formation of the transitional pulaskite, and finally, in the later stages of differentiation, by an aphyric sequence of pulaskite and foyaite showing an imperfect layered structure.

The X-ray evidence shows that the phenocrysts have unmixed into low-albite and a monoclinic potassium phase (orthoclase). The peak types in the 2θ region 29° to 31.5° indicate that there is a gradual development from nearly homogeneous feldspars in the outer, quartz-rich nordmarkite, to completely unmixed feldspars in the transitional pulaskite. It is considered that the original feldspars were homogeneous, triclinic anorthoclases which, by reference to the solvus in the alkali feldspar phase diagram (MacKENZIE and SMITH, 1961), reproduced as Fig. 11, commen-

ced unmixing at temperatures above about 610° C, and finally stabilized, on the evidence of the compositions of the potassium phases, just below 400° C. The composition of the most sodic phenocrysts is close to that at which the line indicating the composition-temperature relationship for the monoclinic-triclinic inversion cuts the solvus (MACKENZIE, 1952), and these feldspars may therefore have inverted from monoclinic to triclinic symmetry before beginning to unmix, although in view of the lack of well-developed 'M' type twinning in the more sodic phenocrysts, there is no definite evidence of their original monoclinic symmetry (SMITH and MACKENZIE, 1958); the less sodic feldspars commenced unmixing before inversion.

The groundmass micropertthites must also have unmixed from single homogeneous members of the anorthoclase-sanidine series, (the foyaite micropertthites being monoclinic sanidines at high temperatures), in which unmixing commenced at a temperature, dependent on composition, in the region of 660° C. In these feldspars, unmixing has proceeded further, and the degree of (Al,Si) ordering is greater; final stabilization took place at a temperature of approximately 300° C.

The final assemblages of alkali feldspars in the Kangerdlugssuaq rocks may be placed in the cooling sequence of MACKENZIE and SMITH (1962). The phenocrysts represent type (d), in which the potassium phase is monoclinic and the Na phase is a plagioclase. The groundmass feldspars are of type (e), in which the potassium phases are monoclinic and triclinic, and the Na phase is a plagioclase; or type '(f)', in which the potassium phase is triclinic and the Na phase is a plagioclase. The first two types are both present in the Dartmoor granite, whilst type (e) is characteristic also of the Tugtutôq and Kûngnât syenites of S.W. Greenland, the feldspars of which are similar to those from the Kangerdlugssuaq intrusion. Type '(f)' is represented by four feldspars from Tugtutôq, but MACKENZIE and SMITH consider that there are too little data on this type of feldspar to be certain whether, in comparison with specimens of type (e), they represent a distinctly slower rate of cooling, or cooling to a lower temperature.

The temperature of crystallization of single, homogeneous feldspars in the system albite-orthoclase, is governed by the relationship between the solidus and solvus. As P_{H_2O} increases, the solvus is raised slightly but there is a marked depression of the solidus until, in the Ca-free system, at a P_{H_2O} of something less than 5000 bars (YODER *et al.*, 1957), the solidus and solvus intersect and two discrete feldspars result. The presence of perthitic phenocrysts and perthitic groundmass feldspars in the rocks of the Kangerdlugssuaq intrusion demonstrates that the feldspars crystallized at temperatures above the solvus, and the rocks are thus hypersolvus syenites (TUTTLE and BOWEN, 1958). The presence,

however, of veins of sodic plagioclase indicates that, in the late stages of consolidation, crystallization was subsolidus in character. PARSONS (1965), in his discussion of the crystallization history of the Loch Ailsh feldspathic syenites, argued that the Scottish rocks crystallized at a temperature between 750° and 1060°C, and a water pressure between zero and 3000 bars. The upper temperature limit is determined by the minimum on the feldspar join in the dry system; the lower temperature is an estimate based on the fact that the top of the solvus at P_{H_2O} of 2000 bars is at approximately 680° C in the Ca-free system (ORVILLE, 1963), and is raised by about 40° C by the presence of about 1 per cent anorthite in the compositional range of the Loch Ailsh feldspars. PARSONS also pointed out that considerable water pressure must have been present during the crystallization of the Loch Ailsh rocks, which he regards as sufficiently monomineralic to justify extrapolation of the crystallization history of the alkali feldspars to the leucosyenites as a whole.

These arguments largely apply also to the Kangerdlugssuaq rocks in which the presence of a considerable water pressure is demonstrated by the formation of hydrous phases and by the absence of leucite; the Ca content is also rather higher than in the Loch Ailsh rocks. From Fig. 12 it is clear that a calcium content equivalent to at least 1 per cent An is required to produce a magmatic composition that lies on the albite side of the minimum in the system $NaAlSi_3O_8$ - $KAlSi_3O_8$. The solid line in the figure represents the postulated magmatic composition in the Ca-free system, and the broken line the approximate composition of the liquid having the necessary calcium content for the precipitation of a feldspar of the composition of the phenocrysts. When, in the transitional pulaskite, the cooling magma reached the composition of the minimum, precipitation of phenocrysts ceased, leaving the groundmass microperthite to continue to crystallize as the sole feldspar phase, and which, as sodium preferentially entered the feldspathoids, became more potassium-rich in composition in the final stages. Fig. 12 shows the phase relations in the binary system at P_{H_2O} of 1000 bars, and a portion of the ternary system at P_{H_2O} of 5000 bars. The effect on the minimum in the binary system of raising the water pressure to 2 or 3 kilobars is to shift the minimum slightly towards the albite side (at P_{H_2O} of 5000 bars it is at Or_{29} , YODER *et al.*, 1957), and requires slightly more calcium than is present in the Kangerdlugssuaq magma. Thus the most likely water pressure in syenites of this type would seem, as suggested by PARSONS (1965), to be between 1 bar and 3000 bars.

The method first proposed by BARTH (1951, 1962) for estimating crystallization temperatures of feldspars, based on the amount of the sodium component in coexisting alkali and plagioclase feldspars, has been criticized on the grounds that many rocks depart to some extent from

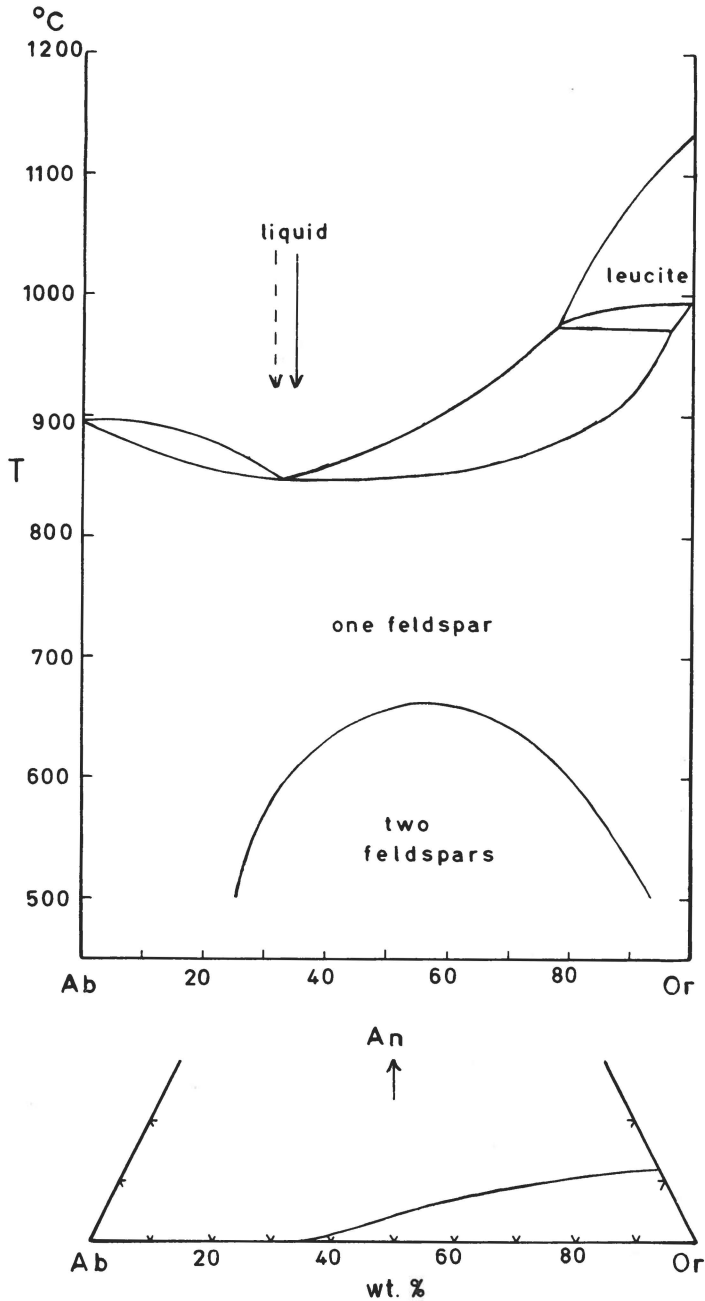


Fig. 12. Upper figure: the binary system Ab-Or at $P_{H_2O} = 1000$ bars (after BOWEN and TUTTLE, 1950). Solid line: Postulated magmatic composition in Ca-free system. Dashed line: approximate position of liquid plot, if some lime is present, in order to precipitate feldspars of the composition of the phenocrysts. Lower figure: projection of the quaternary system Ab-Or-An- H_2O at $P_{H_2O} = 5000$ bars. The minimum in the Ab-Or join is at $695^\circ C$ (after YODER *et al.* 1957).

compositions within the three component feldspar system. However, it is instructive to apply the feldspar geothermometer in the case of the Kangerdlugssuaq intrusion if the earlier conclusion is valid, namely that the alkali feldspars crystallized originally as a single phase, and that the rims of sodic plagioclase are products of primary crystallization and in equilibrium with the micropertthites. Since the groundmass feldspars, with the exception of those in the foyaite, are antiperthitic it is considered (see HALL, 1966) unlikely that the rims of sodic plagioclase are derived by exsolution from the groundmass perthites as they unmixed (resulting in the two phases becoming progressively more potassium- and sodium-rich respectively), but more probable that diffusion would take place between the potassium-rich lamellae and the sodium-rich host. If the above assumptions are accepted and BARTH's method is applied, the approximate crystallization temperatures are:

	Alkali feldspar	Plagioclase	Temperature
Nordmarkites and transitional pulaskite	Or ₃₇	An ₄	970° C
Pulaskite.....	Or ₄₁	An ₄	880° C
Foyaite.....	Or ₅₅	An ₁₀	760° C

Whilst these temperatures can only be regarded as approximations, it is interesting to note the close approach of the crystallization temperature of the foyaite feldspars to that of the undersaturated minimum (750° C), in the system Ne-Ks-Qz-H₂O at P_{H₂O} of 1000 bars (HAMILTON and MACKENZIE, 1965). Additional confirmation of the validity of the results is obtained, in the case of the feldspars from the undersaturated rocks, from the compositions of the nephelines (see next section).

The alkali feldspars of the Kûngnât intrusion (UPTON, 1960) closely resemble the Kangerdlugssuaq groundmass micropertthites in composition. Thus at Kûngnât, the bulk (cumulus) feldspar composition varies from Or₃₂ to Or₅₉, whilst the Kangerdlugssuaq groundmass feldspars range from Or₃₃ to Or₅₉. A similar range occurs in the phenocrysts of the Tugtutôq mid-Gardar microsyenite dykes — Or_{39.5} to Or₅₉ (UPTON, 1964), the groundmass having the composition Or₃₉. More comparable with the Kangerdlugssuaq feldspar phenocrysts are the feldspars from the Tugtutôq central complex, following the sequence Or₂₅→Or₄₀→Or₃₅.

III. NEPHELINES

In the main pulaskite, nepheline is generally present only in small quantities, though locally it amounts to over 10 per cent in some of the pegmatitic segregations. It is an abundant constituent in the veins and pegmatites in both the transitional and main pulaskites, and its presence here is in conformity with the relationship characteristic of the intrusion, namely that the veins and pegmatites are generally more undersaturated than the rocks in which they occur. In the foyaite, nepheline is a major constituent, averaging some 15 per cent, and is somewhat more abundant than sodalite, although the volume of the latter mineral is commonly enhanced by its replacement of nepheline.

The nephelines are generally euhedral and the crystals are considerably smaller than the micropertthites within which small euhedral nephelines sometimes occur. Secondary overgrowth is common and is demonstrated by hexagonal rings of inclusions marking the original crystal boundary (Plate 2), but no unequivocal examples of zoning have been observed. In addition to the alteration to sodalite, the nepheline shows considerable local hydrothermal alteration to cancrinite, plumose giesseckite mica, and calcite.

The refractive indices of the three analysed specimens are given in Table VI and are within the normal range for nephelines. Although the nephelines show some variation in their Na, K and Ca contents this is too small to produce any significant effects on the refractive indices, an effect which in any case is of limited value in estimating variations in composition.

The compositions of these nephelines are given in Table VI and their trace element contents in Table VII. The small quantities of Ti, Mn and Mg present in the analyses are assumed to substitute for Na, K or Ca (DEER *et al.*, 1963b); Fe^{+3} is considered to substitute for Al and is included in Σ , the number of ions in tetrahedral sites. The small calcium content is not unusual for nephelines of plutonic paragenesis.

The total of the framework atoms, $\Sigma(\text{Si} + \text{Al} + \text{Fe}^{+3})$, varies from 16.13 to 16.18 (Table VI), is marginally higher than the ideal cell content of 16, and may be due to a small systematic error in the analytical determination of Al_2O_3 . Towards the centre of the intrusion the nephelines

Table VI. *Nephelines – Chemical Analyses*

	1	2	3
Distance from centre . . . . .	.317	.185	.172
SiO ₂	44.30	43.97	43.21
TiO ₂	0.02	0.02	0.02
Al ₂ O ₃	33.58	34.61	35.34
Fe ₂ O ₃ (total Fe)	0.11	0.07	0.08
MnO	0.01	tr.	tr.
MgO	0.05	0.01	0.02
CaO	0.25	0.32	0.52
Na ₂ O	15.24	15.66	15.49
K ₂ O	5.22	5.27	5.19
H ₂ O ⁺	1.13	0.97	0.89
H ₂ O ⁻	0.13	0.04	0.04
BaO	0.01	0.01	0.01
Rb ₂ O	0.02	0.02	0.01
Total	100.08	100.97	100.84

Numbers of ions on the basis of 32 oxygens

Si	8.510	8.368	8.233
Al	7.604	7.764	7.938
Ti	0.003	0.003	0.003
Fe ⁺³	0.016	0.010	0.011
Mn	0.002	—	—
Mg	0.014	0.003	0.006
Ca	0.051	0.065	0.106
Na	5.676	5.778	5.722
K	1.279	1.280	1.262
Σ	16.13	16.14	16.18
ΣR	7.06	7.19	7.20
□	0.99	0.88	0.91
Si/Al ^{IV}	1.12	1.08	1.04
Ne	73.5	75.0	75.6
Ks	18.5	18.5	18.5
Qz	8.0	6.5	5.9

1. Nepheline, vein in pulaskite, E.G. 4678, S. end Trebjørneberget (total includes ZrO₂, 0.01; ϵ 1.536, ω 1.540).
2. Nepheline, foyaite, E.G. 4781, nunataks, head of Søndre Syenitgletscher (ϵ 1.537, ω 1.541).
3. Nepheline, foyaite, E.G. 4755, Citadellet (total includes SrO, 0.02; ϵ 1.537, ω 1.541).
Anal. D. R. C. KEMPE.

(Note: BaO and Rb₂O values are not included in calculating the numbers of ions).

Table VII. *Nephelines - Trace Elements* (p. p. m.)

	Sensitivity p.p.m.	Ionic radius (Å)	1	2	3
Distance from centre . . . .			.317	.185	.172
Ga ³⁺	3	0.62	36	24	24
Li ¹⁺	0.5	0.68	3	13	9
Cu ²⁺	0.5	0.72	11	4	9
V ³⁺	5	0.74	11	14	15
Zr ⁴⁺	10	0.79	71	35	21
Yb ³⁺	10	0.86	1*	—	—
Sr ²⁺	5	1.12	22	30	138
Ba ²⁺	5	1.34	103	63	53
Rb ¹⁺	1	1.47	161	101	178

Anal. D. R. C. KEMPE.

* Approximate value.

show a small but progressive increase in aluminium. The nepheline structure is based on a tridymite-type framework, in which the negative charge on the framework, due to the substitution of Si by Al, is balanced by the intra-framework ions $\Sigma R = (Na + K + 2Ca)$. In the Kangerdlug-

Table VIII. *Nepheline Compositions from X-ray Data*

Specimen number	Distance from centre	2θ 2130	Com- position Ne	2θ 2022	Com- position Ne	Feldspar Or
<i>Main rocks</i>						
2986-P . . . . .	.370	27.247	74.5	29.652	72.0	40.0
4770-F . . . . .	.200	27.254	75.7	29.680	75.0	55.3
4779-F . . . . .	.185	27.237	73.2	29.648	71.6	52.7
4781-F . . . . .	.185	27.247	74.5	29.674	74.3	55.4
2116-F . . . . .	.177	27.243	73.6	29.668	73.4	51.0
4755-F . . . . .	.172	27.255	76.0	29.687	76.0	59.3
<i>Veins and pegmatitic segregations</i>						
4666-V in TP . . .	.483	27.228	72.3	29.657	72.5	80.0
4587-V in P . . . .	.391	27.240	73.4	29.662	73.4	46.0
4678-V in P . . . .	.317	27.263	77.7	29.685	75.6	37.5
2940-V in P . . . .	.231	27.258	76.5	29.670	73.5	38.9
4692-V in F . . . .	.198	27.258	76.5	29.675	74.5	55.1
4750-V in F . . . .	.191	27.252	75.3	29.673	74.0	58.8
4754-V in F . . . .	.191	27.235	73.0	29.682	75.2	58.0
4781-V in F . . . .	.185	27.250	75.0	29.667	73.3	58.0
2869-V in F . . . .	.139	27.243	73.6	29.667	73.3	45.7

(Localities are given in Fig. 5).

ssuaq nephelines this value varies from 7.06 to 7.20, indicating either a relatively large number of vacant intra-framework sites, □, or the presence of the hydroxonium ion H_3O^+ (HEIER, 1966).

The compositions of the analysed nephelines and an additional twelve specimens were determined by the X-ray powder methods (Table VIII) of SMITH and SAHAMA (1954) and HAMILTON and MACKENZIE (1960). Both methods utilise the positions of the $20\bar{2}2$ and $21\bar{3}0$ reflections, measured by reference to an internal silicon standard (2θ for the reflection 111 being taken as 28.465°). SMITH and SAHAMA (1954) measured

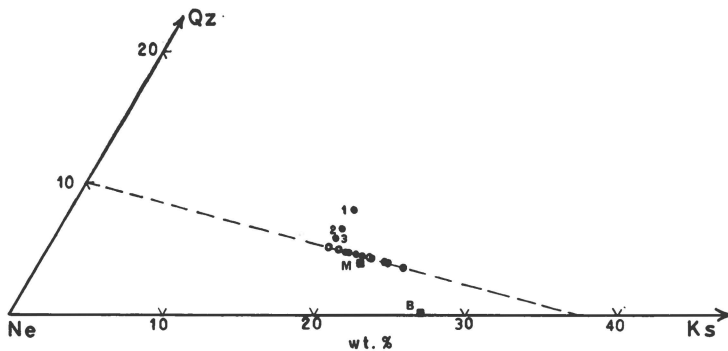


Fig. 13. Compositions of nephelines in system Qz-Ne-Ks (after HAMILTON and MACKENZIE, 1960). Numbered solid circles: analysed samples (see Table VI). Open circles: compositions of analysed samples from X-ray analysis. Un-numbered solid circles: compositions from X-ray analysis, plotted on the Ne ss field boundary at 700°C of HAMILTON and MACKENZIE. M: the MOROZEWICZ (1928) composition. B: The BUERGER (1947) composition.

the positions of the two reflections in the nepheline solid solutions of the system $NaAlSi_3O_8-KAlSi_3O_8$, whilst HAMILTON and MACKENZIE (1960) determined the limits of solid solution of SiO_2 in nephelines at 700°C and P_{H_2O} of 15000 lbs/sq. in. (≈ 1.02 kb.), and related the positions of the reflections to the compositions of nepheline in equilibrium with alkali feldspar at a temperature of 700°C , i.e. along the field boundary.

These authors stressed that their curves, relating 2θ $20\bar{2}2$ and $21\bar{3}0$ to composition, should be used in preference to those of SMITH and SAHAMA only when it could be predicted from the paragenesis that the nepheline contained relatively large amounts of SiO_2 in solid solution. Since this is the case in the present investigation, the compositions of the nephelines from X-ray analysis are given in Table VIII in terms of the nepheline coordinate along the field boundary at 700°C (HAMILTON and MACKENZIE, 1960) and plotted in Fig. 13. In this figure, the analysed compositions are plotted as solid circles and the compositions estimated from the 2θ reflections as open circles, which represent the average composition obtained from the $20\bar{2}2$ and $21\bar{3}0$ reflections. Agreement is good

for two of the nephelines but in the third there is a difference of some 2 per cent between the two compositions. The separation of the two reflections in each case falls within the range obtained by HAMILTON and MACKENZIE (1960), but the data are insufficient to indicate which of the two reflections gives the more precise estimate of composition.

The three analysed nephelines (Fig. 13) contain rather more SiO_2 in solid solution than those crystallized at 700°C by HAMILTON and MACKENZIE. A later investigation by HAMILTON (1964) of the limits of solid solution of nepheline at 775° and 500° , at a pressure of H_2O of 15000

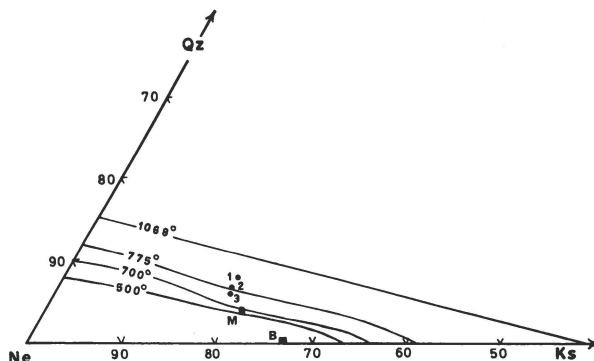


Fig. 14. Analysed nephelines in system Qz-Ne-Ks, with field boundaries at 500° , 700° , 775° and 1068°C (after HAMILTON, 1964).

lbs/sq. in., showed that the effect on the field boundary of increasing $\text{P}_{\text{H}_2\text{O}}$ is small. In this paper HAMILTON discussed the possibility of using the magnitude of the excess SiO_2 in nepheline as a geological thermometer, basing his argument on the premise that nepheline co-existing with feldspar will take the maximum possible amount of SiO_2 into solution at the temperature of its formation, and concluded that, although in the case of volcanic rocks a useful indication of temperature of crystallization may be obtained, its applicability to plutonic rocks is restricted due to compositional changes which may take place during and after crystallization of the nepheline. While the already crystallized nepheline is still in contact with magmatic liquid continuous reaction may take place in two ways: (a) by a change in the Na/K ratio and (b) by a change in the Si/Al ratio, Si being replaced by Al. With the disappearance of the liquid the main sub-solidus adjustment in composition is restricted to an exchange of K and Na atoms between feldspar and nepheline, the Si/Al ratios in the solid phases remaining fixed. This alkali exchange between feldspar and nepheline results in compositional changes in the nepheline that can be represented in the Ne-Ks-Qz system by a line parallel to the base, which thus cuts the nepheline solid solution isotherms, and converges towards the ideal (BUERGER) composition of $\text{Ne}_{72.9}\text{Ks}_{27.1}$

or $\text{Na}_3\text{KAl}_4\text{Si}_4\text{O}_{16}$ (see TILLEY, 1952, 1954 and 1956). The positions of the analysed nephelines from Kangerdlugssuaq lie outside the MOROZEWICZ-BUERGER convergence field (see Fig. 13) and it seems likely therefore that any post-crystallization adjustments in composition were limited in magnitude. If this conclusion is valid it follows that the magma may have consolidated at a rather higher temperature than is considered usual

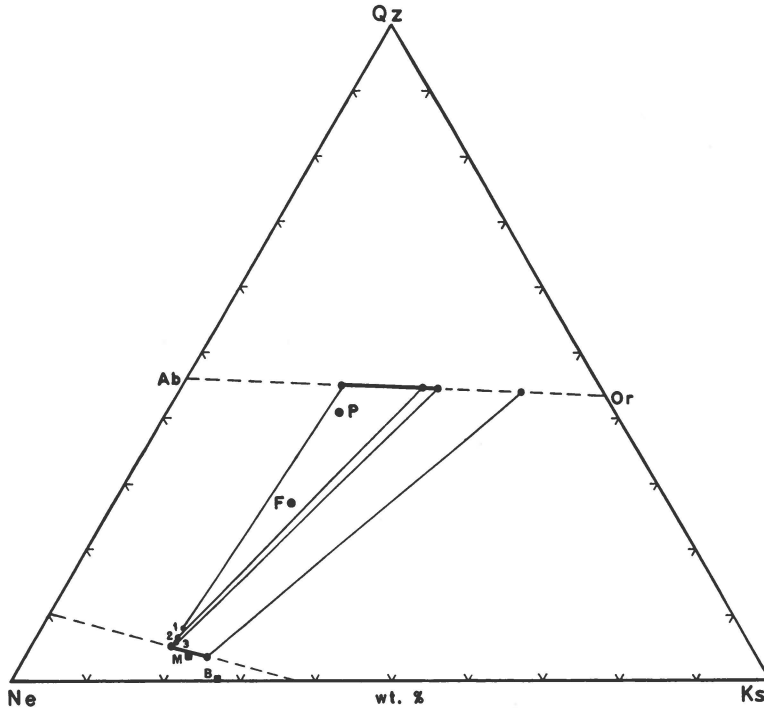


Fig. 15. Feldspar-nepheline tie-lines in the system Qz-Ne-Ks between pairs with analysed nephelines, and the most potassic pair. All remaining tie-lines would connect points on the two bold lines.

for plutonic nepheline syenites, and cooled fairly rapidly. Thus the crystallization temperatures deduced from the excess SiO_2 in solution may have some reliability, and are as follows (see Fig. 14):

1. Pulaskite (4678) 880° C
2. Foyaite (4781) 780° C
3. Foyaite (4755) 760° C

These temperatures conform with the hypothesis of centripetal cooling, and are in good agreement with those deduced for the feldspars.

Tie-lines between co-existing analysed nephelines and feldspars, together with that joining nepheline with the most potassic feldspar measured (4666-V in TP), and the average compositions of the main pulaskite and foyaite, are given in Fig. 15.

The tie-lines pass near to or through the average bulk composition of the pulaskite but not that of the foyaite. This is due, in part, to the nepheline and feldspar three-phase boundaries becoming three-phase triangles in this compositional range (HAMILTON and MACKENZIE, 1965), and because the presence of sodalite is not taken into account in the norm. In consequence the position of the foyaite is displaced in the diagram to the sodium side of the feldspar and nepheline join.

Tie-lines between compositions obtained by X-ray methods lie within the two heavy lines represented on the feldspar join and on the field boundary indicating the limit of nepheline solid solution at 700° C (HAMILTON and MACKENZIE, 1960). These have been omitted from the figure as they do not display a consistent parallelism, due probably to the limited accuracy of the X-ray method, especially with regard to the amount of SiO₂ in solid solution.

IV. ALKALI PYROXENES

Alkali pyroxenes, although rare or locally absent in the nordmarkites, are present in each unit of the Kangerdlugssuaq intrusion; in the veins, pyroxene is the most common ferromagnesian mineral, and is locally abundant.

The pyroxenes fall generally into two groups: aegirines and aegirine-augites. The aegirine ($Ac > 70$ per cent) is green to black in colour, and in thin section is strongly pleochroic from green to yellow. The crystals are subhedral and relatively unzoned, although weak zoning is present in some of the vein pyroxenes. The aegirine-augite ($\simeq Ac_{30}$) is present only in the foyaite; the crystals are strongly zoned with neutral coloured cores and green rims. In the pegmatitic segregations within the foyaite, zoning is strong but lacks the sharp core and rim structure of the pyroxenes in the foyaite. The bulk composition of both types of aegirine-augite is, however, almost identical.

Simple and lamellar twinning, parallel to $\{100\}$, is common and the pleochroic scheme of the aegirine in the various units is relatively constant: α grass green, β yellow-green, γ orange.

Absorption parallel to α is somewhat variable and ranges from pale green or pale yellow-green to a more vivid green colour. The extinction angle $\alpha \wedge z$ varies from 6° to 0° (β obtuse) in the aegirines (nos. 1 to 5, Table IX) and within this group there is a reasonable correlation between $\alpha \wedge z$ and the number of Fe^{+3} ions per formula unit (DEER *et al.*, 1963a). In the aegirine-augites, the extinction angle varies with the zoning but has an average value of about 22° (β acute).

In the aegirines the optic axial angles range from $2V\alpha$ 60° in the most acmitic minerals (Table IX, nos. 1 and 3) to between 70° and 74° in the less acmitic varieties. In the aegirine-augites, the optic axial angle varies greatly with the zoning; thus the acmitic rims have a $2V\alpha$ range of 72° to 90° , and the cores are zoned to a $2V\gamma$ of 61° . Approximate values of the γ -index for the analysed pyroxenes are:

Aegirine (vein in quartz-nordmarkite)	1.802
Aegirine (transitional pulaskite)	1.795
Aegirine (vein in transitional pulaskite)	1.800 to 1.810
Aegirine (pulaskite)	1.795
Aegirine (vein in pulaskite)	1.797
Aegirine-augite (vein in foyaite)	1.750 to 1.755
Aegirine-augite (foyaite)	1.750 to 1.755

Table IX. *Alkali Pyroxenes – Chemical Analyses*

	1	2	3	4	5	6	7	A
Distance								
from centre	.947	.494	.483	.450	.359	.198	.172	—
SiO ₂	50.74	50.67	50.12	49.78	50.52	48.82	48.33	52.43
TiO ₂	1.48	1.38	1.14	1.74	0.76	0.43	0.57	3.48
Al ₂ O ₃	0.89	2.23	2.57	3.11	2.08	2.60	3.45	0.96
Fe ₂ O ₃	27.03	24.45	28.74	25.11	25.05	10.29	10.11	24.21
FeO	5.10	3.65	1.57	3.94	3.29	9.91	10.51	2.26
MnO	0.59	0.63	0.60	0.94	0.93	2.93	2.91	0.79
MgO	0.25	2.07	0.59	1.29	1.42	4.08	3.52	1.59
CaO	3.22	5.26	1.30	3.88	5.15	16.48	17.27	1.38
Na ₂ O	11.16	10.13	12.24	10.46	10.27	3.92	3.71	10.57
K ₂ O	0.13	0.16	0.19	0.34	0.10	0.16	0.14	0.74
H ₂ O ⁺	nil	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.56
H ₂ O ⁻	0.05	0.03	n.d.	0.02	0.04	0.25	0.01	—
ZrO ₂	0.28	0.25	0.65	0.57	0.40	0.19	0.15	0.47
V ₂ O ₃	0.02	0.04	0.01	0.05	0.06	0.03	0.03	0.03
SrO	tr.	0.03	tr.	0.02	tr.	0.01	0.01	—
BaO	0.01	0.01	0.01	0.01	0.01	0.01	0.01	—
Total	100.95	100.99	99.73	101.26	100.08	100.11	100.73	99.63

1. Aegirine, vein in quartz-nordmarkite, E.G. 2046, west side large nunatak, south of Fangetårnet. Anal. D. R. C. KEMPE.
 2. Aegirine, transitional pulaskite, E.G. 4789, north side, Søndre Syenitgletscher. Anal. D. R. C. KEMPE.
 3. Aegirine, vein in transitional pulaskite, E.G. 4666, southwest side Trebjørnebjerg. Anal. D. R. C. KEMPE.
 4. Aegirine, pulaskite, E.G. 4786, north side, Søndre Syenitgletscher. Anal. D. R. C. KEMPE.
 5. Aegirine, vein in pulaskite, E.G. 4616, nunatak southeast of Kælvegletscheren. Anal. D. R. C. KEMPE.
 6. Aegirine-augite, vein in foyaite, E.G. 4692, Citadellet. Anal. D. R. C. KEMPE.
 7. Aegirine-augite, foyaite, E.G. 4755, Citadellet. Anal. D. R. C. KEMPE.
- A. Aegirine, Sengisyavr, Lovozero (VLASOV *et al.*, 1966). Anal. VLADIMIROVA (total includes Cl, 0.07; Σ RE₂O₃, 0.09).

a) Chemistry

Seven alkali pyroxenes — three from main rocks and four from veins and pegmatitic segregations — have been analysed and their compositions given in Table IX, and their structural formulae and other data in Table X. The trace element content of the Kangerdlugssuaq pyroxenes is given in Table XI.

A general comparison with the aegirines and aegirine-augites given in DEER *et al.* (1963a), shows that the Kangerdlugssuaq pyroxenes are fairly typical examples of the group. The Kangerdlugssuaq pyroxenes are, however, rather lower in silica than minerals having a comparable Fe_2O_3 content and this is compensated by a slightly higher content of alumina and titania. Thus Al in tetrahedral coordination averages 0.07 in the

Table X. *Alkali Pyroxenes — Numbers of Ions on the Basis of 6 oxygens*

	1	2	3	4	5	6	7
Distance from centre	.947	.494	.483	.450	.359	.198	.172
Si.....	1.957	1.930	1.932	1.900	1.946	1.913	1.884
Al.....	0.040	0.070	0.068	0.100	0.054	0.087	0.116
Al.....	—	0.030	0.049	0.040	0.040	0.033	0.043
Ti.....	0.043	0.040	0.033	0.050	0.022	0.013	0.017
Zr.....	0.005	0.005	0.012	0.011	0.008	0.004	0.003
Fe ⁺³	0.785	0.701	0.834	0.721	0.726	0.303	0.297
V.....	0.001	0.001	—	0.002	0.002	0.001	0.001
Fe ⁺²	0.164	0.116	0.051	0.126	0.106	0.325	0.343
Mn.....	0.019	0.020	0.020	0.030	0.030	0.097	0.096
Mg.....	0.014	0.118	0.034	0.073	0.082	0.238	0.205
Ca.....	0.133	0.216*	0.054	0.159	0.213	0.692	0.721
Na.....	0.834	0.748	0.915	0.774	0.767	0.298	0.280
K.....	0.006	0.008	0.009	0.017	0.005	0.008	0.007
Z.....	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Y.....	1.03	1.03	1.03	1.05	1.02	1.01	1.00
X.....	0.97	0.97	0.98	0.95	0.99	1.00	1.01
Si/Al ^{IV}	48.9	27.6	28.4	19.0	36.0	22.0	16.2
Fe ⁺³ /(Fe ⁺³ + Fe ⁺²)	0.83	0.86	0.94	0.85	0.87	0.48	0.46
Tsch.....	4	7	7	10	5	9	12
Ac + Jd.....	84	76	93	79	77	31	29
Hd.....	12	14	—	11	14	42	44
Di.....	—	3	—	—	4	18	15
<i>Lattice parameters</i>							
a (Å).....	9.673	9.664	9.645	9.669	9.676	9.741	9.765
b (Å).....	8.820	8.818	8.789	8.813	8.824	8.934	8.931
c (Å).....	5.274	5.278	5.287	5.273	5.295	5.264	5.296
β.....	107.03°	106.95°	107.32°	106.99°	107.00°	105.69°	105.92°
Volume (Å ³).....	430.2	430.2	427.9	429.7	432.3	441.0	444.2

* Includes Sr, 0.001.

Table XI. *Alkali Pyroxenes - Trace Elements (p.p.m.)*

	Sensi- tivity p.p.m.	Ionic radius (Å)	1	2	3	4	5	6	7
Distance from centre			.947	.494	.483	.450	.359	.198	.172
Ga ³⁺	3	0.62	15	14	24	19	18	16	19
Li ¹⁺	0.5	0.68	42	33	61	44	20	32	18
Nb ⁵⁺	30	0.69	—	—	92	69	—	—	—
Ni ²⁺	5	0.69	8	17	25	19	11	5	3*
Cu ²⁺	0.5	0.72	9	8	10	7	13	10	6
V ³⁺	5	0.74	105	286	71	368	415	226	205
Zr ⁴⁺	10	0.79	2075	1878	4800	4181	2950	1440	1080
Sc ³⁺	2	0.81	46	60	5	33	15	5	—
Y ³⁺	10	0.92	25	28	55	—	—	—	—
Yb ³⁺	10	0.86	12	12	12	10	9*	8*	4*
Sr ²⁺	5	1.12	8	250	12	128	13	66	72
La ³⁺	10	1.14	202	148	115	43	36	256	336
Ba ²⁺	5	1.34	82	89	61	103	61	63	58
Rb ¹⁺	1	1.47	6	1	8	1	2	8	7

Anal. D. R. C. KEMPE.

* Values approximate.

five Kangerdlugssuaq aegirines compared with 0.02 in comparable analyses. The pyroxenes have a high manganese content and average 0.7 per cent MnO in the aegirines; the value increases slightly centripetally, and is 2.9 per cent in the aegirine-augites. The average MnO in comparable

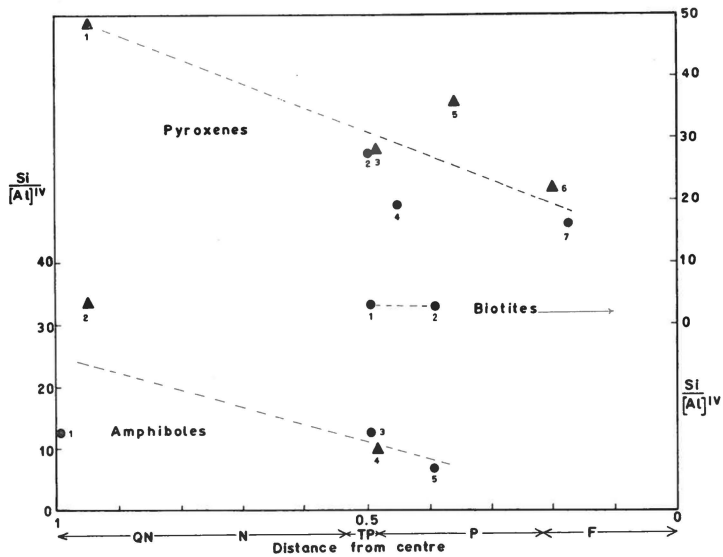


Fig. 16. $\text{Si}/\text{Al}^{\text{IV}}$ ratios in pyroxenes, amphiboles, and biotites plotted against the distance from the centre.

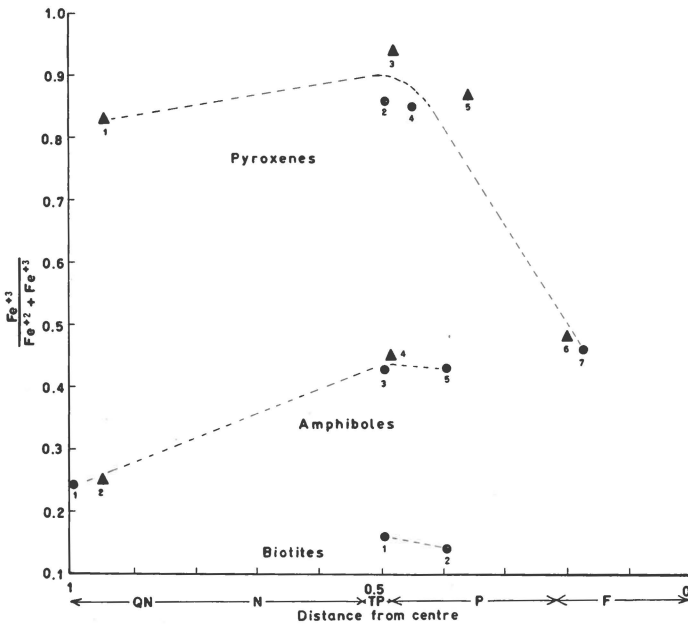


Fig. 17. $\text{Fe}^{+3}/(\text{Fe}^{+3} + \text{Fe}^{+2})$ ratios in pyroxenes, amphiboles, and biotites plotted against the distance from the centre.

pyroxenes listed by DEER *et al.* (1963a) is respectively 0.2 per cent and 0.5 per cent. The high manganese content has no effect on the pleochroic scheme of the aegirines as in the case of the manganese-rich aegirine, blandfordite. Comparison with the aegirines from the Lovozero massif (VLASOV *et al.*, 1966) shows that these pyroxenes have a higher content of Si and a considerably greater content of Ti (average 2.2 per cent TiO_2). Among the minor elements present the high content of ZrO_2 is notable, but V_2O_3 is present only in minor amounts. Of these two oxides, a similar content is shown by two or three of the Lovozero pyroxenes, although one contains 0.24 per cent V_2O_3 . The ionic substitution in the aegirines and (1950), augites follows the normal pattern and, as shown by SABINE aegirine- sodium and potassium together vary directly with ferric iron, titanium, aluminium in octahedral coordination, and vanadium; magnesium, ferrous iron and manganese together vary directly with calcium; and sodium and potassium together vary inversely with calcium.

The $\text{Si}/\text{Al}^{\text{IV}}$ ratio of the aegirines (Table X and Fig. 16) in the main units of the intrusion shows a general decrease centripetally, while the iron oxidation ratio (Fig. 17) remains approximately constant until the pulaskite, and then decreases sharply, due to ferric iron entering preferentially into melanite, in the foyaite. All the pyroxenes are undersaturated, containing normative nepheline (see YAGI, 1953) but, as might be expected, the norm of no. 1 contains by far the least amount of *ne*.

The compositions of the pyroxene series in terms of the four end-member components Tsch, Ac + Jd, Hd and Di, are given in Table X (see YODER and TILLEY, 1962, pp. 366-7) and are plotted on this basis in Fig. 18. The Tsch component is represented by the triangle of closure, the size of which is directly related to the amount of aluminium in tetra-

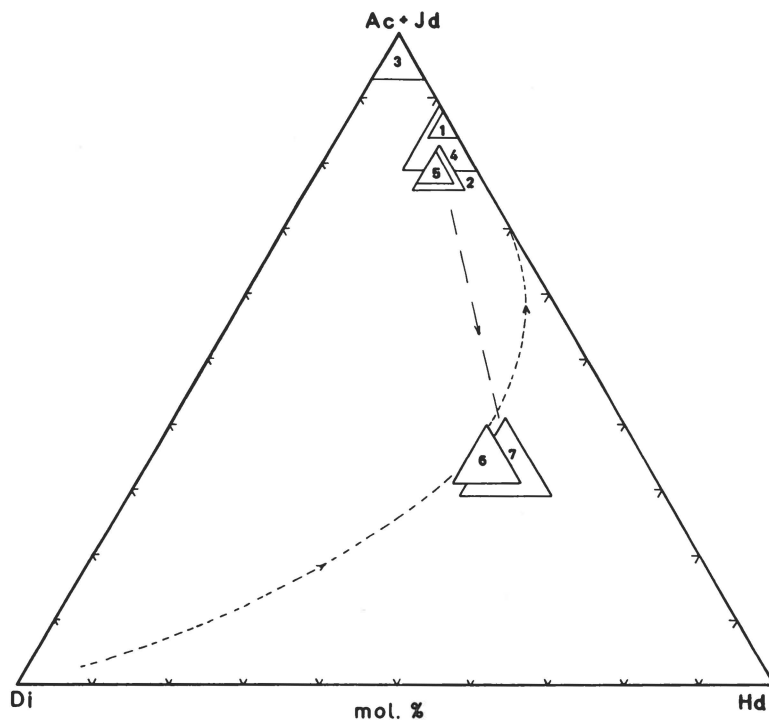


Fig. 18. Compositions of the alkali pyroxenes, in the system (Ac+Jd)-Di-Hd (after YODER and TILLEY, 1962). Triangles of closure represent Tsch. Long-dashed line: Kangerdlugssuaq trend. Short-dashed line: course of crystallization of alkali pyroxenes from Sakhalin (YAGI, 1953). Numbers refer to analyses in Table IX.

hedral coordination, and becomes smaller as the percentage of acmite increases. An empirical estimate of the Ac + Jd component may be obtained directly from the sum of the Na₂O and K₂O weights per cent, provided, as is usually the case, the K₂O (wt. per cent) and Jd (mol. per cent) are small. The two parameters are approximately related linearly according to the equation:

$$(\text{Ac} + \text{Jd}) \text{ mol. per cent} = 7.45 \times (\text{Na}_2\text{O} + \text{K}_2\text{O}) \text{ wt. per cent.}$$

The unit cell dimensions of the Kangerdlugssuaq pyroxenes are given in Table X. These agree in general with the data for the synthetic end-members acmite, diopside and hedenbergite (NOLAN and EDGAR, 1963; NOLAN, 1969), and the *a* and *b* parameters and cell volume increase

as the contents of the diopside and hedenbergite components increase. Since NOLAN (1969) has shown that there is complete solid solution between the three end-members, the fact that no. 3 (Ac_{93}) has smaller dimensions than synthetic (pure) acmite is tentatively ascribed to the presence in solid solution (or exsolution) of a small amount of ferrosilite.

b) Conclusions

Variation in the compositions of the Kangerdlussuaq alkali pyroxenes has been found to be limited to two main types. The majority of the main rocks contain an aegirine with a composition of about Ac_{80} , and similar compositions also occur in most of the veins. In a vein (4666-V) in the transitional pulaskite the aegirine has the composition Ac_{93} , but this is exceptional and the vein contains other minerals of extreme composition. The foyaite and its veins and pegmatitic segregations contain an aegirine-augite of composition Ac_{30} . This compositional trend is in direct contrast to that shown in the alkali pyroxenes of the sheets, laccoliths and dykes of the Morotu district, Sakhalin (YAGI, 1953), in which the order of crystallization is augite \rightarrow sodic-augite \rightarrow aegirine-augite \rightarrow aegirine. In the Kangerdlugssuaq intrusion, however, the trend is related essentially to the mineralogy of two rock types, both of which crystallized from an alkaline magma and not, as is the case in the Morotu district, from a wide range of liquids. At Kangerdlugssuaq the major change is associated with the chemical composition of the residual foyaitic fraction in which the content of Ca was increased and that of Fe^{+2} decreased, the latter leading to an increase in the oxidation ratio. Thus, with Na being increasingly extracted from the magma by nepheline, the residual liquids became relatively enriched in Ca, Mg and Fe^{+3} , from which the melanite garnet and aegirine-augite were precipitated. As observed by TYLER and KING (1967), the titanium content is lower in the aegirine-augites in rocks containing melanite.

The petrographic evidence of the nordmarkites and pulaskites shows that some of the aegirine, with the complementary development of biotite, began to form from sodic amphibole at a temperature close to the incongruent melting point, $990^{\circ}C$, of the pyroxene. Since these changes may have occurred during cooling this temperature cannot be used with certainty as an indication of the upper limit of crystallization. Where, however, primary crystals of aegirine are present, as in the pulaskites, an upper temperature limit near $990^{\circ}C$ can be applied, and is in reasonable general agreement with the alkali feldspar data.

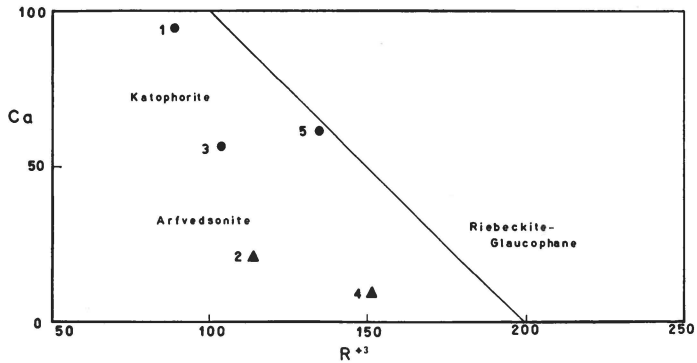


Fig. 19. Alkali amphiboles: Ca plotted against R^{+3} (after MIYASHIRO, 1957). Numbers refer to analyses in Table XII.

V. ALKALI AMPHIBOLES

Alkali amphibole is the main ferromagnesian mineral in the nordmarkites, decreases in the transitional pulaskite in which it is less abundant than either aegirine or biotite, shows a small increase in the main pulaskite, but is virtually absent in the foyaite. The analyses of the amphiboles show that in the nordmarkites they are katophorites while in the other rocks of the intrusion the amphiboles are members of the arfvedsonite series (Fig. 19). This change in the chemistry of the amphiboles, since katophorite is a higher temperature mineral than arfvedsonite, is in accord with the concept of the centripetal cooling of the intrusion. The arfvedsonite of the veins formed at lower temperatures than the magnesioarfvedsonite of the pulaskites.

The amphiboles occur in euhedral crystals, frequently in clustered groups with the other ferromagnesian minerals, and are often partially altered to pyroxene and biotite. Many of the crystals show some exsolution of iron oxide, sometimes as a 'peppering' on oriented planes (Plate 3), and often contain many small crystals of accessory minerals, notably apatite, sphene and iron oxide. Twinning on $\{100\}$ sometimes occurs; zoning shown by higher extinction angles in the core is present in some crystals and is probably related to its lower iron content compared with the crystal margins.

The optical properties of the alkali amphibole are difficult to measure precisely because of their strong dispersion, very varied pleochroism and strong absorption, the latter giving rise to anomalous interference colours and wavy or incomplete extinction. The three pleochroic schemes given below illustrate the main variations:

katophorite (from quartz-nordmarkite)

α yellowish
 β greyish-green
 γ olive-grey

absorption: $\gamma > \beta > \alpha$; positive elongation

arfvedsonite (from vein in quartz-nordmarkite)

α greyish-green
 β yellowish-grey
 γ indigo

absorption: $\gamma > \alpha > \beta$; negative elongation

magnesioarfvedsonite (from pulaskite)

α greyish-green
 β greyish-brown
 γ greyish-yellow

absorption: $\alpha > \beta > \gamma$; negative elongation.

The optic axial angles show considerable variation. In the katophorite $2V\alpha$ is about 41° , whilst in the arfvedsonites it varies from about 20° to 60° , the majority having $2V\alpha$ between 47° and 56° , comparable with those of magnesioarfvedsonites (DEER *et al.*, 1963a). The extinction angle ($\alpha \wedge z$) is approximately 62° in the katophorite, and varies from 5° to 40° , with 30° to 34° the most common values, in the arfvedsonites. The γ refractive index was determined for the analysed specimens (Table XII) and shows an almost linear variation with the $100 \text{ Mg}/(\text{Mg} + \text{Fe}^{+2} + \text{Fe}^{+3} + \text{Mn})$ ratio.

a) Chemistry and Conclusions

Five amphiboles have been analysed. The amphiboles show a considerable variation in composition, the variation being particularly marked in the range of substitutions in both the X and Y positions. The katophorite from the quartz-nordmarkite has, however, a sufficiently distinctive composition, especially in relation to its high Ca and low Na + K contents, to separate it from the other four amphiboles. In general the Kangerdlugssuaq amphiboles show a close chemical resemblance with comparable members of the eckermannite-arfvedsonite group from other localities (DEER *et al.*, 1963a), but have a higher Mn content than most of the amphiboles of this series, except for the manganarfvedsonite, juddite. Similar Mn contents are, however, present in the arfvedsonite of the Lovozero massif (VLASOV *et al.*, 1966). The total numbers of ions

Table XII. *Alkali Amphiboles – Chemical Analyses*

	1	2	3	4	5	A	B
Distance							
from centre	.996	.947	.494	.483	.391	—	—
SiO ₂	48.68	49.28	49.82	47.88	46.05	48.41	50.86
TiO ₂	1.39	2.30	1.25	1.38	1.73	1.32	1.65
Al ₂ O ₃	3.17	1.23	3.29	4.14	5.93	1.81	3.29
Fe ₂ O ₃	6.81	8.29	8.74	12.25	9.93	11.25	8.61
FeO	19.36	22.16	10.32	13.26	11.62	23.81	10.85
MnO	1.43	2.27	1.57	3.09	1.84	0.75	1.26
MgO	5.53	1.52	9.75	5.00	7.44	0.06	9.32
CaO	5.83	1.25	3.59	0.90	3.77	1.18	1.40
Na ₂ O	4.75	7.84	7.39	8.24	6.89	7.37	8.08
K ₂ O	1.19	1.58	1.55	1.75	1.78	1.52	3.08
H ₂ O ⁺	2.42*	2.37*	2.60*	2.54*	2.46*	0.94	} 1.40
H ₂ O ⁻	0.03	nil	0.06	nil	0.07	0.13	
ZrO ₂	0.04	0.06	0.03	0.33	0.26	—	—
V ₂ O ₃	tr.	tr.	0.01	tr.	0.02	—	—
SrO	tr.	tr.	0.03	tr.	tr.	—	—
BaO	0.02	0.01	0.05	0.02	0.01	—	—
Li ₂ O	0.01	0.06	0.02	0.09	0.02	—	—
F	—	—	—	—	—	2.95	0.42
Cl	—	—	—	—	—	—	0.08
	100.66	100.22	100.07	100.87	99.82	101.50	100.30
O ≡ F, Cl . . .	—	—	—	—	—	1.24	0.18
Total	100.66	100.22	100.07	100.87	99.82	100.26	100.12

1. Katophorite, quartz-nordmarkite, E.G. 1397, coast northwest of snout of Kælvegletscheren. Anal. D. R. C. KEMPE. (γ , 1.681).
 2. Arfvedsonite, vein in quartz-nordmarkite, E.G. 2046, west side large nunatak, south of Søndre Fangetårnet. Anal. D. R. C. KEMPE. (γ , 1.695).
 3. Magnesianarfvedsonite, transitional pulaskite, E.G. 4789, north side Søndre Syenitgletscher. Anal. D. R. C. KEMPE. (γ , 1.672).
 4. Arfvedsonite, vein in transitional pulaskite, E.G. 4666, southwest side Trebjørnebjerg. Anal. D. R. C. KEMPE. (γ , 1.694).
 5. Magnesianarfvedsonite, pulaskite, E.G. 4582, north side Søndre Syenitgletscher. Anal. D. R. C. KEMPE. (γ , 1.683).
- A. Arfvedsonite, arfvedsonite-aegirine syenite, Kap Boswell, Kangerdlugssuaq (DEER *et al.*, 1963b). Anal. W. A. DEER.
- B. Arfvedsonite, hornblende lujavrite, Lovozero (VLASOV *et al.*, 1966). Anal. MOLEVA.
- * Loss on ignition.

in the X + Y + A sites are also lower than in most arfvedsonites, a deficiency that is largely due to the smaller number of Na + K ions in the Kangerdlugssuaq amphiboles which show a centripetal increase in the latter ion (Table XIII). This is compensated in part by the greater sub-

Table XIII. *Alkali Amphiboles – Numbers of Ions on the Basis of 24 (O, OH, F)*

	1	2	3	4	5	A
Distance						
from centre ...	.996	.947	.494	.483	.391	—
Si.....	7.388	7.664	7.359	7.218	6.945	7.618
Al.....	0.567	0.226	0.573	0.736	1.054	0.334
Al.....	—	—	—	—	—	—
Ti.....	0.159	0.269	0.139	0.156	0.196	0.156
Zr.....	0.003	0.005	0.002	0.024	0.019	—
Fe ⁺³	0.778	0.970	0.972	1.390	1.127	1.332
V.....	—	—	0.001	—	0.002	—
Fe ⁺²	2.457	2.883	1.275	1.672	1.466	3.134
Mn.....	0.184	0.299	0.196	0.395	0.235	0.100
Mg.....	1.251	0.352	2.146	1.123	1.672	0.014
Li.....	0.006	0.038	0.012	0.055	0.012	—
Ca.....	0.948	0.208	0.571*	0.145	0.609	0.199
Na.....	1.398	2.364	2.116	2.408	2.014	2.248
K.....	0.230	0.314	0.292	0.337	0.343	0.304
Ba.....	0.001	0.001	0.003	0.001	0.001	—
OH,F.....	2.450	2.459	2.562	2.555	2.475	2.456
Z.....	7.96	7.89	7.93	7.95	8.00	7.95
Y.....	4.84	4.82	4.74	4.82	4.73	4.74
X.....	2.58	2.89	2.98	2.89	2.97	2.75
Si/Al ^{IV}	13.0	33.9	12.8	9.8	6.6	22.8
Fe ⁺³ /(Fe ⁺³ + Fe ⁺²).....	0.24	0.25	0.43	0.45	0.43	0.30
100 Mg/ (Mg + Fe ⁺² + Fe ⁺³ + Mn)....	26.8	7.8	46.8	24.5	37.1	0.3

* Includes Sr, 0.003.

stitution of Si by Al, and in none of the amphiboles does Al occupy 6-fold coordination sites (Fig. 16). There are two levels of the iron oxidation ratio, the higher ratio occurring in the amphiboles from the inner part of the intrusion (Fig. 17), and is in contrast with the near constant iron oxidation ratio in the pyroxenes from the same units of the intrusion. Normatively, three amphiboles are saturated (nos. 1, 3 and 4), whilst no. 2 is highly over-saturated and no. 5 contains normative nephe-line. The trace element content of the amphiboles is detailed in Table XIV. Compared with the pyroxenes they contain less Zr, particularly in the early-formed amphiboles, have rather less V, and considerably more Li.

The amphiboles are primary constituents of the syenites, but in the pulaskites partial replacement by pyroxene and biotite has occurred. This is in agreement with the experimental investigation of the riebeckite-

Table XIV. *Alkali Amphiboles – Trace Elements (p.p.m.)*

	Sensiti- vity p.p.m.	Ionic radius (Å)	1	2	3	4	5
Distance from centre			.996	.947	.494	.483	.391
Ga ³⁺	3	0.62	16	13	14	26	21
Li ¹⁺	0.5	0.68	57	288	112	424	110
Nb ⁵⁺	30	0.69	79	56	—	—	100
Ni ²⁺	5	0.69	2*	3*	1*	9	6
Cu ²⁺	0.5	0.72	6	13	4	9	4
Co ²⁺	10	0.72	—	—	—	15	—
V ³⁺	5	0.74	26	27	75	42	124
Zr ⁴⁺	10	0.79	293	455	248	2470	1915
Sc ³⁺	2	0.81	85	20	53	4	33
Yb ³⁺	10	0.86	12	14	6*	7*	7*
Y ³⁺	10	0.92	40	19	15	—	—
Sr ²⁺	5	1.12	23	13	292	44	22
La ³⁺	10	1.14	136	42	115	—	80
Ba ²⁺	5	1.34	143	81	437	140	89
Rb ¹⁺	1	1.47	26	24	10	31	63

* Values approximate.

Anal. D. R. C. KEMPE.

arfvedsonite solid solution series, which has shown that the group exists stably at magmatic temperatures only when the oxygen fugacity is low and the fluid pressure is some 1000 or more bars. At higher temperatures and oxidation states, and at lower fluid pressures, the riebeckite-arfvedsonite amphiboles are unstable (ERNST, 1962). The experimental data are thus not in conflict with the evidence of the Kangerdlugssuaq syenites as amphibole did not crystallize from the foyaite liquid in which the highest oxidation state was developed. Since the lower temperature and higher fluid pressure prevailing in the foyaite would favour the crystallization of arfvedsonite, the high oxidation state appears to be the controlling factor, although, as previously stated, the bulk chemistry of the foyaite and the presence of other hydrous phases in this rock may have contributed to the absence of amphibole.

Note: The lattice parameters of the Kangerdlugssuaq alkali amphiboles are given by KEMPE (1969). In this paper, the Mg ratio is calculated as: 100 (Mg + Li) / (Mg + Li + Fe⁺² + Fe⁺³ + Mn).

VI. BIOTITES

Minor amounts of biotite are present in the nordmarkites, and in the pulaskites biotite is one of the main ferromagnesian minerals. Small quantities of a yellow to dark green pleochroic biotite are occasionally present in the foyaite, and a yellow to very dark green-brown pleochroic mica, probably derived from the alteration of aegirine-augite, is found in some of the foyaite veins.

The biotite in the pulaskites is pleochroic from pale yellow to fairly dark brown, and from the textural evidence some of the biotite is primary, but it also occurs, with alkali pyroxene, as a breakdown product of alkali amphibole. The optic axial angles range from 2° to 13° , and the high refractive indices of the two analysed micas are consistent with their composition.

Analyses of the two pulaskite biotites, and their structural formulae, are given in Table XV. In composition they are less rich in Al and Ti, and have a higher content of Mn and K, than most biotites of igneous paragenesis. The high Mn content of the Kangerdlugssuaq biotites matches the high contents of this element in the pyroxenes and amphiboles, and in this respect is comparable with the biotite in the hornblende syenite of the Lovozero massif (VLASOV *et al.*, 1966). The total iron content of the Kangerdlugssuaq biotites is relatively small and is probably due to the preferential entry of Fe^{+2} and Fe^{+3} ions into the alkali amphiboles and pyroxenes. It is not known whether the iron content of the primary biotites differs from that of the biotites derived from the breakdown of the amphibole. The trace elements in the biotites are shown in Table XVI; they contain notable quantities of Ba, Rb and Zr, and are the only minerals of the intrusion in which Cs was detected. The biotite from the main pulaskite has a somewhat greater content of Fe^{+2} , and is less rich in Mg, than the mica in the transitional pulaskite but otherwise the two minerals show little significant chemical differences.

It is not possible, except in a general way, to account in terms of the stability field of synthetic annite (EUGSTER and WONES, 1962) for the changing amounts of biotite present in the main units of the intrusion. In the presence of potassium feldspar, annite is stable at a $P_{\text{H}_2\text{O}}$ of 2070 bars over a temperature range between 425° and 825° C, the precise

Table XV. *Biotites – Chemical Analyses*

	1	2	A
Distance from centre .....	.494	.391	—
SiO ₂	39.38	37.75	42.80
TiO ₂	2.26	2.95	2.80
Al ₂ O ₃	11.94	11.63	10.36
Fe ₂ O ₃	3.68	3.55	0.69
FeO	17.69	20.03	10.55
MnO	1.54	1.72	1.12
MgO	10.37	9.01	16.25
CaO	0.15	0.13	—
Na ₂ O	0.68	0.50	2.61
K ₂ O	9.07	9.25	8.76
H ₂ O ⁺	2.98*	3.08*	} 1.72
H ₂ O ⁻	nil	0.03	
ZrO ₂	0.01	0.01	—
BaO	0.17	0.02	—
Rb ₂ O	0.07	0.10	—
Li ₂ O	0.02	0.02	—
F	—	—	3.84
	100.01	99.78	101.50
0 ≡ F	—	—	1.62
Total	100.01	99.78	99.88

Numbers of ions on the basis of 24 (O, OH, F)

Si	6.073	5.922
Al	1.927	2.078
Al	0.244	0.073
Ti	0.262	0.348
Fe ⁺³	0.427	0.419
Fe ⁺²	2.282	2.628
Mn	0.201	0.229
Mg	2.384	2.107
Ca	0.025	0.022
Na	0.203	0.152
K	1.785	1.852
Ba	0.010	0.001
Rb	0.007	0.010
OH, F	3.066	3.223
Z	8.000	8.000
Y	5.800	5.804
X	2.030	2.037
Si/Al ^{IV}	3.2	2.8
Fe ⁺³ /(Fe ⁺³ + Fe ⁺²)	0.16	0.14

1. Biotite, transitional pulaskite, E.G. 4789, north side, Søndre Syenitgletscher, Anal. D. R. C. KEMPE. (γ , 1.639).

2. Biotite, pulaskite, E.G. 4582, north side, Søndre Syenitgletscher. Anal. D. R. C. KEMPE. (γ , 1647).

A. Biotite, hornblende syenite, Koklakhtivai Valley, Lovozero (VLASOV *et al.*, 1966). Anal. VLADIMIROVA.

* Loss on ignition.

Zr and Li are not included in structural formulae.

Table XVI. *Biotites – Trace Elements* (p. p. m.)

	Sensitivity p.p.m.	Ionic radius (Å)	1	2
Distance from centre . . . . .			.494	.391
Ga ³⁺	3	0.62	36	34
Li ¹⁺	0.5	0.68	74	95
Ni ²⁺	5	0.69	2*	1*
Cu ²⁺	0.5	0.72	†	7
Co ²⁺	10	0.72	16	17
V ³⁺	5	0.74	28	70
Zr ⁴⁺	10	0.79	100	115
Yb ³⁺	10	0.86	6*	5*
Y ³⁺	10	0.92	15	—
Sr ²⁺	5	1.12	48	5
La ³⁺	10	1.14	226	—
Ba ²⁺	5	1.34	1520	180
Rb ¹⁺	1	1.47	628	925
Cs ¹⁺	2	1.67	3	3

Anal. D. R. C. KEMPE.

* Values approximate.

† No value given due to contamination of specimen.

temperature being dependent on the oxygen fugacity, P_{O_2} . In the presence of quartz, the stability field of annite is more restricted. Increasing P_{H_2O} , at constant T and P_{O_2} , favours the formation of mica in the reaction sanidine + magnetite \rightleftharpoons annite. Thus in the Kangerdlugssuaq liquids the final cessation of biotite crystallization from the foyaitic magma can be related to relative changes in the P_{H_2O} and P_{O_2} pressures, and on the basis of the experimental data leads to the conclusion that the absence of biotite in the foyaite is mainly related to increasing P_{O_2} .

VII. ACCESSORY MINERALS

a) Quartz

Although not an accessory mineral in the earlier units of the intrusion, it is convenient to consider quartz under this heading since it has not been studied in detail. Quartz is present in the nordmarkites and forms as much as 15 per cent of some of the outer quartz-nordmarkites; it decreases in amount in the nordmarkite and is absent from the stage at which the outer rim of the transitional pulaskite was formed.

The quartz is anhedral, occurs interstitially, contains both fluid and opaque inclusions, and on the textural evidence was the last of the nordmarkite minerals to crystallize.

b) Sodalite

Sodalite occurs in the main pulaskite and foyaite in which it is found only as a late-stage mineral. In the latter rock, and in veins in the main pulaskite, sodalite is a major constituent, and in the foyaite may form as much as 23 per cent of the rock. In some of the foyaite veins it is present in large blue crystals.

The sodalite occurs in subhedral dodecahedra crowded with exsolved iron-rich inclusions. The boundaries of the sodalite are commonly enlarged, mainly at the expense of nepheline, and these secondary overgrowths, although showing considerable clouding, are marked by the absence of iron inclusions, a pattern that is clearly displayed in hand specimen.

A partial analysis of the alkalis in the sodalite ($n = 1.486 \pm 0.001$) from the foyaite gave, after correction for iron inclusions, Na_2O , 24.42 per cent; K_2O , 0.58 per cent. Because of the corrections, necessitated by the inclusions in the sodalite, the oxide values are only approximate, but the ratio of the alkalis is considered to be reliable. Qualitative analysis of the trace elements showed the presence of Ga, Li, Cu, V, Zr, La, Ba and Rb, as well as a relatively high content of Sr; the Cu, V and La are probably derived from the impurities. The presence of a chlorine-rich mineral such as sodalite is unequivocal evidence of the increased concentration of volatiles in the residual magma from which the final undersaturated unit of the intrusion crystallized.

c) Melanite Garnet

Melanite garnet is present only in the foyaite in which it commonly occurs as an accessory mineral, although in some parts of the foyaite it constitutes up to 2.5 per cent of the rock, and is, after aegirine-augite, the second most important ferromagnesian mineral. It is black in hand specimen and dark reddish-brown in thin section, shows some colour zoning, and usually contains inclusions of the earlier-formed minerals.

An analysis of the melanite from a vein in the foyaite is given, together with its structural formula, in Table XVII. It is fairly typical in composition although, compared with many melanites, it has a somewhat small Ca and high Fe content. The cell-edge length, $a = 12.056 \text{ \AA}$, is consistent with the composition. A qualitative determination of the trace elements showed the presence of Ga, Nb, Ni, Cu, V, Zr, Yb, Y, La and Ba. Nb, V, Zr, Yb, Y and La appear to be present in large or very large concentrations, and presumably substitute for Fe^{+3} , Ti and Ca.

Table XVII. *Melanite Garnet*

SiO_2	35.31	<i>Numbers of ions on the basis of 24 (0)</i>	
TiO_2	4.09	Si	5.884
Al_2O_3	2.51	Al	0.116
Fe_2O_3	24.87	Al	0.377
FeO	4.47	Fe^{+3}	3.119
MnO	0.66	Ti	0.513
MgO	0.65	Mg	0.161
CaO	27.01	Fe^{+2}	0.623
Na_2O	0.45	Mn	0.093
K_2O	0.14	Na	0.145
Total	100.16	Ca	4.823
		K	0.030
n	1.888 ± 0.005	Almandine	11.0
a	$12.056 \pm 0.005 \text{ \AA}$	Andradite	84.6
		Grossular	0.0
		Pyrope	2.8
		Spessartine	1.6
		} mol. per cent.	

Melanite garnet, vein in foyaite, E.G. 2109, Citadellet. Anal. W. A. DEER.

d) Iron Oxides

Little work on the iron oxides has been undertaken and their identity was established mainly by testing with a hand magnet during the mineral separations. Both ilmenite and magnetite are present, in the approximate proportions 4:1, in the quartz-nordmarkite and transitional pulaskite. In the main pulaskite and foyaite the ilmenite is present in very small

amounts and most of the oxide is magnetite. Hematite has been found in some twenty rocks (nordmarkites, transitional and main pulaskites, and their veins), and is most common in the transitional and, to a lesser extent, the main pulaskite. It sometimes occurs as shapeless aggregates but more usually as large euhedral crystals presumed to be altered cubes of pyrite (Plate 3), of which only two or three are normally found in a single thin section.

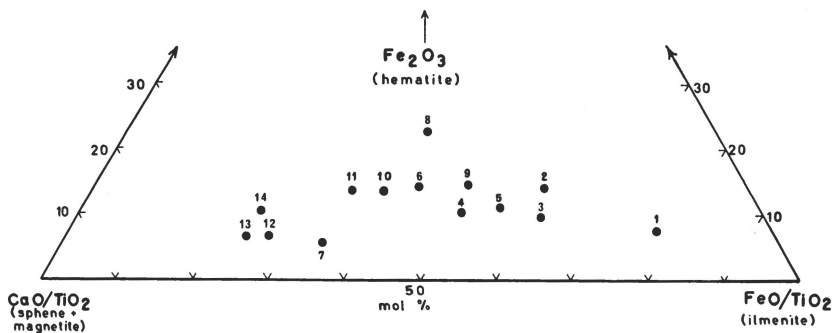


Fig. 20. Rock analyses: triangular plot of FeO/TiO_2 - CaO/TiO_2 - Fe_2O_3 . This 'ore potential' diagram illustrates the modal occurrence of ilmenite, sphene + magnetite and hematite, respectively. Numbers refer to analyses in Table XXVI.

The pattern of change in the iron oxide is thus from ilmenite, sometimes altering to sphene, in the early outer rocks, to magnetite in the later inner units of the intrusion, together with some hematite in the pulaskites. This trend is illustrated in Fig. 20, in which the 'ore potential' of the rocks is obtained by plotting the ratios FeO/TiO_2 and CaO/TiO_2 against Fe_2O_3 . The early development of ilmenite in the quartz-nordmarkite is illustrated in the figure by analyses 1 to 3, and the late development of magnetite and increased concentration of sphene in the foyaite by analyses 12 to 14, while the formation of hematite in the pulaskites may be related to the slight increase in the Fe_2O_3 value of these rocks. Although these data indicate that the oxygen fugacity reached its peak during the formation of the pulaskites it must be remembered that, during the differentiation of the Kangerdlugssuaq magma, ferrous iron decreased at a greater rate than the increase in ferric iron, and that the highest iron oxidation ratio is found in the foyaite.

e) Sphene and Apatite

These accessory minerals are considered together since they are ubiquitous in all the units of the intrusion. Sphene, often in simple and lamellar twinned crystals, increases in quantity in the later rocks,

especially the foyaite, where it may reach 1 per cent. Both minerals are early-formed and euhedral and frequently occur as inclusions in other minerals.

f) Zircon and Perovskite

These two minerals are restricted to the early part of the intrusion. Zircon is rare, but relatively large crystals have been noted in the nordmarkites and their veins, while perovskite, in small, euhedral, yellow-brown crystals (Plate 4), occurs in the nordmarkite and pulaskite and, more commonly, in the veins in these rocks, but is absent in the foyaite.

g) Astrophyllite

Astrophyllite is a relatively common constituent of the veins in the transitional and main pulaskites. In some of the albite-rich, aplitic veins, astrophyllite constitutes as much as 10 per cent of the rocks, and occurs in bronze-coloured crystals up to 10 mm in length (Plate 4). The astrophyllite is strongly pleochroic in sections normal to the perfect cleavage, with α brownish-gold, β golden yellow, and γ lemon yellow; the refractive indices are α 1.680, β 1.704, γ 1.738, all \pm 0.002. The mineral has a large positive optic axial angle, and the $\rho > \nu$ dispersion is strong. The refractive indices of the astrophyllite minerals show a considerable range and are related to compositional variation, particularly of Fe^{+2} , Fe^{+3} , Mn and Ti. Because the contents of each of these ions do not vary systematically it is not possible, however, to relate precisely the refractive indices to composition. Those minerals in which the sum of these cations is low and the content of Mg correspondingly high have lower indices, as for example the more magnesium-rich astrophyllite (Table XVIII, anal. D), the refractive indices of which are $\beta \sim 1.69$, $\gamma \sim 1.72$, compared with the more usual values of $\beta \sim 1.705$, $\gamma \sim 1.74$.

The formula of astrophyllite is given variously as $(\text{K}, \text{Na})_2 (\text{Fe}^{+2}, \text{Mn})_4 \text{Ti}[\text{Si}_2\text{O}_7]_2 (\text{OH}, \text{F})_2$ (STRUNZ, 1957); $(\text{K}, \text{Na})_3 (\text{Fe}^{+2}\text{Mn})_7 \text{Ti}_2 [\text{Si}_4\text{O}_{12}]_2 (\text{O}, \text{OH}, \text{F})_7$; and $(\text{K}, \text{Na})_3 (\text{Fe}^{+2}, \text{Mn})_7 \text{Ti}_2 \text{Si}_8 (\text{O}, \text{OH}, \text{F})_{31}$ (WOODROW, 1963). The latter formula is based on a structure determination, the full details of which have not been published, but which led WOODROW to propose that the astrophyllite structure is similar to that of biotite, and to consist of continuous sheets of Si-O and Ti-O tetrahedra with octahedrally coordinated $(\text{Fe}^{+2}, \text{Mn})$ atoms between the sheets, these double sheets being themselves separated by planes of (K, Na) atoms. The composition of the Kangerdlugssuaq mineral is given in Table XVIII, and the analysis, calculated on the basis of 31 $(\text{O}, \text{OH}, \text{F})$, in Table XIX. From the latter it may be seen that the Kangerdlugssuaq astrophyllite contains less than the ten tetravalent cations of the formula unit, as is also the case

Table XVIII. *Astrophyllite – Chemical Analyses*

	1	A	B	C	D
SiO ₂	33.92	34.78	35.23	37.98	39.00
TiO ₂	8.61	11.86	11.40	12.18	9.73
ZrO ₂	1.52	0.57	1.21	tr.	n.d.
Al ₂ O ₃	nil	0.60	tr.	1.11	3.26
Fe ₂ O ₃	9.34	2.76	3.73	2.95	4.39
Nb ₂ O ₅	n.d.	n.d.	n.d.	n.d.	0.71
Ta ₂ O ₅	n.d.	n.d.	0.34	n.d.	n.d.
FeO	21.05	26.71	29.02	17.91	21.91
MnO	10.98	6.65	5.52	4.00	4.96
MgO	0.96	1.54	0.13	6.39	2.83
CaO	1.04	1.66	0.22	1.15	2.33
BaO	n.d.	0.15	n.d.	n.d.	n.d.
Na ₂ O	3.08	3.00	3.63	5.38	4.10
K ₂ O	6.09	5.90	5.42	7.28	6.35
H ₂ O ⁺	2.28	2.98	4.18	3.44	—
H ₂ O ⁻	0.51	0.11	—	nil	—
F	1.58	0.86	—	0.45	—
Cl	—	0.35	—	—	—
	100.96	100.48	100.03	100.28	99.57
O ≡ F, Cl	0.67	0.44	—	0.19	—
Total	100.29	100.04	100.03	100.09	99.57

1. Astrophyllite, vein in pulaskite, E.G. 2777, southeastern point Trebjørneberget. Anal. W. A. DEER.
- A. Astrophyllite, Kukisvumchorr, Kola (FERSMAN and BONSHADT, 1937). Anal. N. VLODAVEZ (value for CaO includes SrO, 0.05).
- B. Astrophyllite, pegmatite, Mount Rosa area, Colorado (GROSS and HEINRICH, 1966). Anal. EAKINS.
- C. Magnesian astrophyllite, U.S.S.R. (PENG and MA, 1963) (includes P₂O₅, 0.06).
- D. Astrophyllite, pegmatite, Kola (SEMENOV, 1959). Anal. C. H. FEDORCHUK.

for those of the four astrophyllites shown for comparison. This deficiency of tetrahedrally coordinated cations is compensated by the presence of more than seven octahedrally coordinated cations, and it is possible that some of the tetrahedral sites are occupied by trivalent, Fe⁺³ or Al, cations. The number of interlayer alkali cations in the Kangerdlugssuaq astrophyllite is close to that required by the ideal formula but in the other minerals shown in the tables, and especially in the magnesian astrophyllite (Table XIX, anal. C), the number of monovalent cations shows a less close approach. Except, however, for the Mount Rosa astrophyllite for which H₂O⁺ and F have not been determined, the total number of cations is approximately 20 ± 0.5. The analyses show a variable monovalent anion

Table XIX. *Astrophyllite* – Numbers of Ions on the Basis of 31 (O, OH, F)

	1	A	B	C	D
Si.....	7.552	7.565	7.606	7.810	8.499
Ti.....	1.442	1.941	1.853	1.886	1.596
Zr.....	0.165	0.061	0.127	—	—
Al.....	—	0.154	—	0.270	0.838
Fe ⁺³	1.560	0.452	0.610	0.458	0.720
Nb.....	—	—	—	—	0.068
Ta.....	—	—	0.021	—	—
Fe ⁺²	3.921	4.858	5.242	3.080	3.993
Mn.....	2.074	1.226	1.009	0.697	1.100
Mg.....	0.318	0.498	0.042	1.958	0.918
Ca.....	0.248	0.384	0.050	0.253	0.543
Ba.....	—	0.011	—	—	—
Na.....	1.330	1.268	1.320	2.144	1.731
K.....	1.731	1.636	1.492	1.908	1.765
OH.....	3.585	4.324	6.010	4.718	—
F.....	1.113	0.432	—	0.289	—
Cl.....	—	0.128	—	—	—
R ^{IV}	9.16	9.57	9.58	9.70	10.10
R ^{VI}	8.12	7.57	6.97	6.72	8.18
(Na,K).....	3.06	2.90	2.81	4.05	3.50
(OH,F,Cl).....	4.70	4.88	6.01	5.01	—
Total cations ..	20.3	20.0	19.4	20.5	21.8

content, and it is likely that some replacement of (OH,F) by oxygen also occurs. Thus the astrophyllite formula can be expressed as:



The Kangerdlugssuaq mineral is richer in manganese than most astrophyllites but contains less than half the manganese present in kuplet-skite, the manganese end-member of the astrophyllite isomorphous series.

h) Låvenite

Låvenite is present as a minor accessory mineral in the nordmarkites and pulaskites in which it occurs as rare, small yellow prismatic crystals (Plate 5); it is a common constituent of the veins in both the nordmarkites and pulaskites. In thin section the crystals show moderate pleochroism with α colourless, β very pale lemon yellow, γ golden yellow. The refractive indices are α 1.712, β 1.730, γ 1.755 \pm 0.002; $2V\alpha \sim 80^\circ$, and the extinction angle $\alpha \wedge z$ varies between 18° and 20° . Lamellar twinning on {100} is present in some crystals.

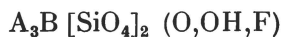
Table XX. *Låvenite* – *Chemical Analyses*

	1	A	B	C
SiO ₂	29.75	30.28	30.94	30.92
TiO ₂	4.56	2.08	5.28	11.30
ZrO ₂	29.22	30.00	23.20	16.72
(Nb,Ta) ₂ O ₅	4.01	4.29	2.97	3.01
Fe ₂ O ₃	0.47	0.81	2.29	0.12
FeO.....	3.90	3.14	3.73	4.89
MnO.....	4.11	7.57	6.00	10.34
MgO.....	2.26	—	—	—
CaO.....	7.92	7.19	13.61	10.92
Na ₂ O.....	11.05	11.66	9.74	10.70
K ₂ O.....	0.05	—	0.11	tr.
H ₂ O ⁺	0.37	0.67	0.96	—
H ₂ O ⁻	0.05	—	—	—
F.....	4.02	3.97	2.41	1.55
	101.74	101.66	101.24	100.47
O ≡ F.....	1.69	1.66	1.00	0.65
Total.....	100.05	100.00	100.24	99.82

1. Låvenite, vein in transitional pulaskite, E.G. 2352, north side, head of Amdrup Fjord. Anal. W. A. DEER.
- A. Låvenite, pegmatite, nepheline syenite, Langesundfjord, Southern Norway (BRÜGGER, 1890). Anal. KLEVE.
- B. Låvenite, poikilitic hydrosodalite syenite, Muruai River, Lovozero (VLASOV *et al.*, 1966). Anal. KAZAKOVA.
- C. Titan-låvenite, aplite, Kokluktiuai, Lovozero (VLASOV *et al.*, 1966). Anal. BUROVA.

An analysis of the låvenite is given in Table XX, together with those of the Langesundfjord and Lovozero minerals, including the titan-låvenite from the latter complex. The chemistry of the Kangerdlugssuaq låvenite compares closely with that of the Langesundfjord mineral and both have similar contents of Zr, (Nb,Ta), Fe⁺², Ca, Na and F, while the main differences are the lower Mn and higher Ti of the Kangerdlugssuaq låvenite. The Ti content is, however, smaller than that of the Muruai River material and much less than of the titan-låvenite; in addition both these minerals have a higher Mn content.

Låvenite was originally considered to be an orthosilicate having a general formula of the type:



with: A = Na,Ca,Fe⁺², Mn, and B = Zr,Ti,Nb,Ta.

A recent structural determination by SIMONOV and BELOV (1963) has shown that the structure of låvenite is based on the diorthogroup [Si₂O₇]

Table XXI. *Låvenite* – Numbers of Ions on the Basis of 9 (O, OH, F)

	1	A	B	C
Si	1.973	2.034	2.049	2.058
Zr	0.944	0.981	0.716	0.542
Ti	0.227	0.110	0.263	0.566
(Nb,Ta)	0.090	0.098	0.067	0.034
Fe ⁺³	0.024	0.041	0.115	0.003
Fe ⁺²	0.216	0.176	0.205	0.272
Mn	0.231	0.431	0.337	0.583
Mg	0.224	—	—	—
Ca	0.563	0.517	0.966	0.779
Na	1.420	1.518	1.250	1.360
K	0.004	—	0.010	—
OH	0.164	0.300	0.414	—
F	0.843	0.842	0.505	0.326

in which the Si-O tetrahedra are linked by columns consisting of four crystallographically independent octahedrally coordinated cation sites which are occupied respectively by Na, Ca, (Mn,Fe⁺²) and (Zr,Ti). The general formula of låvenite is thus more correctly expressed as:



In all four minerals the content of Na is greater than can be accommodated in one of the independent sites and some of the Na is thus probably located in the second, Ca, site. In the Kangerdlugssuaq and Langesundfjord låvenites, approximately a fourth of the octahedral sites is occupied by Zr. It is clear, however, from the composition of the Lovozero minerals that this site is also partially occupied by Ti, and that replacement of Zr by Ti is a characteristic substitution in the låvenite minerals (Table XXI).

i) Eudialyte-Eucolite

Eudialyte-eucolite minerals occur mainly as constituents of the veins in the transitional and main pulaskite. Eudialyte, the optically positive member of the group, is present as a rare accessory mineral in the foyaite; in some of the veins the eudialyte is isotropic, while in other veins the mineral is the optically negative variety, eucolite. The minerals are dark red to reddish yellow in hand specimen and colourless in thin section. The analysed specimen is a eucolite with very low birefringence, refractive indices: ω 1.624, ε 1.623 \pm 0.002. This eucolite shows a well developed rhombohedral cleavage and is commonly altered to aggregates consisting

Table XXII. *Eudialyte (Eucolite) – Chemical Analyses*

	1	A	B
SiO ₂	46.11	49.65	50.09
TiO ₂	0.52	0.35	0.39
ZrO ₂	15.53	13.73	12.82
Fe ₂ O ₃	0.67	1.88	0.60
Nb ₂ O ₅	1.05	1.15	0.54
Ta ₂ O ₅	—	—	0.06
ΣRE ₂ O ₃	2.48	2.38	2.12
FeO.....	5.22	1.98	1.79
MnO.....	1.13	2.33	2.31
MgO.....	0.05	0.09	tr.
CaO.....	8.25	8.79	8.96
Na ₂ O.....	15.69	13.58	15.55
K ₂ O.....	0.97	0.64	0.62
H ₂ O ⁺	1.55	2.05	3.06
H ₂ O ⁻	0.05	0.32	—
Cl.....	0.78	1.84	0.74
	100.05	100.76	99.65
O ≡ Cl.....	0.16	0.41	0.15
Total.....	99.89	100.35	99.50

1. Eucolite, vein in pulaskite, E.G. 2777, southeastern point Trebjørnebjæret. Anal. W. A. DEER.
- A. Eudialyte, foyaitite, Lovozero (VLASOV *et al.*, 1966). Anal. KAZAKOVA.
- B. Eudialyte, pegmatite, Angvundaschorr, Lovozero (VLASOV *et al.*, 1966). Anal. VLADAVETS.

of small randomly oriented crystals of catapleiite. The *d* spacings of this mineral, and one from another vein, have been measured from X-ray powder films, and are identical, except that some reflections, especially that at 2.15 Å, are weaker in the latter.

The analysis of the Kangerdlugssuaq eucolite is given in Table XXII, and although showing a general similarity with the Lovozero eudialytes differs from these minerals particularly in its lower content of Si and hydroxyl, and high content of Zr and Fe⁺².

The formula of the eudialyte-eucolite minerals is given by ZACHARIASEN (1930) and STRUNZ (1957) as (Na,Ca)₆Zr [Si₆O₁₈] (OH,Cl). The compositions of the eudialytes of the Lovozero syenites and pegmatites do not conform closely to this formula and VLASOV *et al.* (1966) have suggested that the composition is more correctly expressed as (Na,Ca)₅Zr [Si₆O₁₆] (O,OH,Cl)₂. The numbers of ions in the Kangerdlugssuaq eucolites and two of the Lovozero eudialytes on the basis of 19 and 18 (O,OH,Cl) and on 6 Si are given in Table XXIII. Calculated on the basis

Table XXIII. *Eudialyte (Eucolite) – Numbers of Ions on the Basis of 19 and 18 (O, OH, Cl) and 6 Si*

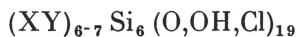
	On basis of 19 (O,OH,Cl)			On basis of 18 (O,OH,Cl)			On basis of 6 Si		
	1	A	B	1	A	B	1	A	B
Si	5.937	6.173	6.146	5.625	5.849	5.823	6.000	6.000	6.000
Ti	0.050	0.033	0.036	0.048	0.031	0.034	0.051	0.032	0.035
Zr	0.973	0.831	0.765	0.922	0.787	0.725	0.984	0.807	0.747
Nb	0.060	0.062	0.029	0.057	0.060	0.028	0.061	0.062	0.029
Ta	—	—	7.001	—	—	0.001	—	—	0.001
RE	0.138	0.136	0.112	0.130	0.122	0.106	0.139	0.125	0.109
Fe ⁺³	0.065	0.176	0.056	6.061	0.167	0.053	0.066	0.171	0.055
Fe ⁺²	0.563	0.206	0.184	0.533	0.195	0.172	0.568	0.200	0.180
Mn	0.123	9.245	0.240	0.117	0.232	0.227	0.124	0.238	0.234
Mg	0.009	0.016	—	0.009	0.016	—	0.009	0.016	—
Ca	1.138	1.171	1.178	1.078	1.109	1.116	1.150	1.138	1.150
Na	3.928	3.275	3.699	3.709	3.102	3.504	3.956	3.183	3.610
K	0.159	0.101	0.097	0.151	0.096	0.092	0.160	0.099	0.095
OH	1.332	1.700	2.504	1.262	1.611	2.372	1.346	1.653	2.444
Cl	0.170	0.388	0.158	0.161	0.368	0.146	0.172	0.378	0.151
(Zr,Ti)	1.02	0.86	0.80	0.97	0.82	0.76	1.04	0.84	0.76
Fe ⁺² etc.	0.96	0.86	0.62	0.91	0.79	0.59	0.97	0.81	0.61
(Na,Ca)	5.22	4.55	4.97	4.94	4.31	4.71	5.22	4.42	4.86
(OH,Cl)	1.50	2.09	2.66	1.42	1.98	2.52	1.52	2.03	2.60
$\Sigma(\text{Zr} + \text{Fe}^{+2}$ + Na)	7.2	6.3	6.4	6.8	5.9	6.1	7.2	6.1	6.2

of 19 anions, the Kangerdlugssuaq eucolite and the Lovozero eudialytes, in addition to the number of Si atoms, contain 7.2, 6.3 and 7.4 cations respectively, compared with an ideal content of 7 in the ZACHARIASEN and STRUNZ formula, while the sum of the hydroxyl and chlorine anions is high in all three minerals.

On the basis of the formula proposed by VLASOV *et al.* (1966), the eudialyte-euolite minerals contain 12 cations including 6 silicons, values from which the Kangerdlugssuaq euolite, with 12.4 and 6.8 cations respectively, shows a marked difference compared with the close approach to the ideal formula by the two Lovozero eudialytes which contain 11.8 and 11.9, and 5.9 and 6.1 cations respectively.

VLASOV *et al.* (1966) have emphasized the variable composition of the eudialyte-euolite minerals, and in particular the range in the ratio of the silicon atoms to the other cations from 6:6 to 6:7. Until a complete structural analysis of the eudialyte minerals is available the formula of this group is best expressed on the basis of six silicons per formula unit, and the compositions of the three minerals calculated on this basis and shown in Table XXIII, give general support to this approach. It is

significant that the high cation value of the Kangerdlugssuaq eucolite, and its low value in the Lovozero eudialytes, are accompanied respectively by lower and higher contents of the (OH,Cl) anion group. Thus the general formula of the eudialyte-euolite minerals may be expressed as:



where: X = Na,Ca,K and Y = Fe⁺²,Fe⁺³,Mn,RE,Nb,Ti and Zr.

j) Catapleite

Catapleite occurs less commonly than astrophyllite, euolite and l avenite and is found only in some of the vein rocks, particularly those associated with the main pulaskite. In hand specimen the catapleite is pale brown in colour; in thin section it is colourless. The catapleite is a secondary mineral and occurs as irregular stringers of small crystals in some

Table XXIV. *Catapleite Chemical Analyses*

	1	A	B	C	D
SiO ₂	43.27	44.10	43.14	44.73	44.49
TiO ₂	0.03	0.43	—	0.16	0.06
ZrO ₂	30.62	31.06	29.16	31.24	31.00
Al ₂ O ₃	—	} 0.83	0.79	0.80	0.60
Fe ₂ O ₃	0.69		—	0.48	0.36
RE ₂ O ₃	—	—	—	0.24	0.28
FeO.....	—	—	0.17	—	—
MnO.....	0.05	—	—	—	—
MgO.....	0.03	0.03	—	0.04	—
CaO.....	2.49	3.40	2.26	2.06	13.82
Na ₂ O.....	14.22	10.36	13.59	9.28	0.32
K ₂ O.....	0.38	2.44	0.14	0.80	0.10
H ₂ O ⁺	8.51	7.35	10.75	10.28	9.15
H ₂ O ⁻	0.11	—	—	0.22	0.18
Cl.....	0.22	—	—	—	—
Total.....	100.57	100.00	100.00	100.33	100.36

1. Catapleite, vein in pulaskite, E.G. 2777, southeastern point, Trebj ornebjerget. Anal. W. A. DEER. (total corrected for oxygen equivalent of chlorine).
- A. Light yellow catapleite, pegmatite, Kukisvumchorr, Khibina (FERSMAN and BONSHTEDT, 1937). Anal. E. KOSTYLEVA.
- B. Light bluish catapleite, Norra K arr (ADAMSON, 1944). Anal. A. BYGD EN. (H₂O⁺ by difference).
- C. Pale brown catapleite, pegmatite, Suoluai Valley, Lovozero (VLASOV *et al.*, 1966). Anal. VLADIMIROVA.
- D. Yellowish cream calcium catapleite, pegmatite, Burpala alkaline massif, Northern Baikal (PORTNOV, 1964). Anal. G. P. SINYUGINA.

Table XXV. *Catapleiiite* – Numbers of Ions on the Basis of 11 Oxygens

	1	A	B	C	D
Si	2.928	3.014	2.826	2.924	2.936
Al	—	0.066	0.060	0.061	0.064
Ti	0.002	0.022	—	0.008	0.003
Fe ⁺³	0.036	—	—	0.023	0.018
Zr	1.009	1.033	0.930	0.994	0.996
RE	—	—	—	0.005	0.012
Fe ⁺²	—	—	0.009	—	—
Mg	0.003	0.003	—	0.004	—
Mn	0.003	—	—	—	—
Ca	0.180	0.249	0.159	0.145	0.977
Na	1.866	1.372	1.729	1.184	0.040
K	0.033	0.213	0.012	0.067	0.008
OH	3.842	3.351	4.692	4.484	4.028
Cl	0.025	—	—	—	—

eudialyte-eucolite minerals, which less commonly are completely replaced by catapleiiite. In both cases the catapleiiite occurs as small 0.04–0.1 mm, pseudo-hexagonal plates; the aggregates of small crystals forming the pseudomorphs display no orientation (Plate 5). The refractive indices are α 1.589, $\beta = \gamma$ 1.618 \pm 0.002; the optic axial angle is small, 2–3°, and the extinction angle $\gamma \wedge z = 3^\circ$; twinning has been observed in some crystals.

The chemical analysis of the catapleiiite from a vein in the main pulaskite, together with four analyses from other alkaline complexes, and including the calcium end-member of the sodium-calcium catapleiiite isomorphous series (PORTNOV, 1964), is given in Table XXIV. The number of ions on the basis of 11 oxygens is shown in Table XXV. The composition of the Kangerdlugssuaq catapleiiite does not depart significantly from the ideal formula, $(\text{Na,Ca})_2\text{Zr} [\text{Si}_3\text{O}_9] \cdot 2\text{H}_2\text{O}$, of the sodium-rich catapleiiites. The silicon content is a little less than the ideal value, and in Table XXV the small amounts of Ti and Fe⁺³ present in the analyses have been included with silicon. The zirconium content approaches closely the ideal one atom per formula unit, while the (Na,Ca) group and H₂O are respectively somewhat higher and lower than the composition derived from that formula. Chlorine is not recorded in analyses of catapleiiite, and the small amount shown in the analysis of the Kangerdlugssuaq mineral may be due to contamination of the sample by eucolite. This may also be the cause of the slightly high value of (Na + Ca) shown by this mineral, as the value of this group should decrease as Na is replaced by Ca in accordance with the formula $(\text{Na,Ca})_{2-1}\text{Zr} [\text{Si}_3\text{O}_9] \cdot 2\text{H}_2\text{O}$.

k) Hiortdahlite

Hiortdahlite, composition approximately $(\text{Ca,Na})_{13}\text{Zr}_3\text{Si}_9(\text{O,OH,F})_{38}$, occurs in the foyaite and veins in the foyaite. It forms colourless tabular crystals (Plate 5), has a maximum extinction, α' to the cleavage, of 15° , and a birefringence ~ 0.012 . Patchy extinction, possibly due to irregular zoning, is sometimes present. The optical identification has been confirmed by X-ray powder photograph.

l) Chevkinite

Chevkinite, composition approximately $(\text{Fe}^{+2},\text{Ca})(\text{Ce,La,Y})_2(\text{Si,Ti})_3\text{O}_{10}$, was identified by X-ray powder photograph and has been noted in the quartz-nordmarkites and nordmarkites. It is dark red-brown in thin section, pleochroic to black, and forms prisms with a moderately large extinction angle. It is associated with the katophorite, rather than arfvedsonite, and thus may be a relatively high-temperature mineral.

m) Fluorite and Analcite

Both minerals are common in the foyaite, although fluorite also occurs as an accessory mineral in the other rocks and veins of the intrusion. The fluorite usually forms interstitial patches but large crystals are found in some vein rocks.

The analcite is frequently anisotropic and occurs as large patches in the foyaite. Some analcite is secondary after nepheline but some probably formed as a late-stage, low temperature mineral instead of nepheline.

n) Other Volatile-Rich Minerals

Cancrinite and muscovite occur in the foyaite and are considered to be primary in origin. Cancrinite, gieseckite mica, and calcite are also found in the foyaites as hydrothermal alteration products of nepheline.

Many of the micropertthites show local clouding but there is little development of sericite in the Kangerdlugssuaq rocks, except locally in the foyaite.

VIII. SUMMARY OF THE MINERALOGY

Alkali feldspar is the most abundant mineral of the intrusion and varies in amount from some 90 per cent in the nordmarkite to 60 per cent in the foyaite. Two alkali feldspars are present in the earlier-formed rocks of the two outer rings of nordmarkite and transitional pulaskite. The groundmass feldspar consists of a coarse low-albite-orthoclase or-microcline microperthite, ranging in composition from $\text{Or}_{33}(\text{Ab} + \text{An})_{67}$ to $\text{Or}_{59}(\text{Ab} + \text{An})_{41}$, while the phenocrysts are fine low-albite-orthoclase microperthites with a compositional range between $\text{Or}_{24}(\text{Ab} + \text{An})_{76}$ and $\text{Or}_{32}(\text{Ab} + \text{An})_{68}$. Microperthitic feldspars also occur in the basalt xenoliths, with a compositional range from $\text{Or}_{17}(\text{Ab} + \text{An})_{83}$ to $\text{Or}_{30}(\text{Ab} + \text{An})_{70}$, but although they contain many small inclusions of ferromagnesian minerals, these feldspars have similar optical properties to those of the phenocrysts in the nordmarkites and transitional pulaskite. Both types of phenocryst have a sodium-rich core and zoned margins showing progressive enrichment in potassium, and the main compositional difference between them and the perthites of the groundmass is their smaller content of potassium and higher content of calcium and sodium. The anorthite content, which amounts to nearly 12 per cent in some of the phenocrysts in the basalt xenoliths, is considerably higher than in the normal phenocrysts, where it averages 5.5 per cent. Thus the compositional range of the phenocrysts of the rocks of the two outer zones of the intrusion bridges the gap between the composition of the phenocrysts in the basalt inclusions and the microperthites of the groundmass. The genetic relationship between the two types of phenocryst is also indicated by the similarity of their barium and strontium contents, and by the absence of any systematic differences in their diffractometer traces. The latter show that the feldspars change progressively from relatively high structural state, nearly homogeneous, feldspars in the outer quartz-nordmarkite to a low structural state, completely unmixed feldspar in the transitional pulaskite. The groundmass microperthites include both low-albite-orthoclase and low-albite-microcline feldspars but show no systematic variation in ordering from the outer quartz-nordmarkite inwards to the foyaite, an apparent anomaly that may be related to variations in the cooling history of the main units of the intrusion. Further evidence that the

phenocrysts have unmixed into low-albite and a monoclinic potassium-rich phase (orthoclase), and that the feldspars were originally homogeneous triclinic anorthoclases is obtained from X-ray investigations. Likewise the groundmass microperthites have unmixed from single homogeneous members of the anorthoclase-sanidine series. Thus the presence of perthitic phenocrysts and perthitic groundmass feldspars demonstrates that the feldspars in the Kangerdlugssuaq intrusion crystallized at temperatures above the solvus and that the rocks are hypersolvus syenites.

Chemical analyses of three coarse groundmass microperthites from nordmarkite, pulaskite and foyaite respectively, and three microperthite phenocrysts from modified basalt inclusions in the nordmarkite have been made. In addition the alkalis, and in some cases, lime have been determined on a further four phenocrysts from the modified basalt inclusions, seven phenocrysts from the syenites and a further two groundmass microperthites. The compositions of 74 homogenised feldspars have also been determined by the $\bar{2}01$ X-ray method. The average compositions of the groundmass microperthite for the main units of the intrusion are: nordmarkites, Or_{38.4}; transitional pulaskite, Or_{36.2}; main pulaskite, Or_{40.9} and foyaite, Or_{54.7}.

Plagioclase feldspar is only a minor constituent of the rocks of the intrusion. It is present as small subhedral interstitial grains and as irregular rims around the coarse microperthites of the groundmass. In the nordmarkites and pulaskites the composition of the plagioclase is An₄, but in the foyaite its composition varies between An₄ and An₁₃. The groundmass feldspars, with the exception of those in the foyaite, are antiperthitic and it is considered that the rims of sodic plagioclase are not derived by exsolution from the groundmass perthites as they unmixed, but are the products of primary crystallization, in equilibrium with the microperthites. In view of this and the evidence that the alkali feldspars crystallized originally as a single phase it is reasonable to apply BARTH'S method for estimating crystallization temperatures of feldspars, based on the amount of the sodium component in coexisting alkali and plagioclase feldspar, to the rocks of the Kangerdlugssuaq intrusion, the crystallization temperatures of which are indicated to be: nordmarkites and transitional pulaskite, 970° C; main pulaskite, 880° C; and foyaite, 760° C.

Nepheline first appears in the pulaskite, in which it is usually present only in small amounts, although it is an important constituent of the veins and pegmatites in the transitional and main pulaskites. Nepheline is a major constituent of the foyaite, in which the average content is some 15 per cent. The nepheline is generally euhedral but it occurs in

considerably smaller crystals than the microperthite, within which small euhedral nepheline crystals are sometimes present. Three nephelines, one from the main pulaskite and two from the foyaite, have been analysed chemically, and twelve nepheline compositions have been determined by X-ray powder methods. Their compositions lie outside the MOROZEWICZ-BUERGER convergence field, and post-crystallization changes in composition, due to exchange of potassium and sodium between the nepheline and alkali feldspars, appear to have been small. Crystallization temperatures, deduced from the amount of SiO_2 in solid solution, range from 880°C in the pulaskite to between 780° and 760°C in the foyaite.

Alkali pyroxenes, although they are only sparingly present in the nordmarkites, occur in all the major units of the intrusion, and are the most common ferromagnesian mineral in the veins. In most of the rocks and the veins the pyroxene is an aegirine, $\sim \text{Ac}_{80-90}$, but in the foyaite and its veins and pegmatitic segregations the pyroxene is an aegirine-augite, $\sim \text{Ac}_{30}$ in composition. This change from aegirine to aegirine-augite is related firstly to the increase in the amount of nepheline that crystallized from the foyaitic magma, with the consequent depletion of sodium in the residual liquids, and secondly due to the preferential entry of ferric iron into melanite garnet. On the petrographic evidence an upper temperature limit of about 990°C is indicated for the crystallization of the aegirine in the pulaskite.

In contrast to the alkali pyroxene, alkali amphibole is the main ferromagnesian mineral in the nordmarkites, and is virtually absent in the foyaite. In accord with the general petrological and mineralogical evidence that the intrusion cooled centripetally, the amphibole in the nordmarkites is the higher temperature variety, katophorite, while in the later-formed rocks the amphibole is a magnesioarfvedsonite, and in the veins an arfvedsonite. The amphibole in the pulaskite is partially replaced by pyroxene and biotite. This replacement is in conformity with the experimental data on the riebeckite-arfvedsonite solid solution series which show that these minerals are unstable in the high oxidation environment that obtained during the formation of the foyaite.

Biotite is present in only minor amounts in the nordmarkites; it occurs in greater amounts in the pulaskites, but is present in only very minor amounts in the foyaite where its almost complete absence is probably related to the higher P_{O_2} in the residual foyaitic liquid.

Sodalite is a major constituent in the main pulaskite and foyaite, and in the latter rock it may form as much as 23 per cent of the rock, in which its presence is further evidence of the increased concentration of volatiles in the residual magma from which the final unit of the intrusion crystallized.

Melanite garnet is present only in the foyaite in which it is, after aegirine-augite, the most abundant ferromagnesian mineral, in some parts of the foyaite constituting up to 2.5 per cent of the rock.

Ilmenite is more abundant than magnetite in the nordmarkites and transitional pulaskite, but magnetite is present in much greater amounts relative to ilmenite in the main pulaskite and foyaite. Some hematite is present in all the main units except the foyaite, but is most abundant in the pulaskites. Sphene and apatite are ubiquitous in all the units of the intrusion but zircon and perovskite are restricted to the earlier members.

Of the Zr, Ti, Mn and rare earth-rich minerals, chevkinite occurs in the nordmarkites, l avenite in the nordmarkites and pulaskites, astrophyllite and members of the eudialyte-eucolite series in the pulaskites, and hiortdahlite in the foyaite. With the exception of chevkinite the above minerals are also more common in the vein-rocks. Catapleiite does not occur in the rocks of the main units of the intrusion and is found only in the veins, particularly those associated with the main pulaskite.

Fluorite and analcite, some of the latter secondary after nepheline, are both present in the foyaite, and fluorite occurs as an accessory mineral in the other units of the intrusion and in the veins. Primary cancrinite and muscovite are also present in the foyaite, and cancrinite, giaseckite mica and calcite occur as hydrothermal minerals in the foyaite.

IX. TRACE ELEMENT CHEMISTRY AND THE DISTRIBUTION OF ELEMENTS IN COEXISTING MINERALS

The major and trace element compositions of some of the analysed rocks are given in Table XXVI; trace element compositions of the minerals have already been presented in the appropriate sections (Tables IV, VII, XI, XIV and XVI). In this section, an attempt is made to discuss briefly the relationship between the trace element concentration within each mineral group, to tabulate and comment on some critical element ratios, and to give some data on the distribution of elements in coexisting minerals.

a) Gallium (Ga^{+3} 0.62 Å)

Gallium, proxying for aluminium, is present in the Kangerdlugssuaq rocks in quantities ranging from 20 to 40 p.p.m., in agreement with the average value for syenites of 30 p.p.m., given by TUREKIAN and WEDEPOHL (1961). VLASOV *et al.* (1966) quote a mean value of 74 p.p.m. for the Lovozero massif. Gallium occurs in an average concentration of rather less than 20 p.p.m. in the pyroxenes and amphiboles, and rather more in the feldspars, nephelines and, especially, biotites. There is little variation within each group but the highest values occur in the pulaskite minerals.

b) Lithium (Li^{+1} 0.68 Å)

Lithium substitutes for magnesium in most of the ferromagnesian minerals and reaches concentrations of 300 to 400 p.p.m. in the vein arfvedsonites. In the other amphiboles, the biotites and pyroxenes, there is a smaller concentration of Li, and values as low as 20 p.p.m. are recorded in the pyroxenes.

The nephelines contain from 2 to 13 p.p.m. and the feldspars about 1 p.p.m. although in one of the basalt phenocrysts, the concentration of Li is 50 p.p.m.; this high value, however, is probably due to the mafic inclusions, a factor that is probably also responsible for the high concentrations of other trace elements in the feldspar phenocrysts. These

Table XXVI. *Analyses of*

	1	2	3	4	5	6	7	8
Distance from centre ...	.996	.996	.992	.677	.670	.616	.519	.485
SiO ₂	67.98	66.14	64.96	64.81	66.78	64.62	61.32	63.04
TiO ₂	0.55	0.61	0.94	0.80	0.66	0.65	0.42	0.90
Al ₂ O ₃	15.87	16.49	16.75	17.02	16.19	17.91	21.20	17.92
Fe ₂ O ₃	1.06	1.85	0.96	1.36	1.48	1.54	1.32	2.11
FeO	2.29	1.81	2.16	2.05	1.84	1.12	1.38	1.23
MnO	0.07	0.19	0.16	0.09	0.11	0.10	0.07	0.11
MgO	0.36	0.48	0.66	0.79	0.50	0.45	0.33	0.73
CaO	0.35	0.62	0.81	1.28	0.89	0.90	1.86	0.93
Na ₂ O	6.02	6.11	6.87	6.06	6.07	7.16	7.58	7.62
K ₂ O	4.98	5.32	5.18	4.79	5.11	5.60	4.52	5.15
H ₂ O ⁺	0.16	0.15	0.43	0.11	0.15	0.19	0.10	0.21
H ₂ O ⁻	0.11	0.12	0.04	0.09	0.08	0.01	0.12	0.02
P ₂ O ₅	0.17	0.18	0.19	0.24	0.16	0.09	0.36	0.27
Total	99.97	100.07	100.11	99.49	100.02	100.34	100.58	100.24
<i>Trace elements</i>								
Ga ³⁺	25			20		40		40
Li ¹⁺	25			60		3		15
Ni ²⁺	2			12		—		—
Co ²⁺	—			—		2		2
Cu ²⁺	< 10			< 10		20		< 10
V ³⁺	—			20		20		20
Zr ⁴⁺	1000			1000		200		200
Y ³⁺	100			200		50		100
Sr ²⁺	50			500		20		300
La ³⁺	600			300		100		100
Ba ²⁺	1500			400		500		3000
Rb ¹⁺	300			300		70		100

1. Quartz-nordmarkite, E.G. 2784. Small nunatak southwest of Hovedvejsnuntakker.
2. Quartz-nordmarkite, E.G. 1399. Coast northwest of snout of Kælvegletscheren.
3. Quartz-nordmarkite, E.G. 1397. Immediately northwest of E.G. 1399.
4. Nordmarkite, E.G. 2084. Small nunatak southwest of Trebjørneberget.
5. Nordmarkite, E.G. 2779. Fangetårnet.
6. Nordmarkite, E.G. 2690. Nunatak north of Nordre Syenitgletscher.
7. Transitional pulaskite, E.G. 2344. Amdrup Fjord.
8. Transitional pulaskite, E.G. 2696. Nunatak north of Nordre Syenitgletscher.
9. Pulaskite, E.G. 1300. Western nunatak, Nordre Syenitgletscher (WAGER, 1934). (Includes CO₂, 0.07; ZrO₂, 0.02; Cl, 0.04; SO₃, 0.09)
10. Pulaskite, E.G. 2986. West end of mountains, south of Nordre Syenitgletscher.

Kangerdlugssuaq Rocks

9	10	11	12	13	14	A	15	16
.393	.370	.231	.187	.179	.139	—	—	—
61.70	61.22	58.97	54.48	53.21	55.21	65.40	62.47	58.12
0.80	1.18	0.71	0.38	0.29	0.52	0.71	0.86	1.33
18.35	18.83	21.21	24.06	24.78	23.08	16.99	17.75	18.20
1.63	1.24	1.64	1.38	1.73	1.89	1.40	1.83	2.67
1.62	1.56	1.14	0.82	0.73	0.87	1.83	2.25	3.46
0.32	0.13	0.13	0.08	0.07	0.11	0.12	0.09	0.14
0.61	0.63	0.55	0.26	0.21	0.30	0.54	0.97	1.89
0.95	1.53	1.35	1.59	1.69	1.88	0.86	1.61	2.84
7.50	7.32	6.63	9.95	10.84	8.97	6.48	7.11	7.24
5.53	5.92	6.48	6.68	5.59	6.64	5.20	4.57	3.56
0.73	0.33	0.46	0.47	0.75	0.55	0.22	0.12	0.32
0.04	0.18	0.35	0.14	0.15	0.14	0.08	0.11	0.08
0.08	0.11	0.18	0.19	0.12	0.24	0.17	0.33	0.58
100.08	100.18	99.80	100.48	100.16	100.40	100.00	100.07	100.43

(p.p.m.)

35	20	29	25	40
15	5	28	40	100
3	3	5	10	8
—	—	1	—	3
20	< 10	10	< 10	10
30	70	~ 20	15	50
300	500	687	1000	1000
80	100	117	150	200
200	200	194	1000	2000
100	200	309	200	250
200	25	841	1000	2000
200	150	214	200	100

11. Pulaskite, E.G. 2939. Small nunatak, north of the head of Søndre Syenitgletscher.

12. Foyaite, E.G. 2108. West end Citadellet.

13. Foyaite, E.G. 2760. Nunataks at the head of Søndre Syenitgletscher.

14. Foyaite, E.G. 2866. Nunataks at the head of Søndre Syenitgletscher.

A. Average for the main rocks (calculated on the basis of the relative proportions of the main units of the intrusion).

15. Inclusion with porphyritic feldspars, E.G. 2089. Nunatak northwest of Stakken.

16. Inclusion with porphyritic feldspars, E.G. 2085. Small nunatak southwest of Trebjørnebjæget.

After Tables III, IV, VI, IX, X, and XI (KEMPE *et al.*, 1970).

average concentrations are close to those determined by HEIER (1966) for felsic minerals in the Stjernøy (North Norway) nepheline syenites and related rocks. HEIER, and VLASOV *et al.* (1966), reviewing the role of Li in salic minerals, conclude that it will replace Al and, probably, Na. In biotite, it is considered to substitute for Al rather than Mg. Apart from a possible decrease in the foyaites, the Li contents show little systematic variation in the major rock units. The average value of 28 p.p.m. is similar to that given by TUREKIAN and WEDEPOHL (1961) for syenites. The mean content in the Lovozero massif is stated as 37 p.p.m., by GERASIMOVSKII and LEBEDEV (1959), and as 200 p.p.m. by VLASOV *et al.* (1966).

c) Niobium (Nb^{+5} 0.69 Å)

Niobium, in quantities varying from 50 to 100 p.p.m., was found in some alkali pyroxenes and amphiboles. In the pyroxenes it is probably substituting for zirconium, whilst in the amphiboles the association is more likely to be with titanium. The rock content of Nb has not been investigated but may be below the syenite average of 35 p.p.m. (TUREKIAN and WEDEPOHL, 1961), and considerably below the mean value for the Lovozero massif of 700 p.p.m. (VLASOV *et al.*, 1966).

d) Nickel (Ni^{+2} 0.69 Å), Copper (Cu^{+2} 0.72 Å) and Cobalt (Co^{+2} 0.72 Å)

These three elements are present in only small amounts and are of little importance in the Kangerdlugssuaq intrusion. Most of the rocks and ferromagnesian minerals contain nickel in concentrations of 10 p.p.m. or less, although three of the pyroxenes have higher quantities. Copper follows a similar pattern, but was also detected in the nephelines and one of the groundmass feldspars; cobalt was only detected in two rocks, a vein amphibole and in the biotites.

e) Vanadium (V^{+3} 0.74 Å)

Vanadium, substituting for Fe^{+3} , reaches minor element status in the pyroxenes and is present in all the analysed minerals. In the pyroxenes and amphiboles, the vanadium concentration follows Fe^{+3} , except in two of the early veins in which its concentration is low. Relative to Fe^{+3} , however, there is an almost linear enrichment in the vanadium content of the pyroxenes and amphiboles (and also in the biotites), from nordmarkites to foyaite.

The rocks show a typical concentration (20 to 30 p.p.m.) for syenites, and show a final enrichment, amounting to 70 p.p.m., in the foyaite, in which some of the vanadium is probably present in the magnetite. The

mean vanadium content of the Lovozero massif is 30 p.p.m. (VLASOV *et al.*, 1966), the same average value as TUREKIAN and WEDEPOHL (1961) gave for syenites.

f) Zirconium (Zr^{+4} 0.79 Å)

In common with other syenites, the Kangerdlugssuaq rocks and minerals are very rich in zirconium. In all the ferromagnesian minerals, and especially the pyroxenes, Zr reaches minor element proportions and is present in unusually large amounts in the feldspars and nephelines. Zirconium generally substitutes for titanium, but when present in high concentrations in the ferromagnesian minerals, it may follow Fe^{+2} , and occasionally, as suggested by VLASOV *et al.* (1966), may replace niobium and the rare earths.

The concentrations of Zr in the rocks range from 200 to 1000 p.p.m. and the mean value of 687 p.p.m. is close to TUREKIAN and WEDEPOHL's (1961) average of 500 p.p.m. for syenites, but is much higher than the value (average 26 p.p.m.) given by HEIER (1964) for the Stjernøy nepheline syenite. HEIER and TAYLOR (1964), commenting on the low values of Zr and other elements in the Stjernøy rocks, concluded that these syenites may have a different petrogenetic origin from those, such as the Oslo syenites, in which higher concentrations are present. In contrast the mean content for the Lovozero massif is 5500 p.p.m. (VLASOV *et al.*, 1966).

The Zr/Hf ratios for some Kangerdlugssuaq minerals have been determined by Dr. C. K. BROOKS (personal communication). The early pyroxenes have an average ratio of 32, which rises to 41 in the aegirine-augite of the foyaite, consistent with the general tendency for the Zr/Hf ratio to increase with increasing alkalinity. No regular pattern is seen in the amphibole ratios (average 39) but the two analysed biotite ratios rise from 91 to 128. In the melanite, astrophyllite and eudialyte, the ratios are 47, 66 and 128 respectively. KOSTERIN, ZUEV and SHEVALEE-VASKII (1958) give an average ratio of 45 for zircons from syenites, and in the Lovozero massif the ratios in various minerals vary from 37 to 78.

g) Scandium (Sc^{+3} 0.81 Å)

Scandium occurs in the amphiboles and in the pyroxenes, except that it is not present in the foyaite aegirine-augite. Similar amounts, within the range 85 to 4 p.p.m., occur in both mineral groups. The concentration decreases in the minerals of the later-formed units, and the vein minerals follow a parallel trend but at lower concentrations. Scandium was not detected in the Kangerdlugssuaq rocks, but as the sensitivity of the method used in the analysis of the rocks is 10 p.p.m. this is not surprising in view of the average value for syenites of 3 p.p.m. given by TUREKIAN and WEDEPOHL (1961).

h) Yterbium (Yb^{+3} 0.86 Å) and Yttrium (Y^{+3} 0.92 Å)

These elements are present in the ferromagnesian minerals, in which they substitute for calcium; yterbium was found in all the specimens in fairly constant amounts, whilst yttrium is only present in some of the minerals. In the rocks, yttrium averages 117 p.p.m., half the concentration of the Lovozero massif (VLASOV *et al.*, 1966), but is some six times the average for syenites (TUREKIAN and WEDEPOHL, 1961). Yterbium was not determined.

i) Strontium (Sr^{+2} 1.12 Å)

Strontium, substituting for calcium and possibly potassium, is present in the rocks in amounts varying from 20 to 500 p.p.m. (mean value 194, compared with TUREKIAN and WEDEPOHL's average for syenites of 200 p.p.m.), but displays no regular pattern. Strontium occurs in all the analysed minerals, and in the pyroxenes shows a progressive decrease from 250 p.p.m. in the transitional pulaskite to some 70 p.p.m. in the foyaite, while the pyroxenes of the early veins have much lower contents of between 8 and 13 p.p.m. In the amphiboles there is no regular variation, but in the two biotites there is a marked decrease from the transitional to the main pulaskite.

The nephelines show a variable content of Sr but in the groundmass feldspars there is progressive enrichment towards the foyaite, whilst the phenocrysts have high concentrations. A similar pattern is found in the feldspars of the Tugtutôq nordmarkite (UPTON, 1964).

The average Sr content for the Stjernøy rocks is 3500 p.p.m. (HEIER, 1964), a value consequent on the high Sr content in both the nephelines and feldspars. In this complex the Sr contents of the feldspars are greater than those of the nephelines by a factor of ten, and a similar relationship is shown by the coexisting pair ratio, 200:30, in the foyaite of the Kangerdlugssuaq intrusion. HEIER and TAYLOR (1964) comment on the enrichment in Sr and Ba in the Stjernøy rocks, compared with their low Zr content. VLASOV *et al.* (1966) give a mean value for the Lovozero massif of 900 p.p.m. of Sr.

j) Lanthanum (La^{+3} 1.14 Å)

The syenites and nearly all the ferromagnesian minerals are rich in lanthanum, commonly reaching concentrations of up to 300 p.p.m. and even 600 p.p.m. in a quartz-nordmarkite. This is greatly in excess of the average content of 155 for the Lovozero massif (VLASOV *et al.*, 1966), and the syenite average of 70 p.p.m. (TUREKIAN and WEDEPOHL, 1961). Lanthanum follows calcium but in the Kangerdlugssuaq minerals shows no obvious pattern.

k) Barium (Ba^{+2} 1.34 Å)

The concentration of barium varies in the Kangerdlugssuaq rocks from 25 to 3000 p.p.m., but, except for the final depletion of Ba in the foyaite, there is no regular trend. The highest value occurs in the transitional pulaskite and similar high concentrations of Ba occur in the amphibole, biotite and feldspar phenocrysts, in this rock type.

Comparison with the Stjernøy rocks (Ba average 2400 p.p.m.) and minerals shows some similarity with the behaviour of Sr. Apart from overall enrichment, not shown by the Kangerdlugssuaq rocks, the feldspar:nepheline Ba ratio is greater than for Sr (e.g. 4400:55 and 4300:140) while in the foyaite of the Kangerdlugssuaq intrusion the feldspar:nepheline ratio is 212:63. This difference in the two ratios is due to the high content of barium in the Stjernøy feldspars, with their more potassic composition, compared with those of the foyaite of the Kangerdlugssuaq intrusion. TUREKIAN and WEDEPOHL give the average syenite value as 1600 p.p.m. while the mean value for the Lovozero massif is 1100 p.p.m. (VLASOV *et al.*, 1966).

l) Rubidium (Rb^{+1} 1.47 Å)

Rubidium is present in the Kangerdlugssuaq syenites in concentrations ranging from 70 to 300 p.p.m. (mean value, 214 p.p.m.). TUREKIAN and WEDEPOHL's (1961) average syenite value is 110 p.p.m., the average for the Stjernøy rocks 115 p.p.m., and the average for the Lovozero massif 10–50 p.p.m. (VLASOV *et al.*, 1966).

The Rb values in the pyroxenes of the main units of the intrusion are very low, and small but somewhat higher values are shown by the vein pyroxenes. The Rb content of the amphiboles is considerably higher but, as expected, the highest concentrations, 268–925 p.p.m., are found in the biotites. Both the nepheline and feldspar contain relatively large amounts of Rb, and in the feldspars the concentration increases in the later rock units. Both minerals contain about twice the amount of Rb as the Stjernøy feldspar and nepheline, but the Kangerdlugssuaq feldspars have a similar content to those of the Tugtutôq intrusion (UPTON, 1964). The Stjernøy feldspar:nepheline ratio of approximately 2:1 p.p.m. compares closely with that of the minerals in the foyaite of the Kangerdlugssuaq intrusion.

m) Cesium (Cs^{+1} 1.67 Å)

This element has only been detected in the biotites (ca. 2.5 p.p.m.). It was not found in the feldspars and nephelines, although it is present (0.5 p.p.m.) in one Stjernøy nepheline (HEIER, 1966). TUREKIAN and WEDEPOHL (1961) give an average syenite figure for Cs of 0.6 p.p.m.,

and although VLASOV *et al.* (1966) do not regard it as a typical element of the Lovozero massif, GERASIMOVSKII and LEBEDEV (1960) give a mean value of 1.5 p.p.m.

n) Element Ratios

Five element ratios have been evaluated for the rocks and minerals (Tables XXVII and XXVIII) and the variation in K/Rb and Ba/Sr ratios of the minerals, in relation to their position, in the intrusion, are shown in Figs. 21 and 22. In the Kangerdlugssuaq syenites the K/Rb ratio varies from 114 to 572, compared with the range of 98 to 648 in the rocks of the Lovozero massif (GERASIMOVSKII and LEBEDEV, 1959). The highest ratio occurs in the syenites close to the inner margin of the nordmarkite, and a similar maximum (Fig. 21) is shown by both the pyroxenes and amphiboles of the transitional pulaskite. In both these mineral groups the lowest ratio occurs in the foyaite and a similar minimum is shown by the feldspars and nephelines.

Table XXVII. *Element Ratios in some Analysed Rocks*

	Distance from centre	K/Rb	K/Ba	Rb/Sr	Ca/Sr	Ba/Sr
Quartz-nordmarkite (2784) .	.996	119	24	6.0	58	30.0
Nordmarkite (2084) . . . . .	.677	114	86	0.6	21	0.8
Nordmarkite (2690) . . . . .	.616	572	80	3.5	457	25.0
Transitional Pulaskite (2696)	.485	368	12	0.3	28	10.0
Pulaskite (2986) . . . . .	.370	212	212	1.0	64	1.0
Foyaite (2760) . . . . .	.179	266	1598	0.8	73	0.1

The nepheline K/Rb ratios are generally lower than those of the feldspars, as is also the case for the Stjernøy minerals (HEIER, 1966). The K/Rb ratios in the Stjernøy nephelines and feldspars are, however, approximately twice as large as those from the Kangerdlugssuaq intrusion.

The K/Ba ratios in the rocks increase generally throughout the sequence and show a marked increase in the foyaite, a trend that is followed by the feldspars and nephelines. In the transitional pulaskite the K/Ba ratio is low and is probably significant as similar low ratios are shown by both the amphibole and biotite. Because the Stjernøy feldspars have a high barium content, their K/Ba ratios are very much lower than those of the Kangerdlugssuaq feldspars; similar ratios are, however, shown by the nephelines of both intrusions.

The Rb/Sr ratios of the Kangerdlugssuaq syenites show no consistent pattern, although both the feldspar and nepheline ratios decrease to a

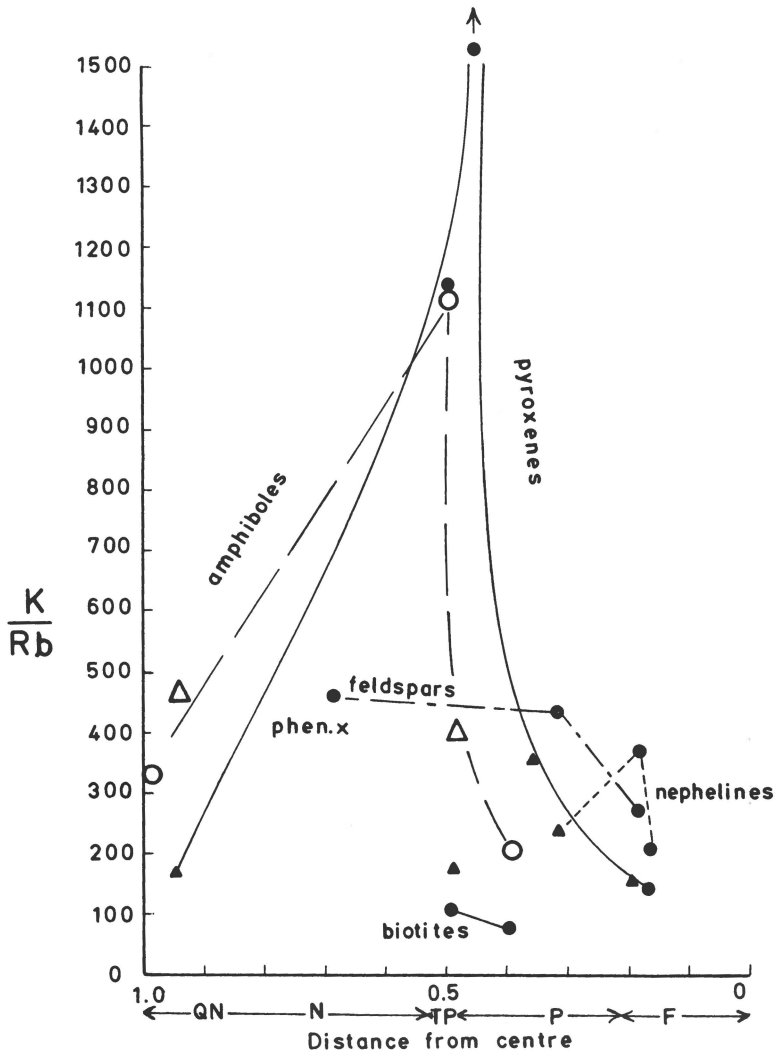


Fig. 21. The K/Rb ratios in minerals plotted against the distance from the centre. Circles: main rocks. Triangles: veins. Open symbols: amphiboles. Solid symbols: other minerals. x: feldspar phenocryst.

minimum in the foyaite; as would be expected, however, they are much higher than those for the strontium-rich minerals of the Stjernøy intrusion.

The Ca/Sr ratios in the syenites do not show a regular pattern, but the feldspar and nepheline ratios converge to a minimum in the foyaite, while those of the ferromagnesian minerals reach a minimum in the transitional pulaskite.

Table XXVIII. *Element Ratios in Analysed Minerals*

		Num- ber in tables	Di- stance from centre	K/Rb	K/Ba	Rb/Sr	Ca/Sr	Ba/Sr
Feldspar (phenocryst)	Nordmarkite (4656)	1	.677	401	9	0.04	14	1.7
Feldspar (phenocryst)	Transitional pulaskite (4662)	—	.485	—	13	—	21	4.5
Feldspar	Nordmarkite (4564)	4	.681	463	168	5.2	310	14.3
Feldspar	Pulaskite (4624)	5	.311	435	256	3.6	185	6.2
Feldspar	Foyaite (4781)	6	.185	266	316	1.3	22	1.1
Nepheline	Vein in pulaskite (4678)	1	.317	232	362	7.3	95	4.7
Nepheline	Foyaite (4781)	2	.185	373	598	3.4	89	2.1
Nepheline	Foyaite (4755)	3	.172	208	670	1.3	31	0.4
Aegirine	Vein in quartz-nordmarkite (2046)	1	.947	169	11	0.73	3564	10.9
Aegirine	Transitional pulaskite (4789)	2	.494	1140	13	0.004	175	0.4
Aegirine	Vein in transitional pulaskite (4666)	3	.483	170	22	0.7	938	5.3
Aegirine	Pulaskite (4786)	4	.450	2430	24	0.008	252	0.8
Aegirine	Vein in pulaskite (4616)	5	.359	355	12	0.15	3288	4.7
Aegirine-augite	Vein in foyaite (4692)	6	.198	152	18	0.11	2073	1.0
Aegirine-augite	Foyaite (4755)	7	.172	143	17	0.1	1991	0.8
Katophorite	Quartz-nordmarkite (1397)	1	.996	327	59	1.13	2104	6.2
Arfvedsonite	Vein in quartz-nordmarkite (2046)	2	.947	471	140	1.92	830	6.5
Mag.arfvedsonite	Transitional pulaskite (4789)	3	.494	1110	25	0.03	102	1.5
Arfvedsonite	Vein in transitional pulaskite (4666)	4	.483	403	89	0.71	170	3.2
Mag.arfvedsonite	Pulaskite (4582)	5	.391	202	143	2.86	1422	4.0
Biotite	Transitional pulaskite (4789)	1	.494	103	43	13	26	32
Biotite	Pulaskite (4582)	2	.391	72	367	206	240	40

Finally, the Ba/Sr ratios, with one exception, decrease through the rock sequence. This is well illustrated by the convergence of the feldspars, nephelines and vein pyroxenes (Fig. 22) to a minimum in the foyaite.

The above trends may be summarised as follows. In the foyaite enrichment of Rb relative to K, and Sr relative to Ba, is demonstrated by most of the mineral groups, while the feldspars and nephelines show enrichment of K relative to Ba, and Sr relative to both Rb and Ca. In the transitional pulaskite, most of the mineral groups show a decrease in Rb relative to K, while the ferromagnesian minerals, in contrast to the silic constituents, show an enrichment of Sr in relation to Ca.

The significance of these trends is not entirely clear but the convergences which culminate in the foyaite indicate that chemical equilibrium was established, while the changes which occur in the transitional pulaskite may represent the stage at which a major change in the mag-

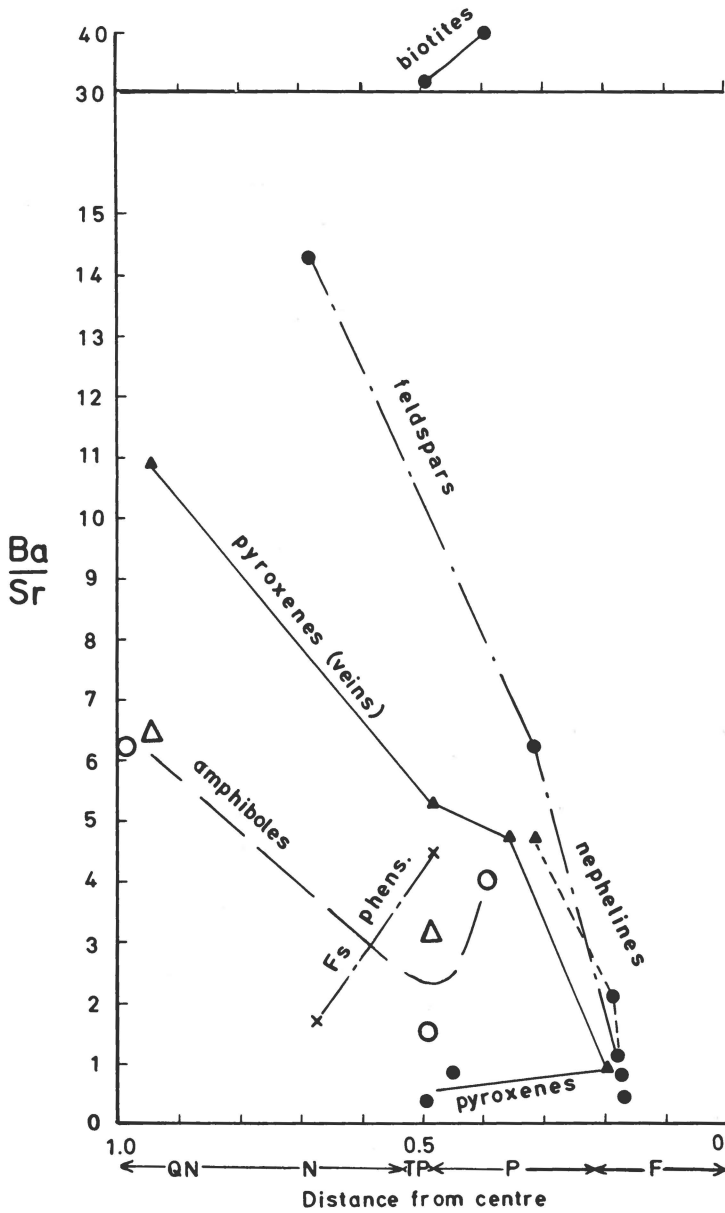


Fig. 22. The Ba/Sr ratios in minerals, plotted against the distance from the centre. Circles: main rocks. Triangles: veins. Open symbols: amphiboles. Solid symbols: other minerals. x: feldspar phenocrysts.

matic fractionation occurred, and at which the nature of the intrusion changed from a porphyritic nordmarkite to a layered series of undersaturated rocks.

o) Element Distribution in Coexisting Minerals

The concentrations of major, minor and trace elements have been calculated for the following coexisting mineral pairs: four pyroxenes and amphiboles, two pyroxenes and biotites, two amphiboles and biotites, and two feldspars and nephelines. In the case of the pulaskites the term "coexisting" has been extended to include minerals from different specimens of the same rock: this procedure is not ideal but was necessary due to the difficulty of separating sufficient quantities of two or three minerals from the limited amount of material available.

In rocks crystallizing in equilibrium under constant external PT conditions, the distribution of elements between the coexisting minerals is related by the distribution coefficient (K_D):

$$K_D = \frac{X_M^a (1 - X_N^a)}{X_N^a (1 - X_M^a)}$$

where X_M^a and X_N^a are the concentrations of element a in the mineral phases M and N (KRETZ, 1961). The concentrations of an element in two minerals may vary, and the relative concentrations can be influenced by the presence of a third phase containing the same element, and by the nature of other elements in similar structural sites; if, however, equilibrium is maintained and external conditions remain unaltered, the regularity of the distribution of the element within the two minerals, as measured by constant K_D , will be maintained.

KRETZ and others have generally confined their studies of element distribution to coexisting mineral pairs in metamorphic rocks. In these investigations either constant PT conditions are assumed, and the data used to test the degree of equilibrium attained, or if equilibrium can be demonstrated from textural evidence, regular distribution curves may provide evidence of variations in temperature, since pressure variations have little effect on the distribution coefficients (see BARTHOLOMÉ, 1962; HOUNSLOW and MOORE, 1967). BARTHOLOMÉ (1962) applied the principle to igneous rocks and in the present investigation a regular distribution is considered to indicate relatively constant temperature and pressure. Some evidence of disequilibrium is afforded by the alteration of amphibole to pyroxene and biotite, and of ilmenite to sphene, and may result from increasing vapour pressure. Moreover, a progressive decrease in temperature throughout the sequence from quartz-nordmarkite to foyaite must be assumed.

The distribution of major and minor elements in coexisting pyroxenes and amphiboles is shown in Fig. 23. The concentration (X) is calculated as the proportion of the elements present in the total number of appropriate atomic sites available, the maximum in X or Y being

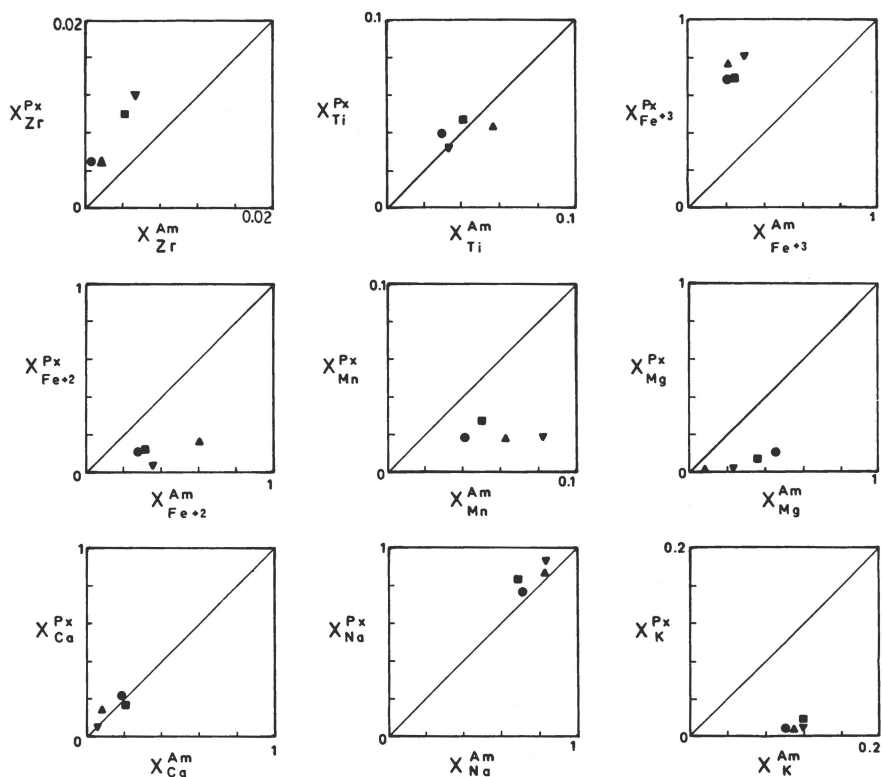


Fig. 23. Distribution of major and minor elements in coexisting pyroxenes and amphiboles. Diagonal line: $K_D = 1$. Upper left, $K_D > 1$. Lower right, $K_D < 1$. Circles: TP; Squares: P; Triangles: V in QN; Inverted triangles: V in TP.

taken as unity. In the diagrams the diagonal lines represent $K_D = 1$; to the upper left of the line, K_D is greater and to the lower right, less than unity.

The distribution of Zr is rather irregular, the main rocks and veins being intermixed. Ti shows regular behaviour in the minerals of the rocks but not in the veins in which there is an enrichment bias towards the amphiboles. K_D values for Fe^{+3} are similar for both pairs, but Fe^{+2} shows nearly regular behaviour in the rocks but not in the vein minerals in which there is a bias towards the amphiboles. Manganese shows a similar pattern to Fe^{+2} .

Both pairs show nearly constant distribution in the Mg plot, but the vein minerals are again biased in favour of the amphiboles. For Ca, the four pairs are in near-equilibrium in terms of constant K_D , but the main rock minerals are enriched relative to the veins. Na is enriched in the veins but all four pairs have similar K_D values, while potassium shows the closest value for all four.

This evidence suggests that the transitional and main pulaskites show equilibrium distribution, whilst the veins, as might be expected, show irregular behaviour with a bias to the amphiboles in Ti, Fe⁺², Mn and Mg, and the pyroxenes in Fe⁺³. In terms of overall concentration, only Mg and Ca show clear enrichment in the main rocks, and of Na in the veins.

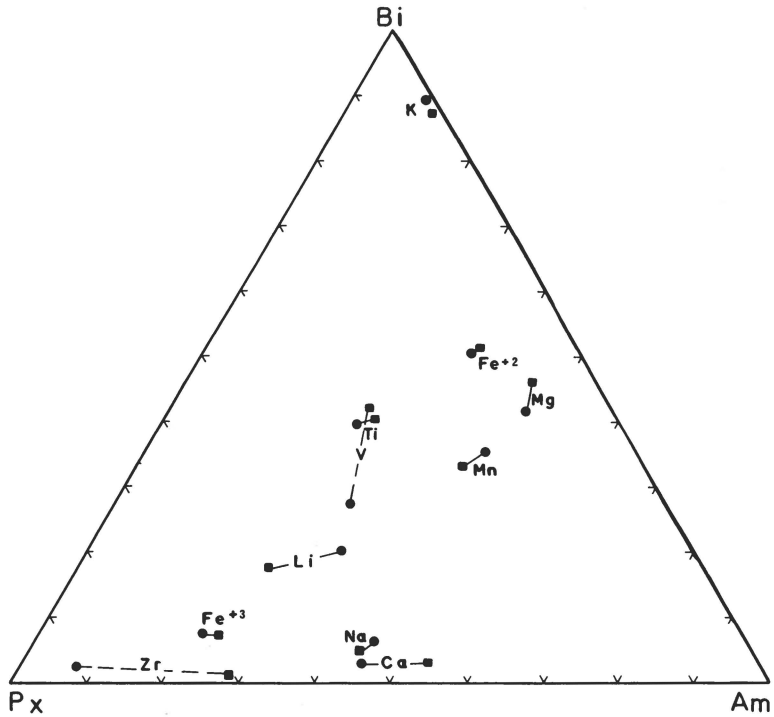


Fig. 24. Distribution of major and minor elements in coexisting pyroxenes, amphiboles and biotites. Circles: TP; Squares: P.

In coexisting pyroxenes further evidence of equilibrium conditions is afforded by the distribution relationship in coexisting pairs of Fe⁺² and Mg (atomic per cent), expressed as the Fe⁺²/Mg ratio (see BINNS, 1962). It was found that a near-linear relationship exists between the (Fe⁺³ + Fe⁺²)/Mg ratios for three of the coexisting pairs of alkali pyroxenes and amphiboles, but that the vein in the transitional pulaskite (4666-V) exhibits independent behaviour. Understandably, a less regular distribution relationship is observed for the Fe⁺²/Mg ratios.

In the pyroxene and biotite coexisting in the transitional and main pulaskites, regular distribution of all elements except Ti, Mn and Na is apparent; of these three, Ti in the transitional pulaskite shows a bias in favour of the pyroxene, as do Mn and Na in the main pulaskite. In

coexisting amphibole and biotite in the two pulaskites, regular behaviour is exhibited by all elements except Mn, which shows a slight bias in favour of the amphibole in the main pulaskite. Overall enrichment in the transitional pulaskite is shown by Mg, and in the main pulaskite by Ti, Fe⁺² and Mn.

These data suggest that equilibrium and constant external conditions were maintained in the two pulaskites; but the change in the mineralogy of the foyaite, where marked differences might have been expected, make impossible any comparison between this rock and the pulaskites.

The distribution of some of the trace elements, Yb, V, Sr, Ba, Ga, Rb, Li, Sc and La, was studied, their concentrations expressed as their proportions relative to their 'host' elements, and it was found that in the coexisting pyroxenes and amphiboles there is less regular behaviour than in the major and minor elements. In no case do the veins show similar behaviour to the main rock minerals. Nevertheless, with the exception of Sr and Ba in the main rocks, and Yb, Ba and La in the veins, the pairs of vein and main rock minerals show similar K_D values. Ga and Li show enrichment in the vein minerals relative to the main rock minerals, and Rb and La in the veins show a bias in favour of the pyroxenes. The most irregular behaviour is shown by Yb in the veins and Sr in the main rocks, where the latter shows marked depletion in the amphibole in the main pulaskite. Trace element distribution between pyroxene and biotite in the pulaskites is fairly regular for the same elements except La and especially, V, although there are several cases of unequal concentrations. A similar pattern is seen in the trace-element distribution of the amphibole and biotite in the pulaskites; here, irregular distribution is shown especially by V and Ba, only Yb and Sr having very close values. Major, minor and three trace elements are plotted on a triangular diagram (Fig. 24) showing the distribution between the three coexisting ferromagnesian minerals in the pulaskites. Although less regular behaviour is shown by Ca, Zr, V and Li, the close proximity of the points for Ti, Fe⁺³, Fe⁺², Mn, Mg, Na and K is strong confirmatory evidence that the pulaskites crystallized in equilibrium under constant external conditions.

X. APPENDIX

Chemical Analysis

Four minerals were analysed on a macro scale (1 g samples), the remainder on a semi-micro scale (0.1 g samples). SiO₂, MgO and CaO were determined by the classical, gravimetric methods; Al₂O₃, TiO₂, (total) Fe₂O₃ and MnO by the rapid, colorimetric methods (in duplicate) of RILEY (1958). R₂O₃ was weighed and used as a check on the total colorimetric values, all the MnO being precipitated by the addition of ammonium persulphate. For the feldspars and nephelines, Al₂O₃ was determined gravimetrically as well as colorimetrically. In the pyroxenes and amphiboles, the alumina value was corrected for zirconia, determined colorimetrically; in practice, it was found that the alumina value needed to be reduced by (wt. % ZrO₂ × 0.26). FeO (in duplicate) was determined by the method of WILSON (1955), and Na₂O and K₂O (in duplicate) by flame photometer. Total H₂O was usually determined by ignition in an open boat, recorded as total loss on ignition; H₂O⁻ was measured by weight loss in a furnace at 110° C. P₂O₅ was not determined and F, in amphiboles and biotites, was not measured as it was not considered that the information derived would justify the extra time involved.

For the partial analyses of feldspars, the alkalis were determined by flame photometer and the lime by titration with E.D.T.A., using calcein (versene) as indicator.

Spectrographic Analysis

The trace elements and some minor elements were determined by emission spectroscopy, using a HILGER and WATTS large quartz-glass spectrograph, with anode excitation. A palladium internal standard was used for the blue (Pd: 3958 Å) and ultra-violet (Pd: 3258 Å) ranges, and variable internal standards (K, Na) for the alkalis. The techniques used are standard in the spectrographic laboratory in the Department of Geology and Mineralogy, Oxford. G-1, W-1, and the Canadian Standard Syenite rock - 1 were used as standards and the following lines were measured (in Å):

Blue	Ultraviolet	Alkalis
Ti 3990	Mn 2801	Li 6707 (K 6939 and Na 5688)
Mn 4035	Mg 2802	Rb 7800 (Na 5688)
Sc 4246	Ga 2944	Cs 8521 (K 6939)
La 4333	Nb 3094	
V 4379	Cu 3274	
Ca 4425	Yb 3289	
Sr 4607	Y 3327	
Ba 4934	Ni 3414	
	Zr 3438	
	Co 3453	

X-ray Diffractometry

X-ray powder work was carried out on a Philips PW 1051 X-ray diffractometer, with a PW 1010 generator.

For feldspars, nephelines and melanite garnet, Ni-filtered $\text{Cu}K\alpha$ radiation (36 kV, 20 mA) was used, with slits 1° - 0.1 - 1° and a chart speed of 800 mm/hr. Goniometer scanning speeds and rate meter settings were as follows:

Feldspar lattice parameter measurements:	$1/2^\circ/\text{min.}$, 2.8.1.
Other feldspar, and nepheline work:	$1/4^\circ/\text{min.}$, 8.8.1.
Melanite garnet:	$1/2^\circ/\text{min.}$, 4.8.0.6.

The single-crystal work was carried out on a Philips PW 1008 generator, using Ni-filtered $\text{Cu}K\alpha$ radiation (36kV, 20 mA).

The pyroxene lattice parameters were determined using Mn-filtered $\text{Fe}K\alpha$ radiation (30kV, 10 mA), with slits 4° - 0.2 - 4° ; silicon was used as an internal standard.

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PLATES

Plate 1

- Fig. 1. Photomicrograph of main pulaskite, showing tabular feldspars with multiple Carlsbad twinning. $\times 14$. Crossed nicols.
- Fig. 2. Photomicrograph showing Manebach-twinned alkali feldspar with herringbone structure, rimmed with sodic plagioclase, in quartz-nordmarkite. $\times 14$ Crossed nicols.

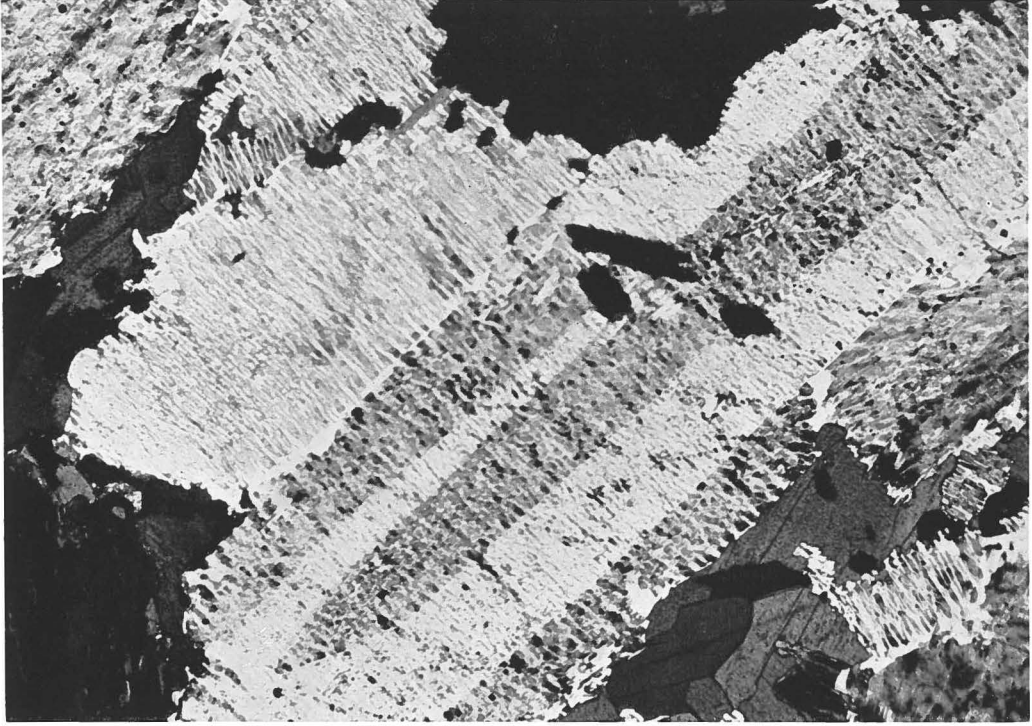


Fig. 1.

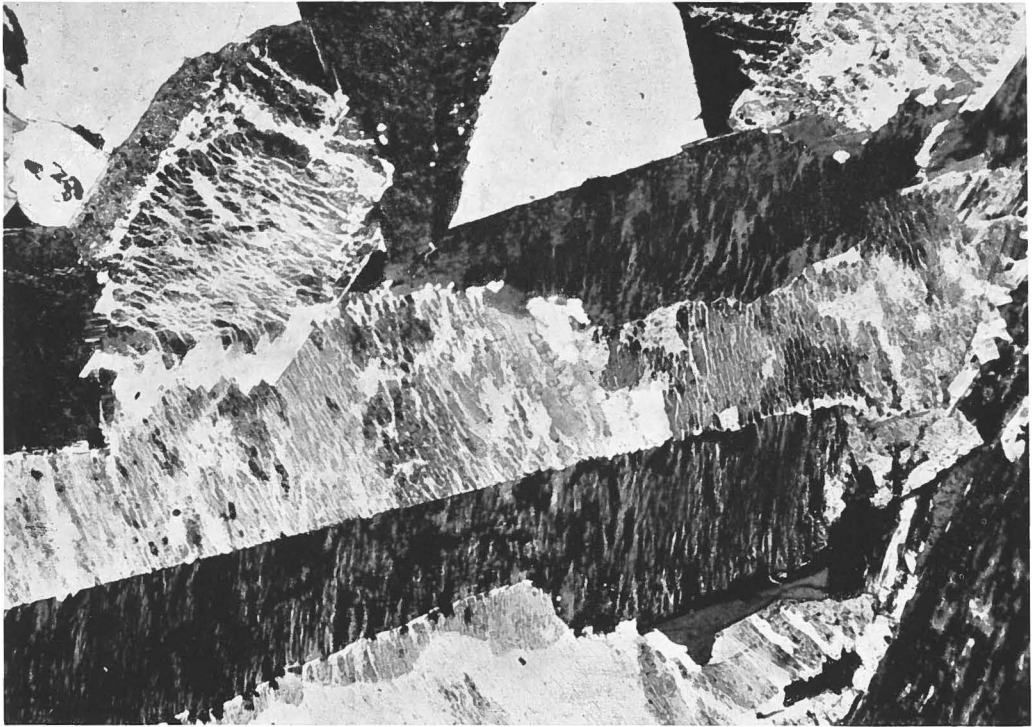


Fig. 2.

Plate 2

Fig. 1. Photomicrograph of normal phenocryst of alkali feldspar, strongly zoned, in quartz-nordmarkite. $\times 14$. Crossed nicols.

Fig. 2. Photomicrograph of foyaite, showing nepheline with secondary overgrowths marked by rings of inclusions. $\times 35$. Crossed nicols.

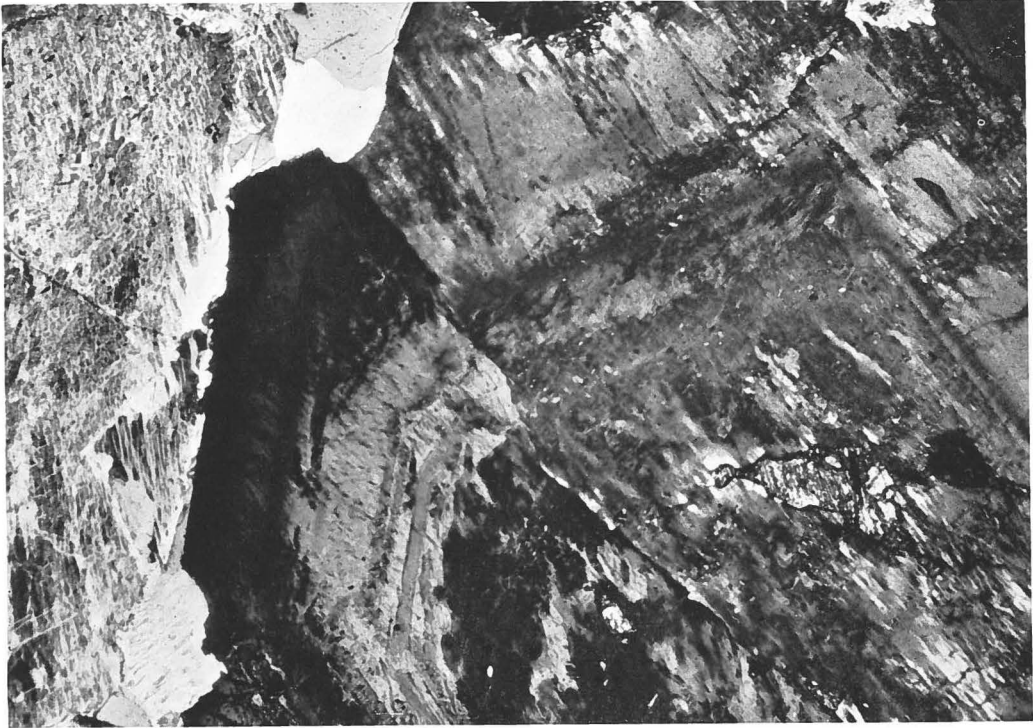


Fig. 1.

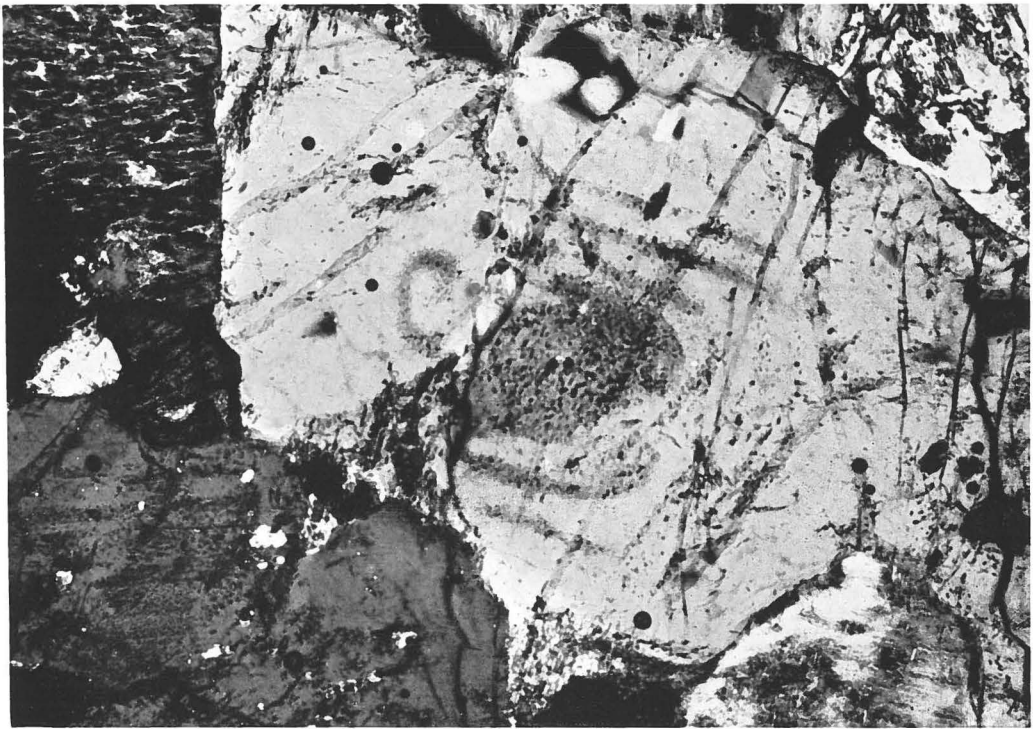


Fig. 2.

Plate 3

- Fig. 1. Photomicrograph of nordmarkite, showing katophoritic amphibole with exsolved iron oxide. $\times 35$. Plain light.
- Fig. 2. Photomicrograph of transitional pulaskite, showing crystals of hematite. The dark mineral (upper left) is aegirine. $\times 57$. Plain light.



Fig. 1.

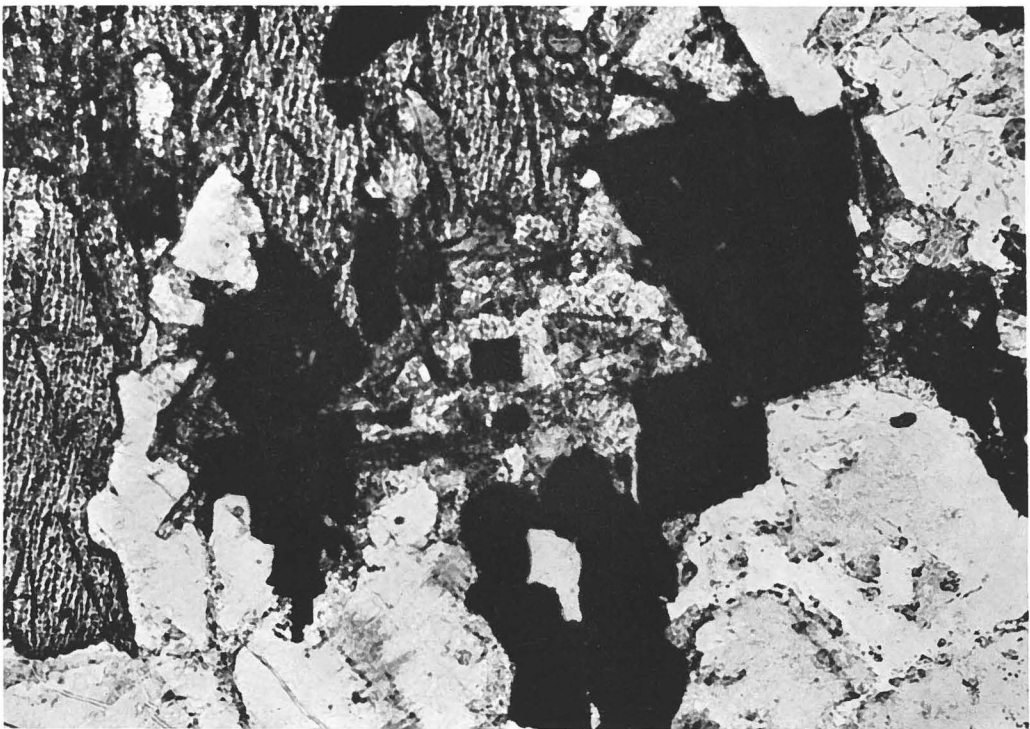


Fig. 2.

Plate 4

Fig. 1. Photomicrograph of vein in transitional pulaskite, showing acicular aegirine and perovskite. $\times 57$. Plain light.

Fig. 2. Photomicrograph of vein in transitional pulaskite with astrophyllite (dark). $\times 57$. Plain light.

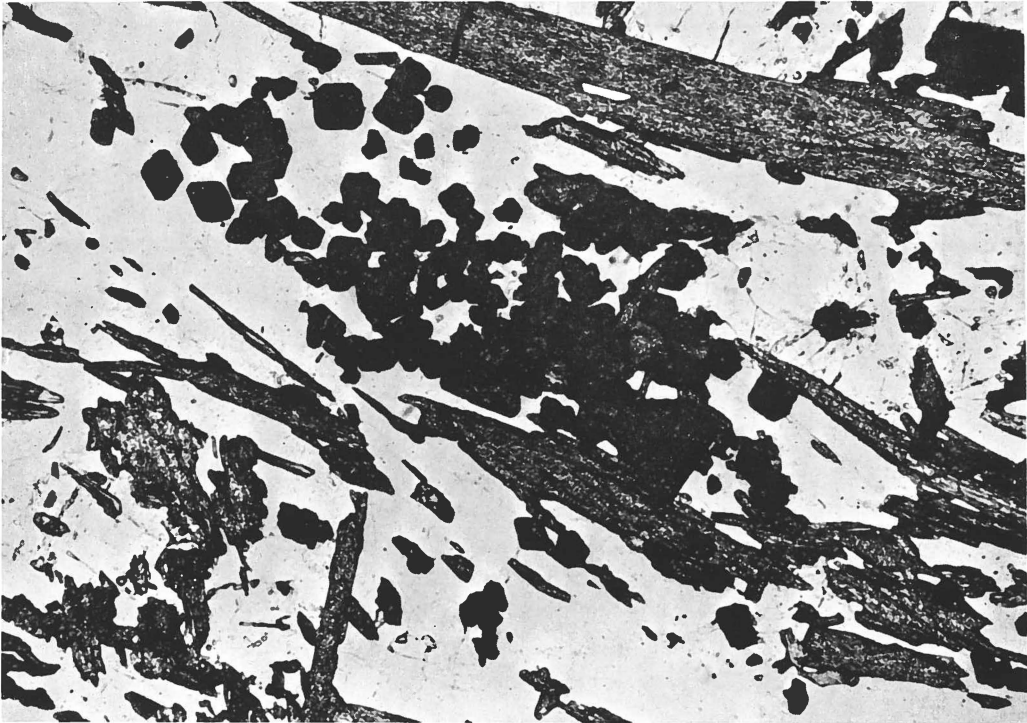


Fig. 1.

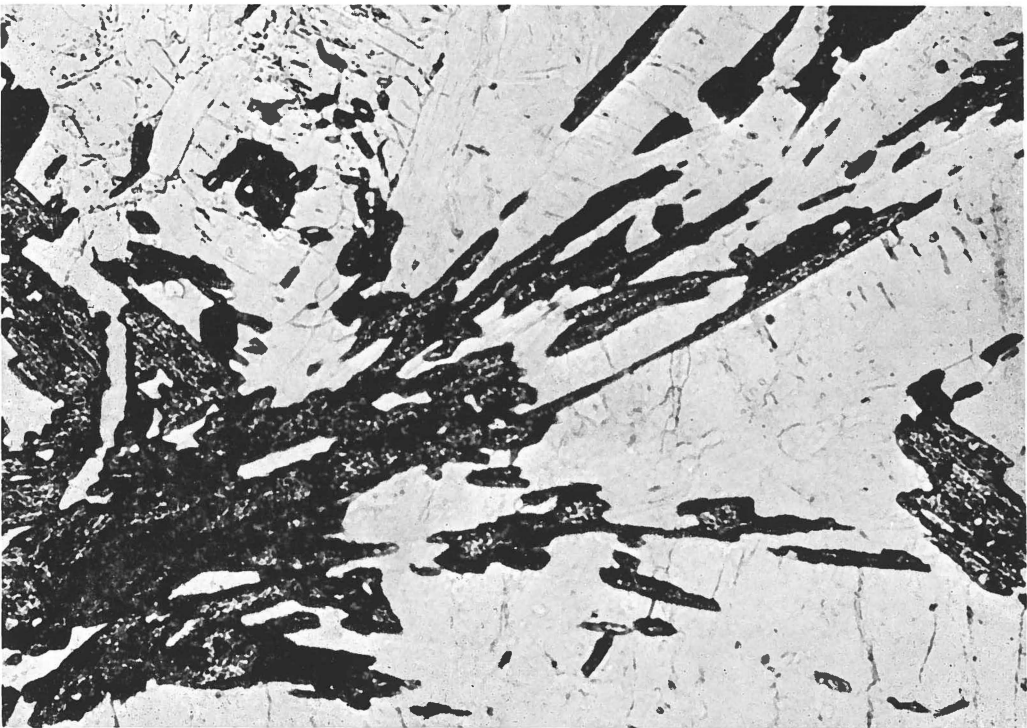


Fig. 2.

Plate 5

Fig. 1. Photomicrograph of vein in main pulaskite showing crystals of lävenite (sharply outlined, upper left), mainly in a mosaic of small plates of catapleite. $\times 57$. Plain light.

Fig. 2. Photomicrograph of foyaite with hiordahlite (sharply outlined, from left to right across centre). The large crystals of melanite (dark) form part of a layer of this mineral. $\times 57$. Plain light.

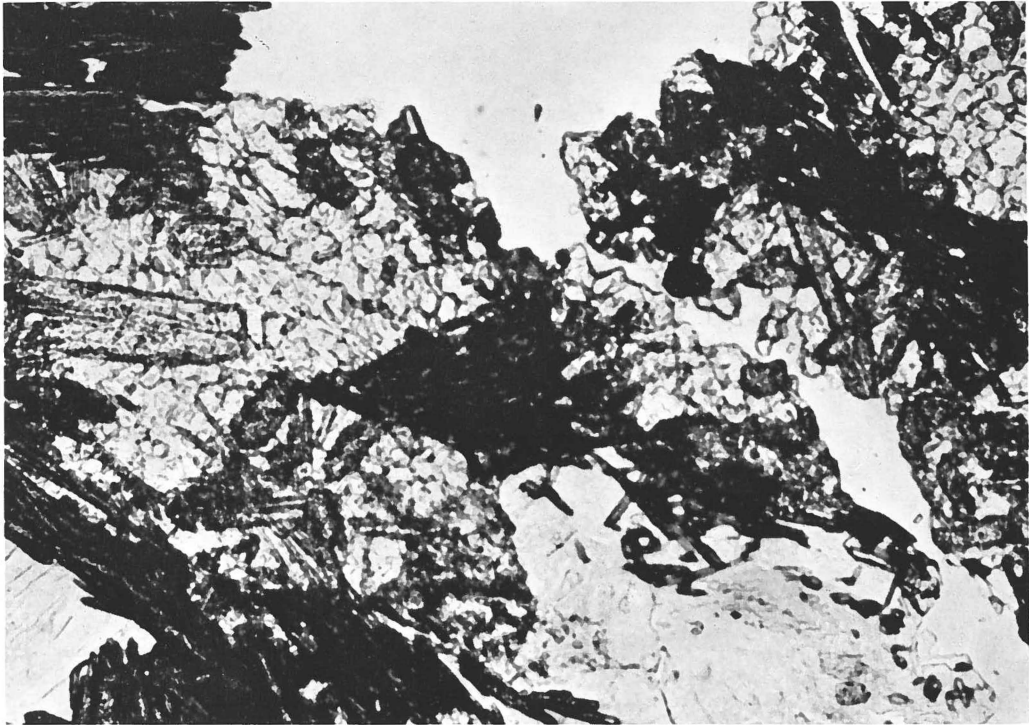


Fig. 1.

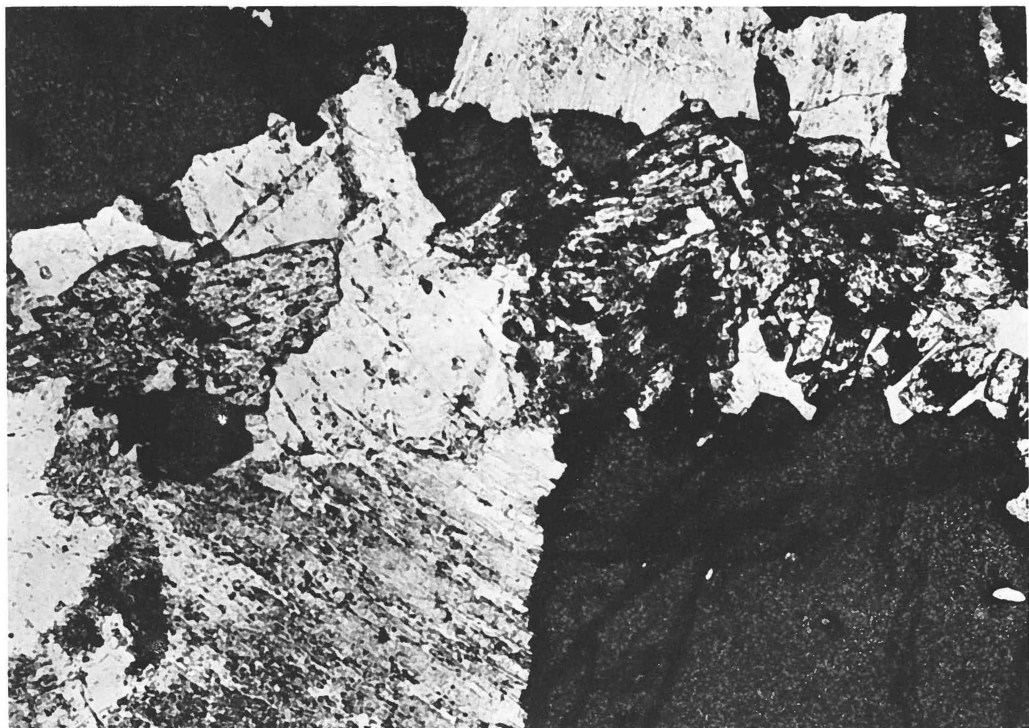


Fig. 2.