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Compositional variation in the pyroxenes and amphiboles of the Kangerdlugssuaq intrusion, East Greenland: further evidence for the crustal contamination of syenite magma

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ABSTRACT. Pyroxenes and amphiboles from the under-saturated to over-saturated syenites of the Kangerdlugssuaq intrusion have been examined to see what light they throw on the two contrasting petrogenetic models for the intrusion. Pyroxene crystals are strongly zoned outwards from augitic to more acmitic compositions, with the most calcic cores present in the foyaite, contrary to the expected pattern if the foyaite is the most evolved rock type as previously postulated. Amphiboles, which are absent in the foyaites, show an exceptionally wide compositional field varying from actinolite through richterite and katophorite to arfvedsonite. Many are manganoan and potassian varieties. However, there is no consistent variation throughout the intrusion as previous work has suggested. These results are not favourable to the idea of a crystal fractionation model for the intrusion and we suggest that the foyaite is closest to the original magma which has hybridized with the enclosing gneisses and basalts to produce the over-saturated rocks. Such a model is consistent with the existing isotopic data.

THE Kangerdlugssuaq alkaline intrusion, described first by Wager (1965), who regarded it as having formed by gravitational sinking of early formed crystals, has been regarded as a typical example of a syenite intrusion in which a range of rock types has developed by simple differentiation *in situ* (Sørensen, 1974, p. 38). In surface outcrop it is a large circular body, 30 km in diameter, having a volume estimated to be about 6500 km^3. It is therefore the largest Tertiary pluton in East Greenland. Trains of basalt blocks and the lamination of platy feldspars together define a gross layering resembling a pile of saucers (Kempe *et al.*, 1970), within which the distribution of rock types appears to be concordant. Silica contents are found to decrease inwards and upwards, the rock types varying from quartz nordmarkite at the margins through nordmarkite and pulaskite to foyaite at the centre of the intrusion. There is no field evidence for more than one phase of injection, and the intrusion is a prominent example of the class of alkaline complexes in which a homogeneous syenite magma appears to have differentiated from an initially over-saturated composition to an under-saturated residual liquid, in apparent violation of phase relations in the system $NaAlSiO_4$-$KAlSiO_4$-SiO_2 (see Tilley, 1957). Kempe and Deer (1976), treating the intrusion as a closed system, discussed several mechanisms by which the magma composition might have crossed the thermal barrier in this system, but reached no conclusion as to which, if any, had operated. On the basis of isotopic evidence, however, Pankhurst *et al.* (1976) demonstrated that the outer parts of the intrusion had undergone considerable chemical interaction with the surrounding gneisses, and the notion of simple differentiation of an isolated magma *in situ* could no longer be regarded as an acceptable explanation of the development of the intrusion.

In view of the important bearing of the Kangerdlugssuaq intrusion on the petrogenesis of alkaline rocks, we are undertaking more detailed mineralogical and chemical studies, and present here an electron microprobe investigation of the pyroxenes and amphiboles of the intrusion. The work supplements by microprobe methods the study of Kempe

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and Deer (1970), who reported wet-chemical analyses on mineral separates of seven pyroxenes and five amphiboles. For the sake of consistency, the rock names employed by Kempe *et al.* (1970) and Kempe and Deer (1970) have been retained in subsequent work and are retained by us. Previously unreported major element analyses of the rock samples are given in Table I. Mineral analyses were executed on the Cambridge Instruments Microscan-9 electron microprobe at the Department of Geology and Mineralogy in Oxford. Methods and standards were similar to those of Sweatman and Long (1969). ZAF corrections were calculated using an on-line program developed at the University of Cambridge.

Pyroxenes. Pyroxenes are most abundant in the foyaite, where they occur as large subhedral zoned crystals, amounting to a few percent of the rocks by volume. The cores of these crystals could be interpreted as being of cumulus origin. Pyroxenes are much less common in the other syenites, and may indeed be locally absent. Thus, of the samples

TABLE I. *Kangerdlugssuaq intrusion: major-element analyses of the investigated samples*

	1	2	3	4	5	6	7	8	9	10
SiO_2	55.77	56.47	62.49	64.19	62.82	63.77	64.90	63.50	65.15	67.42
Al_2O_3	21.96	21.46	17.46	17.12	17.54	16.66	16.92	16.17	17.60	14.84
Fe_2O_3	1.36	0.95	1.22	1.22	1.93	2.12	1.43	1.66	1.03	1.51
FeO	1.00	1.47	1.29	1.44	1.43	0.74	1.38	1.79	0.87	1.69
MgO	0.13	0.24	0.58	0.51	0.31	0.56	0.49	0.75	0.29	0.38
CaO	1.20	1.82	0.83	0.73	0.47	0.43	0.61	0.90	0.37	0.34
Na_2O	8.61	6.96	6.69	8.88	6.78	7.23	7.26	6.94	6.46	6.32
K_2O	6.90	6.66	6.09	5.04	5.73	5.39	5.00	4.81	6.09	5.19
MnO	0.12	0.16	0.14	0.16	0.16	0.13	0.11	0.19	0.07	0.14
TiO_2	0.48	0.50	0.98	0.64	1.01	0.80	0.45	0.95	0.55	0.55
P_2O_5	0.04	0.08	0.12	0.13	0.03	0.15	0.09	0.16	0.05	0.07
H_2O	0.81	2.36	0.66	0.27	0.57	0.58	0.43	0.53	0.34	0.55
Sum	98.38	99.13	98.55	100.33	98.78	98.56	98.26	98.35	98.87	98.82
CIPW norm:										
Q	—	—	—	—	0.42	1.26	1.35	2.81	3.28	10.60
Or	40.78	39.36	35.99	29.79	33.86	31.85	29.55	28.43	35.99	30.67
Ab	23.97	29.26	53.45	57.46	57.37	55.69	59.20	56.40	54.67	47.44
An	0.89	7.65	—	—	0.50	—	—	—	1.04	—
Ne	26.48	16.06	1.33	1.38	—	—	—	—	—	—
Ac	—	—	0.62	3.53	—	4.84	1.97	2.05	—	4.37
Ns	—	—	—	2.59	—	—	—	—	—	0.25
Di	0.97	0.73	2.63	2.33	1.27	0.90	2.03	2.80	0.36	1.05
Wo	1.50	—	—	—	—	—	—	—	—	—
Hy	—	—	—	—	0.18	0.98	1.59	1.79	0.55	2.87
Ol	—	1.21	0.28	1.48	—	—	—	—	—	—
He	—	—	—	—	0.41	0.11	—	—	0.04	—
Mt	1.97	1.38	1.46	—	2.20	0.49	1.09	1.38	1.44	—
Il	0.91	0.95	1.86	1.22	1.92	1.52	0.85	1.80	1.04	1.04
Ap	0.09	0.19	0.28	0.30	0.07	0.35	0.21	0.37	0.12	0.16
Q	31.34	35.91	44.10	44.21	45.09	45.64	45.76	46.70	46.70	51.38
Ks	25.39	26.40	22.52	19.09	20.99	20.37	18.63	18.42	2.76	19.64
Ne	43.27	37.69	33.38	36.70	33.93	33.99	35.61	34.88	31.54	28.99

Sample localities and descriptions are given in Pankhurst *et al.* (1976)

1. Foyaite, CKB70-25
2. Foyaite, CKB70-58
3. Pulaskite, CKB70-29
4. Pulaskite, CKB71-68
5. Pulaskite, CKB70-31
6. Transitional pulaskite, CKB70-20
7. Transitional pulaskite, CKB70-44
8. Nordmarkite, CKB70-42
9. Nordmarkite, CKB70-37
10. Quartz nordmarkite, CKB71-78

examined, pyroxenes have not been detected in CKB70-29 and CKB70-31 (pulaskites), CKB70-37 (nordmarkite) and CKB70-57 (quartz nordmarkite). Where present, they occur interstitially, and seem to be mainly of intercumulus origin. About sixty pyroxene analyses have been carried out for the present study, and the results are shown in figs. 1 and 2. Table II gives a selection of typical analyses and corresponding mineral formulae, in which ferric iron has been calculated from stoichiometry.

In common with many other alkaline complexes, the pyroxenes of the Kangerdlugssuaq intrusion are strongly zoned (figs. 1 and 2). Microprobe analysis shows that the earliest-formed pyroxenes in most units are much less acmitic in composition than previous work has revealed. Pyroxene cores in the nordmarkite and pulaskite have Ac contents as low as 30 %, in contrast to the compositions of about Ac_{80} given by Kempe and Deer (1970) for pyroxenes of the same units. Likewise the cores of some pyroxenes in the foyaite have Ac contents of less than 10 %, compared to the bulk figure of 30 % suggested by Kempe and Deer. These discrepancies arise not only from the zoning itself, but also as a result of the sparse distribution of pyroxene in most units: samples containing sufficient pyroxene for mechanical separation (such as vein syenites) are often atypical of the major rock types.

TABLE II. *Representative clinopyroxene analyses from the Kangerdlugssuaq intrusion*

	1	2	3	4	5	6	7
SiO_2	50.37	49.76	48.59	52.06	50.81	50.57	52.06
TiO_2	0.41	0.87	1.98	0.47	0.50	0.38	5.61
ZrO_2	0.37	0.08	0.05	0.02	0.28	0.04	—
Al_2O_3	1.90	2.94	4.58	0.58	0.33	0.44	0.27
FeO_{tot}	23.05	14.29	9.43	27.24	24.78	16.66	25.35
MnO	2.81	1.53	0.54	0.77	1.27	1.47	0.22
MgO	1.95	7.60	10.81	1.30	2.46	7.15	0.30
CaO	13.01	21.44	23.06	4.47	10.11	17.68	0.04
Na_2O	5.99	1.75	1.05	10.95	7.60	3.45	13.28
Sum	99.05	100.26	100.09	97.86	98.14	97.84	97.13
Fe_2O_3	14.63	5.15	4.22	26.84	19.19	9.68	22.68
FeO	9.89	9.66	5.63	3.09	7.51	7.95	4.94
New sum	100.52	100.78	100.51	100.55	100.06	98.81	99.40
Cations on basis of four cations and six oxygens							
Si	1.970	1.898	1.821	1.993	1.978	1.967	1.998
Al^{IV}	0.030	0.102	0.179	0.007	0.015	0.020	0.002
Al^{VI}	0.020	0.030	0.023	0.032	0.000	0.000	0.162
Ti	0.012	0.025	0.056	0.014	0.015	0.011	0.011
Zr	0.007	0.001	0.001	0.001	0.005	0.001	—
Fe^{3+}	0.431	0.148	0.119	0.773	0.562	0.283	0.655
Fe^{2+}	0.323	0.308	0.177	0.099	0.245	0.259	0.158
Mn	0.093	0.050	0.017	0.025	0.042	0.048	0.007
Mg	0.114	0.432	0.604	0.074	0.143	0.414	0.017
Ca	0.545	0.876	0.927	0.183	0.422	0.737	0.002
Na	0.454	0.129	0.077	0.813	0.574	0.260	0.988

1. Aegirine augite from foyaite (CKB70-58), outer green zone.
2. Same crystal, intermediate zone.
3. Same crystal, pale green core.
4. Aegirine from transitional pulaskite (CKB70-44), margin of grain.
5. Aegirine, same sample, intermediate zone.
6. Aegirine, same sample, interior of crystal.
7. Interstitial aegirine from quartz nordmarkite (CKB71-78).

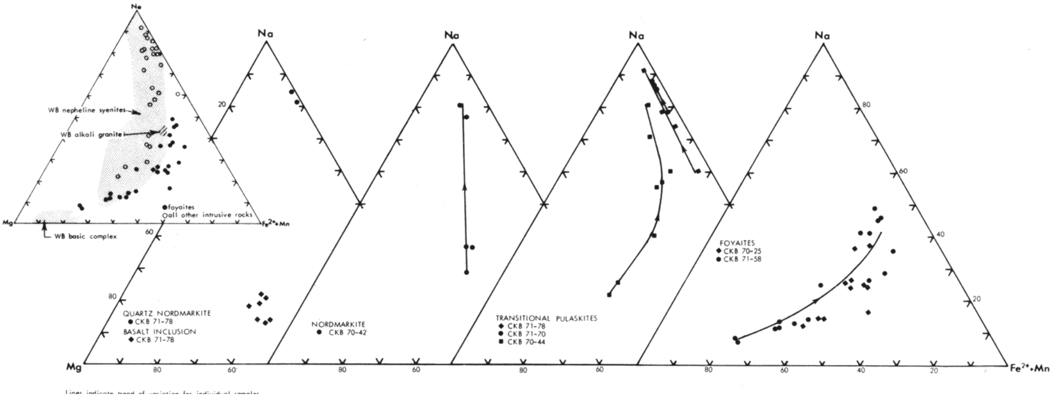

FIG. 1. Pyroxene variation in the Kangerdlugssuaq intrusion in terms of Mg–(Fe^{2+} + Mn)–Na. Inset shows total data set compared to the Werner Bjerge (WB) complex, after Brooks *et al.* (1981).

Fig. 1 shows that, in those units in which zoning is strongly developed, presumably as a result of intercumulus growth, pyroxene margins are consistently more acmitic than the corresponding cores. It is clear therefore that, at all stages in the crystallization of the intrusion, progressive crystallization of syenite magma in a closed system led to successively more alkaline residual liquids, as would normally be expected.

Comparison of the compositions of the earliest-formed pyroxene cores in each unit (fig. 1), on the other hand, shows that the least-evolved pyroxenes are found in the foyaite at the centre of the intrusion, and that in the outer units (pulaskite, nordmarkite, and quartz nordmarkite respectively, henceforth referred to collectively as the 'outer syenites') the pyroxenes become progressively more acmitic. Viewed in conjunction with the trend of intracrystal zoning, this observation rules out the suggestion that the foyaite might represent the residual magma remaining after the inward crystallization of the rest of the intrusion, from a single magma body. Had it formed in this way, one would expect the foyaite to contain the most alkaline cumulus pyroxene, the opposite of the trend observed. To explain the acmite-poor compositions of the pyroxenes in the foyaite, relative to other units, Kempe and Deer (1976) suggested that the course of crystallization of the foyaite may have been influenced by flotation and volatile enrichment, but no evidence has been found in the present more detailed study to support such proposals. Indeed, the dominance of pyroxene over amphibole in the foyaite, more marked than in the other units, suggests that water enrichment cannot have materially influenced the course of its crystallization.

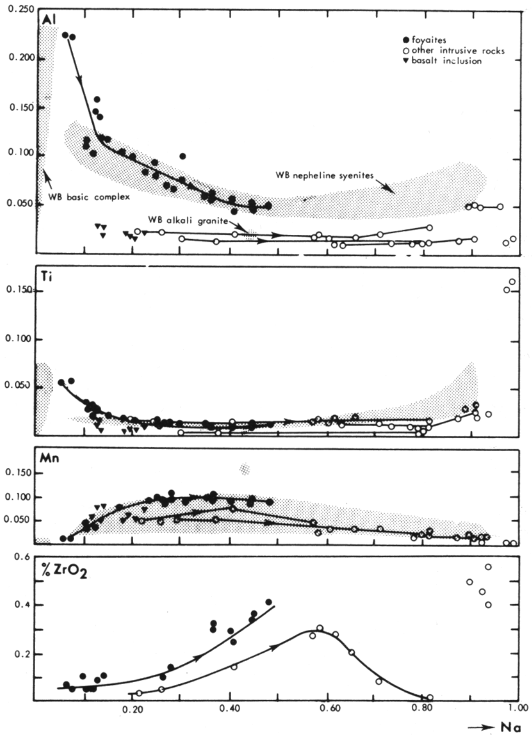

FIG. 2. Variation in selected constituents in Kangerdlugssuaq pyroxenes as a function of Na (all concentrations except ZrO_2 in terms of atoms per formula unit). Werner Bjerge pyroxenes (Brooks *et al.*, 1981) indicated by shaded areas.

Pyroxenes in the margin of a small basaltic inclusion from the quartz nordmarkite (CKB71-78) fall, perhaps coincidentally, with those of the foyaites. They have developed from the original augite of the basalt by exchange of alkalis with the surrounding liquid.

Although the pyroxenes of the foyaite overlap in acmite content with those of other units, several aspects of their chemistry indicate a discontinuity in magma composition between the outer syenites and the foyaite. In the first place, the trend of foyaite pyroxene compositions in fig. 1 (see inset) is offset to lower values of $Mg/(Fe^{2+}+Mn)$ compared to pyroxenes from other units. Secondly, reference to fig. 2 shows that the Al, Mn, and Zr (but not Ti) contents of the foyaite pyroxenes lie on trends which are not continuous with those of the other syenites, but lie at distinctly higher values. (The exceptional transitional pulaskite specimen which has high Al and Zr is permeated by thin veins containing aegirine and låvenite, which may be derived from the foyaites.) In both respects an abrupt change of magma composition is indicated. One may argue that the discontinuities merely record changes in the partition coefficients for the elements concerned between pyroxene and magma, but it would be difficult to account for such a change unless it were caused by a pronounced shift in at least some aspects of magma composition (such as f_{H_2O}). This conclusion indicates the introduction of new material, possibly in the form of new magma or perhaps as circulating ground water (cf. Pankhurst *et al.*, 1976).

Kempe and Deer (1976) remarked on the similarity between the Kangerdlugssuaq alkali pyroxenes and those of the Gardar province (or Precambrian age) in south-west Greenland. There are, however, differences, the most important being the course taken by the Kangerdlugssuaq pyroxene compositions across the centre of the aegirine-augite field in Na-Mg-$(Fe^{2}+Mn)$ space. Gardar alkali pyroxenes show a greater tendency to approach the $(Fe^{2}+Mn)$ apex of the diagram, although this tendency varies between individual intrusions (Stephenson, 1972; Larsen, 1976; Powell, 1978; Parsons, 1979; Stephenson and Upton, unpubl.). The approach towards hedenbergitic compositions is most extreme in the case of the Ilímaussaq intrusion, a fact which Larsen (1976) attributes to unusually low f_{O_2}. It is possible that the discontinuity between the pyroxenes of the foyaite and the other syenites in the Kangerdlugssuaq intrusion reflects a difference in f_{O_2} during crystallization, but we believe other factors must also be considered.

A closer comparison (figs. 1 and 2) may be drawn with the pyroxenes of the Werner Bjerge alkaline complex, a Tertiary intrusion situated 500 km north of Kangerdlugssuaq (Brooks *et al.*, 1981). The evolution of the Werner Bjerge pyroxenes traces a similar course in the Na-Mg-$(Fe^{2}+Mn)$ diagram to that seen at Kangerdlugssuaq, although there are differences in detail. In both intrusions the pyroxenes from oversaturated and under-saturated rocks show distinctly different trends in Al content (fig. 2), the higher concentrations being found in the under-saturated syenites in each case. Unusually Mn-rich pyroxenes are characteristic of both intrusions, although there is no equivalent in the Kangerdlugssuaq intrusion of the exceptionally Mn-rich pyroxenes in the Werner Bjerge alkali granite. A further parallel lies in the occurrence of melanite garnet of similar composition in the foyaites of both intrusions (Table III).

TABLE III. *Analyses of mica and melanite garnet from the Kangerdlugssuaq intrusion*

	1	2		1	2
SiO_2	36.94	34.47	Si	5.519	2.902
Al_2O_3	10.03	2.69	Al	1.763	0.267
TiO_2	3.15	3.72	Ti	0.353	0.235
FeO_{tot}	9.26	23.57	Fe^{3+}	—	1.458
MnO	1.99	1.99	Fe^{2+}	1.153	0.201
MgO	23.62	0.22	Mn	0.251	0.142
CaO	0.00	30.67	Mg	5.293	0.027
Na_2O	0.29	0.00	Ca	0.000	2.767
K_2O	9.18	0.00	Na	0.083	0.000
			K	1.750	0.000
Sum	94.46	97.33			
Fe_2O_3	—	23.01			
FeO	—	2.85			
New sum	—	99.62			

1. Mica from pulaskite CKB70-31. Average of five analyses, cations calculated on the basis of twenty-two oxygens.
2. Melanite garnet from foyaite CKB70-25. Cations calculated on the basis of eight cations and twelve oxygens to give Fe^{3+} and Fe^{2+} as shown.

Amphiboles. The distribution of amphibole in the intrusion has been described by Kempe *et al.* (1970). It is an important constituent of most rocks of the outer syenites where it occurs as large subhedral crystals. Locally in the pulaskites its abundance is reduced at the expense of biotite. In the foyaites, amphibole is absent.

About 100 spot analyses have been made of amphiboles in all units of the intrusion in which amphibole is found. The fourteen representative analyses given in Table IV have been recalculated on the basis of a formula having thirteen cations in the Y and Z sites combined (incorporating Si, Al^{IV}, Al^{VI}, Ti, Fe, Mn, and Mg) and twenty-three oxygens in the unit cell, disregarding the water content, which cannot be determined by electron microprobe. Recalculation to this formula allows a crude maximum estimate to be calculated of $Fe^{3+}:Fe^{2+}$ for each microprobe analysis (Stout, 1972). The calculation is only moderately reliable,

TABLE IV. *Selected amphibole analyses from the syenites of the Kangerdlugssuaq intrusion*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	51.15	50.20	50.36	50.01	52.41	49.89	49.52	51.03	51.28	50.02	51.02	48.42	47.14	51.33
Al_2O_3	1.35	0.80	2.33	1.11	2.61	2.75	2.78	2.26	1.28	2.89	0.71	3.77	4.71	2.17
TiO_2	1.33	1.55	1.43	0.98	0.51	1.19	1.33	0.84	1.24	1.27	0.45	1.48	1.58	1.14
FeO_{tot}	21.72	28.49	19.20	27.59	12.44	21.09	23.29	18.55	21.88	14.97	28.94	19.08	21.39	14.71
MnO	1.84	1.96	1.43	1.47	1.38	1.54	2.38	1.72	2.00	1.55	1.46	2.36	2.06	1.71
MgO	8.08	3.53	10.31	4.98	15.29	8.86	6.04	10.59	7.86	12.15	3.77	9.75	7.88	13.11
CaO	5.04	2.51	6.70	3.71	9.65	1.87	0.67	5.40	2.56	7.18	1.32	4.20	3.76	7.76
Na_2O	6.62	7.59	5.60	6.26	3.02	8.86	9.43	6.27	7.55	5.50	7.86	7.47	7.43	4.42
K_2O	1.10	1.37	0.78	1.10	0.61	1.41	1.86	1.14	1.27	1.11	1.09	1.41	1.36	0.80
Sum	98.23	98.00	98.14	97.21	97.92	97.46	97.30	97.80	97.92	97.64	96.62	97.94	97.31	97.15
Fe_2O_3	0.82	3.01	2.31	6.14	3.77	6.35	4.35	3.72	4.98	0.00	6.74	5.62	6.32	3.04
FeO	20.98	25.79	17.13	22.06	9.05	15.38	19.38	15.21	17.40	14.97	22.88	14.02	15.70	11.98
New sum	98.31	98.31	98.38	98.82	98.30	98.10	97.74	98.18	97.42	96.64	97.30	98.50	97.94	94.46
Structural formulae on the basis of $Y+Z = 13$ cations														
Si	7.777	7.859	7.541	7.758	7.551	7.526	7.637	7.618	7.803	7.533	7.967	7.280	7.188	7.580
Al^{IV}	0.223	0.143	0.411	0.203	0.443	0.474	0.363	0.382	0.197	0.467	0.033	0.668	0.812	0.378
$Fe^{3(IV)}$	—	—	0.048	0.039	0.006	—	—	—	—	—	—	0.052	—	0.042
	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Al^{VI}	0.019	0.005	—	—	—	0.015	0.142	0.016	0.033	0.046	0.098	—	0.035	—
Ti	0.152	0.182	0.161	0.114	0.055	0.135	0.154	0.094	0.142	0.144	0.053	0.167	0.181	0.127
$Fe^{3(IV)}$	0.094	0.354	0.212	0.678	0.403	0.721	0.504	0.418	0.570	—	0.792	0.584	0.726	0.295
Fe^2	2.668	3.375	2.145	2.862	1.090	1.940	2.500	1.899	2.214	1.885	2.988	1.763	2.002	1.479
Mn	0.237	0.260	0.181	0.193	0.168	0.197	0.311	0.218	0.258	0.198	0.193	0.301	0.266	0.214
Mg	1.831	0.823	2.301	1.151	3.283	1.992	1.388	2.356	1.783	2.727	0.877	2.185	1.791	2.885
	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
Ca_B	0.821	0.421	1.075	0.617	1.490	0.302	0.111	0.864	0.417	1.159	0.221	0.677	0.614	1.228
Na_B	1.179	1.579	0.925	1.383	0.510	1.698	1.889	1.136	1.583	0.841	1.779	1.323	1.386	0.772
	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
Na_A	0.772	0.724	0.701	0.500	0.334	0.894	0.931	0.679	0.645	0.765	0.601	0.855	0.811	0.494
K_A	0.213	0.274	0.149	0.218	0.112	0.271	0.366	0.217	0.247	0.213	0.217	0.270	0.265	0.151
	0.985	0.998	0.850	0.718	0.446	1.165	1.297	0.896	0.892	0.978	0.818	1.125	1.076	0.645
$\frac{Mg}{Mg+Fe^2}$	0.407	0.196	0.517	0.287	0.750	0.507	0.357	0.554	0.446	0.591	0.227	0.553	0.472	0.661

1. Most magnesian amphibole in quartz nordmarkite CKB71-73. Ferrorichterite.
2. Same sample, most Fe-rich analysis. Manganoan potassian arfvedsonite.
3. Most magnesian amphibole in nordmarkite CKB70-47. Richterite.
4. Same sample, most Fe-rich analysis. Calcian arfvedsonite.
5. Typical analysis from nordmarkite CKB70-37. Sub-calcic actinolite.
6. Typical analysis from transitional pulaskite CKB70-20. Richterite.
7. Typical analysis from transitional pulaskite CKB71-70. Manganoan potassian arfvedsonite.
8. Most magnesian amphibole from transitional pulaskite CKB70-44. Richterite.
9. Same sample, most Fe-rich analysis. Manganoan arfvedsonite.
10. Most magnesian amphibole in pulaskite CKB71-68. Richterite.
11. Same sample, most Fe-rich analysis. Arfvedsonite.
12. Typical analysis from pulaskite CKB70-29. Manganoan potassian katophorite.
13. Typical analysis from pulaskite CKB70-31. Manganoan potassian arfvedsonite.
14. Typical analysis from basalt inclusion in quartz nordmarkite CKB71-78. Richterite.

NB. Where only single analyses are given the variation was limited.

as can be seen from Table V, in which Fe^{3+} and Fe^{2+} concentrations calculated by this procedure for Kangerdlugssuaq amphiboles given by Kempe and Deer (1970), assuming only total iron content to be known, are compared with the analysed values. None the less even a rough estimate of Fe^{3+} is preferable to the assumption that none is present.

The cations of the fourteen recalculated analyses have been apportioned between the various sites as recommended by the IMA subcommittee on Amphiboles (Leake, 1978). All but one of them are found to fall in the sodic-calcic and alkali amphibole groups, in the range richterite or katophorite to arfvedsonite (Table IV). Some are sufficiently enriched in Mn and K to warrant the prefix manganoan or potassian. One analysis falls marginally in the calcic amphibole field and is formally a subcalcic actinolite, but it lies on an extension of the trend defined by the other amphiboles and is not fundamentally different. Little significance should be attached to the formal division between amphibole categories in cases such as this, a point further illustrated by analyses of amphiboles from two pulaskites (CKB70-29 and 70-32), which are very similar but which, owing to a trivial difference in the calculated Na_B value, fall on opposite sides of the katophorite-arfvedsonite boundary.

The fourteen recalculated analyses are shown in fig. 3, where they are compared with the five amphibole analyses given by Kempe and Deer (1970), recalculated on the same basis. The microprobe data bear a moderate resemblance to the previously published analyses, but extend the distribution to much more magnesian compositions (fig. 3), as noted for the pyroxenes. Amphiboles from veins have not been considered in the present work, and accordingly no amphibole as iron-rich as the extreme example given by Kempe and Deer (1970) has been found.

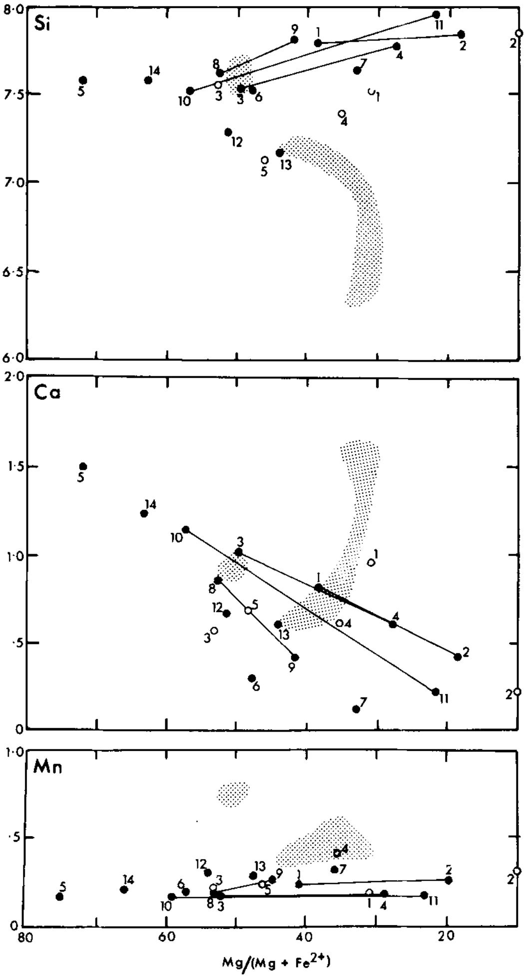

FIG. 3. Variation in some parameters for the recalculated amphiboles shown in Table IV (closed symbols) compared to those of Kempe and Deer (1970) (open symbols) and those of Werner Bjerge (shaded areas, after Brooks *et al.*, 1981). Numbers adjacent to points refer to analysis number in relevant table. Lines join extreme compositions in individual samples.

TABLE V. *Comparison between calculated and observed oxidation states of iron in some amphiboles from the Kangerdlugssuaq intrusion*

Analysis no.	1	2	3	4	5
Fe_2O_3 (calc)	4.23	2.52	3.21	8.45	5.46
Fe_2O_3 (obs)	6.81	8.29	8.74	12.25	9.93
FeO (calc)	21.69	27.35	15.30	16.33	15.65
FeO (obs)	19.36	22.16	10.32	13.26	11.62

Calculated values obtained on the basis of Y + Z = 13 and 23 anions as in Table II.

Observed values obtained by wet chemical analysis and reported by Kempe and Deer (1970, Table XII, p. 52).

Variation diagrams showing all of the amphibole analyses carried out in the present study are presented in fig. 4. The function Mg/(Mg + Fe + Mn) varies from 0.65 to 0.15, but much of the considerable range in composition is found to occur within individual rocks, where a fairly consistent trend of zoning runs from Ca-rich to Na-rich compositions. However, the variation *between* units, discernible with difficulty above this wide intra-unit zoning, takes no consistent form. The quartz nordmarkites show the most iron-rich range of amphibole compositions, the nordmarkites have the most magnesian amphiboles, though with a wide range to more iron-rich types, and the pulaskites have amphiboles of intermediate composition. No pattern emerges that can be related to differentiation of the intrusion as a whole. Thus, the suggestions of Kempe and Deer (1970), that (*a*) the amphibole characteristic of the nordmarkite (supposedly katophorite) is distinguishable from the amphiboles in the other syenites (nominally arfvedsonite), and (*b*) that the amphiboles exhibit a consistent radial variation in Al^{IV} and $Fe^2:Fe^3$ for the intrusion as a whole, are not consistent with the much larger body of amphibole data now available. Two pulaskites (CKB70-31 and 70-29) contain amphiboles which deviate from the general trend seen in figs. 3 and 4, having lower contents of Si and Ca and higher Al contents. These rocks are unusually poor in amphibole but have high contents of sphene and biotite. It is possible that the appearance of biotite (Table III), a relatively Si-poor and Al-rich phase like the amphibole in these rocks, represents a shift in magma composition at the pulaskite stage, perhaps heralding the crystallization of the foyaite in which the Si-poor Al-rich tendency is more clearly developed in the form of feldspathoid.

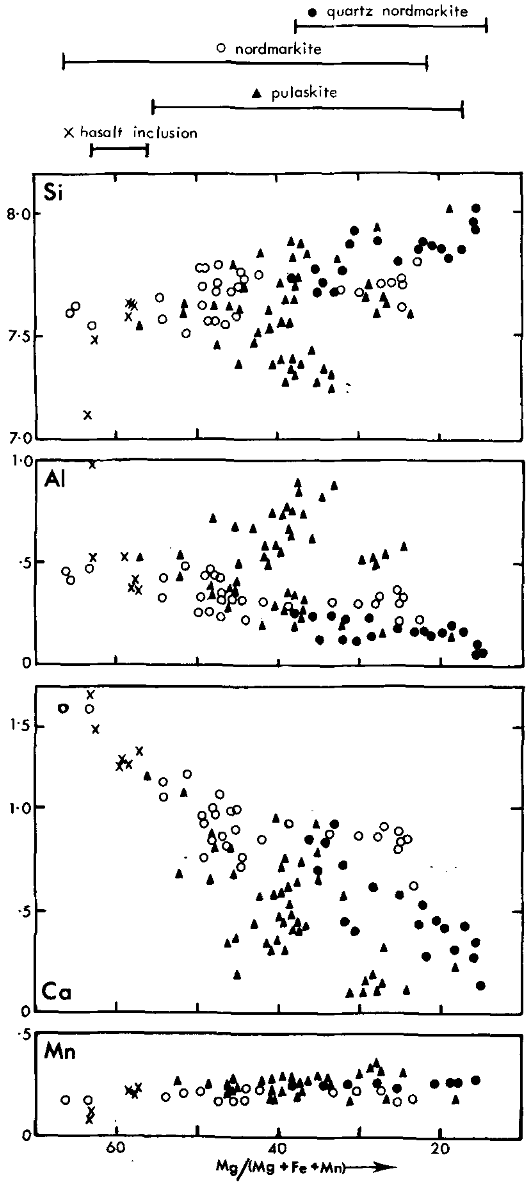

FIG. 4. All Kangerdlugssuaq amphibole analyses of the present study showing the lack of systematic variation.

The stippled areas in fig. 3 indicate the range of amphibole compositions found in the Werner Bjerge intrusion. The latest amphiboles in the nepheline syenite unit of this body intersect the trend of the Kangerdlugssuaq amphiboles, but have developed from quite a different direction. The least-evolved amphiboles in the Werner Bjerge nepheline syenites are hastingsitic, whereas those of the Kangerdlugssuaq intrusion have more actinolitic compositions. It is notable that actinolitic amphibole occurs at Werner Bjerge only as a deuteric alteration product in the gabbros of the basic unit, suggesting that perhaps the partial assimilation of the basalt xenoliths so common in the Kangerdlugssuaq intrusion has strongly influenced the development of amphibole in the units in which they occur. One such block investigated in the present study contains an amphibole which, though nominally a richterite, is not dissimilar to the actinolitic amphibole at the magnesian end of the syenite amphibole trend.

We conclude that the amphibole variation in these rocks does not reflect any simple trend of magmatic evolution. If these rocks were formed from a steadily differentiating magma as visualized by Wager (1965) and Kempe *et al.* (1970), the amphibole compositions were surprisingly insensitive to the change from over- to under-saturated magmas. We believe that other explanations are more acceptable.

Discussion. Our investigations of the pyroxenes and amphiboles of the Kangerdlugssuaq intrusion are not favourable to the idea that the intrusion has formed by progressive crystal fractionation from the quartz nordmarkites through to the under-saturated foyaites as originally visualized by Kempe *et al.* (1970). In particular, the presence of the most primitive calcic pyroxenes in the foyaites, and the lack of any systematic variation in the amphiboles, which are the most important ferromagnesian minerals in the rest of the intrusion, militate against this view. Indeed, the evidence from experimental petrology and isotope studies already makes this model untenable, as recognized by Kempe and Deer (1976).

We propose the following model for the development of the intrusion which we believe to be the simplest explanation of the existing facts, both from this work and from previous studies. The foyaite is the closest rock type of the complex to a primitive magma, both in terms of Sr isotopic composition (Pankhurst *et al.*, 1976) and pyroxene variation. Such a foyaitic magma might be derived by extensive fractionation of a nephelinitic parent of the type which has given rise to the syenites, ijolites, and urtites of the nearby Gardiner complex (Nielsen, 1979). This magma has reacted to varying degrees with the enclosing gneisses and basalts to produce the encircling pulaskites and the nordmarkites. These rocks are all more or less contaminated: the pulaskites (which have relatively primitive $^{87}Sr/^{86}Sr$ initial ratios) are the least affected, the quartz nordmarkites the most. Basaltic inclusions, often strongly digested, are a prominent feature of the nordmarkites and also occur in the transitional pulaskites.

Two lines of evidence suggest that digestion of these blocks has been a major source of magma contamination. The nordmarkites and transitional pulaskites contain large dark-coloured crystals of low-albite and orthoclase microperthite, which are identical to those developed in the basaltic inclusions. Secondly the more magnesian amphiboles in the outer syenites are chemically similar to amphiboles taking the place of pyroxenes in the basaltic blocks, and resemble amphiboles seen developing from pyroxene in other hydrothermally altered basic environments (cf. the Werner Bjerge basic unit, and Deer *et al.*, 1963, p. 260).

Mineralogical evidence for hybridization with gneiss is less clear and Kempe *et al.* (1970) report very few recognizable gneiss inclusions. However, the high $^{87}Sr/^{86}Sr$ ratios for the nordmarkites reported by Pankhurst *et al.* (1976) are unmistakable evidence that some type of interaction has taken place. We thus suggest that the quartz-rich nature of these rocks relative to the rest of the intrusion is due to the wholesale incorporation of gneiss, evidence for which has been largely obliterated in the field. However, in some of the adjacent nordmarkitic bodies of the area clear field evidence of melting of gneiss and hybridization with other magmas may be seen (Brooks and Beckinsale, Brooks and Nielsen, unpubl.). The Kangerdlugssuaq intrusion is the only undersaturated syenite of any significance in the immediate area and this may be due to its very large size in which only the central part, of the order of 1 % by volume, has been preserved in a relatively pristine condition, insulated from the surroundings by a thick envelope of progressively more hybridized syenites.

Hybridization and contamination have not been popular mechanisms in petrogenesis since they were discussed by Bowen, 1928 (but see also McBirney, 1979), largely due to the problem of providing sufficient heat energy. However, the Kangerdlugssuaq area was one of prolonged magmatism and the crust was probably already at an elevated temperature when the highly reactive alkaline magmas from deeper levels were intruded. It is perhaps therefore not surprising that considerable interaction with the crustal rocks took place here.

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