THE DIFFERENTIATION OF AGPAITIC MAGMAS : THE ILIMAUSSAQ INTRUSION, SOUTH GREENLAND

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ABSTRACT

In the nepheline – and sodalite – rich rocks of the Ilímaussaq Intrusion, alkalies are in excess of alumina, and total Fe, Zr, H_2O, Cl and F is high with a corresponding paucity of Ca and Mg. Furthermore, Na is considerably in excess of K. The major chemistry has resulted in the development of the agpaitic suite of minerals.

The fractionation trend displayed by the K:Rb ratio shows a remarkably strong correlation with the chronology determined from the field evidence. Other ratios used include the agpaitic index, Na:K, Sr:Ca, Ba:Rb, Ba:Sr, Ti:Zr, Ti:Nb and Zr:Nb. In general these ratios conform to established behaviour patterns during fractionation ; an exception is the Zr:Nb ratio which increases with fractionation.

INTRODUCTION

As a result of regional mapping of the Ilímaussaq Intrusion during the field seasons of 1958, 1960 and 1961 (Ferguson 1964), petrochemical work was done on selected rock types in order to substantiate the crystallization sequence and help correlate controversial rock types (Ferguson, in press). The results used in this paper are largely selected minor and trace element analyses taken from this publication. In addition, a compilation of all major oxide analyses is presented to facilitate an evaluation of the overall composition of the undersaturated per-alkaline rocks of the Intrusion.

The petrochemistry of the Intrusion has been dealt with in a general way by Gerassimovsky *et al.* (1966), Gerassimovsky & Kuznetsova (1967) and Gerassimovsky (1968). For an account of research on the Ilímaussaq Intrusion the reader is referred to an historical résumé compiled by Sørensen (1967).

GENERAL GEOLOGY

The Ilímaussaq Intrusion is one of a number of pultonic alkaline bodies of Precambrian age occurring in South Greenland. The intersection of

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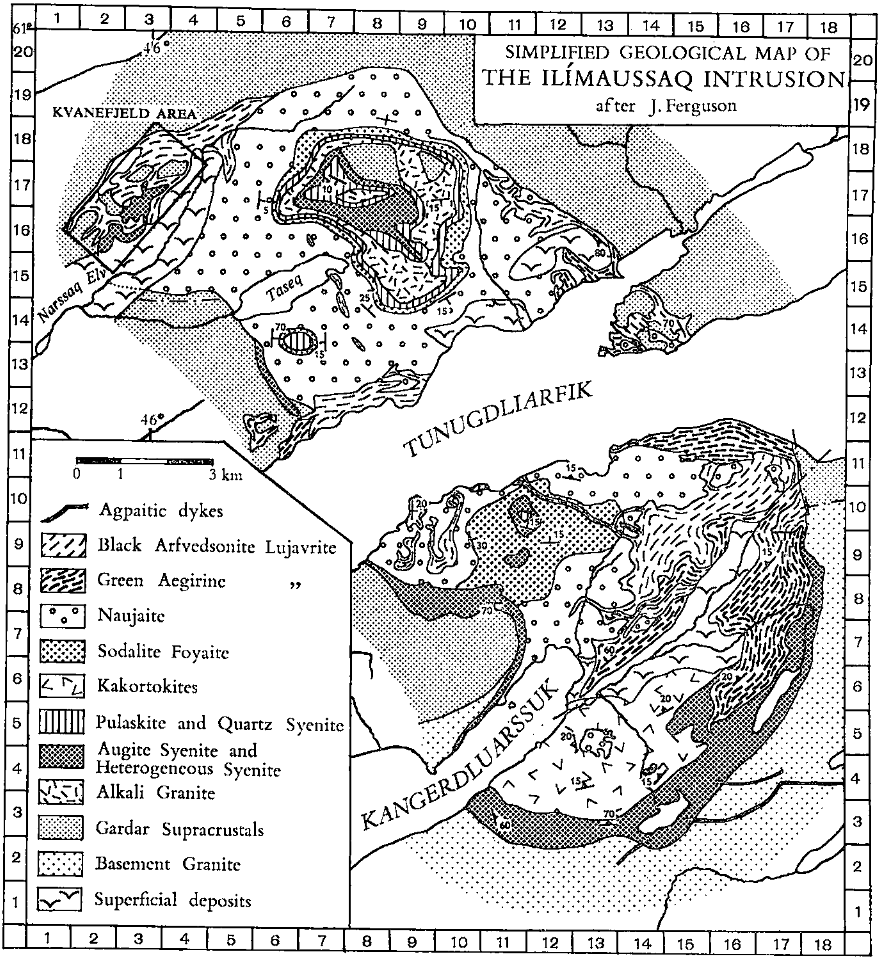

ESE and ENE faults appears to have played an important role in the location of the alkaline centres (Berthelsen 1962 and Bridgwater & Walton 1964). The dominant ENE trend of Gardar dyking is evidence that this fault direction was the major control in the emplacement of these magmas. The Ilímaussaq Intrusion has been dated at 1020 ± 24 m. y. (Bridgwater 1965) giving it a late-Gardar age.

The Intrusion has an elliptical plan view measuring 17 km along a NW-SE axis and 8 km in a NE-SW direction (Fig. 1) and has penetrated basement granite and gneisses in the lower level and supracrustal sandstones and effusives of Gardar age in the higher levels.

The rock types encountered in the Ilímaussaq Intrusion comprise satured syenites and per-alkaline over - and under - saturated units (Table 1). As a result of his work on the Ilímaussaq Intrusion, Ussing (1912) introduced the term agpaitic to describe the per-alkaline nepheline syenites which make up the dominant layered series of the Intrusion. The term was defined as follows :

$$\frac{na + k}{al} \geq 1.2$$ (where na, k and al are the relative amounts of Na, K and Al atoms in the rock)

TABLE 1. MAJOR ROCK TYPES OF THE INTRUSION

saturated syenite	agpaitic nepheline syenites	per-alkaline oversaturated rocks
augite syenite	sodalite foyaite naujaite kakortokite green lujavrite black lujavrite	alkali granite

Despite the good rock exposure in the area, various workers have given different interpretations to the chronological order of crystallization and controversies of origin and correlation also exist.

Wegmann (1938), who studied the Ilímaussaq Intrusion only briefly in passing, advanced a transformation hypothesis to account for most of the rocks, but subsequent workers consider the majority of the rock units to be of truly igneous origin. As illustrated in Figure 1, the various types of feldspathoidal syenites occur within an outer discontinuous shell of augite syenite. Some writers, notably Ussing (1912, p. 327) and Hamilton (1964, p. 99) interpreted this as being due to the replacement of an earlier batholith of saturated syenite by nepheline-syenitic magma. Sørensen (1958, p. 29) and the author (Ferguson 1962, 1964) however regarded the agpaitic rocks as having been produced by volatile enrichment of the inner portion of the syenitic magma.

The initial magma intrusion of Ilímaussaq is now represented by chilled augite syenite of saturated composition. As crystallization proceeded, this magma developed a more undersaturated nature as indicated by the presence of nepheline in the coarse-grained inner facies of this rock type. An undersaturated but not per-alkaline facies of this rock, called the "heretogeneous syenite" has been interpreted by the author as representing the roof-development of the innermost differentiate of the augite syenite. This interpretation differs from that of Ussing (1912, p. 341) who termed the rock "foyaite" and favoured a hybrid origin for it. With the production of the agpaitic magma, crystallization took place from the roof downwards with simultaneous gravity accumulation on the floor of the Intrusion (Ussing 1912, Ferguson 1964 and Sørensen 1968). The roof-zone development of sodalite foyaite probably represents the first rock of this suite to crystallize by the flotation of sodalite (Ferguson 1964 and Sørensen 1968). Ussing (1912, pp. 353-354) however viewed this rock type as being a product of volatile-rich magma accumulated above the cooled and contracted naujaite. By a continuation of the flotation of sodalite, the spectacular poikilitic sodalite-rich naujaite formed (Ussing *op. cit.*; Ferguson *op. cit.* and Sørensen *op. cit.*). Cyclic precipitation of the heavier agpaitic minerals led to the formation of the remarkable series of rhythmically layered kakortokite (Ussing *op. cit.*; Sørensen 1958; Ferguson 1964 and Hamilton 1964). It is possible that deposition of these gravity-accumulated crystals started during the formation of the sodalite foyaite and continued during the crystallization of the naujaite. All workers, except Wegmann (*op. cit.*), regard the lujavrites as being the rest magma, rich in volatiles, injected during the slumping and faulting of the closing stages of evolution of the intrusion. The author (1962 and 1964) and Hamilton (1964, p. 100) regarded the lujavrite magma as a residual trapped between the naujaite and kakortokite whereas Ussing (*op. cit.*) and Sørensen (1958) were of the opinion that the lujavrite originated at a level below that of the kakortokite. The author considers that the lujavrites are cumulates with the black arfvedsonite-rich variety overlying the green aegirine-rich variety.

The origin and chronological placing of the per-alkaline granite is also strongly controversial. Whether the granite pre- or post-dates the agpaitic rocks is open to question. Ussing (*op. cit.*), the author (1964, in press) and Sørensen (1964) regarded the granite as pre-dating the agpaites. Hamilton (1964, p. 67) viewed the alkali granite as post-dating both the agpaites and augite syenite. Theories on the origin of the alkali granite range from differentiation (Ussing 1912, p. 339), assimilation (Ussing *op. cit.*, p. 366 and Hamilton 1964, p. 61) and fenitization (Backlund 1932). Rock types of minor distribution found in the layered sequence include quartz syenite and pulaskite. Late-stage pegmatites and veins also occur, as well as small syenitic intrusives.

To summarize, the author views the consecutive consolidation of the major Ilímaussaq rock units to be in the order: 1) augite syenite and heterogeneous syenite; 2) alkali granite; 3) sodalite foyaite and kakortokite; 4) naujaite and kakortokite and 5) lujavrites.

The differentiation of the agpaitic suite together with the 'parental' augite syenite and heterogeneous syenite is considered in this paper.

PETROGRAPHY

Detailed petrographic accounts of the major rock units from the Ilímaussaq Intrusion have been presented by Ussing (1912), Ferguson (1964) and Hamilton (1964).

The augite syenite varies from fine- to coarse-grained; the major minerals are alkali feldspar, augite, acmitic pyroxenes, olivine, kaersutite, magnetite and biotite. The heterogeneous syenite contains pockets of coarse-grained rock enclosed in pegmatitic material; there is however very little mineralogical difference between the two textural varieties. The major minerals are alkali feldspars, acmitic pyroxenes, soda-amphiboles, olivine and nepheline.

The agpaitic rocks are comprised of essentially similar minerals but in varying proportions. The major minerals, for the most part, include alkali feldspar, acmitic pyroxenes, Na-amphiboles, eudialyte, sodalite and nepheline.

The sodalite foyaite is a coarse-grained rock and shows no sign of a foyaitic texture. Eudialyte is erratically distributed within layers both enriched and impoverished in this mineral. Pegmatites of this rock type are rather rare. Naujaite is characterized by a poikilitic texture in which the groundmass minerals have pegmatitic dimensions and contain 2-3 mm diameter inclusions of sodalite. Rhythmic layering has been observed throughout the naujaite, produced by compositional and textural change. All the major minerals of the naujaite vary quantitatively, sodalite more extensively than the others. The average sodalite content of the naujaite is approximately 40 per cent by volume (Table 2) but can increase to 80 per cent producing well-defined layers. Concordant agpaitic pegmatites are also a common feature of the naujaite. The kakortokite comprises rhythmically-layered, medium-grained agpaitic rock, developed through an exposed thickness in excess of 400 m. Twenty-eight to thirty units occur, each comprising repetitive alternations of black, red and white layers, corresponding to concentrations of arfvedsonite-aegirine, eudialyte and feldspar respectively (Table 2). The compositional sequence is never varied although the red layers may be inconspicuous. The lujavrites are characterized by being medium- to fine-grained rocks which display a strong preferred orientation of the prismatic minerals, giving the rock a distinct fissility. There are two main varieties, an arfvedsonite-rich black lujavrite and an aegirine-rich green lujavrite (Table 2). Layering is found throughout the lujavrite but is concentrated at the boundary of the two varieties in a mixed zone approximately 50 m thick. Rhythmic layering

TABLE 2. MAJOR ELEMENTS

Chemical components	Augite syenite	Hetero-geneous syenite	Sodalite foyaite	Naujaite	Kakortokite				Green lujavrite	Black lujavrite	Average composition of agpaitic nepheline syenites at Ilímaussaq	Average composition of Lovozero rocks
					Black layers	Red layers	White layers	Weighted average				
	(8)	(3)	(2)	(9)	(4)	(4)	(4)	(12)	(7)	(6)		
SiO_2	55.75	53.61	49.97	46.85	49.93	50.83	52.22	51.83	53.12	52.89	49.79	53.62
TiO_2	1.43	0.47	0.55	0.30	0.40	0.28	0.28	0.29	0.28	0.35	0.33	1.12
ZrO_2	—	0.27	0.43	0.41	1.16	3.46	0.93	1.16	1.12	0.64	0.72	0.48
Al_2O_3	16.31	18.14	18.35	22.30	10.91	10.91	17.24	15.97	15.96	14.59	18.72	17.39
Fe_2O_3	3.09	4.96	4.96	3.07	8.92	4.64	5.89	6.15	9.15	6.30	5.02	4.93
FeO	6.23	4.27	4.04	2.21	10.98	6.86	3.79	4.90	1.32	6.77	3.58	1.01
MnO	0.21	0.34	0.15	0.13	0.54	0.59	0.22	0.29	0.22	0.41	0.23	0.34
MgO	1.32	0.13	0.43	0.09	0.40	0.22	0.23	0.25	0.20	0.54	0.22	0.98
CaO	3.54	1.78	1.79	1.40	1.98	4.21	1.80	2.01	0.74	0.39	1.40	1.22
Na_2O	5.91	9.30	12.67	15.76	8.85	10.66	10.60	10.40	11.20	10.72	12.99	10.97
K_2O	4.92	4.19	3.17	3.58	2.98	3.02	4.38	4.10	3.35	3.28	3.67	5.86
P_2O_5	0.50	0.09	—	0.03	0.06	0.04	0.02	0.03	0.03	0.41	0.07	0.20
$H_2O\pm$	0.57	2.13	1.70	1.46	2.78	2.22	2.14	2.22	3.15	2.67	1.97	1.13
Cl	—	0.07	1.40	2.86	0.07	0.41	0.17	0.19	0.04	0.12	1.38	0.16
F	—	—	0.29	0.29	0.42	0.51	0.16	0.22	0.05	0.22	0.25	0.14
SO_3	—	0.05	0.16	n.d.	n.d.	n.d.	0.05	0.05	0.21	0.42	0.17	0.102
CO_2	—	0.04	n.d.	0.16	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Sum	99.87	99.84	100.06	100.90	100.38	98.86	100.12	100.06	100.14	100.72	100.51	100.17*
$-O \simeq Cl_2\ F_2$		—0. 2	—0.43	—0.75	—0.20	—0.80	—0.11	—0.13	—0.03	—0.12	—0.41	—0.10
Total	99.87	99.82	99.63	100.15	100.18	98.56	100.01	99.93	100.11	100.60	100.10	100.07

number of analyses indicated in parenthesis
— = absent
n.d. = not determined
tr. = trace amount
* = main pseudomorphing minerals of nepheline

* Including 0.11% $(Nb, Ta)_2O_5$, 0.24% Tr_2O_3 and 0.27% loss due to calcination.

Analyses taken from Ussing (1912), Ferguson (1964, in press), Hamilton (1964), Gerassimovsky & Kuznetsova (1967) and Piotrowski & Edgar (in press).

TABLE 2. MAJOR ELEMENTS (continued)

Quantative partial analyses (unless indicated all values given as p.p.m.)

Chemical components	Augite syenite	Hetero-geneous syenite	Sodalite foyaite	Naujaite	Kakortokite				Green lujavrite	Black lujavrite	Average composition of agpaitic nepheline syenites at Ilímaussaq	Average compo-sition of Lovozero rocks
					Black layers	Red layers	White layers	Weighted average				
	(2)	(2)	(5)	(5)	(20)	(4)	(24)	(48)	(4)	(5)	(67)	
Rb	195	214	213	189	109	131	220	200	167	159	187	
Li	44	99	132	130	120	90	164	153	90	226	146	
Be	5	11	18	15	17	18	31	28	16	26	20	
Zr	532	1785	3367	2660	8107	1.74%	7139	8076	8243	5526	5181	
Ba	1490	55	46	51	91	168	226	205	176	58	110	
%TiO_2	2.31	0.51	0.19	0.20	0.25	0.07	0.13	0.14	0.09	0.12	0.16	
Nb	73	160	186	121	243	593	274	296	189	264	200	
Sr	203	105	114	74	133	246	148	154	132	145	118	
La	143	236	252	210	320	613	335	355	427	729	343	
Ga	42	63	90	94	59	55	86	80	80	102	89	
%CaO	3.48	2.44	2.86	2.47	2.23	3.69	2.30	2.40	1.55	0.56	2.13	
%Na_2O	5.45	6.58	9.66	15.17	9.25	10.40	9.63	9.65	9.84	10.29	12.24	
%K_2O	5.09	4.80	4.46	3.88	2.26	2.58	4.08	3.74	3.40	2.88	3.68	

TABLE 2. MAJOR ELEMENTS (continued)
Modal analyses (volume per cent)

Minerals	Augite syenite	Hetero-geneous syenite	Sodalite foyaite	Naujaite	Kakortokite				Green lujavrite	Black lujavrite	Average composition of agpaitic nepheline syenites at Ilímaussaq	Average compo-sition of Lovozero rocks
					Black layers	Red layers	White layers	Weighted average				
	(2)	(4)	(6)	(7)	(20)	(3)	(24)	(47)	(4)	(5)		
K-feldspar/ perthites	72.4	62.7	32.8	25.7	12.8	29.9	36.1	32.8	26.6	16.9	26.8	
albite laths	—	—	—	—	3.9	3.3	5.2	4.9	12.9	14.2	4.5	
nepheline	tr.	4.6	10.2	9.9	10.4	12.8	15.9	15.0	8.8	4.0	10.7	
altered	—	3.1	0.2		4.4	7.0	7.4	7.0	6.2	16.2	4.8	
pyroxenes	6.9	14.6	9.4	6.6	6.2	2.9	8.8	8.0	32.2	5.4	9.3	
amphiboles	3.7	10.1	9.2	5.6	42.9	10.4	9.7	13.8	3.3	36.8	11.9	
aenigmatite	—	—	tr.	1.7	tr.	0.3	0.2	0.2	tr.	tr.	0.8	
eudialyte	—	0.1	3.1	4.9	0.5	27.0	1.6	3.5	3.1	2.2	3.8	
altered	—	—	0.1	—	9.2	3.3	7.6	7.4	6.9	4.3	3.6	
olivine	6.3	0.2	0.1	—	—	—	—	—	—	—	—	
sodalite	—	tr.	18.7	40.2	0.7	—	0.8	0.7	tr.	tr.	18.9	
analcime*	—	2.8	7.4	3.6	4.2	1.3	5.0	4.6	pseudomorph nepheline		3.2	
natrolite*	—	1.8	8.8	1.7	4.7	1.8	1.6	2.0			1.6	
fluorite	—	—	tr.	0.1	0.1	tr.	0.1	0.1	tr.	tr.	0.1	
mica	5.5	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.	
apatite	1.0	—	—	tr.	—	—	—	—	—	—	—	
opaque(s)	3.6	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.	
chlorite	0.6	—	—	—	—	—	—	—	—	—	—	

is produced by enrichment of aegirine, arfvedsonite, feldspar and nepheline.

GEOCHEMISTRY

General

The geochemical characteristics of the agpaitic rocks have been discussed at some length by Gerassimovsky (1956, 1963 and 1967) and Sørensen (1960). It is sufficient to note that the geochemical characteristics of these rocks are largely determined by the high ratio of alkalies to aluminum. Due to the extreme mineral fractionation of the agpaitic rocks at Ilímaussaq representative sampling is a difficult problem. The naujaite offers additional sampling difficulties due to the pegmatoid dimensions of some of the minerals. In an effort to overcome these difficulties, specimens as large as 60 kg were taken from this group.

The average modal analyses of the agpaites, augite syenite and heretogeneous syenite are presented in Table 2. The kakortokite values have been quoted for the respective layers and a weighted average is also quoted. The latter average was calculated on the basis of the layers having the following thicknesses; black : red : white = 1.5 : 1 : 10 m. Other ratios have been used for these layers *viz.* 3 : 1 : 9 (Ussing, 1912) and 3 : 1 : 12 (Gerassimovsky and Kuznetsova, 1967). Estimates of these ratios are complicated by the transitional development of the red layers into the black and white layers. In addition, the weighted modal analyses for the agpaitic rocks are also given in Table 2. This calculation has been based on thickness estimates by the author (Ferguson, in press) which differ significantly from the figures quoted by Ussing (1912). These respective values, expressed as a percentage, are given in Table 3.

TABLE 3

	Ussing (1912)	Ferguson (in press)
sodalite foyaite	10	3
naujaite	30	45
kakortokite	10	30
green lujavrite	50	9
black lujavrite		13

Gerassimovsky & Kuznetsova (1967) used Ussing's values in their calculations. As only the thickness of the sodalite foyaite sheet is known with any certainty, these figures can at best be only very approximate. The average analysis of the major oxides does however show remarkable similarity to the equivalent analysis of the Lovozero agpaitic magma

(Gerassimovsky & Kuznetsova 1967) as reproduced in Table 2. The minor differences are that the latter intrusion is richer in Si, Ti, Mn, Mg, K, P and the Fe^{3+}/Fe^{2+} ratio is very high, whereas Ilímaussaq is richer in Na, Zr, Al, Cl and F.

Differentiation trends

The assembling of geochemical data was originally undertaken in order to evaluate the chronological classification of the rocks and to assess the validity of the correlation of two controversial rock types. In addition, 48 specimens of kakortokite were subjected to detailed geochemical analysis in an attempt to evaluate the validity of postulating that these rocks crystallized from the floor upwards (Ferguson, in press). Elements were selected for analysis on the basis that they had previously been useful in establishing fractionation trends.

The Na:K ratio of the Ilímaussaq rocks varies considerably (Table 4) from a near unity value for the augite syenite and heterogeneous syenite to a maximum average ratio of 3.91 in the green lujavrite. This value can reach as high as 8.85 in late-stage zeolite-rich rocks. It may be anticipated that rocks containing a high zeolite content would show a corresponding increase in the Na:K ratio due to their higher Na content. It was however found that a number of agpaitic rocks showed a reversal of this trend : namely, the rocks containing more than 10 per cent zeolites display a Na:K decrease compared to equivalent rocks with less than this amount of zeolite alteration. The main variations of the Na:K ratio are largely accounted for by the fluctuations in the proportions of the primary Na- and K-rock-forming minerals present. This fluctuation was particularly evident in the rhythmically-layered kakortokite sequence where extreme variations in this ratio occur. The respective enrichment of sodalite in the naujaite and sodalite foyaite and of aegirine in the green lujavrite account for the high Na:K values of these rocks in their relative positions in the differentiated sequence (Table 4). The progressive increase of the agpaitic index with differentiation correlated with the chronology deduced from field evidence.

The *Rb* content of the Ilímaussaq rocks varies within relatively narrow limits (Table 2). Volkov & Savinova (1959, p. 636) found that in the rocks from Lovozero the *Rb* content decreases with zeolitization. This applies in general to the Ilímaussaq rocks (Ferguson, in press). Ahrens *et al.* (1952) and other workers (Taylor *et al.*, 1956) have shown that the ratio of the K:Rb varies within restricted limits for a wide variety of rock types. The Ilímaussaq rocks are no exception ; they do however display a consistent Rb enrichment relative to K, as is the case for strongly differentiated magmas (Taylor *et al., op. cit.*). The augite syenites values approach the average K:Rb curve given by Ahrens *et al* (*op. cit.*) and the heterogeneous syenite values occupy a position intermediate to the augite syenite and the Rb enriched agpaites. As noted by various authors, a further feature of the K:Rb ratio is a decrease in this value with progressive differentiation (Demin & Khitarov 1958; Gerassimovsky & Lebedev 1959; Volkov & Savinova 1959; Butler *et al.*, 1962 and Siedner, 1965). For the Ilímaussaq rocks containing less than 10 per cent zeolites, the order of decrease of the K:Rb ratio coincides with the differentiated sequence established from the field evidence (Table 4). In the detailed kakortokite sequence there is a general decrease with height of the K:Rb ratio for the white and red layers and a similar but less well-defined trend for the black layers which, by contrast, display overall higher K:Rb values.

TABLE 4. AVERAGE RATIOS OF THE ILÍMAUSSAQ ROCKS

	Augite syenite	Hetero-geneous syenite	Sodalite foyaite	Naujaite	Kakortokite †	Green lujavrite	Black lujavrite
Na : K*	0.96	1.15	3.03	3.12	2.49	3.91	2.61
K : Rb*	217	187	172	171	162	146	146
Ba : K × 10^3	35.0	1.4	1.2	1.6	6.5	5.9	2.5
Ba : Rb	7.64	0.26	0.22	0.27	1.06	0.91	0.36
Ba : Sr	7.34	0.52	0.40	0.69	1.33	0.95	0.40
Sr : Ca × 10^3	8.2	6.2	5.4	5.3	10.2	19.4	42.8
Ti : Zr	26.00	1.71	0.34	0.90	0.11	0.06	0.13
Ti : Nb	189.5	19.1	6.2	8.6	2.8	2.7	2.7
Zr : Nb	7.3	11.2	18.1	22.0	27.3	43.6	20.9
Fe^{3+} : Fe^{2+}	0.44	1.05	1.11	1.25	1.13	6.21	0.84
Agpaitic index	0.92	1.09	1.32	1.34	1.35	1.38	1.45

increasing differentiation ⟹

† Weighted value

* For specimens containing less than 10 per cent zeolites

Li proved to be an entirely unsatisfactory element in the evaluation of differentiation trends, displaying erratic distribution (Table 2). The behaviour of Li may be attributed to the wide but irregular distribution of accessory lepidolite in the agpaitic rocks.

There is a general tendency for the rocks having the highest Ca contents to have a correspondingly high Sr content and vice versa but the covariance is by no means clearly marked. The sodalite foyaite and naujaite behave anomalously in this respect in that they show Sr deficiency relative to Ca (Table 2). A similar relationship was found to hold at Lovozero (Gerassimovsky & Lebedev 1958, p. 703) where the sodalite-rich rocks display a Sr deficiency relative to Ca. The Sr:Ca ratio of the Ilímaussaq rocks show some interesting trends (Table 4) ; except for a small reversal of the augite syenite and heterogeneous syenite values and the anomalous position of the sodalite-rich rocks, they display a progressive increase of this ratio with differentiation. The kakortokite suite also exhibits a general progressive increase of this ratio with differentiation. The presence of a high zeolite content in the rocks has no consistent effect on the Sr and Ca contents. Only minor variations exist between the Sr and Ca contents of the rock specimens low in zeolites and those of their zeolite-rich equivalents. In keeping with the alkaline rocks of Lovozero (Gerassimovsky & Lebedev *op. cit.*) and Kûngnât (Upton 1960), the Ilímaussaq rocks show a general decrease in the absolute amount of Ca and Sr with progressive differentiation. Gerassimovsky & Lebedev (*op. cit.*) accounted for the absence of a direct inter-dependance of these two elements by postulating isomorphous replacement of Sr by not only Ca, but also K. No covariance was shown by either a plot of Sr versus K or a plot of Ca + K versus Sr for the Ilímaussaq rocks. As pointed out by Siedner (1965, pp. 124-125) the concept of Sr-K diadochy results from the frequently substantial amounts of Sr in alkali feldspars in which Ba can be present in large amounts. Siedner suggested that Sr could substitute for either Ba or K with equal facility. As with the Paresis Complex (Siedner *op. cit.*) there is a fairly marked covariance between Ba and Sr for the Ilímaussaq suite, with the sodalite-rich rocks once again slightly anomalous by showing Sr enrichment relative to Ba. A further consideration is that Sr:K and Sr:Ca diadochy can be dependant on crystallochemical factors of the individual minerals (Heier 1966) so would vary with the mode.

Titanium and zirconium show antipathetic variation ; the augite syenite and heterogeneous syenite are richer in Ti, and the agpaites are richer in Zr (Table 2). Except for two very minor reversals the Ti:Zr ratio displays a progressive decrease with differentiation. Nb is concentrated in the agpaites and deficient in the augite syenite (Table 2). From a study of bond strengths, Ahrens (1953) predicted that the Ti:Nb + Ta and the Zr + Hf:Nb + Ta ratios would fall with increasing differentiation, as is the case at Lovozero (Gerassimovsky *et al.* 1959, p. 811). It is interesting in this respect that the Ti:Nb and Zr:Nb ratios of the Ilímaussaq rocks vary antipathetically. Except for minor reversals of the Ti:Nb and Zr:Nb ratios (Table 4) there is a progressive change which coincides with the chronology established from the field evidence. In contrast to

Lovozero where the Ti and Nb + Ta contents both increase with differentiation with progressive enrichment of the latter, at Ilímaussaq Ti decreases with differentiation, while it is Zr that becomes progressively enriched. A further exaggeration of the Zr:Nb ratios at Ilímaussaq may be due to the alteration of eudialyte resulting in a loss of Nb (Gerassimovsky & Kenkina 1960, p. 843). In the Ilímaussaq rocks, no correspondence could be established between the degree of eudialyte alteration or zeolitization and the Zr:Nb ratio. The Ti:Zr ratio for the layered kakortokite sequence showed an ill-defined decrease with height. A similar plot of the Ti:Nb and Zr:Nb ratios displayed an irregular trend.

CONCLUSIONS

The general correlation of fractionation trends with chronology is surprisingly good in view of the highly fractionated nature of the Ilímaussaq rocks. All the rock units discussed have rhythmic layering and, in addition, the presence of large grain-size presents major difficulties for representative sampling. The minor reversals present in some of the fractionation ratios employed can generally be accounted for by the variable mineralogical composition resulting in the partitioning of the elements.

ACKNOWLEDGEMENTS

The author is indebted to A.D. Edgar and J.M. Piotrowski for use of unpublished chemical analyses.

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