

A CLOSED SYSTEM CRYSTAL-FRACTIONATION MODEL FOR THE AGPAITIC ILÍMAUSSAQ INTRUSION, SOUTH GREENLAND WITH SPECIAL REFERENCE TO THE LUJAVRITES

JOHN ENGELL

ENGELL, J.: A closed system crystal-fractionation model for the agpaitic Ilímaussaq intrusion, South Greenland with special reference to the lujavrites. *Bull. geol. Soc. Denmark*, vol. 22, pp. 334-362. Copenhagen, December, 10th, 1972.

A differentiation trend for the Ilímaussaq magma, which is based on existing petrological and experimental data on the rocks of the intrusion, together with a consideration of the relevant synthetic investigations, suggests that the evolution was iron-depleted rather than iron-enriched products. The distribution of Zr and Be indicates that the agpaitic stage was reached after at least 75 wt % and probably 90-95 wt % of the original intrusion had solidified. The agpaitic rock sequence includes a flotation cumulate, the naujaite, and gravity sorted floor cumulates, the kakortokite and the lujavrite. It is suggested that the last two rock types formed simultaneously with the naujaite in the order listed. The large scale recurrent, mineral-graded layering in the kakortokite is explained as a direct consequence of the formation of the naujaite. Nine new analyses of lujavrites are reported, together with some mineralogical data.

John Engell, Mineralogisk Institut, Danmarks Tekniske Højskole, bygn. 204, 2800 Lyngby, Danmark. October 4th, 1972.

The Ilímaussaq intrusion (Fig. 1) (Ussing, 1912; Sørensen, 1958; Ferguson, 1964; 1970b; Hamilton, 1964) forms part of the Gardar magmatic province of South Greenland (Sørensen, 1966; Upton, in press).

The intrusion as defined by Ferguson (1964) (fig. 1) covers an area of approximately 150 square Km. and is composed of a discontinuous margin of augite-syenite chilled against the country rocks, and a central stratified series of more or less saucer-shaped units of alkali granite, quartz-syenite, pulaskite, heterogeneous syenite and the agpaitic rock sequence, namely: sodalite-foyaite, naujaite, lujavrite and kakortokite, the whole series being named from the top downwards. The naujaite is strongly brecciated and interveined by lujavrite, especially in its lower parts.

There is some disagreement about the time and mode of formation of the acid rock sequence, the pulaskite and the heterogeneous syenite (for a

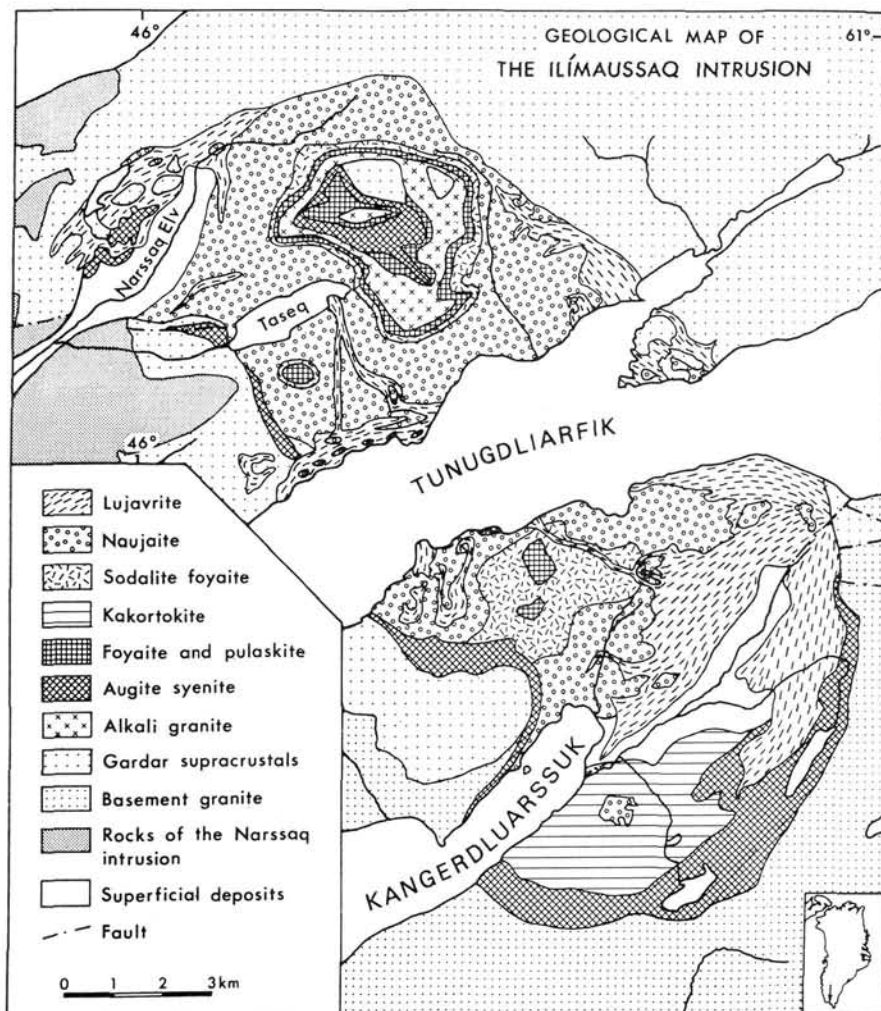


Fig. 1. Simplified geological map of the Ilímaussaq intrusion after J. Ferguson (1964).

discussion of this see Ferguson, 1964; 1970a; 1970b). Only the agpaite rock sequence and its assumed augite syenitic parental magma will be considered here. The evolution of this part of the intrusion as viewed by Ferguson (1964) is summarized in fig. 2. This model is based on field evidence (Ferguson, 1964) and supported by geochemical data, (Hamilton, 1964; Ferguson, 1970a, b) especially the variation in K:Rb, Sr:Ca, Ti:Zr and Ti:Nb ratios.

The present contribution to the discussion of the evolution of the Ilímaussaq magma investigates the consequences of a closed system, crystal-fractionation model for the intrusion. Although this model probably is a sim-

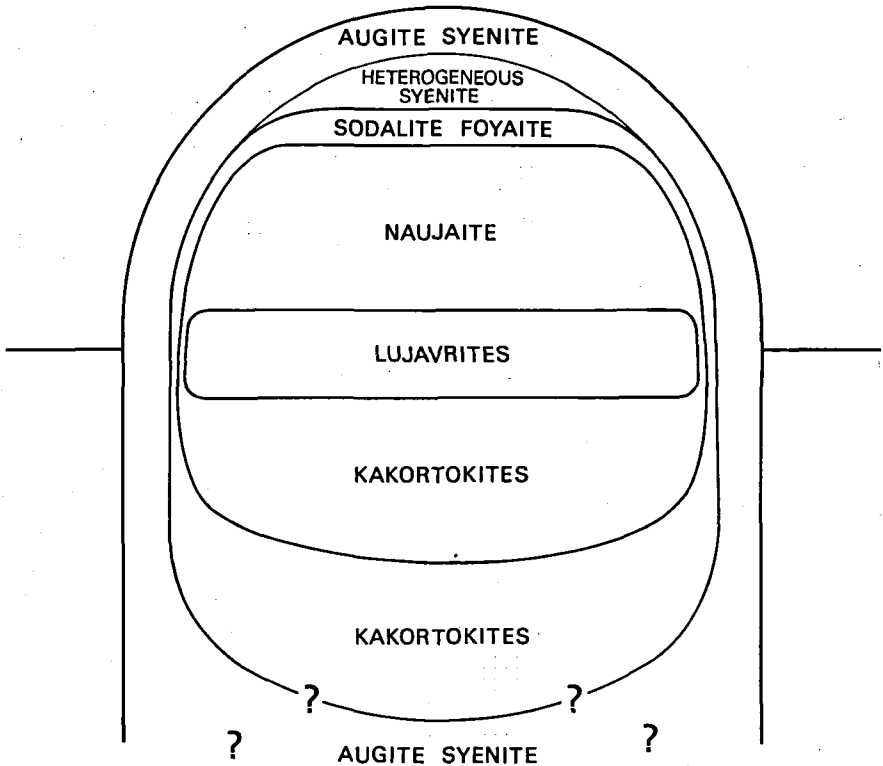


Fig. 2. Schematic representation of the evolution of the Ilímaussaq intrusion after J. Ferguson (1964).

plification it is thought to be useful as a limiting case.

To visualize the differentiation trend of the "Ilímaussaq magma" and to facilitate a comparison with experimental results, in particular the peralkaline-residua system, $\text{Na}_2\text{O}-\text{Al}_2\text{O}_3-\text{Fe}_2\text{O}_3-\text{SiO}_2$ (Bailey & Schairer, 1966), the rock compositions have been projected into a quaternary variation diagram N-A-F-S where N is total alkalis recalculated as Na_2O , Al is Al_2O_3 , F is total iron recalculated as Fe_2O_3 and S is SiO_2 . The oxides Na_2O , K_2O , Al_2O_3 , Fe_2O_3 , FeO and SiO_2 together make up about 90 wt % of the totals of all the rock in question. To locate where the rocks plot in this diagram two projections are given (fig. 3 & 4):

- 1) The projection from S into the bounding plane N-A-F (fig. 3).
- 2) The projection from F into the plane Ab-Ne-Ac in the peralkaline residua system (fig. 4).

The average compositions of the different rock types (table 1) as well as 28 analyses of lujavrites from the intrusion have been plotted. The 28 lujavrites include nine samples analysed in connection with the present

work (table 2) as well as analyses taken from Ussing (1912), Gerassimovsky & Kuznetsova (1967) and Sørensen et al. (1969).

In the following, the individual rock types will be discussed relative to the plots in figs. 3 & 4 in the order in which they are assumed to have formed (Ferguson, 1964) to see what limitations each places on the composition and fractionation path of the magma. Finally, the proposed trend is discussed relative to phase relations in synthetic systems.

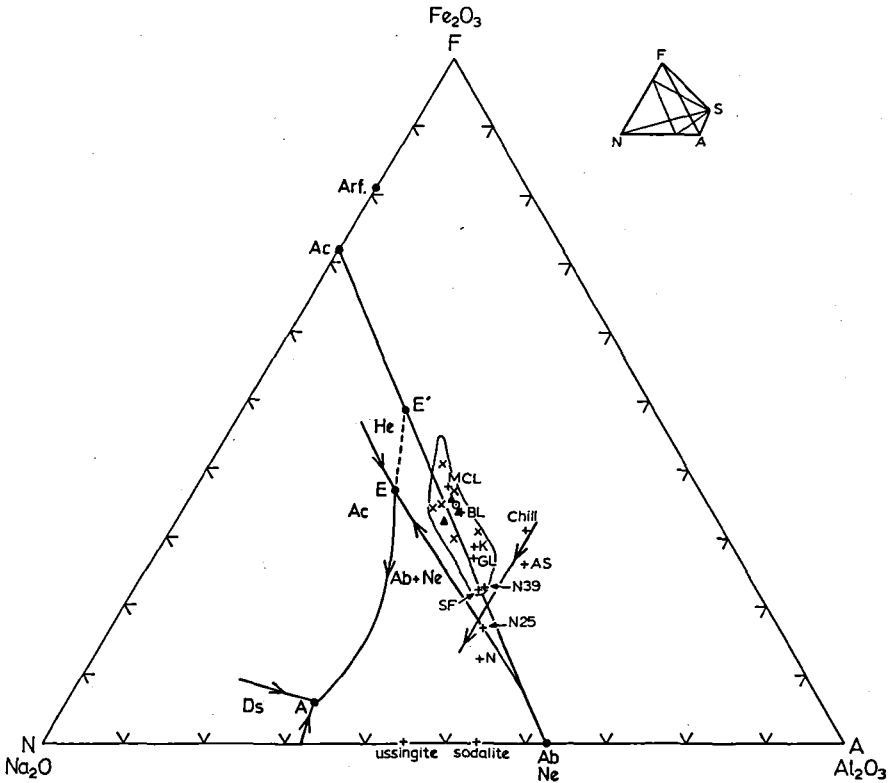


Fig. 3. Projection in the N-F-A-S diagram from S into NFA. Chill: Average chilled augite syenite. AS: coarse-grained augite syenite. SF: Sodalite foyaite. N: Naujaite. N25: Naujaite minus 25 wt % sodalite. N39: Naujaite minus 39 wt % sodalite. K: Kakortokite. GL: Green lujavrite. BL: Black lujavrite. MCL: medium-coarse-grained lujavrite from the Kvanefjeld area. X: Nepheline-eudialyte lujavrite (table 2). ▲: Naujaka-site-steenstrupine lujavrite (table 2). ○: Analcime-steenstrupine lujavrite (table 2). The area in which all analysed lujavrites (28) from the Ilímaussaq intrusion plots is outlined by a thin solid line. The proposed differentiation trend is indicated by a heavy solid line. The phase relation (1 atm, P_{O_2} = air) close to the albite-nepheline surface in the peralkaline residua system have been projected into the diagram (based on Bailey & Schairer, 1966). E: reaction point where Ab, Ne, Ac, He and liquid coexist. E': projection from F of this point into the trace of the other projection used (fig. 4). A: eutectic point where Ab, Ne, Ac, Ds and liquid coexist.

Table 1. Average composition of rocks from the Ifmaussaq intrusion; number of analyses indicated in parenthesis.

	Augite ¹ Syenite Chill (4)	Augite ¹ Syenite coarse- grained (4)	Sodalite ² Foyaite (2)	Naujaite ² (9)	Kakortokite ² (12)	Green ³ lujavrite (6)	Black ³ lujavrite (6)	Medium-to coarse-grained lujavrite Kvanefield (4)
SiO ₂	53,91	57,58	49,97	46,85	51,83	53,15	52,89	53,55
TiO ₂	1,65	1,20	0,55	0,30	0,29	0,28	0,35	0,42
ZrO ₂	nd	nd	0,43	0,41	1,16	1,12	0,64	0,11
Al ₂ O ₃	15,96	16,65	18,35	22,30	15,97	16,03	14,59	12,17
Fe ₂ O ₃	3,43	2,75	4,96	3,07	6,15	9,39	6,30	5,26
FeO	6,83	5,80	4,04	2,21	4,90	1,18	6,77	8,01
MnO	0,21	0,22	0,15	0,13	0,29	0,23	0,41	0,60
MgO	2,02	0,73	0,43	0,09	0,25	0,41	0,54	0,14
CaO	4,55	2,20	1,79	1,40	2,01	0,72	0,39	0,67
Na ₂ O	5,56	6,25	12,67	15,76	10,40	11,13	10,72	7,95
K ₂ O	4,73	5,10	3,17	3,58	4,10	3,45	3,28	6,01
P ₂ O ₅	0,55	0,48	-	0,03	0,03	0,07	0,41	0,47
H ₂ O [±]	0,60	0,53	1,70	1,46	2,22	3,15	2,52	3,07
Cl	nd	nd	1,40	2,86	0,19	0,07	0,12	nd
F	nd	nd	0,29	0,29	0,22	0,05	0,22	nd
Total	100,00	99,49	99,90	100,74	100,01	100,43	100,15	98,43

-- not detected

nd=not determined

1 Hamilton (1964); average augite syenite contains 532 ppm Zr and 5 ppm Be Ferguson (1970b)

2 Ferguson (1970b); average sodalite foyaite contains 3.367 ppm Zr and 18 ppm Be

3 Gerassimovsky & Kuznetsova (1967)

4 Sørensen et al. (1969)

Table 2. Lujavrites from minor intrusions in the naujaite.

1. Nepheline-eudialyte lujavrite. 2. Naujakasite-steenstrupine lujavrite. 3. Analcime-steenstrupine lujavrite

G.G.U.	Tuperssuatsiait				Taseq area							
	No. 64832 ¹	64855 ¹	93682 ²	77019 ²	65917 ¹	65923 ²	65942 ³	85708 I ¹	85708 III ¹	85708 IV ¹	*85708 IV ¹	
SiO ₂	52.25	52.93	52.07	50.58	51.78	53.31	53.27	53.16	49.79	52.49	52.29	
TiO ₂	0.34	0.29	0.26	0.33	0.27	0.23	0.23	0.24	0.29	0.21	0.22	
ZrO ₂	0.84	0.27	0.45	0.34	1.03	0.17	0.20	1.31	0.39	0.72	0.72	
Al ₂ O ₃	12.11	13.61	14.19	14.97	11.23	12.19	13.03	12.26	12.01	13.67	14.02	
Fe ₂ O ₃	5.00	3.63	4.19	4.42	10.94	4.27	6.10	10.35	5.77	9.66	9.97	
FeO	9.24	10.18	8.70	9.03	1.14	8.11	6.42	2.82	10.16	1.34	1.34	
MnO	0.77	0.60	1.18	1.04	0.54	0.93	0.59	0.38	0.17	0.54	0.43	
MgO	0.07	0.12	0.10	0.08	0.11	0.09	0.11	0.09	0.08	0.07	0.56	
CaO	0.41	0.30	0.49	0.31	0.79	0.43	0.27	1.15	0.30	0.32	0.00	
Na ₂ O	10.33	10.42	11.01	14.04	10.15	9.39	10.05	11.14	10.43	10.91	11.35	
K ₂ O	2.50	3.46	2.96	2.10	3.52	3.76	2.93	3.05	3.40	3.07	3.22	
H ₂ O	2.76	2.70	3.15	1.66	3.03	3.03	3.35	3.11	1.50	3.70	3.70	
Cl	0.02	0.05	0.01	-	0.15	0.12	0.03	0.10	0.43	0.09	0.09	
F	-	-	-	0.14	-	-	-	-	-	-	-	P ₂ O ₅ 0.80
Total	96.64	98.56	98.76	99.04	94.68	96.03	96.58	99.16	95.26	96.79	98.71	
ppm												
Th	424	100	354	-	149	846	1160	131	154	260	ZrO ₂ & Cl	
U	540	157	445	-	177	448	312	117	202	352	determined by	
Sr	50	50	50	-	50	50	50	80	50	50	XRF	

77019 from Gerassimovsky & Kuznetsova (1967)

Methods of analysis: XRF fusion technique Si, Ti, Al, Fe, Ca and K briquettes of powdered rocks Zr, Sr, Mn and Cl atomic absorption MgO and Na₂O

Geochem. Lab. G.G.U. FeO H₂O

γ-spectrometry U and Th

* Analysed by Geochem. Lab. G.G.U. as a control on the XRF major element analyses. A high concentration of P₂O₅ and RE not analysed for is thought to be the reason for the low sums.

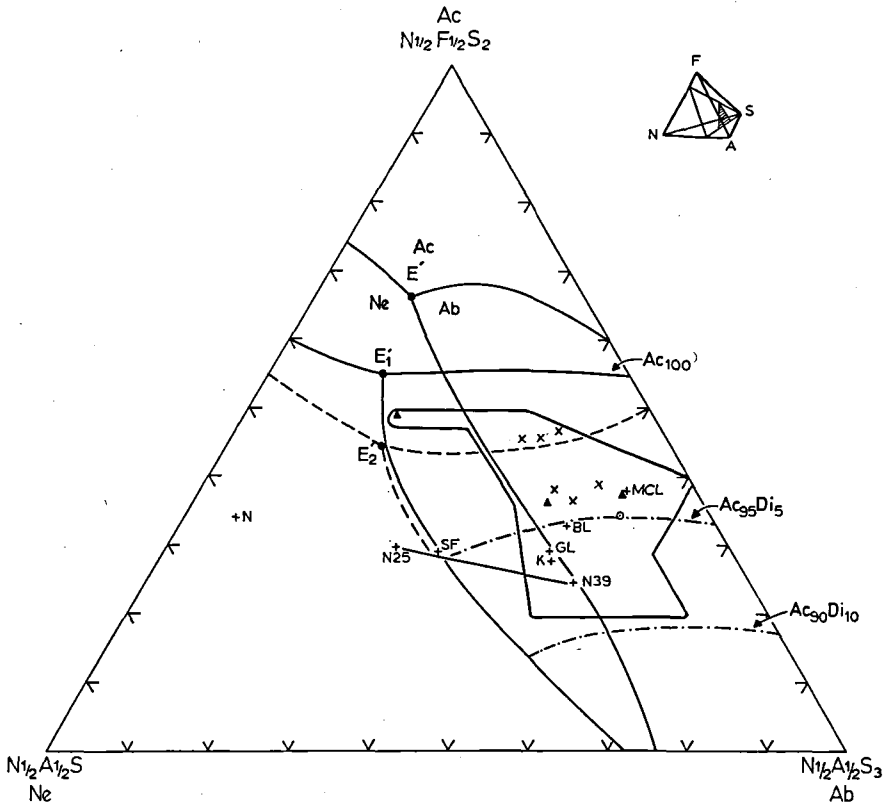


Fig. 4. Projection in the N-F-A-S diagram from F into the plane



Abbreviations as in fig. 3. The chill and the coarse-grained augite syenite plots close to the "albite" corner, but have negative "acmite" coordinates and are therefore not shown. The phase relations on the surface of the ironoxide volume in the peralkaline residua system have been projected into this plane. E': is the projection of the reaction point where Ab, Ne, Ac, He and liquid coexist at 1 atm and $P_{O_2} = \text{air}$ (Bailey & Schairer 1966). E'1 and E'2 represent the analogous reaction points at 1 and 2 Kb water pressure respectively and $P_{O_2} = \text{NNO}$ (Nolan, 1966; Edgar & Nolan, 1966). The marked expansion of the clinopyroxene field with the addition of a small amount of diopside to the system is shown in a projection from F and diopside (dash - dot line) (Nolan, 1966).

The augite syenite

According to Ferguson (1970b) the apgaitic rock sequence in the Ilímaussaq intrusion was derived from a slightly undersaturated syenitic magma now represented by the discontinuous marginal zone of augite-syenite chilled against the country rock. The average of four analyses of the fine-grained chill (table 1, figs. 3 & 4) is thought to approximate the composition of the

initial magma fairly closely except for volatile elements (Hamilton, 1964), i.e. H_2O , $NaCl$, CO_2 etc.

There is some disagreement about the sequence of crystallization for this syenite magma (Ferguson, 1964; Hamilton, 1964). The marginal syenite probably formed under somewhat supercooled conditions and it is likely that the texture of the rock does not reflect the equilibrium order of crystallization. The evidence from other intrusions in the Gardar province where layered syenites of similar composition occur is that feldspar, olivine, clinopyroxene, ilmenomagnetite and apatite crystallized simultaneously (Upton, 1960; 1964).

As the fractionation proceeded, the initial magma developed in an undersaturated direction as is indicated by the increase in modal nepheline from less than 1 vol % in the chill-zone to about 5 vol % near the contact with the stratified rock sequence (Hamilton, 1964). The average composition of the coarse-grained augite-syenite is also given in Table 1 and plotted in the variation diagram.

The sodalite-foyaite stage

According to Sørensen (1958; 1968; 1969) and Ferguson (1964; 1970 a; 1970 b) the heterogeneous syenite and sodalite foyaite was formed by successive congealing of the magma from the roof. These rocks are regarded as analogous to the upper border group of the Skaergaard intrusion (Sørensen, 1969).

The sodalite foyaite marks the beginning of the agpaitic stage and is generally assumed to approximate the composition of the magma fairly closely because the calculated average composition of the agpaitic rock sequence is very similar to the composition of the sodalite-foyaite itself (Ussing, 1912; Sørensen, 1958; 1968; 1969; Garassimovsky & Kuznetsova, 1967). The lack of any obvious cumulus mineral, except for small quantities of sodalite (Ferguson, 1964, p. 47), the complex mineralogy, the marked zoning in the clinopyroxene and the well-developed reaction relationship between clinopyroxene and alkali amphibole, olivine and magnetite, alkali feldspar and analcime etc. (Ferguson, 1964) also favour this interpretation.

From the plots in figs. 3 & 4 it appears to be possible to form a magma of sodalite-foyaite composition from the assumed initial Ilímaussaq magma by crystal-fractionation of an assemblage, including a calcic alkali feldspar (plotting between Ab and A in fig. 3) and at least one iron rich phase, but it is impossible if no iron-rich phase fractionates.

Because of the different habits of the individual minerals in the sodalite-foyaite it is very difficult if not impossible to evaluate on textural evidence the order of crystallization of minerals belonging to different reaction series.

Petrographic evidence (Ferguson, 1964) does not conflict with, and partly supports the premise that alkali feldspar, fayalitic olivine, calcic clinopyroxene, sodalite, nepheline and possibly eudialyte and apatite (one crystal observed by Ferguson, 1964, p. 48) were liquidus phases at this stage. Too little is known about the Ti-Fe oxide to decide if it still remained on the liquidus or had reacted out. Most, if not all of the magnetite appears to be secondary after fayalitic olivine, and no primary Ti-Fe oxide has been recorded from the later agpaitic rocks, these containing aenigmatite instead. The olivine apparently reacts out at this stage as it has not been recorded from the later rocks.

A simultaneous crystallization of felsic and mafic minerals is not favoured by the melting experiments on rocks from the Ilímaussaq intrusion performed by Piotrowsky & Edgar (1970) and Sood & Edgar (1970). These experiments were however done at relatively high P_{O_2} above the NNO buffer. As the sodalite-foyaite is undersaturated and contains nearly pure fayalite partly altered to magnetite it is likely that P_{O_2} in the magma at this stage was close to that of the QFM buffer and possibly lower (Nash et al., 1969). This could perhaps explain the divergence.

In the sodalite-foyaite, the concentration of Zr is about six times higher and Be is about four times higher than in the augite-syenite (table 1). The average sodalite-foyaite is only based on two analyses, but it appears that if the "sodalite-foyaite magma" was formed by crystal fractionation, a minimum of 75 % of the original intrusion must have solidified before this stage. This is assuming total rejection of the two elements by the fractionating phases and a sequence of cumulates which is composed of 100 % cumulus material. Both of these assumptions appear unlikely and one might hazard a guess that about 90 to 95 % of the original intrusion had solidified before the sodalite-foyaite stage was reached. Assuming a cylindrical form for the intrusion and that the whole of the exposed agpaitic rock sequence, about 1500–1800 metres, was formed later than the sodalite-foyaite (Ferguson, 1964), then the original magma chamber would have been 15–36 km deep and could thus have reached down to the upper mantle. This rough calculation stresses the difficulties in the approach adopted here.

All petrologists, who have studied agpaitic rocks, agree on the importance of volatiles in the formation of these rocks. Sørensen (1958; 1960) believes that the formation of the Ilímaussaq agpaitic magma involved volatile transfer of alkalis and trace elements in the way discussed by Saether (1948) and Kennedy (1955). Burnham (1967) discussing volatile transfer on a physiochemical basis, points out the weakness in Kennedy's (1955) analysis of the distribution of water in oversaturated silicate melts and concludes that volatile transfer is unlikely unless a separate gas phase evolves from the magma, i.e. unless the magma is saturated with volatiles. There

is no evidence for this in the intrusion. Further, in the lower part of the kakortokites there is evidence for convection which would have kept the magma homogeneous (Sørensen, 1969). This rock sequence is assumed to have formed partly simultaneously and partly after the sodalite foyaite (Ferguson, 1964). Lacking any positive evidence for volatile transfer the author prefers to explain the "sodalite foyaite magma" as a residual magma formed by fractional crystallization alone.

It is important for the following discussion to put limits on the Cl-content of the magma at this stage. The sodalite-foyaite contains two Cl-bearing minerals, sodalite and eudialyte. It further contains nepheline with inclusions of small irregular blebs of sodalite (Ferguson, 1964, p. 48). It is likely that the formation of sodalite instead of nepheline is controlled by the Cl-content of the magma, and it seems that the Cl-content was too low to convert all the nepheline to sodalite. As mentioned, the sodalite-foyaite contains a small amount of cumulus sodalite, but no estimate of the amount is available. It is also likely that some Cl was lost together with other volatiles as the magma crystallized. It thus appears that at present the best estimate of the Cl content of the magma at this stage is the average concentration in the corresponding rock, that is 1.4 wt % Cl. If as suggested above, 90–95 % of the original intrusion had solidified at this stage, one can estimate that the Cl-content of the initial magma must have been of the order of 0.1–0.2 wt %. This is not an unreasonably high concentration as Macdonald & Edge (1970) find that about 0.04–0.08 wt % Cl has been retained in trachydolerites belonging to the Gardar magmatic province.

The naujaite-kakortokite stage

The sodalite-foyaite passes gradually downwards into a poikilitic sodalite-syenite, the naujaite. The naujaite is composed of numerous small crystals of sodalite poikilitically enclosed in large grains of alkali feldspar, aegirine, arfvedsonite and eudialyte of varying sizes and forms (Ussing, 1912; Ferguson, 1964 and Hamilton, 1964).

Ussing (1912) recognized the naujaite as a sodalite-flotation-cumulate, a view held by subsequent students of the intrusion. Ferguson (1970b) further regards nepheline as an occasional cumulus mineral in the naujaite.

The deepest exposed zone in the intrusion is represented by the kakortokites (Sørensen, 1958; Ferguson, 1964). This sequence comprises about 30 layered units. Each unit is about 12 m thick with a lower arfvedsonite-rich layer (black), upwards passing into a eudialyte rich layer (red) which again passes into a feldspar-rich layer (white). Frequently the eudialyte-rich layer is suppressed and sometimes entirely lacking. Both upwards and downwards the regular large scale mineral layering disappears. The lower-most exposed

part of the kakortokites is composed of thin mainly gravity-stratified layers separated by thicker layers of fairly homogeneous feldspar – or eudialite – rich kakortokite. Current-bedding and wash-out troughs filled by gravity stratified layers, all lacking in the main layered series, are common here (Upton, 1961; Sørensen, 1969). Upwards the kakortokite shows a rapid transition into aegirine lujavrite in which mineral layering although not entirely lacking is much suppressed (Ferguson, 1964; Bohse et al. 1971).

It is generally agreed that aegirine and arfvedsonite (as well as aenigmatite) are cumulus minerals in black layers and that alkali feldspar, nepheline and eudialyte are cumulus minerals in all layers. It is possible that small prisms of aegirine and arfvedsonite in the red and white layers are of cumulitic origin too (Sørensen, 1969). Lack of compositional zoning of the kakortokite minerals is taken as evidence for extensive accumulative growth (Ferguson, 1964) and makes an estimate of the amount of intercumulus liquid impossible with the data available at present.

Ussing (1912) recognized the kakortokite as gravity sorted cumulates. Sørensen (1969) gives a detailed discussion of possible mechanisms for the formation of the layering. He concludes that convection was of some importance for the formation of the lowest part of the kakortokites, but after that the magma was stagnant, i.e. a density gradient was developed. Sørensen (1969) further concludes that the large scale layering most likely is produced by a combination of intermittent crystallization and gravity settling.

According to the generally accepted model (Ferguson, 1964) the kakortokite is believed to have formed partly simultaneously with the naujaite. The complementary relation between the two rock types relative to the proposed fractionation trend is clearly seen in figs. 3 & 4.

With the presumption that sodalite is the only important cumulus mineral in the naujaite, and that accumulus growth has been negligible it is possible to estimate the composition of the intercumulus material in the naujaite (Ussing, 1912).

Sørensen (1969) elaborated Ussing's calculations on the basis of more extensive chemical data for the naujaite (Gerassimovsky & Kuznetsova, 1967). Assuming that most of the Cl present in the naujaite is found in sodalite, he calculated the composition of the interstitial material. Taking this as the composition of the top part of the magma at this stage he then compared it with the average agpaite (Gerassimovsky & Kuznetsova, 1967) and found that "the uppermost part of the magma was enriched in SiO_2 , K_2O , CaO , H_2O and F, probably by gaseous transfer of material or liquid fractionation (Hamilton, 1965)" (Sørensen, 1969, p. 296). Sørensen's calculations are reproduced in table 3. It is a maximum estimate; clearly some sodalite must also form from the intercumulus material. The method of

calculation requires that the amount of sodalite formed in this way is proportional to the amount of Cl in the magma. As a first approximation the Cl content of the intercumulus material can be taken to be equal to the Cl content of the sodalite foyaite magma. The amount of cumulus sodalite estimated in this way is about 25 wt %, two thirds of the amount estimated by Ussing and Sørensen. As can be seen from table 3 the effect of this assumption is to decrease the difference between the composition of the "intercumulus material" and the average agpaite.

Table 3.

	Average Naujaite ¹	Sodalite ²	Naujaite minus 39 % Sodalite	Naujaite minus 25 % Sodalite	Average agpaite ¹
SiO ₂	46.82	36.50	53.31	50.25	50.66
TiO ₂	0.30		0.49	0.40	0.35
ZrO ₂	0.41		0.69	0.55	0.75
Al ₂ O ₃	22.42	31.53	16.57	19.39	17.57
Fe ₂ O ₃	3.00	0.19	4.79	3.93	5.86
FeO	2.10		3.43	2.80	3.77
MnO	0.13		0.21	0.17	0.25
MgO	0.16		0.26	0.21	0.38
CaO	1.24	0.25	1.86	1.57	1.09
Na ₂ O	15.93	26.30	9.27	12.49	12.65
K ₂ O	3.61	0.18	5.79	4.76	3.40
P ₂ O ₅	0.03		0.05	0.04	0.14
H ₂ O	1.52		2.49	2.03	2.27
SO ₃	0.15		0.25	0.20	0.24
Cl	2.90	7.30	0.08	1.43	1.11
F	0.29		0.47	0.39	0.19
	101.01	102.25	100.01	100.61	100.68

¹ Gerassimovsky & Kuznetsova (1967)² Lorenzen (1881)

As the average naujaite contains approximately twice as much Cl as the sodalite-foyaite, it can be argued that the Cl-content of the magma would decrease as the naujaite is formed, and therefore that the 25 wt % cumulus sodalite represents a minimum estimate. If, however, as proposed, the karkortokite (0.2 % Cl) formed simultaneously with the naujaite by bottom accumulation, the average Cl-content of the fractionating phases would be less and it is possible that the average Cl-content of the magma stayed constant or perhaps even increased. A further difficulty in estimating the Cl-content of the intercumulus material exists if the magma was stratified at this stage (Sørensen, 1969).

The compositional range covered by the average naujaite minus 25 to 39 wt % sodalite has been plotted in figs. 3 & 4. The minimum estimate is thought to be closer to the true value than the maximum estimate.

One of the consequences of the proposed model is the postulation of an original magma chamber somewhat larger than that proposed for the Skaergaard intrusion, but with approximately the same vertical dimension. As in the Skaergaard intrusion it is assumed that crystallization took place in the peripheral parts and especially in the top of the magma chamber where the heat loss was highest.

Bottinga & Weill (1970) discuss the relation between density, temperature and composition of magmas. Their data strongly suggest that unless the differentiation trend is towards strong iron-enrichment, a stratified magma can form by crystal fractionation alone. Their data indicate that if the trend is as advocated here, convection would only be possible if some degree of super-cooling occurred at the top of the magma chamber. The disappearance of structures indicating current activity in the main layered series of the kakortokite could be taken as evidence that for some reason supercooling at the top of the magma chamber decreased in importance (Sørensen, 1969). It is suggested here that the reason is the formation of the naujaite.

The temperature distribution at the top of the magma chamber must be strongly affected by the transition from a situation where, the magma is congealing slowly at the roof to form the "upper border group" and nearly all the crystals formed sink out and convection periodically transports super-cooled material away; to a situation where crystals are accumulated at the top by flotation. The heat released by crystallization of the trapped intercumulus material must certainly slow down the rate of heat extraction from the magma below. Further as the intercumulus material crystallizes excess volatiles and sodium silicates etc. are expelled preferably downwards. This will cause a decrease in density as well as a decrease in the liquidus temperature at the top of the magma chamber and perhaps even prevent crystallization for some time. The efficiency of this process depends strongly on the combined effect of the rate of heat extraction, the rate of accumulation of sodalite crystals, and the diffusion rate of volatiles etc. in the magma.

It is suggested here that the large-scale mineralogical layering in the kakortokite is the result of intermittent crystallization produced in this way. Sodalite, nepheline, alkali feldspar, aegirine-augite, arfvedsonite, aenigmatite and eudialyte are supposed to be on or very close to the liquidus at this stage.

The lujavrite stage

The youngest agpaitic rocks in the intrusion are the lujavrites. These rocks

occupy the space between the kakortokite and the naujaite forming an irregular unit 200 m (Ferguson, 1964) to 350 m (Ferguson 1970 a; 1970 b; 1970 c) thick. The lujavrites overlie the kakortokite conformable (Ferguson, 1964; Bohse et al. 1971), but intrude the overlying rocks. At the junction between the naujaite and the main lujavrite sheet a breccia zone is developed with huge angular blocks of naujaite often several tens of metres long separated by fissile lujavrite. Because of this any earlier contact relations between these two rocks are obscured.

According to Ferguson (1964) the central main sheet can be divided into a lower aegirine lujavrite zone "the green lujavrite" and an upper arfvedsonite lujavrite zone "the black lujavrite". The two zones both of equal thickness are separated by a transition zone of about 50 m. Arfvedsonite lujavrites of different types dominate among the intrusive lujavrites.

An interesting feature of the lujavrites is their structure. Except for a few special varieties (Sørensen et al. 1969; Petersen, 1966) they are medium to fine-grained displaying trachytoid structure and often paralleling this a marked schistosity. Other signs of deformation include abundant occurrences of deformed crystals, boudinage, brecciation and auto-intrusion (Ferguson, 1964; 1970 c). These structures are thought to be the result of "penecontemporaneous deformation" related to the closing stage of the evolution of the intrusion (Ussing, 1912; Sørensen, 1958; 1962; 1968; Ferguson, 1964; 1970 c). Ferguson (1964; 1970 c) has described small-scale layering in the lujavrites. The layering is best developed in the transition zone. Layering due to alternating arfvedsonite and aegirine-rich lujavrite is common. Feldspar-rich layers showing density stratification have been observed in both types of lujavrite. Other types of layering involving both compositional and textural changes have also been reported by Ferguson (1964). Sørensen (1968 b) classifies the lujavrites as "ad-to meso-flow-cumulates". Both authors agree that the cumulus minerals in the main lujavrite sheet are sodalite, nepheline, albite, microcline, eudialyte and aegirine. The amount of cumulus aegirine in the black lujavrite is small.

The arfvedsonite forms a special problem. Distinctly poikilitic arfvedsonite enclosing all the other minerals of the rock is of widespread occurrence in the green lujavrite. This arfvedsonite post dates the fissility of the rock (Ferguson, 1964). According to Sørensen (1962; 1969) the texture of the black lujavrite also indicate an intercumulus origin of the arfvedsonite in these rocks. On the other hand the layering is difficult to explain if all the arfvedsonite is of intercumulus origin and Ferguson (1964, p. 76) regards arfvedsonite as a cumulus mineral in the black lujavrites. Minor amounts of needle shaped arfvedsonite in the green lujavrite reported by Ferguson (1964, p. 69) could be of cumulus origin too.

Observations from a lujavrite sheet at Tuperssuatsiait described below

lead to the suggestion that most of the arfvedsonite in the black lujavrite originally crystallized in, and was accumulated in radiating groups of prisms, and that the present interstitial character was inherited from the superimposed deformation combined with recrystallization.

The most important intercumulus mineral in the lujavrite is analcime (Ussing, 1912; Sørensen, 1962 and Ferguson, 1964). Due to the weakly-developed or entirely-lacking zoning of the minerals in the lujavrites it appears at present impossible to make a quantitative estimate of the amount of cumulus and intercumulus material in these rocks.

The lujavrites studied here all come from minor intrusion in the naujaite, from Tuperssuatsiait in the southern part of the intrusion (Petersen, 1966) and from the Taseq area in the northwestern part (Engell et al. 1971). They range from lujavrite *sensu stricto*, i.e. a melanocratic nepheline-eudialyte syenite to naujakasite-steenstrupine lujavrite and analcime-steenstrupine lujavrite. The three types being related through discontinuous reaction series among the sodium-alumina-silicates (Danø & Sørensen 1959; Sørensen, 1962) and the Zr-RE minerals (Sørensen, 1962):



At Tuperssuatsiait only the first two types occur whereas all three types are represented in the Taseq area. The modes and chemistry of the analysed rocks are given in tables 4 & 2 respectively. Petrographic evidence fails to prove any order of crystallization among a large number of minerals in each type of lujavrite. These minerals are listed in table 5. On the other hand a simultaneously crystallization of these minerals cannot be proved although it appears likely. The nepheline-eudialyte lujavrites and the naujakasite-steenstrupine lujavrites contain a variable amount of analcime in cm sized poikilitic crystals including all the other minerals. The analcime also replaces albite, nepheline and naujakasite to a varying degree. The replacement is strongest where the rocks are richest in poikilitic analcime. A variable amount of natrolite replacement is also seen.

Judging from their optical properties, the major minerals of the lujavrites appear to have roughly the same composition in all the lujavrites. The compositions of the coexisting nepheline, albite, microcline and arfvedsonite have been determined in one lujavrite (85708 IV) using microprobe, X-ray and wet chemical methods. The results are summarized in table 6.

Table 4. Mode of analysed lujavrites.

G.G.U. no.	Tupersuatsiait					Taseq slope					
	64832	64855	93682	85708 I	85708 III	85708 IV	65917	65923		65912	
	1000	1000	800	1000	1000	1000	500	700	500	420	estimated
Aegirine	tr	-	tr	25	2	29	30	-	tr	5	20
Arfvedsonite	30	34	28	11	44	7	2	36	36	26	60
Microcline	7	7	11	13	7	19	22	16	11	6	10
Albite { fresh	+ }	27	3	-	20	+ }	-	13	tr	-	-
{ altered to { analcime	+ }	-	tr	tr	-	+ }	tr	-	+	-	-
{ natrolite	+ }	14	-	-	-	-	-	-	-	-	-
Nepheline { fresh	+ }	6	-	9	15	+ }	-	-	-	-	-
{ altered to { sodalite	+ }	-	-	7	-	- }	-	-	-	-	-
{ analcime	+ }	-	-	-	-	+ }	-	-	-	-	-
{ natrolite	+ }	6	-	-	-	-	-	-	-	-	-
Sodalite	tr	2	6	4	tr	-	-	5	9	-	tr
Naujakasite (fresh & altered)	-	-	49	-	7	3	1	25	8	-	-
Analcime	-	-	tr	22	tr	31	30	tr	28	60	tr
Natrolite	10	14	tr	-	tr	-	-	tr	tr	-	-
Eudialyte (fresh & altered)	8	4	-	9	-	-	+ }	-	-	-	-
Steenstrupine	-	-	3	-	-	tr	+ }	2	4	3	10
"Green Mineral" (fresh & altered)	-	-	-	-	4	6	+ }	-	-	-	-
Other accessory minerals	tr	tr	tr	tr	1	1	5	3	4	tr	tr

tr < 1 %
 + precise amount not determined
 65923 a naujakasite rich part
 b analcime rich band
 65912 a analcime rich part
 b arfvedsonite rich part

Table 5. Supposed assemblage of simultaneously-crystallizing minerals in different types of lujavrites.

Nepheline-eudialyte lujavrite	Nepheline, Albite, Microcline, Sodalite, Arfvedsonite, Aegirine and Eudialyte
Naujakasite-steenstrupine lujavrite	Naujakasite, Albite, Microcline, Sodalite, Arfvedsonite (Aegirine) and Steenstrupine
Analcime-steenstrupine lujavrite	Analcime, Microcline, Sodalite, Arfvedsonite, Aegirine and Steenstrupine

At Tuperssuatsiait lujavrites occur in a composite sheet about 4 m thick. Petersen (1966) distinguishes between five types of lujavrites belonging to three phases of intrusion. These lujavrites are atypical in that lamination is either completely lacking or poorly developed. The earliest lujavrite a coarse-grained, light-coloured rock, is composed of radiating groups of thin arfvedsonite prisms in a hypidiomorphic, equigranular matrix. Similar but smaller star-shaped groups of arfvedsonite prisms are occasionally observed in the other rocks in this sheet except the youngest a naujakasite lujavrite. These stars are all in a state of breaking up, and a complete gradation is seen from the texture of the star-lujavrite to that of the normal lujavrite with small apparently interstitial prisms of arfvedsonite between well-shaped, occasionally bent crystals of the other "cumulus minerals". The deformation must have occurred before the final consolidation of the rock as cataclastic textures are absent or nearly so.

The three youngest types of lujavrite from the sheet have been analysed (64855, 64832 and 93682, tables 2 & 4).

At the Taseq slope a concentration of minor lujavrite intrusions cuts the naujaite. The largest intrusion is a sheet-like body which can be followed for more than 300 m attaining a maximum thickness of approximately 10 m. A concentration of dyke-like intrusions of lujavrite together with hydrothermal veins and alteration zones occurs in the naujaite above this sheet (Engell et al. 1971). The lujavrites examined here include a profile of the sheet (85708 I-IV) and three types from the dyke-like intrusions above it (65912, 65917, 65923).

As to the variation in chemistry between the lujavrites only two points shall be made.

Firstly the four elements Zr, Ca, Th and U show a large relative variation (fig. 5). The variations in Zr and Ca are antipathetic relative to Th and U although the scatter in the Th and especially U-content is large. This variation appears to reflect the change from eudialyte-bearing to steenstrupine-bearing lujavrites. There is a strong tendency for Zr and Ca to decrease simultaneously, indicating that the major part of the Ca is fixed in eudialyte with only a small amount occurring in the aegirine and arfvedsonite.

Table 6. Composition of coexisting minerals in a nepheline-arfvedsonite Iujavrite (85708 III).

In the microprobe work natural minerals were used for standards. The nepheline, albite and microcline was investigated using alkali feldspars. No suitable standard was available for the arfvedsonite, this is probably the reason for the high sum. The data for the arfvedsonite is corrected for massabsorption.

Nepheline

Method	Hamilton & Mackenzie 1960		Microprobe Ca, Na & K determined simultaneously
	2130	2022	
Ne	67-71	67-68	66-76
Ks	26-32	29-32	21-24
Qz	1,5-2,8	1,5-2,0	2,5-5,8
			Ca below detection limit

Albite

Method	Wright 1968	Microprobe Ca, Na & K determined simultaneously
Ab	93-97,5	99,6-98,5
Or	7-2,5	0,4-1,5
	extreme low temperature albite	Ca below detection limit

Microcline

Method	Wright 1968	Microprobe Ca, Na & K determined simultaneously
Ab	2,5-0	5,0-2,5
Or	97,5-100	95-97,5
	extreme low temperature microcline	Ca below detection limit

Arfvedsonite

	Wet chemistry analyst N. Hansen	XRF J. Engell	Microprobe J. Engell
SiO ₂	-	-	54,1
TiO ₂	-	-	0,6
ZrO ₂	-	0,16	-
Al ₂ O ₃	-	-	0,8
Fe ₂ O ₃	15,69	-	17,4 ¹
FeO	18,37	-	20,5 ¹
MnO	-	1,27	1,9
MgO	-	-	0,04
CaO	-	-	0,2
Na ₂ O	-	-	9,2
K ₂ O	-	-	2,9
H ₂ O+	1,92	-	-
F	0,22	-	-
Cl	-	0,00	-
			107,64

¹ divided according to the wet chemistry determination

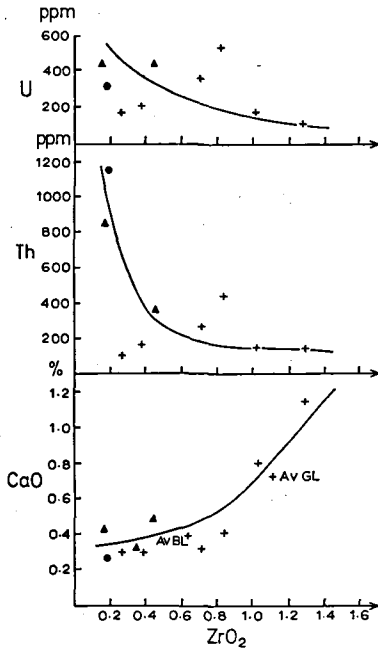


Fig. 5. Variation of CaO, Th and U relative to ZrO_2 in some lujavrites from the Ilímausaq intrusion. AvG1: average green lujavrite. AvB1: average black lujavrite. +: nepheline-cudialyte lujavrite. Δ : naujakasite-steenstrupine lujavrite. \bullet : analcime-steenstrupine lujavrite.

Secondly it should be noticed that the lujavrites containing albite and nepheline as the dominant sodium-alumino-silicates have similar Na_2O , Al_2O_3 and SiO_2 contents to the lujavrites containing albite plus naujakasite or only analcime instead.

The composition of the lujavrite-stage magma

Ussing (1912), Sørensen (1958; 1960; 1962; 1968), Ferguson (1964; 1970 a; 1970 b; 1970 c) and Hamilton (1964) all agree that the lujavrites are the product of a volatile-rich, melanocratic residual magma.

Ussing (1912) saw a close similarity between the composition of the average kakortokite and the lujavrites, and stressing their complementary relation to the naujaite relative to his average agpaite he regarded both as products of a residual magma left after the formation of this rock.

Ferguson (1964; 1970 a; 1970 b; 1970 c) recognizes the lujavrites as cumulates the evidence for this being given above, and he regards these rocks as the products of a residual magma trapped between the naujaite and the kakortokite. (fig. 2). Although not explicitly stated it is clear that Ferguson is of the opinion that the lujavrites approximate the composition of the residual magma fairly closely except for volatiles and perhaps excess sodium silicate. Sørensen and Hamilton are of the same opinion.

Both Ferguson and Sørensen are of the opinion that the lujavrites intruded

into the earlier rocks were emplaced as a crystal mush rather than as a crystal-free liquid.

It has not been possible to make a quantitative estimate of the amount of intercumulus material in the lujavrites. It is therefore impossible to make a direct and independent estimate of the composition of the magma at this stage. Some information can, however, be obtained by comparing the differentiation trend of the intrusion and the overall composition of the lujavrites.

All available analyses (28) of lujavrites from the intrusion have been plotted in figs. 3 & 4. The lujavrites do not fall on the continuation of the proposed trend, but diverge from it in much the same way as the kakortokites. Further the plots show no clear distinction between the different groups of lujavrites, but illustrate what was pointed out above, that no obvious differentiation trend corresponding to the reaction series among the light coloured minerals can be recognized. The average aegirine lujavrite plots at a point slightly poorer in $N_{1/2} F_{1/2} S_2$ ("Ac") and richer in $N_{1/2} A_{1/2} S$ ("Ne") than the average arfvedsonite lujavrite between the average kakortokite and arfvedsonite lujavrite.

The plots thus support a cumulus origin for the lujavrites but strongly suggest that the generally accepted assumption that the lujavrites approximate the corresponding magma closely except for volatiles etc. is wrong. It would require an unrealistically sharp bend towards iron-enrichment in the fractionation paths after the formation of the naujaite for this to be true. Further, if the lujavrites did approximate the magma closely in composition one would expect to see a trend corresponding to the changing mineralogy in these rocks.

If the formation of the lujavrites took place after the formation of the naujaite from a residual magma trapped between this and the kakortokite then the proposed fractionation paths must curve either sharply towards iron enrichment, or more gently towards iron depletion. The first possibility has already been rejected.

The second possibility is not easy to reject completely. Increasing water pressure suppresses the liquidus temperature of alkali feldspar and nepheline more than that of aegirine and arfvedsonite (Yoder, 1958; Bailey, 1969). That the agpaitic magma was rich in volatiles is strongly advocated by Sørensen (1958; 1960; 1962; 1968) and if the intrusion as suggested here behaved as an essentially closed system until the final stage a rapidly increasing partial pressure of water towards this stage is not unlikely. The formation of the lujavrites in this way requires the formation of a leucocratic residual magma. A precise calculation of the ratio of residual magma to lujavrite (in wt %) is not possible, but starting from a magma similar to naujaite minus 30 wt % sodalite one can estimate that the ratio is likely to be close to one or greater. If such a residual magma was present it must

have been removed completely from its original position, and probably extruded at the surface, as no rock which could represent such a magma occurs between the naujaite and the lujavrite.

Referring to an essentially closed system model, the plot of the lujavrites relative to the proposed fractionation trend could suggest a simultaneous formation of the lower part of the naujaite and the lujavrites. However, the "penecontemporaneous deformation of the lujavrites and their intrusion into the overlying earlier rocks, make it questionable whether a closed system model is valid any longer, the critical point being whether a substantial amount of magma was left above the lujavrites at the time of the beginning of the deformation phase or not.

Crystal-fractionation in agpaite magmas in the light of experimental petrology

According to the model proposed above, the Ilímaussaq intrusion differentiated by simultaneous fractionation of a large number of minerals including feldspar, clinopyroxene and, from the sodalite-foyaite stage nepheline. Projected into appropriated synthetic system one would therefore expect the successively formed liquids to have a positive correlation with a low melting area or a univariant line and in the end perhaps an invariant point in this system. The existence of such a relation would be strong evidence for the correctness of the proposed model.

As an introduction the melting (crystallization) relations of some of the rocks in question as determined experimentally by Piotrowsky & Edgar (1970) and Sood & Edgar (1970) and deduced from the phase relations in the peralkaline residua system (fig. 4) are compared (table 7). The agreement is good both at 1 atm, and at 1 kb, especially considering the difference in chemistry. The high Cl-content in the naujaite readily explains the appearance of sodalite before nepheline. Because of the difficulties in determining the fractionation paths of the naujaite from fig. 4 only the two first phases have been listed in table 7. The interesting differences are that, according to the melting experiments, feldspar crystallizes before nepheline in the foyaite at 1 atm and that clinopyroxene at 1 atm comes in before nepheline in the lujavrite both at variance with the deduced order of crystallization. Further, at 1 kb clinopyroxene appears at a higher temperature than expected. This is undoubtedly because of the small, but significant CaO and MgO content in both rocks.

The Ilímaussaq intrusion probably fractionated at a high water pressure and lower P_{O_2} . Sørensen (1968a) estimates that the total vapour pressure was in the range of 1–3 kb and in the section about the sodalite foyaite it was argued that P_{O_2} probably was close to that of the QMF buffer.

Table 7.

1 atm P _{O₂} = air		P _{H₂O} = 1 kb; P _{O₂} in the experiments unspecified; deducted phase relations for P _{O₂} = NNO	
Foyaite (57070) determined	Naujaite (57041) determined	Lujavrite (57033) determined	Foyaite (57070) determined
(T° C)	(T° C)	(T° C)	(T° C)
He	Sod (1187)	He	(He)
Fp (1112)	Ne (1120)	Fp (1102)	Fp (875)
Ne (1075)		Cpx (1095)	Ne (865)
Cpx (1040)		Ne (1062)	Cpx (850)
			(T° C)
			Mt
			Fp (825)
			Ne (810)
			Cpx (715)
			(T° C)
			Sod (895)
			Ne (865)
			Ne
			(T° C)
			(He)
			Fp (875)
			Cpx (845)
			Ne (775)
			Ne (715)
			(T° C)
			Mt
			Fp (825)
			Cpx (725)
			Ne (715)

Comparison of the sequence of crystallization for some rocks from the Ilímaussaq intrusion as determined experimentally (Piotrowsky & Edgar, 1970) and as deduced from synthetic systems (Bailey & Schairer, 1966 and Nolan, 1966). The Foyaite 57070 is a transitional rock between the heterogeneous syenite and the sodalite foyaite. He = Hematite, Mt = magnetite, Fp = alkalic feldspar, Ne = nepheline, sod = sodalite, cpx = clinopyroxene.

In the presence of water, alkali amphibole is a possible phase. From the experiments of Ernst (1968) and Bailey (1969) we know that alkali-amphibole is stable relative to acmite at high P_{H_2O} and low T , P_{O_2} and peralkalinity. The effect of fractionating alkali amphibole instead of acmite is to enrich the liquid relatively in potential sodium-silicate, but it will probably not radically change the liquid paths in the albite-nepheline saturated "surface". To simplify the diagrams, acmite and alkali amphibole have been labeled together in fig. 6.

The effect of increasing P_{H_2O} at constant P_{O_2} (fig. 6a) is to depress the stability field of alkali feldspar and nepheline relative to acmite and alkali amphibole (Yoder, 1958; Bailey, 1969) and probably also relative to iron-oxide. A decrease in the size of the sodium silicate volume is also likely because of the increasing solubility of water in silicate melts with increasing peralkalinity (Tuttle & Bowen, 1958). The phase relations in this part of the system are, however, likely to be extremely complex with the incoming of a number of new phases at high P_{H_2O} and low temperature (naujakasite, analcime, ussingite, etc.). Only the relations between acmite (alkali amphibole), albite and nepheline are considered here. As can be seen from fig. 4 increasing P_{H_2O} , especially the first Kb has also the effect of increasing the albite volume relative to the nepheline volume.

The effect of varying P_{O_2} at constant P_{H_2O} is shown in fig. 6b. At high P_{O_2} the stable iron-oxide is haematite ($P_{O_2} = \text{air}$ Bailey & Schairer (1966)) but at intermediate P_{O_2} this field is replaced by a magnetite field ($P_{O_2} = \text{NNO}$, Nolan, 1966) which in turn at low P_{O_2} is replaced by a fayalite field (Bowen & Schairer, 1938). The limited data at 1 atm indicate a small contraction of the "iron-oxide" field relative to albite and nepheline with falling P_{O_2} . As the temperature at which acmite melts incongruently drops with falling P_{O_2} until it finally is replaced by alkali amphibole (Bailey, 1969) it is likely that the acmite field contract towards Na_2O in fig. 6b with falling P_{O_2} (simultaneously with and increase in the alkali amphibole volume). Thus, increasing water pressure and decreasing P_{O_2} do to some extent counteract each other.

From figs. 4 & 6 it can be seen that increasing P_{H_2O} from zero to 1 or 2 Kb (and decreasing P_{O_2}) improve the correlation between the plot of the rocks and the proposed liquid trend relative to the phase relations in the synthetic system. But all the rocks apart from the naujaite plot in the "iron-oxide" volume. Ignoring acmite for a moment we see that compared with the relations at 1 Kb ($P_{O_2} = \text{NNO}$) all the rocks plot where one would expect them to in the projection from F (fig. 4). The sodalite-foyaite assumed to approximate the liquid closely plots close to the albite-nepheline boundary as does the calculated naujaite-kakortokite magma. The naujaite itself cumulus-enriched in sodalite plots in the nepheline field and the ka-

kortokites and lujavrites assumed to be depleted in sodalite plot further away from this mineral above the feldspar field.

Nolan (1966) demonstrated a marked expansion of the clinopyroxene field in the peralkaline residua system by the addition of even a small amount of diopside. His result is given in fig. 4 in a slightly different projection namely projected from magnetite plus diopside into the plane Ab-Ne-Ac. He further found that the first formed clinopyroxene was more "diopsidic" (di + he) than the pyroxene composition of the starting material (Nolan, 1966 p. 243) i.e. that the liquid differentiates towards the peralkaline residua system. The effect of adding diopside to the system on the phase relations in the other projection used here is sketched in fig. 6c. It is clear that the marked expansion of the clinopyroxene volume caused by even a small amount of diopside make it extremely likely that a liquid having the composition of the sodalite foyaite could crystallize clinopyroxene, nepheline and alkali-feldspar simultaneously, and that it would differentiate along a line roughly parallel with the proposed trend. There is still an important difference between the synthetic system and the natural rocks. In the first there is a constant molecular ratio of 1:1 for CaO and MgO, whereas in the second the ratio changes from nearly 3:1 in the augite syenite to about 10:1 in the sodalite foyaite. This clearly will affect the composition of the clinopyroxene and feldspar. The tendency would be for the clinopyroxene to be richer in hedenbergite and for the feldspar to be more calcic in the actual rocks. All other things equal this means a decreasing stability field for the first and increasing stability field for the second mineral relative to the synthetic system.

It is therefore likely that the amount of normative calcic clinopyroxene necessary to stabilize the aegirine in a liquid of a composition of the sodalite-foyaite as estimated from Nolan (1966) is too low.

Conclusions

The evolution of the Ilímaussaq intrusion has been discussed on the basis of an essentially closed-system, crystal-fractionation model. The model has proved adequate in that it can explain the features of the intrusion as they are known. A simultaneous fractionation of a large number of minerals including both felsic and mafic one throughout the formation of the intrusion is advocated.

In the author's opinion none of the described textures from rocks in the intrusion are in conflict with this idea.

The main conclusion is that the differentiation trend of the initial Ilímaussaq magma was towards iron-depletion rather than towards iron-enrichment. Critical assumptions for the proposed differentiation trend are

that the marginal augite syenite represents the magma from which the agpaitic rocks formed and that the chilled augite syenite and the sodalite-foyaite approximate the correspond magmas closely.

Available data from synthetic system do not contradict the proposed trend. But the phase relations in agpaitic liquids are so complex and dependent on so many factors, that even a comparison with the relatively complex peralkaline residua system is of little help in evaluating the fractionation paths of the liquid.

The distribution of Zr and Be indicates that the agpaitic stage was reached after more than 75 wt % and probably 90–95 wt % of the original intrusion had solidified, and it appears likely that the original intrusion extended down to the base of the crust.

The large scale mineralogical layering in the kakortokites can be explained by the proposed model as a direct consequence of the formation of the naujaite. A likely but not necessary consequence of the model is the suggestion that the lower part of the naujaite formed simultaneously with the lujavrites.

Acknowledgements. The author wishes to thank Professor H. Sørensen for an inspiring introduction to the geology of the Ilímaussaq intrusion and for valuable suggestions to improvements of the manuscript. Thanks are also due to O. V. Petersen for permission to incorporate unpublished data of his about the lujavrites at Tuperssuatsiait and for supplying the analysed samples from this locality, and to J. Rose-Hansen for information about, and samples from, the big lujavrite sheet on the Taseq slope. The author also wishes to thank I. Sørensen and N. Hansen for partial chemical analyses. The English of the manuscript has kindly been improved by D. G. Fraser. This work is published with the permission of the director of the Geological Survey of Greenland.

Dansk sammendrag

Udviklingen af Ilímaussaq magmaet diskuteres ud fra en model baseret på krystalfraktionering i et lukket system. Modellen er af betydning som et simplificeret grænsetilfælde, den kan på konsistent vis sammenkæde de på nuværende tidspunkt eksisterende data for intrusionen. For at anskueliggøre udviklingen af magmaet og for at lette en sammenligning med relevante experimentelle resultater er de kemiske analyser omregnet og propektieret ind i et firekomponent variationsdiagram N-A-F-S, hvor N er total alkalier omregnet til Na_2O , A er Al_2O_3 , F total jern som Fe_2O_3 og S er SiO_2 . Bjergarternes placering i dette system fremgår af to subprojektioner vist i fig. 3 & 4.

Fordelingen af Zr og Be indicerer, at det agpaitiske stadi nåedes efter at mere end 75 vt % og sandsynligvis 90–95 vt % af den oprindelige syenitiske intrusion var størket. Den agpaitiske bjergarts serie omfatter et flotations kumulat, naujaiten og tyngde sortererede bund kumulater, kakortokit og lujavrit. Det foreslås, at de sidste to bjergarter er dannet samtidig med naujaiten i den angivne orden. Lagdelingen i kakortokiten forklares som en direkte konsekvens af dannelsen af naujaiten. Magmaet blev stadig fattigere på jern under differentiationen.

Ni nye kemiske analyser af lujavriter samt nogle mineralogiske data gives.

References

- Bailey, D. K. 1969: The stability of acmite in the presence of H₂O. *Amer. J. Sci.* **267-A**, 1–16.
- Bailey, D. K. & Schairer, J. F. 1966: The system Na₂O–Al₂O₃–Fe₂O₃–SiO₂ at 1 atmosphere, and the petrogenesis of alkaline rocks. *J. Petrol.* **7**, 114–170.
- Bottinga, Y. & Weill, D. F. 1970: Densities of liquid silicate systems calculated from partial molar volumes of oxide components. *Amer. J. Sci.* **269**, 169–182.
- Bowen, N. L. & Schairer, J. F. 1938: Crystallization equilibrium in nepheline-albite-silica mixtures with foyaite. *J. Geol.* **46**, 397–411.
- Bohse, H., Brooks, K. & Kunzendorf, H. 1971: Field observations on the kakortokites of the Ilímaussaq intrusion South Greenland, including mapping and analyses by portable X-ray fluorescence equipment for zirconium and niobium. *Geol. Surv. Greenland, Rept 38*, 43 pp.
- Burnham, C. W. 1967: Hydrothermal fluids at the magmatic stage. In Barnes, H. L. (ed.): *Geochemistry of hydrothermal ore deposits*. pp. 34–76. Holt: Rinehart & Winston.
- Danø, M. & Sørensen, H. 1959: An examination on some rare minerals from the nepheline syenites of South West Greenland. *Meddr Grønland* **162** (5), 35 pp.
- Edgar, A. D. & Nolan, J. 1966: Phase relations in the system NaAlSi₃O₈ (albite) – NaAlSiO₄ (nepheline) – NaFeSi₂O₆ (acmite) – CaMgSi₂O₆ (diopside) – H₂O and its importance in the genesis of alkaline undersaturated rocks. *Miner. Soc. India, IMA vol.*, 176–181.
- Engell, J. E. 1968: *Beskrivelse af forekomst og dannelse af nogle ussingitære i Ilímaussaq intrusionen*. Unpublished prize dissertation, University of Copenhagen.
- Engell, J., Hansen, J., Jensen, M., Kunzendorf, H. & Løvborg, L. 1971: Beryllium mineralization in the Ilímaussaq intrusion, South Greenland. *Geol. Surv. Greenland, Rept 33*, 40 pp.
- Ernst, W. G. 1968: *Amphiboles. Miner. Rocks and Inorganic materials, sub series, Exp. Mineralogy* vol. 1, 125 pp. Berlin: Springer.
- Ferguson, J. 1964: Geology of the Ilímaussaq alkaline intrusion South Greenland, description of map and structure. *Meddr Grønland* **172** (4), 1–82.
- Ferguson, J. 1970a: The significance of the kakortokite in the evolution of the Ilímaussaq intrusion, South Greenland. *Meddr Grønland* **190** (1), 193 pp.
- Ferguson, J. 1970b: The differentiation of agpaitic magmas: The Ilímaussaq intrusion, South Greenland. *Canad. Miner.* **10**, 335–349.
- Ferguson, J. 1970c: On the schistose structure of some lujavrites. *Bull. geol. Soc. Denmark* **20**, 67–68.
- Ferguson, J. & Pulvertaft, T. C. R. 1963: Contrasted styles of igneous layering in the Gardar Province of South Greenland. *Miner. Soc. Amer., Spec. Paper* **1**, 10–21.
- Fersmann, A. E. 1929: Geochemische migration der elemente und deres wissenschaftliche und wirtschaftliche bedeutung. I. Teil Chibina Tundren. *Abh. prakt. Geol. Bergwirtsch.* 181–273.
- Gerassimovsky V. I. & Kuznetsova, S. Ya. 1967: On the Petrochemistry of the Ilímaussaq intrusion, South Greenland. *Geochem. International* **4** (2), 236–246.
- Hamilton, D. L. & Mackenzie, W. S. 1960: Nepheline solid solution in the system NaAlSiO₄–SiO₂. *J. Petrol.* **1**, 56–72.
- Hamilton, E. I. 1964: The geochemistry of the northern part of the Ilímaussaq intrusion, South West Greenland. *Meddr Grønland* **162** (10), 104 pp.
- Kennedy, G. C. 1955: Some aspects of the role of water in rock melts. *Geol. Soc. Amer., Spec. Paper* **62**, 489–503.

- Lorenzen, J. 1881: Undersøgelse af nogle mineralier i sodalith-syeniten fra Julianehaabs distrikt. *Meddr Grønland* 2, 43–80.
- Macdonald, R. Edge, R. A. 1970: Trace element distribution in alkaline dykes from the Tugutoq region, South Greenland. *Bull. geol. Soc. Denmark* 20, 38–58.
- Nash, W. P., Carmichael, I. S. E. & Johnson, R. W. 1969: The mineralogy and petrology of Mount Suswa, Kenya. *J. Petrol.* 10, 409–439.
- Nolan, J. 1966: Melting relations in the system $\text{NaAlSi}_3\text{O}_8$ – NaAlSiO_4 – $\text{NaFeSi}_2\text{O}_6$ – H_2O and their bearing on the genesis of alkaline undersaturated rocks. *Quart. J. geol. Soc. Lond.* 122, 119–157.
- Petersen, O. V. 1965: *Naujakasite and naujakasite-lujavrite part 2*. Unpublished report Geol Surv. Greenland. 69 pp.
- Piotrowski, J. M. & Edgar, A. D. 1970: Melting relations of undersaturated alkaline rocks from South Greenland compared to those of Africa and Canada. *Meddr Grønland* 181 (9), 62 pp.
- Sood, M. K. & Edgar, A. D. 1970: Melting relations of undersaturated alkaline rocks from the Ilímaussaq intrusion and Grønnedal-Ika complex, South Greenland, under water vapour and controlled partial oxygen pressures. *Meddr Grønland* 181 (12), 41 pp.
- Sørensen, H. 1958: The Ilímaussaq batholith a review and discussion. *Meddr Grønland* 162 (3), 48 pp.
- Sørensen, H. 1960: On the agpaitic rocks. *Rept 21st int. geol. Congr., Norden* 13, 319–327.
- Sørensen, H. 1962: On the occurrence of steenstrupine in the Ilímaussaq massif, South Greenland. *Meddr Grønland* 167, 1–251.
- Sørensen, H. 1966: On the magmatic evolution of the alkaline igneous province of South Greenland. *Geol. Surv. Greenland, Rept* 7, 1–19.
- Sørensen, H. 1968: Über die paragenese einiger alkalischer gesteine in Süd Grönland. *Freiberger Forschungsh. C* 230, 177–186.
- Sørensen, H. 1969: Rhythmic igneous layering in peralkaline intrusions an essay review on Ilímaussaq and Lovozero. *Lithos* 2, 261–283.
- Sørensen, H., Hansen, J. & Bondesen, E. 1969: Preliminary account of the geology of the Kvanefjeld area of the Ilímaussaq intrusion, South Greenland. *Geol. Surv. Greenland, Rept* 18, 40 pp.
- Saether, E. 1948: On the genesis of peralkaline rock provinces. *Rept 18th int. geol. Congr., London* 2, 123–130.
- Tuttle, O. F. & Bowen, N. L. 1958: Origin of granite in the light of experimental studies in the system $\text{NaAlSi}_3\text{O}_8$ – KAlSi_3O_8 – SiO_2 – H_2O . *Geol. Soc. Amer., Mem.* 74, 153 pp.
- Upton, B. G. J. 1960: Textural features of some contrasted igneous cumulates from South Greenland. *Meddr Grønland* 123 (6), 35 pp.
- Upton, B. G. J. 1960: The alkaline igneous complex of Kúngnåtfjeld, South Greenland. *Meddr Grønland* 123 (4), 145 pp.
- Upton, B. G. J. 1964: The geology of Tûgtutôq and neighbouring islands, South Greenland, part IV The nepheline syenites of the Hviddal composite dyke. *Meddr Grønland* 169 (3), 31 pp.
- Upton, B. G. J. (in prep.): The alkaline province of South West Greenland. In Sørensen, H. (ed.): *Alkaline Rocks*.
- Ussing, N. V. 1912: Geology of the country around Julianehaab, Greenland. *Meddr Grønland* 38, 376 pp.

- Wager, L. R. & Brown, G. M. 1968: *Layered igneous rocks*. 558 pp. London: Oliver & Boyd.
- Wager, L. R. & Deer, W. A. 1939: Geological investigations in East Greenland. Part III. The petrology of the Skaergaard intrusion, Kangerdlugssuaq, East Greenland. *Meddr Grønland* **105**, 1-353.
- Wright, T. L. 1968: X-ray and optical study of alkali feldspar: II An X-ray method for determining the composition and structural state from measurement of 20 values for their reflection. *Amer. Miner.* **53**, 88-104.
- Yoder, H. S. 1958: Effect of water on the melting of silicates. *Rept Div. geophys. Lab. Carnegie Instn* **57**, 189-191.