

## Intergrowths of Nepheline-Potassium Feldspar and Kalsilite-Potassium Feldspar: A Re-Examination of the ‘Pseudo-Leucite Problem’

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**Abstract.** The alkalic ultramafic Batbjerg intrusion of East Greenland contains rocks in which nepheline and leucite are important constituents. In addition, there are vermicular, ‘finger print’ intergrowths of nepheline with potassium feldspar, and patchy to micrographic intergrowths of kalsilite with potassium feldspar. The history of the ‘pseudoleucite problem’ is reviewed, and it is suggested that the term pseudoleucite be restricted to intergrowths of nepheline with alkali feldspar that appear to be pseudomorphs with the crystal morphology of leucite. It is further suggested that flame-like or feather-like finger print intergrowths of nepheline with alkali feldspar, that are either interstitial to the other minerals of the rock or have grown perpendicularly on relative large and often euhedral nepheline grains are an entirely different problem and are best explained by late-stage magmatic crystallization within the system  $\text{NaAlSiO}_4 - \text{KAlSiO}_4 - \text{SiO}_2 - \text{H}_2\text{O}$ .

In the Batbjerg intrusion the early crystallization of nepheline was followed by the co-crystallization of nepheline with leucite, or in some cases by nepheline and a silica-rich leucite. Although the magma was essentially dry, as indicated by the dominantly pyroxenitic character of the rocks, water pressure rose toward the late stages of crystallization as indicated by the presence of phlogopite and occasionally both amphibole and zeolite. Shrinkage of the leucite stability field attendant upon this rise in  $P_{\text{H}_2\text{O}}$  left the liquid that was crystallizing nepheline and leucite stranded on the nepheline-alkali feldspar cotectic. Shrinkage occurred too rapidly for the liquid to remain at the reaction point of the system, and leucite, therefore, was not resorbed. The remaining liquid crystallized rapidly as ‘flames’ of vermicular intergrowth of nepheline with potassium feldspar (composition Ne 24.0, Ks 45.9, Qz 30.1), a texture that might be attributable

to supercooling. Silica-rich leucite compositions (Ks 68.8, Qz 31.2) decomposed to intergrowths of kalsilite with potassium feldspar but reaction kinetics, or possibly variations in  $P_{\text{H}_2\text{O}}$  throughout the intrusion, prevented the breakdown of leucite.

### Introduction

The alkalic ultramafic Batbjerg intrusion, of Caledonian age, is part of the westernmost nunatak on the northern side of Kangerdlugssuaq Glacier, East Greenland (68°40'N, 28°50'W). It is composed in large part of feldspathoidal ultramafic rocks with lesser amounts of more leucocratic feldspathoidal rocks, and cut by dikes and sills of alkalic granite and syenite, explosion vents of appinitic character, and rare vents containing nodules of dunite and phlogopite-bearing websterite and lherzolite.

The intrusion contains an interesting variety of intergrowths between feldspathoidal minerals and alkali feldspar that provide more extensive natural examples of crystallization within the system  $\text{NaAlSiO}_4 - \text{KAlSiO}_4 - \text{SiO}_2 - \text{H}_2\text{O}$  than have previously been documented. In addition to crystallization of nepheline and leucite, there is evidence of cotectic crystallization of nepheline and leucite, there is evidence of cotectic crystallization of nepheline and potassium feldspar, as well as sub-solidus breakdown of silica-rich leucites to give intergrowths of kalsilite and potassium feldspar.

### The Problem of Nepheline-Feldspar Intergrowths and “Pseudo-Leucites”

Three types of nepheline-feldspar intergrowth have been documented in the literature: (a) patchy and

vermicular intergrowths of nepheline and alkali feldspar (dominantly potassic) with euhedral outline characteristic of sections through the icositetrahedral form of leucite; (b) vermicular intergrowths of nepheline and potassium feldspar forming areas quite devoid of crystal outline; (c) vermicular intergrowths of nepheline and plagioclase, also without crystal outline. The first type constitutes the classic pseudo-leucite, first described by Hussak (1890), but both of the first two types have been described as pseudo-leucite and have generally been discussed in the context of the "pseudo-leucite reaction" first proposed by Bowen (1928). This is the reaction that occurs in the system  $\text{NaAlSi}_3\text{O}_8 - \text{KAlSi}_3\text{O}_8 - \text{SiO}_2$  at the reaction point which terminates the leucite stability field, and at which previously crystallized leucite reacts with the remaining magmatic liquid to generate nepheline and alkali feldspar. It was a reaction to which Bowen attached considerable significance in the generation of feldspathoidal igneous rocks.

It is generally assumed that intergrowths of nepheline and potassium feldspar which display good crystal morphology crystallized initially as leucite, and considerable argument has ensued as to whether sodic leucite can crystallize from magmas, for the problem is that pseudo-leucites are markedly more sodic than any leucite that has been reported from natural rocks. It was thought that such a sodic leucite might undergo sub-solidus breakdown to an intergrowth of nepheline and potassium feldspar. The sodic-leucite origin was necessitated by the dual problem that reaction at the reaction point in the residua system should destroy the original crystal form and generate a corroded outline, and that there is no clear reason why nepheline and potassium feldspar, as the reaction products, should form vermicular or patchy intergrowths or any other specific crystallographic orientation.

The sodic-leucite suggestion was first voiced by Knight (1906). The principal difficulty is that sodic-leucite is unknown in natural rocks, and this objection was echoed by Bowen and Ellestad (1937) in refuting Knight's interpretation. Their studies of leucitic lavas led them to suggest that normal potassic leucite crystallizes but eventually reacts with an increasingly sodic magma and is converted to a nepheline-feldspar pseudomorph. Again, the problem of retaining good crystal morphology during reaction remains seemingly insuperable.

The problem was later investigated experimentally by Fudali (1963) who showed that at 1 atm leucite can accommodate up to 40 wt.% of  $\text{NaAlSi}_2\text{O}_6$  in the absence of water and up to 27 wt.% at  $P_{\text{H}_2\text{O}} = 1$  Kbar at 800° C. Fudali argued that such sodic leucites are unstable at lower temperature and breakdown to intergrowths of nepheline and potassium

feldspar. Yet it seems strange that despite the intensive study of leucitic rocks, no naturally occurring sodic leucite has been found; surely, somewhere, a lava would have cooled sufficiently rapidly to preserve a sodic leucite if such a mineral exists. Furthermore, one would expect from the Fudali data to find pseudo-leucites with a composition between pure leucite and  $\text{leucite}_{60}(\text{NaAlSi}_2\text{O}_6)_{40}$ . Taylor and MacKenzie (1975) commented that very few analyses plot in this range, and went on to propose a mechanism that involves ion exchange.

The possibility of ion exchange at quite low temperatures in both leucite and analcite has been known since the work of Barrer and Hinds (1953). Kurepin (in Taylor and MacKenzie 1975) proposed ion exchange between leucite and glass. More recently, Taylor and MacKenzie (1975) investigated this exchange further, and suggested that the sodium-rich nature of pseudo-leucite might be explained by ion exchange between early-formed potassium-rich leucite and both sodium-rich glass and sodium-rich aqueous vapour under sub-solidus conditions. The resulting sodic leucite would, upon further cooling exsolve to a mixture of nepheline and alkali feldspar but preserve the crystal form of leucite.

Subsequent work by Roux and MacKenzie (1978) has indicated that at 750° C and 1 Kbar the extensive solid solution of  $\text{NaAlSi}_2\text{O}_6$  in leucite is metastable or unstable and that metastable(?) potassium-rich analcite is formed which may subsequently break down on cooling to give nepheline-potassium feldspar pseudo-leucites.

It now appears likely from this recent work that those intergrowths of nepheline and alkali feldspar which possess leucite crystal morphology were either leucite crystals that subsequently became sodic by sub-solidus ion exchange reactions, and subsequently exsolved, or are the sub-solidus breakdown product of metastable potassium-rich analcite.

The term "pseudo-leucite" is used increasingly loosely in reference to any nepheline-feldspar intergrowth. We suggest that the term should be limited to those intergrowths of nepheline with alkali feldspar that display leucite morphology [type (a) above]. The vermicular intergrowths that lack crystal outline [type (b) above] can probably be best explained by direct magmatic crystallization as outlined by Davidson (1970) for the occurrence at Kaminak Lake in Canada. To refer to them as pseudo-leucites complicates the problem unnecessarily. Intergrowths of nepheline with plagioclase feldspar [type (c) above] are probably of metasomatic or deuteric origin and are not discussed further here. Examples have been described by Tilley (1957), Henderson and Gibb (1972), Rao and Murthy (1974), and Mitchell and Platt (1979).

The Batbjerg intrusion of East Greenland contains excellent examples of the vermicular intergrowths [type (b)] as well as others composed of kalsilite and potassium feldspar. It provides an opportunity to examine both the origin of the vermicular intergrowths and the role of leucite in plutonic rocks.

### Petrography of the Batbjerg Rocks

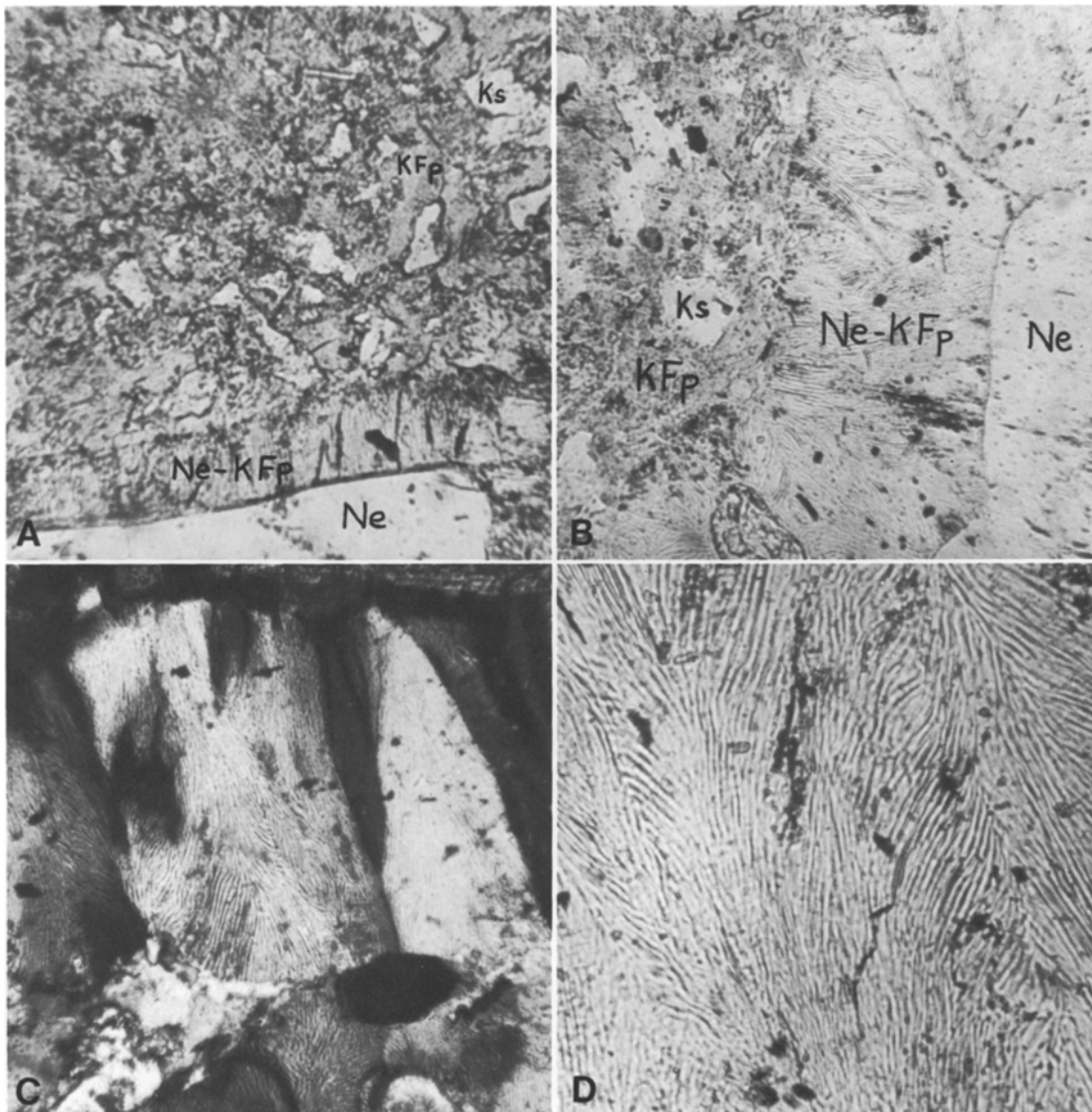
The commonest group of rocks is a clinopyroxenite-jacupirangite-ijolite series grading from nepheline-free to nepheline- and leucite-bearing. Nepheline and leucite occur in these rocks both separately and in various combinations with complex intergrowths as follows:

a) nepheline plus leucite;

b) nepheline plus intergrowths of nepheline with potassium feldspar;

c) nepheline plus intergrowths of nepheline with potassium feldspar, plus patches of kalsilite-potassium feldspar intergrowths.

In most of the rocks the feldspathoidal minerals are interstitial to the pyroxene grains that make up the bulk of the rock. A few rocks, however, are leucocratic and contain anhedral to euhedral nepheline that appears to have crystallized from an early stage. Leucite is always interstitial, and generally displays the characteristic complex twinning. Intergrowths of nepheline with potassium feldspar occur both as shapeless pools and patches in the groundmass of the rock and as fringes on the anhedral to euhedral nepheline grains. These fringes are flame-like or feather-like and perpendicular to the boundaries of the nepheline grain. Within each 'flame' the nepheline and feldspar are generally each in optical continuity. The intergrowths of kalsilite with potassium feldspar are of an entirely different character. They are irregularly patchy



**Fig. 1.** **A** Large grain of nepheline (*Ne*) with a fringe of nepheline potassium-feldspar intergrowth (*Ne-Kfp*); rest of the photograph is intergrowth of kalsilite (*Ks*) with potassium feldspar (*KFp*). Plane polarized light. **B** Enlarged portion of Fig. 1A. **C** 'Flames' of the intergrowth of nepheline with potassium feldspar; crossed nicols. **D** Detail at high magnification of part of Fig. 1C showing the fine fingerprint intergrowth of nepheline with potassium feldspar

to micrographic within grains that are anhedral to sub-rounded. Kalsilite is perfectly clear and colourless, whereas potassium feldspar is slightly cloudy. An important point is that leucite has not been observed in the same thin section as the kalsilite-potassium feldspar intergrowths. The various assemblages are illustrated in Fig. 1.

### Compositions of the Feldspathoidal Minerals and Intergrowths

All analyses were performed on Cambridge Instrument Co. GEO-SCAN electron microprobe with energy dispersive system in the Department of Mineralogy and Petrology, Cambridge University<sup>1</sup>. The intergrowths were analyzed by moving the slide back and forth under the electron beam. Confidence in the validity of the analyses stems from the consistency of the compositions obtained within individual thin sections and between analyses of specimens collected up to a kilometre apart. Typical analyses of the constituent minerals are given in Table 1 together with precision data. Replicate analyses were performed weekly over a six-month period, and in general the analytical precision was found to be approximately one per cent of the amount present.

<sup>1</sup> Analytical conditions: 20 Kv accelerating potential; 50 nA nominal beam current (~35 nA at specimen surface); 80 live seconds counting time; 3–4 Kpps input rate typical; 40° take-off angle; 270 mm specimen-detector distance; detector resolution ~156 eV FWHM at MnK $\alpha$  (5.89 KeV)

Table 1

	1	2	3	4	5	6	7	8	9	10	11	12
SiO <sub>2</sub>	42.94	0.54	57.90	0.27	42.98	64.69	56.75	0.82	38.56	0.28	55.44	0.43
Al <sub>2</sub> O <sub>3</sub>	33.27	0.36	23.22	0.56	34.29	18.28	22.11	0.54	31.49	0.44	22.91	0.20
FeO <sup>a</sup>	1.50	0.26	0.17	0.13	0.34	0.17	0.39	0.14	0.86	0.44	0.43	0.12
CaO	0.10	0.08	0.12	0.13	0.48	0.00	0.21	0.21	0.04	0.06	0.12	0.10
Na <sub>2</sub> O	15.96	0.41	5.23	0.27	15.75	0.00	0.00	0.00	0.00	—	0.17	0.28
K <sub>2</sub> O	7.23	0.12	13.60	0.25	6.85	16.21	20.07	0.24	29.49	0.28	20.45	0.42
	101.00		100.24		100.70	99.36	99.53		100.44		99.52	
FeNe	3.05		0.34		0.69		—		—			
Ne	70.66		23.62		71.51		—		0.00			
FeKs	—		—		—		0.91		2.01			
Ks	24.47		45.72		23.04		66.62		97.27			
An	0.50		0.59		2.38		1.04		0.20			
Qz	1.32		29.98		2.38		30.95		0.09			
Ne	74.1		24.0		74.0		—		—			
Ks	24.6		45.9		23.6		68.8		99.1			
Qz	1.3		30.1		2.4		31.2		0.1			

<sup>a</sup>  $\Sigma$  Fe expressed as FeO

1. Nepheline; mean of 19 analyses from 19 different hand specimens
2. Standard deviations of the 19 analyses comprising the mean in column 1
3. Nepheline-potassium feldspar intergrowths; mean of 10 analyses from 5 different hand specimens
4. Standard deviations of the 10 analyses comprising the mean in column 3
5. Nepheline; a single analysis from one intergrowth
6. Potassium feldspar; a single analysis from the same intergrowth
7. Kalsilite-potassium feldspar intergrowths; mean of 8 analyses from 5 different hand specimens
8. Standard deviation of the 8 analyses comprising the mean in column 7
9. Kalsilite; mean of 9 analyses from the 8 intergrowths reported in column 7
10. Standard deviation of the 9 analyses comprising the mean in column 9
11. Leucite; mean of 10 analyses from 5 different hand specimens
12. Standard deviation of the 10 analyses comprising the mean in column 11

### Nepheline

The anhedral to subhedral grains average (wt.%) FeNe 3.1, Ne 70.7, Ks 24.5, An 0.5, Qz 1.3 (Ne 74.1, Ks 24.6, Qz 1.3) or very close to the Morozewicz-Buerger convergence composition, and with a small excess silica content.<sup>2</sup> The range of composition in this type of nepheline is also small: FeNe 3.9–2.2, Ne 72.3–67.5, Ks 25.1–23.9, An 1.2-nil, Qz 3.6-nil (Ne 75.7–71.5, Ks 25.3–24.0).

### Nepheline-Potassium Feldspar Intergrowths

Both minerals are perfectly fresh. The average composition of the intergrowths is FeNe 0.34, Ne 23.62, Ks 45.72, An 0.59, Qz 29.98 (Ne 24.0, Ks 45.9, Qz 30.1). The single available nepheline analysis from the intergrowths suggests that it contains markedly less Fe than the large discrete nephelines.

### Kalsilite-Potassium Feldspar Intergrowths

The average composition is FeKs 0.91, Ks 66.62, An 1.04, Qz 30.95 (Ks 68.8, Qz 31.2). This does not correspond to the composition of leucite (Ks 72.49, Qz 27.51) but rather to a silica-rich leucite,

<sup>2</sup> It must be noted, however, that this nepheline did not crystallize in equilibrium with alkali feldspar; therefore, experimental data on the temperature of crystallization based on the excess silica content cannot be applied to these nephelines

or to the maximum extent of solid solution of  $\text{KAlSi}_3\text{O}_8$  in leucite found experimentally by MacKenzie, Richardson and Wood (1974) (30 wt.% at  $P_{\text{H}_2\text{O}}=1$  Kbar at  $1,000^\circ\text{C}$ ).

*Kalsilite* within these intergrowths has average composition  $\text{FcKs}$  2.01,  $\text{Ks}$  97.27,  $\text{An}$  0.20,  $\text{Qz}$  0.09.

*Potassium Feldspar* within these intergrowths is very pure, usually with no sodium detected.

*Leucite* is very close to the ideal composition, and although the mean of 10 analyses has  $\text{Na}_2$ -0.17, many of the analyses are  $\text{Na}_2\text{O}$  free.

### Crystallization Within the Bathjerg Intrusion

Because clinopyroxene, olivine, magnetite and, to a lesser extent, phlogopite, form the bulk of the rocks, crystallization can be considered in its entirety only in such complex systems as diopside-nepheline-leucite or diopside-forsterite-nepheline-leucite, but the history of the salic minerals can be followed fairly well by reference to the residua system  $\text{NaAlSiO}_4$ – $\text{KAlSiO}_4$ – $\text{SiO}_2$ – $\text{H}_2\text{O}$ . The phase equilibrium diagram for this system is complete for 1 atm. and is established for its most critical parts at  $P_{\text{H}_2\text{O}}=1$  Kbar, 2 Kbar, 5 Kbar (Fig. 2).

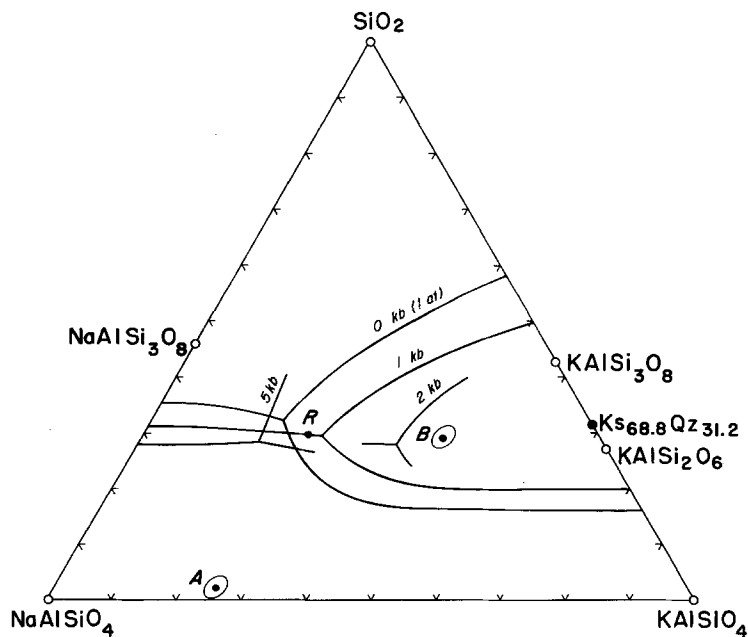
The most striking feature of the system is the shrinking of the leucite stability field as  $P_{\text{H}_2\text{O}}$  increases. At the same time the cotectic between nepheline and alkali feldspar moves away from the silica apex, and the separation of the ternary minimum from the reaction point  $R$  steadily increases. At an as yet unknown  $P_{\text{H}_2\text{O}}$  between 2 and 5 Kbar, the cotec-

tic minimum develops into a eutectic involving nepheline solid solution, sodic feldspar, potassic feldspar, and aqueous vapour (Morse 1969). The leucite field continues to shrink with increasing  $P_{\text{H}_2\text{O}}$  until it is eliminated at 8.4 Kbar; potassium feldspar changes at 2.6 Kbar from incongruent to congruent melting. Under dry conditions leucite is stable to at least 20 Kbar (Lindsley 1967), and thus it seems reasonable to suppose that in most natural magmas where  $P_{\text{H}_2\text{O}} < P_{\text{total}}$  throughout most of the crystallization of the magma, leucite can crystallize at total pressures (greater depths) than 8.4 Kbar, and hence throughout most of the earth's crust.

The absence of leucite from plutonic rocks has always been attributed to the role of water pressure in suppressing the leucite stability field, and to the fact that most leucocratic plutonic alkalic rocks plot on the sodic side of a line joining nepheline solid solution to  $\text{KAlSi}_3\text{O}_8$ , so that at any pressure slightly over 1 Kbar crystallization of nepheline will not result in the liquid reaching the leucite field boundary.

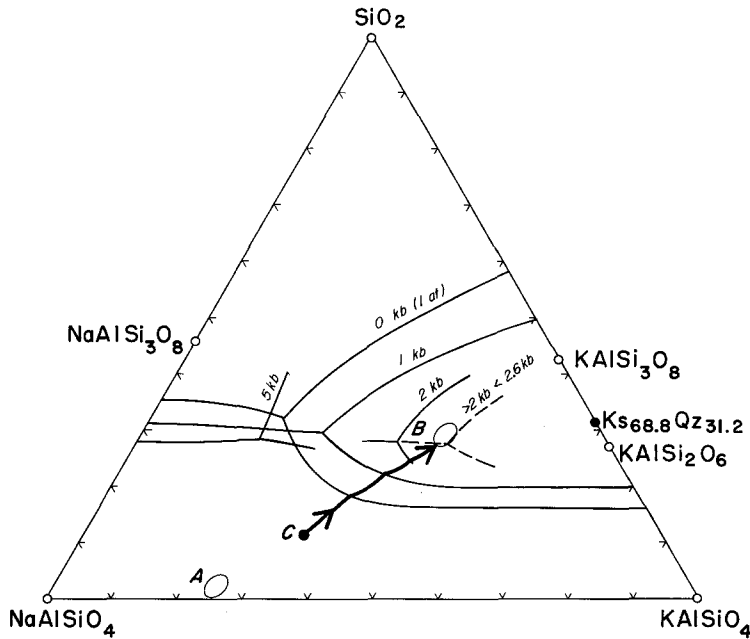
Furthermore, any leucite that crystallized under plutonic conditions could not survive as the rock cooled in the presence of water because of the breakdown reaction  $\text{leucite} \rightleftharpoons \text{kalsilite} + \text{potassium feldspar}$ , the curve for which has a slope of  $30^\circ\text{C/Kbar}$ , passing through  $470^\circ\text{C}$  and 1 atm, and an invariant point at  $750^\circ\text{C}$  and 8.4 Kb under water-saturated conditions (Scarfe, Luth and Tuttle 1966) (Fig. 4).

The compositions of the salic phases and intergrowths are shown in Fig. 3. The proposed crystallization history is that the relatively dry mafic alkalic magma crystallizes a considerable quantity of clinopy-



**Fig. 2.** Phase equilibrium diagram of the system  $\text{NaAlSiO}_4$ – $\text{KAlSiO}_4$ – $\text{SiO}_2$ – $\text{H}_2\text{O}$  for  $P=1$  atm,  $P_{\text{H}_2\text{O}}=1$  Kbar, 2 Kbar, 5 Kbar (Schaier and Bowen 1935; Schaier 1950; Hamilton and MacKenzie 1965; Taylor and MacKenzie 1975; Morse 1969; Roux and Hamilton 1976).

$R$ : reaction point.  $A$  is the compositional range of individual nepheline grains, some being of euhedral outline, of which the black dot represents the mean composition given in Table 1, column 1.  $B$  is the compositional range of the nepheline-potassium feldspar intergrowths, the black dot being the mean composition given in Table 1, column 3. The black dot on the  $\text{SiO}_2$ – $\text{KAlSiO}_4$  join labelled  $\text{Ks}$  68.8  $\text{Qz}$  31.2 is the mean composition of the kalsilite-potassium feldspar intergrowths given in Table 1, column 7



**Fig. 3.** Suggested crystallization path of late-stage magmatic liquid in the Batbjerg rocks. Crystallization of a liquid with composition close to *C* (exact composition not known) commences with nepheline of composition *A* and the liquid follows a curved path to the leucite-nepheline field boundary where it begins to crystallize leucite or silica-rich leucite together with nepheline. Progressive shrinkage of the leucite stability field occurs and the liquid composition remains on the field boundary until at *B* the shrinkage is too rapid for equilibrium to be maintained and the liquid composition is now on the nepheline-alkali feldspar cotectic. This liquid crystallized as a nepheline-potassium feldspar intergrowth, possibly following a period of super-cooling that results in eventual rapid crystallization

roxene together with lesser amounts of magnetite and olivine. From the euhedral shape of some nepheline grains, it seems likely that nepheline began to crystallize fairly early. Since the clinopyroxene is almost devoid of sodium, the alkalis are concentrated in the late magmatic liquid, and it seems reasonable to discuss the late stages of crystallization in terms of the residua system.

It is postulated that nepheline crystallized throughout most of the cooling history of the magma. Crystallization of nepheline eventually drove the liquid to the nepheline-leucite field boundary and the crystallization of leucite began. The interstitial character of the leucite and complete lack of crystal form suggests that the magma was by this time almost completely crystalline. It is clear, however, from the composition of the kalsilite-potassium feldspar intergrowths that in some rocks it was not leucite that crystallized but a silica-rich leucite. Nepheline continued to crystallize together with leucite or silica-rich leucite and by this time  $P_{\text{H}_2\text{O}}$  was beginning to rise by virtue of only anhydrous minerals having crystallized previously. The increased  $P_{\text{H}_2\text{O}}$  stabilized phlogopite which crystallized interstitially throughout the rock and formed coronas on magnetite by reaction with the increasingly aqueous alkali-rich liquid. With steadily increasing  $P_{\text{H}_2\text{O}}$  the remaining liquid became less sodic as it remained on the field boundary of the diminishing leucite field. Eventually, at  $P_{\text{H}_2\text{O}}$  somewhat higher than 2 Kbar, but less than 2.6 Kbar the leucite field, now diminishing in size faster than crystallization of nepheline and leucite could maintain an equilibrium composition, shrank past the liquid

composition which was now on the nepheline-alkali feldspar cotectic (Fig. 2). Shrinkage occurred too rapidly for the liquid to remain at the reaction point of the system, and leucite, therefore, was not resorbed. It is possible that supercooling of the remaining liquid occurred and it eventually crystallized rapidly as 'flames' of vermicular, 'finger-print texture' intergrowths of nepheline with potassium feldspar. The remaining liquid now crystallized as a vermicular intergrowth of nepheline and potassium feldspar. This is essentially the sequence of events envisaged by Davidson (1970) to explain almost identical intergrowths at Kaminak Lake, NWT, Canada. The reason for the vermicular texture rather than a mosaic of nepheline and potassium feldspar grains is unclear. One strong possibility is that water is lost from the intrusion in the very last stages of crystallization. The effect of such loss would be a sharp rise of the liquidus surface to a temperature above that of the remaining liquid and rapid crystallization would ensue. Indeed the 'flame' or 'plume'-like intergrowths are reminiscent of quench textures in experimental systems. Support for the idea of late-stage loss of aqueous fluid is to be found in chert nodules in marble surrounding the intrusion. These nodules have been thermally metamorphosed but chemical gradients within them suggest that they were subsequently metasomatized by sodic and aluminous fluids.

Thus, a magmatic explanation of these nepheline-potassium feldspar intergrowths seems feasible and probably applies to similar intergrowths in other rocks. The intergrowths are not pseudo-leucites and although of similar composition to some true pseudo-

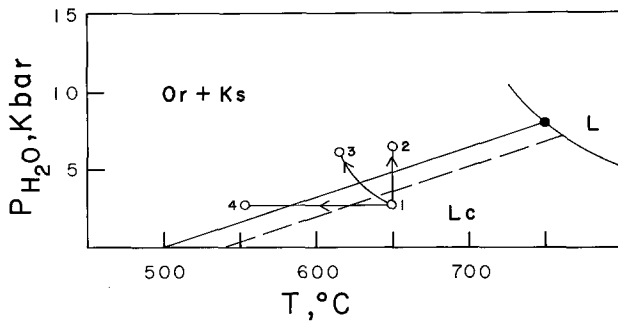


Fig. 4. The subsolidus breakdown of leucite (*Lc*) to kalsilite and potassium feldspar (*Ks*+*Or*). Breakdown paths are indicated as follows: 1-2 with rising water pressure at constant temperature, 1-4 with cooling at constant water pressure, and 1-3 with cooling accompanied by rising water pressure (after Scarfe, Luth and Tuttle 1966). The breakdown curve is intersected by the melting curve at the invariant point 750° C, 8.4 Kbar. Also shown, as a *dashed line*, is a hypothetical breakdown curve for silica-rich leucite

leucites, they constitute a completely different problem.

A further possible variant of the magmatic explanation is to be found in the studies of Roux and MacKenzie (1978) on the composition leucite<sub>50</sub> - (NaAl - Si<sub>2</sub>O<sub>6</sub>)<sub>50</sub> at  $P_{H_2O} = 1$  Kbar at 750° C. These authors suggest that in addition to nepheline<sub>ss</sub> + feldspar<sub>ss</sub> + leucite (with 4 mole% NaAlSi<sub>2</sub>O<sub>6</sub>) a metastable analcite-like mineral might form because of the presence of a 'metastable solvus' between it and leucite. It is perhaps possible that this analcite-like phase crystallizes in the interstices between early-formed nepheline and silica-rich leucite crystals and then, upon cooling, exsolves to the vermicular intergrowth of nepheline with potassium feldspar.

The unique feature of the Batbjerg rocks is the occurrence with the nepheline-potassium feldspar of either kalsilite-potassium feldspar intergrowths or leucite, but never both. These intergrowths of kalsilite with potassium feldspar are interpreted as the result of sub-solidus decomposition of silica-rich leucite. As noted previously, leucite and the silica-rich leucite should break down if cooled in the presence of water. This breakdown is examined in Fig. 4. We have seen previously (Fig. 3) that the  $P_{H_2O}$  during the last stages of crystallization reached 2-2.5 Kbar, at which pressure the decomposition of leucite occurs at about 575° C.

The problem with this interpretation of the kalsilite-potassium feldspar intergrowths as a breakdown product is in explaining why pure leucite has remained as leucite but the silica-rich leucite (Lc<sub>70</sub>Or<sub>30</sub>) has broken down. It is, perhaps, possible, although un-

likely, that the  $P_{H_2O}$  in the interstices of the rocks varies from one part of the intrusion to another and that, therefore, the  $P_{H_2O}$  in some parts of the intrusion was low enough to allow the survival of leucite in some rocks. It would seem unreasonably fortuitous, however, that all the leucite that survived was Lc<sub>100</sub>, whereas that which decomposed was always Lc<sub>70</sub>Or<sub>30</sub>. The most likely explanation seems to be that the decomposition curve for the silica-rich leucite is at higher temperature than that of pure leucite. In this way it is suggested that the silica-rich leucite decomposes during cooling but that by the time cooling has reached the temperature required for leucite decomposition, the kinetics of the process have slowed to the extent that leucite survives.

Alkali exchange mechanisms involving feldspars, feldspathoids, magmatic liquids and super-critical fluids are known to be a very efficient means of altering Na:K (Barrer and Hinds 1953; Orville 1963; Taylor and MacKenzie 1975). The possibility of a metasomatic rather than a magmatic explanation of these intergrowths, does not seem to be viable, however. Because of the presence within the same hand specimen of both nepheline-potassium feldspar and kalsilite-potassium feldspar intergrowths, a metasomatic process would require the operation of both sodium metasomatism and potassium metasomatism. Either is feasible separately but not simultaneously.

Kalsilite is a rare mineral occurring almost exclusively in extrusive volcanic rocks such as Mt. Nyiragongo, Zaire (Sahama 1960); Cupaello, Italy (Graggani 1972); San Venanzo and Villa Senni, Italy (Velde and Yoder 1978); and north-eastern Utah, U.S.A. (Velde and Yoder 1978). It has been reported from a syenite intrusion in the Seward Peninsula, Alaska, U.S.A. (Miller 1972), where it was identified by X-ray diffraction, in association with nepheline and fingerprint intergrowths of nepheline with alkali feldspar similar to those described here, but it is not clear from the description if it is to be thought of as a leucite decomposition product. An accompanying photograph suggests the presence of genuine pseudo-leucites. A further occurrence is reported from the Synnyr intrusion near Lake Baikal, U.S.S.R. (Zhidkov 1963), but the means of identification is not given.

The Batbjerg intrusion is the only one from which fresh leucite has been reported, and it appears to be an indisputable example of leucite decomposition to kalsilite plus potassium feldspar. Other examples of kalsilite-potassium feldspar intergrowths apparently are known but they have not been described in print (footnote in Roux and MacKenzie 1978).

In a sense it is unfortunate that the term pseudo-leucite has become firmly attached to the sodium-rich composition. If the intergrowths of kalsilite and po-

tassium feldspar are truly a breakdown product of a silica-rich leucite, then these might more logically be called pseudoleucites. The usage of the term is, however, thoroughly pre-empted by nepheline-alkali feldspar intergrowths, and it would be unwise to complicate matters by applying it to the kalsilite-potassium feldspar intergrowths.

## Conclusions

Not all vermicular (fingerprint) intergrowths of nepheline-alkali feldspar constitute the 'pseudo-leucite problem'. Those that lack idiomorphic habit and have the flame-, or feather-like form often grown on euhedral nepheline grains, and interstitial to the rest of the minerals of the rock are best interpreted as a magmatic crystallization phenomenon. The Batbjerg rocks display a complex crystallization history in which nepheline has crystallized together with leucite or, in some places, a silica-rich leucite that closely approaches the maximum degree of solid solution found experimentally (MacKenzie, Richardson and Wood 1974) which was 30 wt.%  $\text{KAlSi}_3\text{O}_8$  at  $P_{\text{H}_2\text{O}} = 1$  Kbar at  $1,000^\circ\text{C}$ . With a rapid, late-stage increase in  $P_{\text{H}_2\text{O}}$  the final salic liquid has crystallized a fingerprint intergrowth of nepheline and potassium feldspar, and the leucite solid solution has broken down during cooling in the presence of water to an intergrowth of kalsilite and potassium feldspar.

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