

Plagioclase–Ca-rich-nepheline intergrowths in a syenite from the Marangudzi complex, Rhodesia

C. M. B. HENDERSON *and* F. G. F. GIBB

Department of Geology, The University, Manchester M13 9PL, England

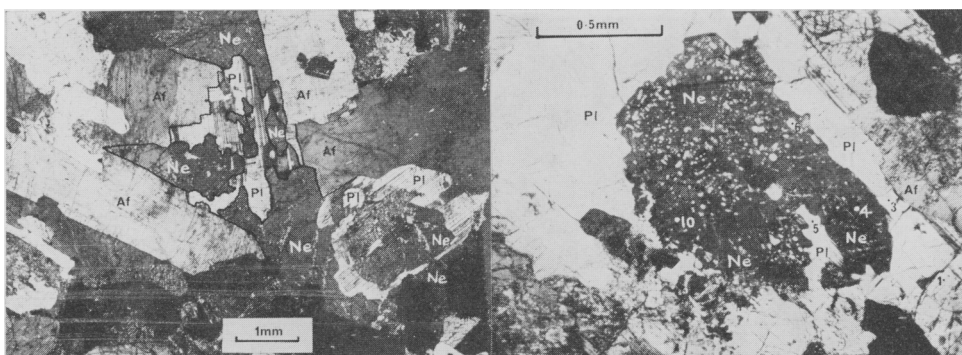
SUMMARY. Nepheline in a basic syenite from the Marangudzi complex is relatively Ca-rich with CaO from 1.9 to 2.4 (wt) %. This Ca-rich nepheline sometimes occurs in intimate intergrowths with plagioclase (andesine). These intergrowths are thought to have formed at temperatures in the order of 750°–850 °C by resorption of plagioclase with simultaneous replacement by nepheline.

THE nepheline-bearing rocks from the Marangudzi Ring Complex, Rhodesia, form a differentiated series varying from nepheline monzonite to pulaskite and foyaitite. In this series the modal alkali feldspar and nepheline increase and plagioclase and hastingsitic amphibole decrease in amount, the plagioclase becoming more Ab-rich and the hastingsite becoming more Fe-rich (Henderson, 1968). The pulaskites and foyaites are hypersolvus syenites containing orthoclase micro- and crypto-perthite and nepheline the compositions of which show typically magmatic tie-lines in the system Ne–Ks–Qz (Tilley, 1957). The pulaskites show the nepheline–plagioclase intergrowths described in this paper.

Textures. One pulaskite sample (R. 26) is described as it shows the nepheline–plagioclase textures particularly well. The rock is medium-coarse grained, containing orthoclase perthite, plagioclase, nepheline, ferrohastingsite, and magnetite. Textures suggest that the first minerals to crystallize were Ca-rich plagioclase (bytownite) and amphibole, both of which are strongly zoned. Alkali feldspar crystallization followed quite soon and many of the larger grains contain cores of zoned Ca-rich plagioclase. Plagioclase occurring as discrete grains is generally more sodic (andesine) but in some cases may have bytownite cores. The bulk of the rock consists of interlocking tabular grains of alkali feldspar, plagioclase, and hastingsite; the interstices being filled with smaller grains of the same minerals with the addition of nepheline. Nepheline seems to be the last formed mineral and occurs either as discrete anhedral grains or in close textural intergrowth with certain plagioclase grains.

The nepheline–plagioclase intergrowths are well shown in figs. 1 and 2. Nepheline and plagioclase grains penetrate each other showing rounded, embayed, serrated, or 'saw tooth' edges. Nepheline is sometimes seen as a core within a plagioclase rim and this nepheline in turn may contain bleb-like inclusions of plagioclase. Nepheline frequently includes fragments of plagioclase, in which particular albite twin lamellae can be matched with the main plagioclase grains nearby. The plagioclase in this texture usually shows very strong zoning.

Tilley (1957) described very similar textures in syenitic rocks from York River, Ontario and attributed them to low-temperature resorption of plagioclase with replacement by nepheline. The origin of the intergrowths in the Marangudzi pulaskites is discussed here with reference to four possible processes: exsolution of plagioclase from nepheline; simultaneous crystallization of the two minerals from the melt; replacement of nepheline by plagioclase; and replacement of plagioclase by nepheline. Discrete nepheline and plagioclase grains and their intergrowths have been analysed by electron microprobe and the origin of the intergrowth is considered in the light



FIGS. 1 and 2: FIG. 1 (left). The plagioclase grain at the bottom-right has a core of nepheline (dark) which in turn contains blebs of plagioclase (light). The nepheline core is seen to be in optical continuity with the nepheline outside. The plagioclase grain in the middle of the figure shows margins embayed by nepheline with some detached plagioclase fragments in optical continuity with the main grain. To the left the shape of the nepheline is seen to be controlled by large euhedral alkali feldspar grains. The margins of some of the grains are accentuated with ink. Af = alkali-feldspar; Ne = nepheline; Pl = plagioclase. (Crossed polars). FIG. 2 (right). Plagioclase rim (light) surrounding nepheline (dark) containing blebs of plagioclase (light). The numbers refer to spots analysed by electron probe and can be used to identify certain analyses in Table I. Abbreviations as in fig. 1. (Crossed polars).

of these results. Analytical data for the rock (R. 26) are given in Table I and data for the component minerals are given in Table II.

Nepheline. The compositions of nepheline in discrete grains and in the intergrowths are very similar. It is noteworthy that the CaO contents vary from 1.9 to 2.4% (9.5 to 12% An) and these are the highest CaO contents described for nephelines from syenitic rocks. Bannister and Hey (1931) found from 1.2 to 4.4% CaO in nephelines from ejected blocks (sometimes limestone) from Monte Somma, Vesuvius. However, Hey now considers the two analyses (nos. IV and IX) showing more than 3% CaO to be doubtful (*priv. comm.*). Bowen (1912) found that nephelines could be synthesized at 1 atmosphere with up to 35% An in solid solution and Edgar (1963) found a similar maximum content in nephelines synthesized at 1000 bars P_{H_2O} . It is unlikely that the high CaO contents of the nepheline in R. 26 have been inherited in some way from the plagioclase, as nepheline in discrete grains and in intergrowths with plagioclase have the same CaO contents (see later). The CaO contents of nepheline from the Marangudzi foyaites are lower (1.3–1.5% CaO) and as might be expected

TABLE I. *Whole-rock data for pulaskite (R. 26); anal. C.M.B.H.*

Chemical analysis		Normative composition (wt. %)		Modal analysis (vol. %)		
SiO ₂	53.96	Or	40.8	Alkali feldspar	54.2	
Al ₂ O ₃	19.42	Ab	16.6	Nepheline	5.8	
Fe ₂ O ₃	1.62	Ne	12.5	Plagioclase	17.9	
FeO	4.27	An	11.6	Amphibole	21.1	
MgO	1.38	Di {	Wo	4.5	Iron Ore	0.3
CaO	4.61		En	1.7	Apatite	0.7
Na ₂ O	4.69		Fs	2.9		
K ₂ O	6.90	Ol {	Fo	1.3	Total	100.0
H ₂ O+	0.73		Fa	2.4		
H ₂ O-	0.07		Mt	2.4		
CO ₂	0.41		Il	0.9		
TiO ₂	0.48		Ap	0.7		
P ₂ O ₅	0.30		Others	1.3		
MnO	0.18					
StrO	0.135	Total	99.6			
BaO	0.615					
F	0.25					
less O=F	0.11					
Total	99.91					

TABLE II. *Electron-probe analyses of minerals in pulaskite (R. 26); anal. F.G.F.G.*

	Mineral components of intergrowths						Minerals as discrete grains						
	Ne. 4	Ne. 10	Pl. 1	Pl. 3	Pl. 5	Pl. 6	Ne. 11	Ne. 12	Ne. 13	Ne. 14	Pl. 15	Pl. 16	Pl. 17
SiO ₂	44.1	44.1	59.5	58.1	57.7	59.4	43.7	44.1	43.6	43.5	47.1	55.8	46.9
Al ₂ O ₃	34.7	33.9	26.5	26.7	27.7	25.6	34.1	33.9	34.2	33.7	33.6	28.3	33.8
Fe ₂ O ₃	0.1	0.2	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.2	0.1	0.2
CaO	2.2	1.9	7.0	8.1	9.0	6.5	2.4	2.1	2.3	2.3	16.4	9.6	16.5
Na ₂ O	14.3	15.0	7.3	6.7	6.2	7.6	14.4	14.9	14.8	14.6	2.0	5.7	2.1
K ₂ O	4.4	4.8	0.4	0.2	0.1	0.2	4.5	4.6	4.7	4.6	0.0	0.3	0.1
Total	99.8	99.9	100.8	99.9	100.8	99.4	99.3	99.8	99.8	99.0	99.3	99.8	99.6

Ne = Nepheline.

Pl = Plagioclase.

the more basic pulaskites have the nephelines with the higher CaO contents. The compositions (minus An) of the nephelines from pulaskite R. 26 are plotted in the system Ne-Ks-Qz (fig. 3). They fall in the field of magmatic nephelines (Tilley, 1954, 1957), containing 5-7 % excess SiO₂.

Plagioclase. Analyses are plotted in the system An-Ab-Or (fig. 4) and show extreme compositional variation. One discrete plagioclase grain has a core of composition An₈₂ while a point further towards its rim is An₅₀ (presumably the rim itself is even more sodic.) Plagioclase in association with nepheline is rather more soda-rich

varying from An_{47} to An_{83} ; there is thus a compositional continuity between discrete plagioclase and that in intergrowth with nepheline. This suggests a continuous fractional crystallization of plagioclase.

Alkali-feldspars. These are perthitic and their bulk composition cannot readily be determined by electron probe, but partial chemical analysis (C.M.B.H.) of a separated fraction gave K_2O 10.6, Na_2O 4.0, CaO 0.6, SrO 0.19, BaO 0.94 %, corresponding to $Ab_{32.8}Or_{61.3}An_{31.7}Cn_{2.2}$ wt. %. X-ray powder diffraction analyses show that the K-rich

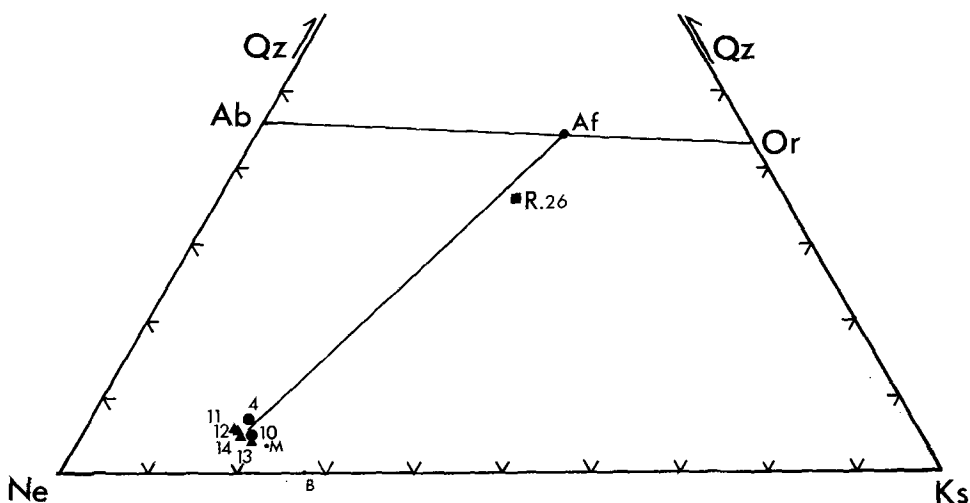


FIG. 3. Plot of normative Ne-Ks-Qz. Symbols: ● = nephelines from intergrowth; ▲ = nephelines forming discrete grains; ■ = bulk rock. Sample numbers can be identified from Table II. M and B refer to nepheline formulae of Morozewicz and Buerger respectively (Tilley 1954, 1957).

phase is monoclinic and the mineral is an intermediate structural state orthoclase micropertite (Wright and Stewart, 1968). The alkali-feldspar-nepheline tieline (fig. 3) is clearly magmatic in trend (Tilley, 1957).

Interpretation of analyses. Although the rock has clearly crystallized under conditions of strong fractionation the compositions of minerals formed at the latest stages (e.g. the nepheline-plagioclase intergrowths) can be used to indicate approximate final crystallization temperatures. The nepheline and plagioclase compositions used here are averages of the analyses carried out on the intergrowth components. The composition of the bulk alkali feldspar is used to derive plagioclase-alkali-feldspar crystallization temperatures.

Na_2O distribution between alkali feldspar and plagioclase indicates crystallization temperatures in the range 825 to 875 °C (Iiyama, 1966; Perchuk and Ryabchikov, 1968). Na_2O distribution between nepheline and alkali feldspar has also been used as a temperature indicator (Perchuk and Ryabchikov, 1968) but the temperatures derived by this method may be suspect. In particular nepheline-alkali-feldspar compositions from phonolites tend to give low temperatures and the synthetic compositions

crystallized at 700 °C and 1000 bars by Hamilton and MacKenzie (1965) give crystallization temperatures of < 400 °C using Perchuk and Ryabchikov's model. The content of 'excess' SiO₂ in the nepheline suggests crystallization temperatures of approximately 750 °C (Hamilton, 1961).

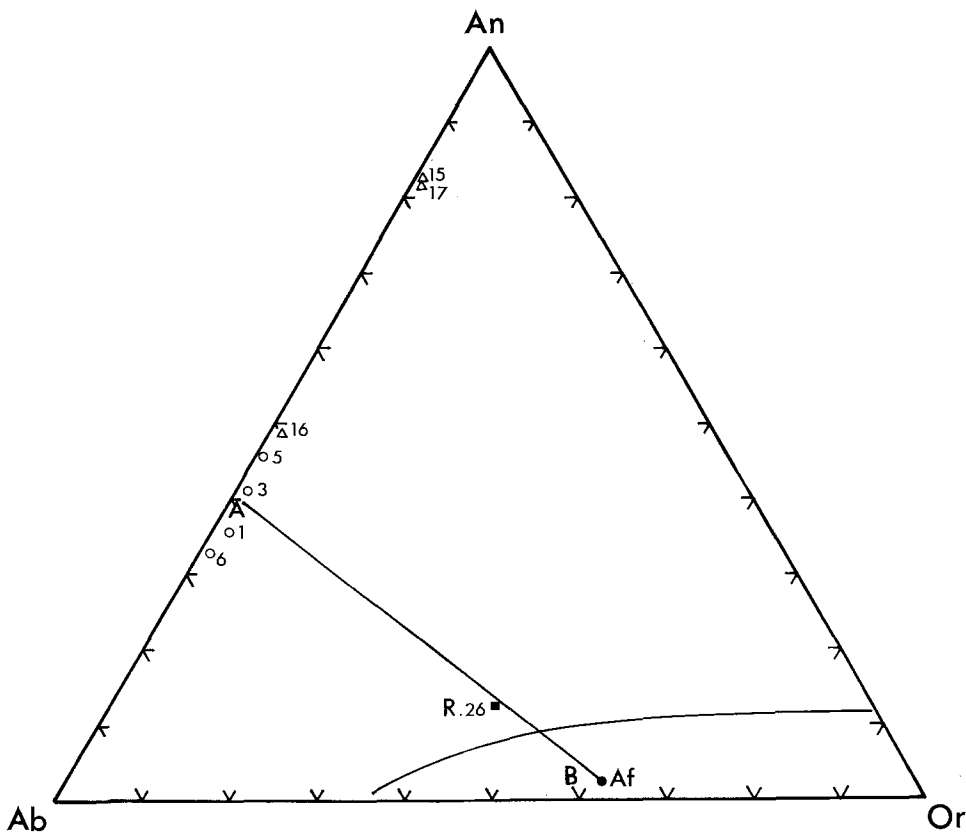


FIG. 4. Plot of normative An-Ab-Or. Symbols: ○ = plagioclases from intergrowth; △ = plagioclases forming discrete grains; ■ = bulk rock. Sample numbers can be identified from Table II. Normative Ne in the rock composition is calculated as Ab, thus the rock composition is projected onto the feldspar plane towards the Qz apex of the system Ne-Ks-Qz-An. AB is the assumed tie-line used in estimating feldspar crystallization temperatures.

Clearly these temperatures are approximate but seem to place the formation of the nepheline-plagioclase-alkali-feldspar assemblage in the region 750–850 °C. The Marangudzi nepheline syenites are thought to have crystallized at 1 to 2 Kbar P_{H_2O} and the range of temperatures of the intersection of the two-feldspar surface with the nepheline phase volume in the system Ne-Ks-Qz-An (Carmichael, 1965) must be of the same order. Thus it seems that the nepheline-plagioclase intergrowths formed during the late stages of magmatic crystallization.

Interpretation of Texture. The above data and textural relations are used to discuss the four possible modes of origin of the plagioclase-nepheline intergrowth:

If the plagioclase blebs had exsolved from nepheline the CaO contents of the nepheline containing the plagioclase blebs would be expected to be lower than in the nepheline not containing blebs. In fact the CaO contents of both types of nepheline are very similar. The presence of plagioclase rims around nepheline and embayed boundaries, etc., also rule out this mode of origin.

Textures alone are sufficient to discount an origin by simultaneous crystallization from the melt; especially the presence of detached plagioclase lamellae in optical continuity with the main plagioclase mass. Simultaneous crystallization from the melt might be expected to produce a more even distribution of mineral phases similar to the nepheline-K-feldspar vermicular intergrowth, which Davidson (1970) attributed to rapid cotectic crystallization.

Fig. 5 shows a plagioclase euhedral to two adjacent alkali-feldspar grains; nepheline fills the space between the alkali feldspars but is seen to penetrate through the plagioclase. Thus replacement of nepheline by plagioclase can be ruled out.

The most likely mode of origin is replacement of plagioclase by nepheline. The embayed plagioclase margins are thought to indicate progressive replacement in which nepheline penetrates the plagioclase grains. During this process plagioclase fragments are cut off from the main grain and are gradually replaced, in some cases leaving only tiny blebs set in a nepheline matrix. In some grains (figs. 1 and 2) the nepheline is seen as a core inside a plagioclase rim; these are thought to form by selective replacement of the Ca-rich plagioclase cores by the nepheline. Some of the plagioclase residual grains show especially strong zoning and the replacement process may have accentuated magmatic zoning effects.

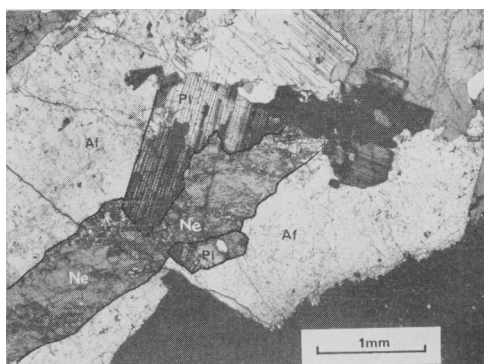


FIG. 5. The plagioclase in the centre is euhedral against two large tabular alkali feldspars. Nepheline (grey) grows in between the alkali feldspars and cuts through the plagioclase grain. The margins of some of the grains are accentuated with ink. Abbreviations as in fig. 1. (Crossed polars).

Mechanism of replacement process. The replacement textures described by Tilley (1957) occur in metasomatized rocks in which nepheline of low-temperature composition is associated with albite-oligoclase (Tilley, 1954). Gummer and Burr (1946) recognized two generations of albite in these rocks; an early one of composition Ab 90-5 and a later one Ab 95-7. They believed that the nepheline formed between these generations, but Tilley (1957) suggested that some of the larger nepheline grains may have formed after the later feldspar generation. The alkali feldspar present in these rocks is microcline.

Subbarao (1969) described a vermicular intergrowth of sodalite and albite from syenitic rocks; the presence of albite presumably indicates that this is another relatively low-temperature assemblage and Subbarao suggests that it was formed by post-magmatic replacement. The Marangudzi felsic mineral assemblages are clearly higher temperature associations formed at 750–850 °C, i.e. late stage magmatic.

The alkali feldspars in these rocks show no textures with nepheline that could be interpreted as being due to replacement and some of the larger alkali feldspar grains are completely euhedral to nepheline (fig. 5). Thus the replacement of only plagioclase by nepheline may indicate that the plagioclase is in fact being resorbed and immediately replaced by nepheline. The crystallization history of the felsic minerals can be elucidated as follows: Ca-rich plagioclase crystallized under fractional conditions and was zoned to more Na-rich compositions. The liquid soon reached the two-feldspar surface in the system Ne–Ks–Qz–An (Carmichael, 1965) at which point K-rich alkali feldspar crystallized. These two minerals crystallized together until at some temperature in the range 750–850 °C the liquid met the intersection of the two-feldspar surface with the nepheline phase volume. At this stage nepheline began to crystallize and plagioclase became resorbed being progressively replaced by nepheline until solidification was complete. If this crystallization history is correct this texture should occur in other basic syenitic rocks. It is noteworthy that Tilley and Gittins (1961) have described a similar texture between nepheline and plagioclase in igneous theralites from Ontario; however these rocks do not contain alkali feldspar. Essexites from Ditro (Tilley, 1957) and Salem Neck, Massachusetts (Shand, 1946) also show similar textures where the plagioclase is presumably more Ca-rich than in syenitic rocks; however, these textures have previously been attributed to metasomatic alteration of the plagioclase (nephelinization).

MacKenzie and Rahman (1969) described the crystallization of Ne-normative trachytes from Ischia and showed how equilibrium crystallization of these bulk compositions could lead to resorption of the plagioclase on the two-feldspar surface. Although the Ischia rocks are more Na-rich than the Marangudzi pulaskite R. 26 it is interesting to note that resorption generally started in plagioclase of compositions close to An_{40} , which is very similar to the composition of plagioclase in association with nepheline in R. 26. Thus it seems likely that plagioclase could resorb in the late stages of fractional crystallization of the Marangudzi pulaskites.

This plagioclase resorption process together with simultaneous replacement by nepheline could indicate a reaction relationship between plagioclase and nepheline. This possibility is to be further investigated experimentally.

Acknowledgement. We would like to thank Professor W. S. MacKenzie for his constructive comments on this paper.

REFERENCES

- BANNISTER (F. A.) and HEY (M. H.), 1931. *Min. Mag.* **22**, 569.
BOWEN (N. L.), 1912. *Amer. Journ. Sci.* **33**, 551–73.
CARMICHAEL (I. S. E.), 1965. *Min. Mag.* **34**, 107–25.
DAVIDSON (A.), 1970. *Canad. Min.* **10**, 191–206.
EDGAR (A. D.), 1963. Unpublished Ph.D. Thesis, Univ. of Manchester.

- GUMMER (W. K.) and BURR (S. V.), 1946. *Journ. Geol.* **54**, 137-68.
HAMILTON (D. L.), 1961. *Ibid.* **69**, 321-9.
— and MACKENZIE (W. S.), 1965. *Min. Mag.* **34**, 214-31.
HENDERSON (C. M. B.), 1968. *Papers Proc. 5th Gen. Meeting I.M.A., Cambridge 1966*, 291-304.
IIYAMA (J. T.), 1966. *Bull. Soc. franç. Min. Crist.* **89**, 442-54.
MACKENZIE (W. S.) and RAHMAN (S.), 1969. *Amer. Journ. Sci.* **267A**, 391-406.
PERCHUK (L. L.) and RYABCHIKOV (I. D.), 1968. *Journ. Petr.* **9**, 123-67.
SHAND (S. J.), 1946. *Journ. Geol.* **54**, 398-401.
SUBBARAO (K. V.), 1969. *Canad. Min.* **9**, 721-3.
TILLEY (C. E.), 1954. *Amer. Journ. Sci.* **254**, 65-75.
— 1957. *Quart. Journ. Geol. Soc.* **113**, 323-60.
— and GITTINS (J.), 1961. *Journ. Petr.* **2**, 38-48.
WRIGHT (T. L.) and STEWART (D. B.), 1968. *Amer. Min.* **53**, 38-87.

[Manuscript received 19 May 1971]