A GEOCHEMICAL COMPARISON OF THE BLUE MOUNTAIN (ONTARIO, CANADA) AND STJERNÖY (FINNMARK, NORTH NORWAY) NEPHELINE SYENITES

BY

K. S. HEIER

(Department of Geophysics, The Australian National University
Canberra, A.C.T., Australia)

Abstract: The chemistries of the Stjernöy and Blue Mountain nepheline syenites are compared. They both belong to the miascitic type of nepheline syenites. They have low concentrations of the rare earths, scandium, yttrium, niobium, uranium, and thorium. They have a characteristically high K/Rb ratio (> 500), and are very low in Cs. Their major chemical difference is in the K/Na ratio and the Ba and Sr concentrations. The Stjernöy nepheline syenite crystallized at the higher temperature. Both are used in the ceramics industries.

Introduction

Economic interest in nepheline syenites comes from their use as raw material in the ceramics industries. To the author's knowledge only two nepheline syenites in the western world are at present mined for this purpose: the Blue Mountain nepheline syenite, Ontario, Canada; and the Stjernöy nepheline syenite, Finnmark, Norway. The Blue Mountain nepheline syenite has been studied by a number of authors, and HEWITT (1960) reviewed the existing literature. Published reports on the Stjernöy nepheline syenite are by HEIER (1961, 1962, 1964). Chemical analyses of nepheline and feldspar from the area are published by BARTH (1963). The geological environment of the two nepheline syenites is very different. The Canadian occurrence, by far the larger of the two, intrudes and partially replaces para-amphibolites, paragneiss, and marble. The nepheline syenite itself is intruded and replaced by pink syenite and syenite pegmatite. Several authors have argued that the nepheline syenite formed through replacement of a folded stratigraphic horizon in the sedimentary sequence, but HEWITT (1960) favours a magmatic emplacement within a folded metasedimentary structure without replacement of sedimentary rocks. The situation is complicated by later metamorphic structures imposed on both sediments and intrusives. The age of the rock is Precambrian.

The Stjernöy nepheline syenite has a magmatic appearance and occurs with a biotite banded carbonatite in an area of largely gabbroic and ultramafic rocks. It is a very homogeneous rock. Foliation and some crushing of minerals is noted close to the eastern contact but the central and western part of the nepheline syenite are only very slightly foliated or not at all. Where observed, the foliation is always parallel to the contacts. Strong deformation of albite-nepheline pegmatites occurring in gabbro, and boudinage structures of similar pegmatites in the carbonatite demonstrate a period of tectonization at the final stages of the geologic activity on Stjernöy. Apparently the major nepheline syenite body was only slightly affected by these forces, and the pseudomonoclinic orthoclase perthite is the stable alkali feldspar even though orthoclase is readily transformed into microcline through mechanical stress. The metamorphic rocks on Stjernöy are in granulite facies in which orthoclase is the stable feldspar phase. The potassium feldspar of the Blue Mountain nepheline syenite is a microcline.

The author spent two months (1959) at Stjernöy studying the nepheline syenite and surrounding rocks. The Blue Mountain nepheline syenite was visited for a few days in July, 1961, and samples were collected from the main quarries. HEIER (1964) made a study of the geochemistry of the Stjernöy nepheline syenite. As both occurrences are used in the ceramics industries it is of interest to compare their geochemistry. Three samples from the Blue Mountain nepheline syenite were analyzed for the same elements as determined in the Stjernöy rock, and the analytical method was identical.

Crystallization temperatures of the nepheline syenites

Both nepheline syenites are characterized by silica deficiency and excess alumina, and are of miascitic type. Table 1 gives the modal composition of the two rocks. A difference between them exists in the feldspar relations. At Stjernöy the feldspar is an alkali feldspar perthite with very little albite as independent grains. At Blue Mountain the potassium feldspar is a microcline and albite is the dominant feldspar phase. The Stjernöy nepheline syenite may be classified as a hypersolvus type, and that from Blue Mountain as a subsolvus type. However, the Blue Mountain nepheline syenite, if magmatic, has been subjected to metamorphic processes after its emplacement, and the feldspar relations will reflect the PT conditions of the metamorphism rather than that of magmatic crystallization.

Table 1. *Average mode of the Blue Mountain and Stjernöy nepheline syenites*

		112 thin sections of Blue Mt. neph. sy. (HEWITT, 1960, p. 135)	19 thin sections of Stjernöy neph. sy.
K-feldspar	microcline..	20 (2–40)	
	orthoclase .		
	perthite....		56 (49–65)
Plagioclase (albite)		54 (35–80)	2 (0–10)
Nepheline		22 (0–40)	34 (19–47)
Calcite		—	3
Muscovite		2	—
Mafic minerals		2	5

Average chemical analyses and norms of the two rocks are shown in Table 2. The significant difference between them is in the Na/K ratios which vary from about 1 (Stjernöy) to 2.5 (Blue Mountain). (The Stjernöy rock is also higher in Ca, largely as calcite, and in iron.) The magnitude of the different Na/K ratios is illustrated in Fig. 1 where the normative and modal compositions of the two rocks are plotted in a nepheline feldspar diagram.

The two rocks and their nepheline and feldspar phases are plotted on the Ne-Ks-Qz diagram in Fig. 2. Some relevant isotherms are indicated. They are from SCHAIRER (1957) for the dry system, and FUDALI (1963) for a P_{H_2O} of 1000 bars. The leucite field decreases rapidly with pressure. The hydrated system corresponds best with the natural conditions of these rocks. 1000 bars water pressure corresponds to a depth of about 3 km assuming the water pressure to be equal to the

Table 2. *Chemical analyses (major elements) and norms of typical Blue Mountain and Stjernöy nepheline syenites*

	Average of five analyses of 'crude nepheline syenite' ore (HEWITT, 1960, no. 10, p. 141).	Chemical analyses of nepheline syenite no. 11 (HEIER, 1961, p. 142).
SiO_2	58.93	52.73
TiO_2	0.06	0.51
Al_2O_3	23.10	23.71
Fe_2O_3	2.09	1.89
FeO	—	1.04
MgO	0.10	0.24
MnO	—	0.06
CaO	0.83	2.54
Na_2O	10.33	7.78
K_2O	4.12	8.08
P_2O_5	0.02	0.05
CO_2	—	0.77
H_2O^+	0.53	0.26
H_2O^-		0.05
Norm:		
Or	24.46	45.75
Ab	46.24	6.62
Ne	22.36	36.09
An	3.89	4.90
Cor.	0.10	—
Ct.	—	1.9
Ol	0.44	—
Mt	1.86	0.51
Rest	0.66	3.23

load pressure. HEIER (1961) pointed to the close association of carbonatite and nepheline syenite at Stjernöy, and postulated that the nepheline syenite crystallized under a high CO_2 pressure. This is also indicated by the presence of calcite in the nepheline syenite. Thus the load pressure must be assumed to be considerably higher than the water pressure. This would result in a further decrease in the leucite field but the effect on the isotherms is uncertain. WYLLIE and TUTTLE (1959) found that carbon dioxide under pressure has little or no effect on the rates of melting or crystallization of granite or alkali feldspars, and the melting temperatures seem to be unaffected except insofar

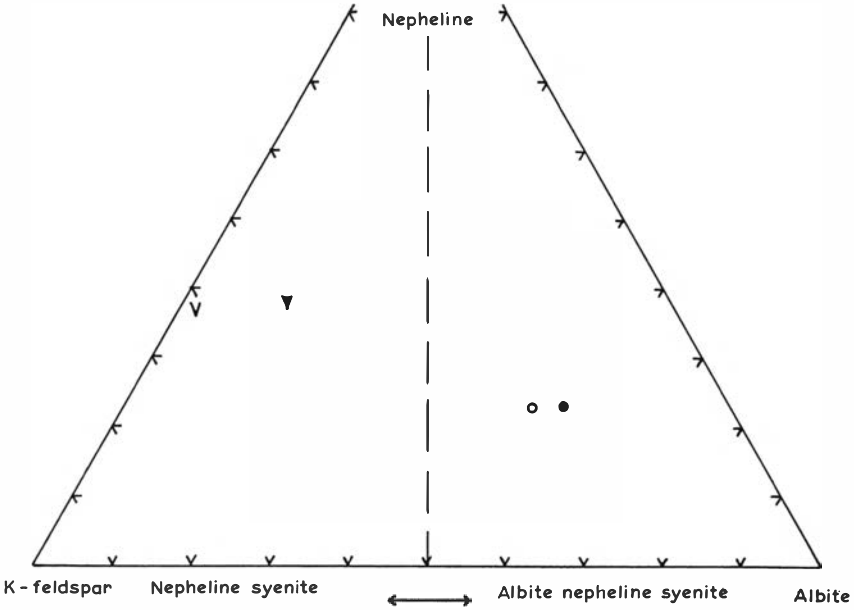

Fig. 1. Plots of the Stjernöy and Blue Mountain nepheline syenite on a K-feldspar-Albite-Nepheline diagram.

V Stjernöy modal composition
▼ Stjernöy normative composition
● Blue Mountain modal composition
○ Blue Mountain normative composition

as pressure *per se* raises the temperature of melting. In the hydrated system the crystallization temperatures for the Stjernöy and Blue Mountain nepheline syenites are about 840° and 800° C respectively. In the dry system they are 1250° and 1050° C respectively.

Tilley (1954, 1957) suggested the use of the tielines in the Ab-Or-Ks-Ne system to distinguish between various nepheline parageneses, and a general discussion of nepheline as a geologic thermometer was given by Barth (1963). The tielines are drawn in Fig. 2. For the Blue Mountain rock the tieline is taken from Tilley (1957, Fig. 7) and is not based on the average chemical analyses of Tables 2 and 3. Hamilton and MacKenzie (1960) determined these tielines at 700° C.

Burnham (1961) studied the composition of the aqueous fluid in coexistence with natural pegmatites and synthetic granite mixtures. He found that the ratios of Na and Li to all anhydrous constituents

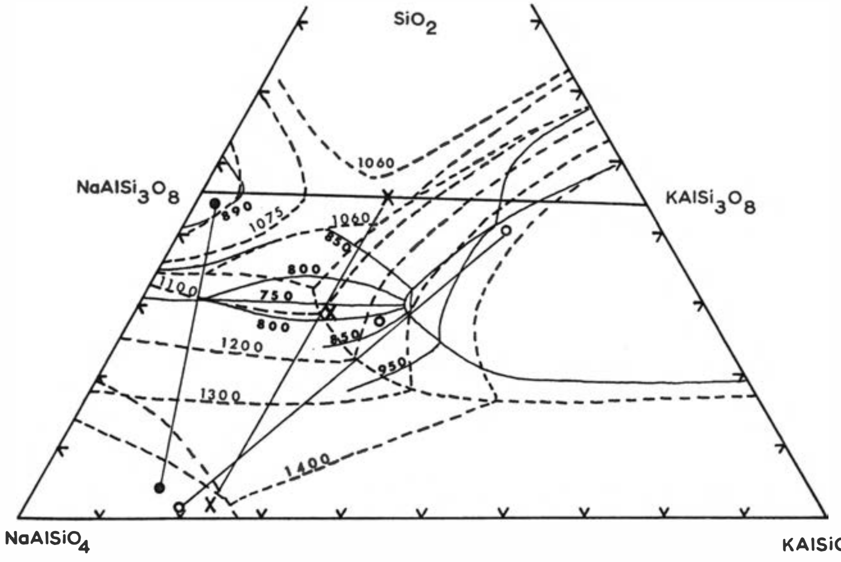

Fig. 2. Plots of host rocks and mineral phases on a Ne-Ks-Qtz diagram.
- - - - isotherms after SCHAIRER (1957)
—— isotherms after FUDALI (1963)
○ Stjernöy; nepheline syenite, K-feldspar, nepheline
● Stjernöy; pegmatite; albite, nepheline
X Blue Mountain; nepheline syenite, total feldspar, nepheline.

generally are higher in the aqueous phase than in the coexisting condensed phases. The corresponding ratios for both K_2O and Al_2O_3 are lower in the aqueous phase.

HAMILTON (1961) showed that an increase in the Si/Al ratio in nephelines took place at increasing temperatures. However, this substitution (Si for Al) is not very temperature sensitive, and an accurate temperature determination depends not only on very accurate Si and Al determinations (not often achieved) but also on accurate Na, K, and Ca determinations. The compositions of the nephelines plotted in Fig. 2 are not accurately enough determined to justify the use of this thermometer.

The structural state of the potassium feldspar in the Stjernöy nepheline syenite shows the temperature to have been above 500° C.

Even though the crystallization temperatures of the two nepheline syenites cannot be derived it may be concluded that:

Table 3. *Chemical composition of the feldspars and nephelines Blue Mountain* (Hewitt, *1960, p. 7*)

	Albite	Microcline	Nepheline
SiO_2	67.90	64.50	43.01
Al_2O_3	20.60	19.31	34.01
Fe_2O_3	nil	nil	0.14
FeO	—	—	—
MgO	0.06	0.42	0.04
CaO	0.24	0.07	0.36
Na_2O	10.78	2.03	15.42
K_2O	0.15	13.59	6.15
H_2O^+	0.22	0.28	0.99
Stjernöy (Heier, unpublished, separated from rock Table 2; see also Barth 1963)			
SiO_2		62.14	42.82
Al_2O_3		20.91	35.17
Fe_2O_3		0.08	0.16
FeO		0.05	0.05
MgO		—	—
CaO		0.48	0.82
Na_2O		3.59	16.27
K_2O		11.32	5.36
Stjernöy, nepheline-albite pegmatite (Heier, unpublished)			
SiO_2	65.81		44.22
Al_2O_3	21.10		34.03
Fe_2O_3	0.13		0.22
FeO	0.04		0.05
CaO	1.04		0.16
Na_2O	10.73		17.24
K_2O	0.60		4.46

(1) the Stjernöy nepheline syenite crystallized at the higher temperature, and

(2) the crystallization temperature of the Stjernöy nepheline syenite was probably below 700° C.

Geochemistry of the nepheline syenites

Heier (1964) discussed extensively the geochemistry of the Stjernöy nepheline syenite. The average concentration of the elements determined is shown in Table 4 (average of 16 rocks). Three samples of the

Table 4. *Chemistry of the Blue Mountain (BM-1, -2, -3) and Stjernöy (4) nepheline syenites*

	BM-1	BM-2	BM-3	4
B	n.d.	tr.	tr.	n.d.
Si %				24.56
Al %				12.42
Ti %	tr.	tr.	0.025	0.28
Cr p.p.m.	5-10	5-10	5-10	5-10
V p.p.m.	n.d.	n.d.	tr.	42
Nb	n.d.	n.d.	n.d.	n.d-tr.
Fe %	3.1	1.8	1.45	2.37
Mg %	n.d.	n.d.	n.d.	0.16
Li p.p.m.	18	33	40	3.5
Ni	n.d.	n.d.	n.d.	n.d.
Zr p.p.m.	140	130	tr.	26
Sc	n.d.	n.d.	n.d.	n.d.
Co	n.d.	n.d.	n.d.	n.d.
Mn %	0.080	0.039	0.030	0.055
Y	n.d.	n.d.	n.d.	n.d.-tr.
Na %	7.26	7.39	6.76	5.75
Nd	n.d.	n.d.	n.d.	n.d.
La	n.d.	n.d.	n.d.	tr.
U p.p.m.	0.2	0.1	—	0.09
Ca %	0.75	0.47	0.27	1.61
Th p.p.m.	0.5	0.4	—	0.55
Sr p.p.m.	49[1]	20	36	3500
K %	3.50	3.92	5.16	6.66
Ba p.p.m.	38	40	28	2400
Rb p.p.m.	44	70	70	115
Cs	n.d.	n.d.	n.d.	n.d.
K/Rb	795	560	737	579
K/Ba	921	980	1842	28

[1] Determined by isotope dilution, courtesy W. Compston, A.N.U.

Blue Mountain nepheline syenite were collected along a north (BM-1)-south (BM-3) profile. The analytical data of the three rocks are listed individually in Table 4 (for description of analytical method see HEIER, 1964).

Both nepheline syenites are very low in the rare earths, scandium, yttrium, niobium, uranium and thorium. These elements are commonly concentrated in nepheline syenites especially of the agpaitic clan.

Zirconium is present in amounts above 100 ppm in two of the Blue Mountain rocks. Of the 16 analyzed Stjernöy rocks it was not detected in 4; traces in 6; ranging between 40 and 80 ppm in 6. Both types are also low in Cr, Ni, and Co.

Rb is depleted relative to K in both types of nepheline syenites. Cs, which is detected down to a concentration level of 1 ppm by the analytical method used, was not seen in any of the samples of either nepheline syenite. In view of the close coherence between K and Rb, and the nearly constant K/Rb ratio of 230 ± 50 in magmatic crustal rocks, the observed ratio between 500 and 800 is significant. This has been commented on by HEIER (1964) and HEIER and TAYLOR (1964). They suggested that it either reflects a primary feature of the system from which the rocks crystallized, or it is evidence of element partition between a crystallizing melt and a gas phase which later escaped. However, it is not known if a gas phase acting on a crystallizing magma can produce the observed result. GAST (1960) suggested that the K/Rb ratio of the upper mantle is probably greater than 400, and HEIER and ADAMS (1963) suggested a value of 300 for this ratio. Recent work by LESSING *et al.* (1963) on Hawaiian basalts indicates that K/Rb ratios above 500 for upper mantle material is not impossible. It is possible that metamorphic processes acting on deep crustal material can cause depletion of Rb relative to K in the material of the deep sialic crust. This is indicated by some mineral transformations taking place at metamorphism under granulite facies conditions (e.g. breakdown of mica and formation of feldspars and pyroxenes), HEIER (1964b). Studies of the Sr^{87}/Sr^{86} ratios in carbonatites from Ontario and Stjernöy suggest a deep seated origin of these rocks (POWELL and HURLEY, 1963).

Differences between the two nepheline syenites are as interesting as the similarities between them. Li is more concentrated in the Blue Mountain deposit, and B has been detected in it but cannot be seen in any of the analyzed Stjernöy specimens. Apart from the different Na/K ratio commented on earlier, the most striking difference is in their Sr and Ba concentrations. The Stjernöy nepheline syenite is very high in Ba and Sr compared with major magmatic rock types. The K/Ba ratio is similar to that in syenites but Sr is concentrated by a factor of 10 relative to major elements compared with other igneous rocks (TUREKIAN and WEDEPOHL, 1961). The Blue Mountain nepheline syenite is, on the other hand, very low in both elements. The mineral phases of the Blue Mountain nepheline syenite have not been analyzed but those from Stjernöy are examined (unpublished). The nepheline structure tends to reject both Ba and Sr. The concentrations of both elements may exceed 100 ppm in nephelines but they are concentrated in coexisting feldspars by a factor of between 10 and 100. The albites from the nepheline-albite pegmatites on Stjernöy are very high in both Ba and Sr. However, they tend to be high in K as well. In the author's opinion the chemistry of the mineral assemblage of the Blue Mountain nepheline is characteristic of a low temperature assemblage. Earlier work (cf. HEIER and TAYLOR, 1959) has shown that Ba and Sr concentrations decrease rapidly in differentiated assemblages, but K/Rb ratios decrease in the same direction.

Conclusions

1. The Blue Mountain and Stjernöy nepheline syenites are miascitic rocks.
2. Both rocks are low in the rare earths, Sc, Y, U, Th, and Nb. The low concentrations of these elements may well be characteristic of the miascitic rocks in general and petrogenetically significant.
3. Both rocks are low in Cr, Ni, and Co.
4. Both rocks are characterized by very high K/Rb ratios. Such ratios are not known to be produced by any magmatic differentiation process. It may be a primary property of the system from which the nepheline syenites formed or result from element partition between a crystallizing melt and a gas phase.
5. The K/Na ratio is very different in the two nepheline syenites.
6. The two rocks differ in their concentrations of Ba and Sr. Both elements are about 100 times more abundant in the Stjernöy nepheline syenite than in the one from Blue Mountain. The former is enriched and the latter depleted in these elements compared with major igneous rocks.
7. A metasomatic origin of the Blue Mountain deposit is difficult to reconcile with the high K/Rb ratio of the rock. This high ratio could not have been retained if much upper crustal material was involved in the process. A crystallization from hydrothermal solutions

that originated at depth without much contamination of upper sialic material seems to explain the formation of the Blue Mountain deposit.

8. The trace element data cannot alone decide the mode of formation of the rocks. They indicate, however, that main differences exist between petrographically similar rocks.

Acknowledgements

Dr. S. R. Taylor has read the manuscript and given constructive criticism.

REFERENCES

BARTH, T. F. W. 1963. The composition of nepheline. Schweiz. Min. Petr. Mitt. v. 43, pp. 153–164.

BURNHAM, C. W. 1961. Experimental studies of pegmatite genesis: The composition of pegmatite fluids. 1961 Annual Meeting, G.S.A. (abstract).

FUDALI, R. F. 1963. Experimental studies bearing on the origin of pseudoleucite and associated problems of alkalic rock systems. Geol. Soc. America Bull. v. 74, pp. 1101–1126.

GAST, P. W. 1960. Limitation on the composition of the upper mantle. Jour. Geophys. Res. v. 65, pp. 1287–1297.

HAMILTON, D. L. 1961. Nephelines as crystallization temperature indicators. Jour. Geol. v. 69, pp. 321–329.

HAMILTON, D. L. and MACKENZIE, W. S. 1960. Nepheline solid solution in the system $NaAlSiO_4$ — $KAlSiO_4$ — SiO_2. Jour. Petr. v. 1, pp. 56–72.

HEIER, K. S. 1961. Layered gabbro, hornblendite, carbonatite and nepheline syenite on Stjernöy, North Norway. Norsk geol. tidsskr. v. 41, pp. 109–155.

— 1962. A note on the U, Th, and K contents in the nepheline syenite and carbonatite on Stjernöy, North Norway. Norsk geol. tidsskr. v. 42, pp. 287–292.

— 1964. Geochemistry of the nepheline syenite on Stjernöy, North Norway. Norsk geol. tidsskr. v. 44, 205–215.

— 1964b. Rubidium/Strontium and Strontium-87/Strontium-86 ratios in deep crustal material. Nature, 202, pp. 477–478.

— and ADAMS, J. A. S. 1964. The geochemistry of the alkali metals. Physics and Chemistry of the Earth, v. 5, pp. 253–381.

— and TAYLOR, S. R. 1959. Distribution of Ca, Sr, and Ba in southern Norwegian pre-Cambrian alkali feldspars. Geochim. et Cosmochim. Acta, v. 17, pp. 286–304.

— and TAYLOR, S. R. 1964. A note on the geochemistry of alkaline rocks. Norsk geol. tidsskr. v. 44, 197–204.

HEWITT, D. F. 1960. Nepheline syenite deposits of southern Ontario. Ontario Dept. of Mines, v. 69, pt. 8, 194 pp.

LESSING, P., DECKER, R. W., and REYNOLDS, R. C. Jr. 1963. Potassium and rubidium distribution in Hawaiian lavas. Jour. Geophys. Res. v. 68, pp. 585–589.

POWELL, J. L. and HURLEY, P. M. 1963. Isotopic composition of strontium in some carbonatites and carbonate rocks of uncertain classification. M. I.T. Dept. of Geology and Geophys. NYO-10, 517 Eleventh Ann. Prog. Rep. for 1963, pp. 51–52.

SCHAIRER, J. F. 1957. Melting relations of the common rock forming silicates. Am. Ceramic Soc. Jour. v. 40, pp. 215–235.

TILLEY, C. E. 1954. Nepheline-alkali feldspar parageneses. Am. Jour. Sci. v. 257, pp. 65–75.

— 1957. Problems of alkali rock genesis. Quart. Jour. Geol. Soc. (London), v. 113, pp. 323–358.

TUREKIAN, K. K. and WEDEPOHL, K. H. 1961. Distribution of the elements in some major units of the Earth's crust. Geol. Soc. America Bull. v. 72, pp. 175–192.

WYLLIE, P. J. and TUTTLE, O. F. 1959. Effect of carbon dioxide on the melting of granite and feldspars. Am. Jour. Sci. v. 257, pp. 648–655.

Accepted for publication July 1964

Printed March 1965