GEOCHEMISTRY OF THE NEPHELINE SYENITE ON STJERNØY, NORTH NORWAY

By

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Abstract. The nepheline syenite on Stjernøy is characterized by silica deficiency and excess alumina. Alkali feldspar and nepheline are the dominant minerals, and femic minerals constitute less than 5 per cent of the rock.

The geochemistry of the rock is discussed, and attention is drawn to the low concentrations of Nb, Li, Zr, Y, Nd, La, U, and Th. All these elements are often concentrated in alkaline rocks. Low concentrations of Rb, Cs, Pb, and Tl, with high concentrations of Sr and Ba may reflect conditions at the site of magma formation but may also reflect partition of elements between the crystallizing magma and a gas phase.

Introduction

The petrology of the nepheline syenite on Stjernøy was discussed by Heier (1961). In the present study a number of elements are determined spectrographically on rock specimens whose locations and modal analyses were given by Heier (1961, Fig. 12 and Table 8 respectively). Uranium and thorium were determined in the same samples by Heier (1962), and the data are included here in Tables 5 and 6.

(1) The present study is a part of a geochemical study of alkaline rocks in general which has been started by the writer (certain aspects of the geochemistry of alkaline rocks have been emphasized by Heier and Taylor (1964), and

(2) gives information about the chemical environment of nephelines and feldspars studied by the writer. Data on these minerals will be published elsewhere.

Analytical methods

The alkali metals: Na and K were determined with a Perkin — Elmer flame photometer using Li as internal standard. K was also determined by HEIER (1962) using a radiometric method.

Li, Rb, and Cs were determined spectrographically using a Hilger large spectrograph with glass optics. Conditions were as follows:

Electrodes: National Carbon L 4260, preformed;
Stepsector: 8, steps 2 : 1 ratio;
Slit: 10 *u*.
Current: 4 amp. d.c.;
Plates: Kodak I N.

The samples were arced until the end of the alkali destillation. Cs could not be detected by this method in any of the samples indicating that its concentration is less than 1 p.pm. Rb 7800 and Rb 7947 were read and both K 6939 and Na 5682 were used as internal standard lines. The agreement between the four results obtained in this way for each samples was $\pm$ 5% or better. It was found that the conventional rock standards used for the determination of the other elements (Table 1) were not suited for the determination of Rb. A matrix effect was found systematically to increase the spectrographic Rb determinations by as much as 50%. The reason for this matrix effect is not known. Other silicate rocks have been found to give good results when based on the international rock standards G — 1, W — 1, Sy — 1. The nepheline syenites differ from other silicate rocks in higher alkali contents, and a lower Si/Al ratio. To overcome this Rb was determined by isotope dilution in sample no. 11 (courtesy of Dr. W. Compston, A. N. U.), and by atomic absorption by Dr. G. K. Billings, Rice University. A nepheline syenite from Blue Mountain, Ontario, containing 35 p.p.m. Rb was also determined by isotope dilution. A working curve based on the readings for these two rocks was constructed and used for the determination of Rb in all the other samples.

Li was determined from the Li 6707 line using the standards in Table 1.

The other elements were determined with a Jarrell Ash Ebert grating spectrograph (1st. order; dispersion = 5.2 A/mm). One part of the sample was mixed with 2 parts of a carbon — palladium mix (4 mg. $(NH_3)_4Pd(NO_3)_2$ to 10 grams of SP-2 graphite powder). The conditions were as follows:

electrodes: National Carbon, L4259, preformed;
stepsector: 8 steps (2 : 1 ratio);
slit: 20 μ;
plates: Ilford ordinary, N 30.

The samples were arced to completion. The lines read are given in Table 1. Pd 3421 served as internal standard line.

The external standards with adopted concentrations of the different elements are given in Table 1. Sr was determined by isotope dilution in two samples, and it was found that the nepheline syenites plotted on the working curve for Sr drawn on the basis of the standards listed in Table 1 with no visible matrix effect. Major chemical analyses of two of the rocks have been made

Table 1. Concentrations of elements in external rock standards.

p.p.m.	G-1	W-1	Sy-1	Milford granite 4983	Sodafeldspar U.S.B.S. 99	Silica brick 102	Firebrick 269	Opal glass 91	Lines read.
B	—	17	70	—					
Ti............	1100	6400	2500	105		290	210		3438
Cr	15	125	50				170		4254
V	15	240	78				190		4374
Fe	13700	77600	59000	13000	470	4600		700	4326
Mg	2400	40000	27000			1300	7000		2780
Li............	24	9			3.7				6707
Ni		75	40	4.8		14	88		3414
Zr	185	110	2500	105		290	210		3438
Sc		35	15	10			24		4246
Co	2.4	50	20				23	5	3453
Cu	15	120	22	9	25	24	52		3274
Mn	230	1300	3000	580			230		4034
Y	13	24	21	450		14	35	10	3327
Nd	55		350	65			53		4303
La	100		230						4337
Ca	9700	78200	73000	5000	2600		2400		3158
Sr............	250	160	205	115	110	20	120	42	4607
									4434
Ba	1250	170	330	1900	115	50	540	64	4554

Table 2. Comparison of chemical (a) and spectrographical (b) data

Elements %	6		11	
	a	b	a	b
Ti............	0.37	0.36	0.31	0.26
Fe	2.25	2.2	2.13	2.15
Mg	0.15	0.18	0.14	0.14
Mn	0.07	0.073	0.05	0.052
Ca	2.22	2.00	1.82	1.45

previously (nos. 6 and 11, HEIER, 1961), and the results agreed well with those determined spectrographically, Table 2. On the basis of these tests it can be concluded that no matrix effect interferred with the determination of the invo-latile elements.

Plate calibration was carried out using the self—calibration method. Lines were read using a Jarrell—Ash Model 23—100 microphotometer.

Discussion of the results

HEIER (1961) showed that the nepheline syenite on Stjernøy is characterized by silica deficiency and excess alumina. It belongs to the miaskitic clan of alkaline rocks. (The Al excess has later been demonstrated by the sporadic occurrence of corundum in the rock). To the east and north it bounds on a carbonatite rock. Both the carbonatite and the nepheline syenite are devoid of rare earths, niobium, and tantalum minerals often associated with alkaline rocks, though especially of the agpaitic clan.*

Table 3. Modal composition of the biotite, no sphene nepheline syenite (column 1, 2), and the pyroxene, sphene nepheline syenite (column 3).

	1 Samples (3—8)	2 Samples (20—21)	3 Samples (9—19)
K-feldspar (perthite)	54	57	57
Albite (individual grains)	6	5	0—tr.
Nepheline	31	27	37
Calcite	4	6	2
Clinopyroxene	—	—	1
Hornblende	—	—	1
Biotite	4	3	0—tr.
Rutile in feldspar	+	+	—
Sphene	0—tr.	—	0.5—1
Apatite	tr.	tr.	tr.
Opaques	1	2	1

* A sample of the Stjernøy carbonatite was given to Dr. J. L. Powell in connection with his work on Sr—isotopes in carbonatites and other carbonate rocks. He (POWELL and HURLEY, 1963) found a Sr^{87}/Sr^{86} ratio identical to the classic carbonatites examined by him (0.7036), and different from metasedimentary limestones.

Table 4. Chemical analyses of representative samples of the biotite (6) and pyroxene (11) nepheline syenites.

%	6	11
SiO_2	52.37	52.73
TiO_2	0.61	0.51
Al_2O_3	23.22	23.71
Fe_2O_3	1.14	1.89
FeO	1.86	1.04
MgO	0.25	0.24
MnO	0.09	0.06
CaO	3.11	2.54
Na_2O	6.87	7.78
K_2O	8.30	8.08
P_2O_5	0.09	0.05
CO_2	1.88	0.77
H_2O^+	0.26	0.26
H_2O^-	0.04	0.05

Similarily HEIER (1962) demonstrated very low U and Th concentrations in both rock types. HEIER (1961) distinguished between a pyroxene—sphene, and a biotite-no-sphene nepheline syenite within the same massif. The arithmetic means of the mineral modes of the two types are given here in Table 3. Chemical analyses (major elements) of one representative sample of each of the two types of nepheline syenite are given in Table 4. All the elements so far determined in the nepheline syenite are listed in Table 5 in order of increasing ionic radii. It is evident that the two petrographic types of nepheline syenite cannot be distinguished on the basis of their chemistry.

The arithmetic means for each element in the 16 analyzed nepheline syenites are given in Table 6. For comparison are listed the elements of the syenite at Lassefjordfjell, close to the nepheline syenite on Stjernøy (described by HEIER 1961, pp. 130—133) together with element concentrations in different magmatic rock types after Turekian and WEDEPOHL (1961). By definition the major elements of the Stjernøy nepheline syenite are closest to the syenite average; but of the trace elements, Nb, Li, Zr, Y, Nd, La, U and Th are much lower than normal, indeed, the concentrations of these elements in the nepheline syenite are similar to those found in ultrabasic (ultra-

Table 5. Element abundances in the Stjernøy nepheline syenite

	5	6	7	8	9	10	11	12
B	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Si %	—	24.47	—	—	—	—	24.64	—
Al %	—	12.29	—	—	—	—	12.55	—
Ti %	0.31	0.36	0.17	0.19	0.23	0.47	0.26	0.18
Cr	5—10	5—10	5—10	5—10	5—10	5—10	5—10	5—10
V	29	50	41	35	47	62	42	29
Fe %	1.85	2.2	2.2	2.4	2.6	3.3	2.15	1.8
Nb	tr.	tr.	n.d.	n.d.	tr.	tr.	n.d.	n.d.
Mg %	0.25	0.18	0.19	0.13	0.12	0.30	0.14	0.10
Li	6.5	4.6	3.1	4.1	3.3	2.0	2.9	2.6
Ni	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Zr	69	n.d.	tr.	n.d.	tr.	80	51	n.d.
Sc	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Co	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Cu	12	10	10	12	10	14	9	9
Mn %	0.041	0.073	0.037	0.051	0.052	0.086	0.052	0.040
Y	n.d.	n.d.	n.d.	n.d.	n.d.	tr.	n.d.	n.d.
Na %	6.40	5.10	6.16	4.28	5.91	5.86	5.77	5.68
Nd	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
La	tr.	tr.	tr.	tr.	tr.	~50	tr.	n.d.
U	0.06	0.1	n.d.	0.1	0.1	0.2	0.2	0.1
Ca %	1.55	2.0	1.45	1.45	1.25	2.7	1.45	1.30
Th	0.9	0.6	0.6	0.4	0.4	1.3	0.8	n.d.
Sr	4800	5000	3200	3200	4000	4300	3285*	2800
K %	5.60	6.86	6.82	6.99	6.99	6.47	6.99	7.05
Ba	3200	3000	2250	1200	2500	4000	2850	1650
Rb	95	125	85	130	135	100	133*	120
Cs	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
K/Rb	589	549	802	538	518	647	526	588

* determined by isotope dilution: n.d. not detected: tr. trace

mafic) rocks. The syenite on Lassefjordfjell appears to show the same pattern as the nepheline syenite, possibly indicating a genetic relation between the two.

The nepheline syenite is very high in Ba and Sr compared with the major magmatic rock types listed in Table 6. The K/Ba ratio is similar to that of syenites but Sr is concentrated by a factor of 10 relative to the major elements compared with the major igneous rock

Ↄoncentrations in p.p.m. where not otherwise stated).

13	13—14	14	15	16	19	20	21	approx. detection limit n.d. less than:
ı.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	10
—	—	—	—	—	—	—	—	
—	—	—	—	—	—	—	—	
0.34	0.41	0.24	0.27	0.25	0.21	0.30	0.31	
5—10	5—10	5—10	5—10	5—10	5—10	5—10	5—10	
35	50	37	38	39	33	52	48	
2.3	2.6	2.0	2.4	1.9	1.9	3.0	3.3	
tr.	n.d.	tr.	tr.	n.d.	tr.	n.d.	n.d.	20
0.17	0.20	n.d.	0.13	0.15	~0.07	0.32	0.17	
2.6	3.0	2.6	3.1	3.1	2.4	5.7	4.1	
ı.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	3
70	tr.	n.d.	47	41	tr.	tr.	tr.	10
ı.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	1
ı.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	2
10	10	9	9	11	11	17	14	
0.053	0.062	0.037	0.055	0.044	0.040	0.082	0.077	
ı.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	5
5.77	6.03	5.93	5.88	6.07	5.86	5.73	5.51	
ı.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	20
tr.	tr.	tr.	tr.	tr.	tr	tr.	tr.	15
0.2	0.1	n.d.	0.1	0.1	0.1	(0.03)	(0.02)	
1.45	1.45	1.30	1.35	1.40	1.10	2.6	2.0	
1.0	1.1	n.d.	0.4	0.8	0.4	0.4	(0.1)	
.50	3100	3000	3700	3650	3100	3350	3300	
6.64	6.54	7.19	6.61	6.86	7.04	5.90	5.93	
ı00	2700	1700	2800	2400	1850	2750	2100	
00	135	145	110	100	140	95	90	
ı.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	1
ı64	484	496	600	686	503	621	659	

types. In the compilation of Turekian and Wedepohl only deep sea carbonate sediments show approximately similar Sr concentrations, and the highest Ba concentrations are found in deep sea clays.

In view of the common average value of 230 ± 50 of the K/Rb ratio in magmatic crustal rocks it is interesting that Rb is significantly depleted in the Stjernøy nepheline syenite and syenite relative to potassium. Cs which was not detected in any of the rocks and is

Table 6. Comparison of element abundances in the nepheline syenite and syenite on Stjernøy with major igneous rock types (after TUREKIAN and WEDEPOHL, 1961).

	1	2	3	4	5	6	7	8
B	n.d.	n.d.	3	5	9	10	9	10
Si %	24.56	26.14	20.5	23.0	31.4	34.7	29.1	
Al % ...	12.42	8.68	2.0	7.8	8.2	7.2	8.8	
Ti % ...	0.28	0.74	0.03	1.38	0.34	0.12	0.35	
Cr	5—10	5—10	1600	170	22	4.1	2	
V	42	35	40	250	88	44	30	
Fe % ...	2.37	7.0	9.43	8.65	2.96	1.42	3.67	
Nb	n.d.—tr.	n.d.	16	19	20	21	35	20
Mg % ...	0.16	0.60	20.40	4.60	0.94	0.16	0.58	
Li	3.5	2.7	0.x	17	24	40	28	
Ni	n.d.	50	2000	130	15	4.5	4	3
Zr	26	110	45	140	140	175	500	10
Sc	n.d.	19	15	30	14	7	3	1
Co	n.d.	n.d.	150	48	7	1	1	2
Cu	11	22	10	87	38	10	5	
Mn % ..	0.055	0.145	0.162	0.15	0.054	0.039	0.085	
Y	n.d.—tr.	n.d.	0.x	21	35	40	20	5
Na % ..	5.75	4.17	0.42	1.80	2.84	2.58	4.04	
Nd	n.d.	n.d.	0.x	20	33	37	65	20
La	tr.	n.d.	0.x	15	45	55	70	15
U	0.09	—	0.001	1	3	3	3	
Ca % ...	1.61	2.65	2.5	7.6	2.53	0.51	1.80	
Th	0.55	—	0.004	4	8.5	17	13	
Sr	3500	330	1	465	440	100	200	
Pb	n.d.—tr.		1	6	15	19	12	6
K %	6.66	4.49	0.004	0.83	2.52	4.20	4.80	
Ba	2400	1700	0.4	330	420	840	1600	
Rb	115	40	0.2	30	110	170	110	
Tl	n.d.		0.06	0.21	0.72	2.3	1.4	0.5
Cs	n.d.	n.d.	0.x	1.1	2	4	0.6	1
K/Rb ..	579	1123	200	277	229	247	436	
K/Ba ...	28	26	100	25	60	50	30	

1. nepheline syenite, Stjernøy, average of Table 5.
2. syenite, Lassefjordfjell, Stjernøy.
3. ultrabasic rocks.
4. basaltic rocks.
5. high Ca-granites.
6. low Ca- granites.
7. syenites.
8. detection limit of spectrographic method.

therefore present in amounts less than 1 to 2 p.p.m. is depleted even more relative to K*. The Rb depletion cannot be explained as the result of Rb being rejected from the system because of restricted entry into the nepheline lattice. Work in progress on coexisting nephelines and feldspars on Stjernøy shows that the potassium feldspars tend to have higher K/Rb ratios than the nephelines.

The depletion of Rb may be a primary feature of the system from which the rocks crystallized. This has been commented on by HEIER and TAYLOR (1964). HAMILTON and DEANS (1963) inferred from their studies of carbonatites (which are associated with many alkaline provinces, including the one on Stjernøy) that all the carbonatites investigated by them have been derived from an area that has always been poor in Rb. It was mentioned above that the carbonatite on Stjernøy has a Sr^{87}/Sr^{86} ratio similar to all classic carbonatites. This ratio is at present interpreted as indicating a deep seated origin of the rocks.

Pb and Tl were not looked for in any of these samples, but alkali feldspars and nephelines separated from the rocks showed no detectable Tl (less than 0.5 p.p.m.) and only faint traces of Pb (less than 6 p.p.m.). These two elements are concentrated in potassium minerals by the same geological processes that concentrate Rb and Cs.

Thus the depletion of Rb, Cs, Pb, and Tl should be considered jointly, and together with the high concentrations of Sr and Ba. The possibility of a primary depletion of the magma in Rb was mentioned. However, if the nepheline syenite crystallized in equilibrium with a gas phase that later escaped, the distribution of the volatile elements Rb, Cs, Pb, and Tl between the crystals and the gas at the temperature of crystallization may be strongly in favor of the gas phase. In this way the volatile elements may be selectively removed from the magma. Experimental work to verify this is lacking, but EUGSTER (1955) found that the distribution of Cs between sanidine and a vapor phase was temperature dependent. Cs enters the sanidine lattice much more readily at high than at low temperatures. At temperatures below 700° C the distribution factor

$$F_{(\bar{T})} = \frac{Cs/K \text{ in sanidine}}{Cs/K \text{ in vapor}}$$

* Similar high K/Rb ratios have recently been published by LESSING et al (1963) for a suite of Hawaiian lavas.

will be less than 1 with Cs concentrations building up in the vapor phase upon crystallization. A similar pattern was found for Tl but the temperature dependance of the distribution factor for Tl is not so pronounced as for Cs.

BARTH (1939, p. 88) wrote: "Hauptziel der Erforschung der Alkaligesteine ist, den Grund zu entdecken, warum dieser Mangel an Al_2O_3 oder SiO_2 entsteht." HEIER and TAYLOR (1964) pointed out that in discussing the petrogenesis of alkaline rocks the depletion of Rb and Cs, and the concentration of Ba and Sr have to be considered; likewise the concentration of Rare Earths, Nb, Zr, and related elements in some nepheline syenites compared with a marked depletion of these elements in others. Not until the chemical patterns of such rocks are understood, can we hope to solve their genesis.

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