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Spinel-lherzolite inclusions in basaltic rocks from Bayuda, Sudan

RECENT investigations on the mineralogy and petrology of ultramafic nodules have shown that spinel-lherzolite inclusions and their host rocks (alkaline undersaturated basaltic rocks) are accidentally related (Griffin, 1973; Kutolin and Frolova, 1970; Frey and Green, 1974; MacGregor, 1974; MacGregor and Basu, 1974; Varne, 1977; Donaldson, 1978). A considerable number of geothermometers and geobarometers reported in the literature have indicated different equilibration temperatures and pressures for the minerals of each inclusion. In this connection, MacGregor and Basu (1974) pointed out that a set of samples from a single locality should define the ambient geothermal gradient at the time of intrusion.

In the Sudan spinel-lherzolite inclusions occur in the Bayuda volcanic field which lies 300 km north of Khartoum, in the northern part of the Bayuda Desert (Almond, 1974). The hosts are young basaltic rocks ranging from basanites to nepheline trachybasalts. In this paper the chemistry and mineralogy of some of these inclusions which occur in basanites and collected from an isolated volcano north of the main field were studied. The results provide more evidence on the origin of these inclusions following application of the recent studies on spinel-lherzolites.

Petrography and chemistry of the inclusions. The inclusions which have course granular texture are rounded in shape with average diameter 2–5 cm. They contain the four-phase assemblage of olivine, orthopyroxene, clinopyroxene and spinel. Olivine is the dominant mineral showing little sign of alteration. A wet chemical analysis of a representative sample of the inclusions together with the analysis of the host rock (after Almond, 1974) are given in Table I.

TABLE I. *Chemical analyses and CIPW norms of a representative spinel-lherzolite inclusion and host rock from Bayuda, Sudan*

	B.30	HBl		B.30A	HBlA
SiO_2	42.90	44.65	or	6.7	0.6
TiO_2	2.52	0.12	ab	10.5	—
Al_2O_3	14.18	2.09	an	14.2	5.3
Fe_2O_3	5.51	2.81	lc	—	—
Cr_2O_3	—	0.15	ne	15.9	—
FeO	7.43	5.22	di	26.5	1.8
MnO	0.31	0.14	ol	10.9	69.5
MgO	8.93	43.31	hy	—	17.4
CaO	10.13	1.52	mt	7.9	4.2
Na_2O	4.64	0.03	cm	—	0.2
K_2O	1.17	0.06	il	4.7	0.3
H_2O	0.87	0.13	ap	1.3	—
P_2O_5	0.58	0.03			
Total	100.17	100.29			

B.30 and B.30A. Basanite, Bayuda, Sudan (Almond, 1974) HBl and HBlA Spinel-lherzolite inclusion, Bayuda, Sudan. Anal. S. el D. Hamad.

Compared with the host rock the inclusion is characterized by high MgO and low CaO and Na_2O. The host rock contains an appreciable amount of TiO_2 but the inclusion only 0.12%. The presence of 0.15% Cr_2O_3 in the inclusion and its absence in the host rock indicate that the basanite magma does not contain enough Cr to produce those minerals of the inclusions that contain high percentages of that element.

Mineralogy of the inclusions. The results of electron microprobe analyses of the minerals of the spinel-lherzolite inclusions are presented in Tables II and III. Total iron is reported as FeO.

The olivine is highly magnesian, with average $Fo_{90.0}$. This is typical of spinel-lherzolite xenoliths collected from basaltic hosts in most parts of the world (Ross *et al.*, 1954; Hamad, 1963; White, 1966, and others). The amount of Ni, lying in the range 3000–3500 ppm, is also typical of olivines in spinel-lherzolite xenoliths (Simkin and Smith, 1970).

The spinel is characterized by high Al_2O_3 and low Cr_2O_3. Since the texture of these inclusions as described earlier is course granular, the results are in agreement with those of Basu (1977) that high Al_2O_3 and low Cr_2O_3 contents occur in xenoliths with this texture.

The Al content in both the ortho- and clinopyroxene is quite sufficient without Ti to make the *Z* group 2.00, the excess Al being added to the *XY* group. Moreover, the high Al_2O_3 content, especially in the clinopyroxene, and the small amount of Cr_2O_3 in comparison with other xenoliths is in close agreement with the views of Varne

TABLE II. *Electron microprobe analyses and compositions of olivine and spinel from a representative spinel-lherzolite inclusion, Bayuda, Sudan*

	Olivine 1	Olivine 2		Spinel 3
SiO_2	41.04	41.22	Al_2O_3	61.96
FeO*	9.96	9.73	Cr_2O_3	7.74
MnO	nil	0.11	*FeO	9.70
NiO	0.32	0.37	NiO	0.45
MgO	49.56	49.52	MgO	21.00
Total	100.88	100.95		100.85
Atomic proportions (oxygens = 4)				
Si	0.998	1.001	Al	1.843
Fe	0.202	0.200	Cr	0.154
Mn	—	0.002	Fe	0.205
Ni	0.006	0.007	Ni	0.009
Mg	1.796	1.790	Mg	0.790
$\frac{100\,Mg}{Mg+Fe}$	89.9	90.1	$\frac{100\,Mg}{Mg+Fe}$	79.4

* FeO = total iron

TABLE III. *Electron microprobe analyses of ortho- and clinopyroxenes from a representative spinel-lherzolite inclusion, Bayuda, Sudan*

	Orthopyroxene		Clinopyroxene	
SiO_2	56.17	55.98	51.89	52.19
TiO_2	0.09	0.10	0.56	0.63
Al_2O_3	2.94	3.32	6.90	6.64
Cr_2O_3	0.19	0.15	0.59	0.64
*FeO	6.26	6.23	2.50	2.47
MnO	0.15	0.11	nil	nil
MgO	34.04	33.67	14.55	14.71
CaO	0.29	0.38	20.35	20.60
Na_2O	nil	nil	2.01	1.73
Total	100.13	99.95	99.32	99.60
Atomic proportions (oxygens = 6)				
Si	1.934	1.930	1.887	1.892
Al	0.119	0.135	0.296	0.284
Cr	0.005	0.004	0.016	0.018
Fe	0.180	0.180	0.076	0.075
Mn	0.004	0.003	—	—
Mg	1.746	1.730	0.788	0.794
Ca	0.011	0.014	0.793	0.800
Na	—	—	0.142	0.121
$\frac{100\,Mg}{Mg+Fe}$	90.7	90.6	91.2	91.4
Mg	90.1	89.9	47.6	47.6
Ca	0.6	0.7	47.8	47.9
Fe	9.3	9.4	4.6	4.5

* FeO = total iron

(1977) that inclusions showing little evidence of reaction contain pyroxenes with comparatively high R_2O_3 contents in which exsolutions are weakly developed or absent. Another feature shown by the pyroxenes of the Bayuda inclusions is that the content of Cr_2O_3 in the clinopyroxene is more than twice that in the coexisting orthopyroxene. This does not support the views of Aoki and Shiba (1973) and Faérseth (1978).

As regards the Fe : Mg ratio, the orthopyroxene is more iron rich than the co-existing clinopyroxene. The Fe/Mg distribution between the two pyroxenes gave a value of $K_{Fe} = \left(\frac{Fe}{Mg}\right)_{opx} \Big/ \left(\frac{Fe}{Mg}\right)_{cpx} = 1.09$. According to Griffin (1973) this figure may be higher because not all the Fe in the clinopyroxene is present as Fe^{2+}. Some of it is converted to Fe^{3+} to balance the substitution of Na for (Ca, Mg, Fe^{2+}) and Al for Si.

The distribution coefficient of Mg between the two coexisting pyroxenes, viz.:

$$K_D = \frac{X_{opx}}{1-X_{opx}} \Big/ \frac{X_{cpx}}{1-X_{cpx}} \text{ where } X = \frac{Mg}{Mg-Fe}$$

was found to be 1.00. In the opinion of Kretz (1963) and White (1966), K_D values for ultramafic xenoliths tend to approach unity more closely than any other rock and these high values are indicative of high temperature.

Estimation of temperature of equilibration. In spite of the uncertainties in most of the geothermometers reported in the literature, some of these were used by the author to estimate the temperature of the source of the Bayuda spinel-lherzolite inclusions. The methods of Wood and Banno (1973), Mysen (1976), and Mori (1977) gave a temperature in the range 1000–1130 °C whereas that of Wells (1977) gave 900 °C. According to Donaldson (1978) part of this difference in temperature may be due to the large errors in estimating the Al^{VI} contents of the pyroxene. Bearing in mind the views of Nielson-Pike (1976) that the complexity of natural systems renders difficult any comparison with simplified model systems, one may state cautiously that the Bayuda spinel-lherzolite inclusions indicate a probable source temperature in the range 900–1130 °C.

Conclusions. This study of spinel-lherzolite inclusions from Bayuda, Sudan, has shown that, like many such other inclusions, they contain the same four minerals: olivine, orthopyroxene, clinopyroxene and spinel. The inclusions have exceedingly low Na_2O and TiO_2 compared with the host rock. Moreover, the presence of Cr-rich minerals in the inclusions and the absence of Cr_2O_3 in the host rock is firm evidence that these inclusions have not been derived from the basanite magma.

The course granular texture of the inclusions, coupled with the relatively high Al_2O_3 content in the spinel as well as in the pyroxenes and the low content of Cr_2O_3 in spinel, are indications of high-temperature equilibration. Further evidence is provided by the high value of the distribution coefficient of Mg between the two coexisting pyroxenes.

The results obtained in this study have confirmed that the Bayuda spinel-lherzolite inclusions are accidental in origin and must have been incorporated in the host rock from a source within the upper mantle. Since these inclusions occur in an area that had undergone volcanic eruptions, it is more likely that they have been brought to the surface by the basanite magma.

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Idocrase from the Boutadiol Valley, near Quérigut, France

THE main purpose of this note is to record the analysis (Table I) of idocrase from contact rocks in the Boutadiol Valley, near the southern border of the Quérigut granite. At this locality light-greenish-grey idocrase is found in calc-silicate hornfels exposed near an old magnetite prospect that had been described briefly by Lacroix (1900) during his classic studies of the Quérigut granite and its contact rocks. The calc-silicate rocks consist of clinozoisite, diopside, idocrase, calcite, and apatite, accompanied by minor quartz, sodic plagioclase, and microcline. Apatite is locally present in two samples in which it forms largely monomineralic areas up to 5 mm across. Typical samples of the calc-silicate rocks, collected by Dr S. O. Agrell and, later, by W. A. Watters, are held in the Department of Earth Sciences, Cambridge (catalogue numbers 61305 and 61633); a small duplicate sample and thin sections are held in the N.Z. Geological Survey collection as no. P16014. Physi-