References

Allan, J. F. and Carmichael, I. S. E. (1984) Lamprophyric lavas in the Colima graben, SW Mexico. *Contrib. Mineral. Petrol.*, **88**, 203–16.

Edgar, A. D. (1979) Mineral Chemistry and Petrogenesis of an Ultrapotassic–Ultramafic Volcanic Rock. *Contrib. Mineral. Petrol.*, **71**, 171–5.

Gallo, F., Giammetti, F., Venturelli, G., and Vernia, L. (1984) The Kamafugitic rocks of San Venanzo and Cuppaello, Central Italy. *Neues Jahrb. Mineral., Mh.*, 198–210.

Hasui, Y. and Cordani, U. G. (1968) Idades Potássio–Argônio de Rochas Eruptivas Mesozóicas do Oeste Mineiro e Sul de Goiása. *Anais do XXII Congresso Brasileiro de Geologia*, 139–43.

Sahama, Th. G. (1954) Minerlogy of mafurite. *C.R. Soc. Geol. Finlande*, **27**, 21 (not seen; extracted from *Journal of Petrology* (1960) vol. **1**, part 2, 146).

Sahama, Th. G., Neuvonen, K. J., and Hytonen, K. (1956) Determination of the composition of kalsilites by an X-ray method. *Mineral. Mag.*, **31**, 200.

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Trevorite in pyroxenite nodules from the Tokinsky Stanovik Mountains (ENE prolongation of Baikal rift zone)

TREVORITE, $NiFe_2O_4$, is a well known meteoritic mineral (Schmidt and Keil, 1966). Terrestrially it has been found only in depleted ultrabasic rocks of the ophiolite complex of the Barberton greenstone belt in South Africa, Bon-Accord Fe-Ni deposits (De Waal, 1969, 1972; Tredoux *et al.*, 1989) and in a serpentinite massif in SW China (Houjan *et al.*, 1976). In iron meteorites, trevorite forms by the oxidation of Fe-Ni alloy; the terrestrial origin (Bon-Accord) resulted from the oxidation of spinel and general Ni-enrichment, resulting from heterogeneity of the Lower Mantle as it ascended to the Earth's surface as a result of convective processes.

This paper reports iron oxides with an anomalously high nickel content which were discovered in pyroxenite inclusions in the Quaternary alkaline basalts of the Tokinsky Stanovik Mountains (ENE prolongation of Baikal rift zone, Russia). The concentration of NiO in magnetite of these samples varies from 0.3 to 29.0 wt.%, which exceeds the upper limit value of 0.2 wt.% given by Medvedev and Almuchamedov, 1990. It has been suggested that Ni-rich magnetites are inhomogeneous and represent a mixture of trevorite and iron oxides. In the microprobe investigation carried out, structural features showing unmixing solid solution structures were recognized (Fig. 1). The composition of the magnetite matrix (dark) and trevorite (light) are listed in Table 1. It is assumed, on account of the chemical composition, that the dark matrix is not solely magnetite, but a mixture of hematite with magnetite or hematite alone. Structural investigations were carried out and confirmed the presence of a member of the spinel group, trevorite (a = 8.337 ± 0.001 Å), and hematite in the magnetic fraction of the pyroxenite sample. The X-ray-diffraction analyses were made with a diffractometer [Dron-3] Co-Kα radiation; the results are listed in Table 2. Apparent variation in the nickel content of the magnetites is probably connected with

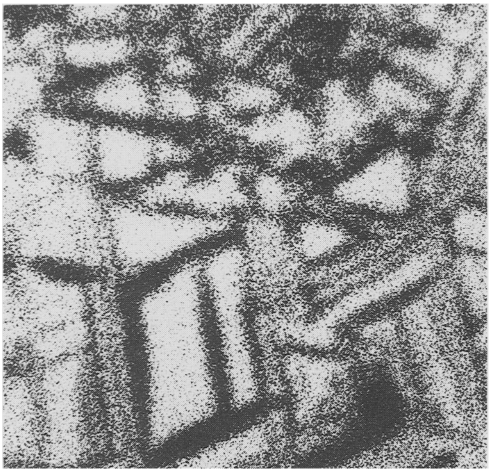

FIG. 1. Trevorite lamellae (light) in hematite-magnetite matrix (dark). Image in Ni-$K\alpha$ radiation, 2000×.

varying proportions of trevorite in the iron oxide matrix, because the grain size (2–10 μm) of this mineral is often close to the diameter of the electron beam. The largest lamellae of Ni-rich magnetite (100 μm) are associated with mica.

The pyroxenite samples can be referred to Group II (Frey and Prinz, 1978) 'black pyroxenites', the origin of which is debatable. The pyroxenite consists mainly of clinopyroxene (65%), olivine (20%), amphibole—kaersutite (5%), mica (5%) and pyrrhotite + spinel + magnetite (5%). Mineral analyses were carried out on a Camebax Microbeam microprobe, while the composition of the rock was obtained using an X-ray fluorescence spectrometer [Philips PW-1600] (Table 1). There are two groups of minerals—two 'parageneses' were found in the petrographic investigation: primary (original), high temperature—Ol, Cpx, (Po, Sp, Amph); and low temperature—mica and magnetite. The mineral equilibrium temperatures were estimated at 727 and 1000 °C respectively using the olivine–clinopyroxene geothermometers (Mori and Green, 1978; Powell and Powell, 1974). The temperature of the second paragenesis is near 500 °C, based on the composition of magnetite.

To elucidate the origin of trevorite in the pyroxenite nodule it is necessary to recognise the source of nickel and estimate the physico-chemical conditions of formation of the exsolution lamellae. It is known that trevorite forms a solid solution with magnetite (Tretyakov, 1967), the stability of which depends on the redox potential. The lamellae of trevorite probably formed in the magnetite matrix as a result of oxidation caused by water-bearing fluids; further evidence was found in the occurrence of mica and amphibole in the sample.

The presence of Ni-rich pyrrhotite (7–9% Ni) was typical of all investigated samples of pyroxe-

Table 1. The composition of the pyroxenite nodule and rock-forming minerals.

Oxide	rock (N 14000)	Ol	Ol	Cpx	Cpx	Sp	Amph	Mica	Mt	Trev	Matrix	Element	Po
SiO2	50.22	37.53	39.49	51.78	49.99	0.17	43.93	38.82	0.04	-	-	Fe	47.89
TiO2	1.05	0.10	0.02	0.86	1.52	0.22	2.18	5.35	-	0.01	0.02	Co	0.24
Al2O3	7.36	n.d.	n.d.	5.55	7.42	46.92	14.92	17.03	-	-	-	Si	0.06
Fe2O3	4.32					14.80			62.19	46.48	99.56	Al	0.01
FeO	3.75	25.92	24.02	5.32	5.64	6.56	7.93	8.16	30.76	23.24	-	S	41.05
MnO	0.13	0.19	0.20	0.02	-	-	0.07	0.02	0.06	0.05	0.04	K	0.04
MgO	15.33	36.19	37.84	13.77	13.35	21.11	16.60	18.98	0.14	-	-	Cr	0.05
CaO	16.22	0.08	0.07	21.77	20.91	0.16	11.32	n.d.	0.01	-	-	Ni	9.85
Na2O	1.04	n.d.	n.d.	0.91	1.27	n.d.	2.52	1.44	n.d.	n.d.	n.d.	Cu	0.11
K2O	0.23	n.d.	n.d.	n.d.	0.09	n.d.	1.01	9.72	n.d.	n.d.	n.d.	Total	99.30
NiO	0.23	0.16	n.d.	n.d.	n.d.	n.d.	n.d.	0.16	7.05	29.00	0.32	Ni/Co	40.36
CoO	0.01	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.78	n.d.	Fe/Ni	4.86
Cr2O3	0.34	n.d.	n.d.	0.67	0.94	8.75	n.d.	0.25	0.01	0.02	n.d.	Fe/S	1.16
Total	100.23	100.00	101.64	100.65	101.04	98.69	100.04	99.93	100.20	99.58	99.92		

Note: Ol, olivine; Cpx, clinopyroxene; Sp, spinel; Amph, amphibole; Mt, magnetite; Trev, trevorite; Po, pyrrhotite.

The content of Fe2O3 in minerals was calculated by stoichiometry.

Table 2. The results of X-ray diffraction analysis

N	d,Å	I	hkl	N	d,Å	I	hkl
1	4.8	16	111	1	3.78	50	012
2	2.94	12	220	2	2.70	100	104
3	2.52	100	311	3	2.52	50	110
4	2.08	10	400	4	2.20	36	113
5	1.913	3	331	5	1.843	25	024
6	1.703	16	422	6	1.689	50	116
7	1.606	16	333,511	7	1.601	18	018
8	1.474	20	440	8	1.434	14	214
9	1.260	8	533	9	1.454	25	300
10	1.204	16	444				
	Trevorite a = 8.337 + 0.001 Å				Hematite		

nite from this area, suggesting that the source of nickel in trevorite was this mineral (monosulfide solid solution). Further evidence is provided by the similar Ni/Co ratio of pyrrhotite and trevorite (from 25 to 40 and from 28 to 50, respectively). It is possible that Ni-rich magnetite formed as a result of low-temperature alteration of pyrrhotite. The initiation of such a process was observed in another pyroxenite sample. The green pyroxenite, 'chromdiopsidite', contained multiphase inclusions which consisted of pyrite, pentlandite, magnetite and opaque iron silicate. The last phase was discovered also in sulphide spherules within olivine, and pyroxene megacrysts in basalt and andesite tephra from a cinder cone on Mount Shasta, California (Stone *et al.*, 1989).

Unmixing solid soluton structures of troilite were discovered in pentlandite (Kullerud, 1969). After oxidation these structures may form the trevorite lamellae in a magnetite–hematite matrix. However, considering a monosulphide solid solution to be the unique source of nickel in magnetite, it is not clear why unaltered parent sulphides and final reaction products coexist in the same sample. There is no evidence of reaction of Ni-rich magnetite with any other mineral in the same sample. It is possible that monosulphide solid solution and Ni-rich magnetite are cogenetic.

The composition of the spinel (Table 1) is simialr but distinct from the compositions of spinels from spinel lherzolites, thus indicating some alteration of primary lherzolites. It is unlikely, however, that such a large degree of Ni-enrichment was due to oxidation and 'ferritisation' of typical mantle spinel. The content of nickel in trevorite-bearing pyroxenite is similar to the Ni content of spinel peridotites (1800 ppm). The characteristics of the compositions of the main rock-forming minerals—olivine ($CaO < 0.1\%$) and clinopyroxene (Cr_2O_3 0.7–0.9%)—supply evidence for the upper-mantle origin of pyroxenite nodules following reaction with fluids of complex composition.

The occurrence of the Ni-rich mineral in pyroxenites of the Tokinsky Stanovik Mountains confirms the mantle origin of these rocks and the widespread mantle metasomatic processes in the district.

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References

De Waal, S. A. (1969) *Am. Mineral.*, **54**, 1204–9.
—— (1972) Ibid., **57**, 1524–6.
Frey, F. A. and Prinz, M. (1978) *Earth Planet. Sci. Lett.*, **38**, 129–76.
Houjan, M., Yingwen, X. and Jiwu, Y. (1976) *Min. Abstr.*, **27**, 76–2805.
Kullerud, G. (1969) In *Experimental petrology and mineralogy*, Moscow, 'Nedra', 138.
Medvedev, A. Ya. and Almuchamedov, A. I. (1990) *Geochimiya (USSR)*, **3**, 419–25.
Mori, T. and Green, D. H. (1978) *J. Geol.*, **86**, 83–97.
Powell, M. and Powell, R. (1974) *Contrib. Mineral. Petrol.*, **48**, 249–63.
Schmidt, R. A. and Keil, K. (1966) *Geochim. Cosmochim. Acta.*, **30**, 471–8.
Stone, W. E., Fleet, M. E., and MacRae, N. D. (1989) *Am. Mineral.*, **74**, 981–93.
Tredoux, M., de Wit, M. J., Hart, R. J., Armstrong, R. A., Lindsley, N. M., and Sellschop, J. P. F. (1989) *J. Geophys. Res.*, **94**, B1, 795–813.
Tretyakov, Yu. D. (1967) *Thermodynamics of ferrites*, Leningrad, Chimiya, 164.

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