

REFERENCES

- BUCKLEY, H. E. (1951) *Crystal Growth*. Wiley, New York.
- JOHNSTON, W. G. (1962) Dislocation etch pits in non-metallic crystals. In J. E. Burke, ed., *Progress in Ceramic Science*, v. 2. Pergamon Press, New York.
- JOSHI, M. S., AND P. N. KOTRU (1968) Hillocks on first-order prism faces of synthetic quartz. *Amer. Mineral.* 53, 825-939.
- , AND ——— (1969) Hydrothermal etching of matched fractured prism faces of quartz. *Kristallogr.* 14, 516-518. [Transl. *Sov. Phys. Crystallogr.* 14, 427-428].
- , ———, AND M. A. ITTYACHEN (1970) Hydrothermal etch method to study dislocations in quartz. *Kristallogr.* 15, 103-111. [Transl. *Sov. Phys. Crystallogr.* 15, 83-89].

American Mineralogist
Vol. 57, pp. 1889-1893 (1972)

TREMOLITE WITH HIGH RICHTERITE-MOLECULE
CONTENT IN KIMBERLITE FROM BUELL PARK, ARIZONA

KEN-ICHIRO AOKI,

*Institute of Mineralogy, Petrology and Economic Geology,
Tohoku University, Sendai, Japan*

AND

R. V. FODOR, KLAUS KEIL, AND ERIC DOWTY,

*Department of Geology and Institute of Meteoritics,
The University of New Mexico,
Albuquerque, New Mexico 87106, U.S.A.*

ABSTRACT

Tremolite of a composition suggesting solid solution between the ideal end members tremolite and richterite occurs in kimberlites from Buell Park, Arizona. Analysis by electron microprobe gave SiO₂ 57.9, TiO₂ 0.05, Al₂O₃ 1.1, Cr₂O₃ 0.06, FeO 2.4, MnO 0.07, MgO 23.5, CaO 10.8, Na₂O 2.3, K₂O 0.51, F 0.35, -O = F 0.15, total 98.89, corresponding to 57 mol % tremolite, 31 mol % richterite, and 12 mol % other amphibole components. The structural formula is (Na_{0.233}K_{0.033})(Ca_{1.574}Na_{0.319})(Mg_{4.763}Fe²⁺_{0.273}Mn_{0.008}Cr_{0.007}Ti_{0.005}Al_{0.051})(Al_{0.123}Si_{7.875})O₂₃. Space group is C2/m, cell parameters are $a = 9.876 \pm 0.002$, $b = 18.065 \pm 0.005$, $c = 5.281 \pm 0.002 \text{ \AA}$, $\beta = 104^\circ 40' \pm 1'$, $V = 911.4 \pm 0.3 \text{ \AA}^3$. The mineral apparently formed as a primary phase in a kimberlite magma under upper mantle conditions.

The possible presence of amphibole as one of the most important hydrous minerals in the upper mantle has been suggested by many

investigators (*cf.* Oxburgh, 1964). This suggestion is supported by high pressure experimental work (Green and Ringwood, 1967; Kushiro, 1970) which indicates that certain amphiboles are stable under pressure and temperature conditions corresponding to those expected in the upper mantle. These amphiboles are predominantly pargasite in composition with subordinate amounts of the tschermakite component. Recently, however, Erlank and Finger (1970) found potassic richterite in a diopside-phlogopite nodule from the Wesselton kimberlite, South Africa, and Kushiro and Erlank (1970) suggested that potassic richterite, on the basis of high pressure experiments, is stable to at least 30 kbar and 1100°C and, hence, may occur in the upper mantle.

In the course of a petrological study on the kimberlites and associated volcanic rocks from Buell Park, Arizona, one of us (K.A.) found amphibole having intermediate composition between the end members tremolite $\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$ and richterite $\text{Na}_2\text{CaMg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$. The kimberlite diatremes at Buell Park, northeastern Arizona, intruded into Permian sediments of the Cutler formation and DeChelly sandstone about 30 m.y. ago (Allen and Balk, 1954; Naeser, 1971). The tremolite with high richterite content occurs in kimberlite consisting of a fine-grained matrix rich in serpentine and is associated with bottle-green olivine, yellowish-green chromian enstatite, emerald-green chromian diopside, red to wine-colored pyrope, ilmenite, titanoclinohumite, and apatite.

Macroscopically, the tremolite is transparent and clear, dark green in color. It is usually stout prismatic, euhedral to subhedral, less than 6 mm in length, and nearly the same size as coexisting enstatite, diopside, and garnet. Under the microscope, the amphibole is colorless and shows no pleochroism. Its optical properties are as follows: $\alpha = 1.608$; $\beta = 1.662$; $\gamma = 1.635$; $2V_\omega$ (meas.) = ca. 80° ; $r < v$ weak; $Z \wedge c = 20^\circ$; $Y = b$, optical axial plane parallel to (010). Optically, it cannot be distinguished from the end members tremolite and richterite.

Buerger precession X-ray photographs of the $h0l$ and $0kl$ nets show no violation of conditions for $C2/m$ symmetry. Powder data were obtained on a diffractometer, using copper as an internal standard. Cell parameters, refined by least squares (Evans *et al.*, 1963), are $a' = 9.876 \pm 0.002\text{\AA}$, $b = 18.065 \pm 0.005\text{\AA}$, $c = 5.281 \pm 0.002\text{\AA}$, $\beta = 104^\circ 40' \pm 1'$, $V = 911.4 \pm 0.3\text{\AA}^3$.

The composition of the amphibole from Buell Park, Arizona, kimberlite is given in Table 1, together with the ideal compositions of the tremolite and richterite end members. This table also shows analyses of potassic richterite from West Kimberley, Australia, and Wesselton, South Africa. It is apparent from Table 1 that the amphibole from

Table 1: Electron microprobe analysis of tremolite with high richterite-molecule content from Buell Park, Arizona (column 1), compared to ideal richterite (column 2) and tremolite (column 3) end members and to potassic richterite from the Wesselton, South Africa, kimberlite (column 4) (average of 3 grains, Erlank and Finger, 1970) and potassic richterite from a leucite lamproite, West Kimberley, Australia (column 5) (Wade and Prider, 1940). All analyses are in weight percent. In column 1' are given the numbers of ions for the analysis in column 1 on the basis of O = 23 (because H₂O was not determined).

	1	2	3	4	5	1' ^b	
SiO ₂	57.9	58.73	59.15	54.3	52.67	Si ⁺⁴	7.875
TiO ₂	0.05			0.59	3.53	Al ⁺³	0.125
Al ₂ O ₃	1.1			1.24	1.72	Al ⁺³	0.051
Cr ₂ O ₃	0.06			0.06		Ti ⁺⁴	0.005
Fe ₂ O ₃					0.58	Cr ⁺³	0.007
FeO	2.4 ^a			4.31 ^a	2.41	Fe ⁺²	0.273
MnO	0.07			0.07	0.06	Mn ⁺²	0.008
MgO	23.5	24.64	24.82	21.2	21.32	Mg ⁺²	4.763
CaO	10.8	6.85	13.81	7.12	6.95	Ca ⁺²	1.574
Na ₂ O	2.3	7.58		3.24	3.64	Na ⁺¹	0.319
K ₂ O	0.51			4.72	5.70	Na ⁺¹	0.288
H ₂ O		2.20	2.22		0.46	K ⁺¹	0.088
F	0.35				1.29		
	99.04	100.00	100.00	96.85	100.48		
Less O for F	0.15				0.54		
Total	98.89	100.00	100.00	96.85	99.94 ^c		

a = Total Fe expressed as FeO.

b = Structural formula calculated to express cations in tetrahedral site (8.000), M-sites (7.000), and A-site (remainder), after Robinson et al. (1971).

c = Includes SrO 0.15.

Buell Park differs from the pure richterite end member by its lower alkali and higher CaO contents; it also differs from the pure tremolite end member by its very high alkali and lower CaO contents. The composition of this amphibole is illustrated in Figure 1, a diagram that considers primarily the Na in the A-site with respect to Al^{IV} and Al^{VI}. This figure was used by Robinson *et al.* (1971) to show the direction, but not the amount, in which calcic amphiboles depart from ideal tremolite. Figure 1 indicates that the Na in the amphibole from Buell Park is present largely as a richterite molecule, discounting it as merely a sodian tremolite. Moreover, recalculation of the analysis to pure end members indicates that the mineral is composed of 57.05 mole percent tremolite, 30.80 percent richterite, 6.25 percent pargasite, 5.35 percent cumingtonite, and 0.55 percent eckermannite. These data suggest that a complete solid solution series exists between the richterite and tremolite end members. Amphibole of the composition reported here has apparently not previously been described (Leake, 1968).

The kimberlite diatremes at Buell Park, Arizona, also contain abundant fragments of gneisses and amphibolites derived from the Precambrian basement. However, amphiboles in these rocks are green

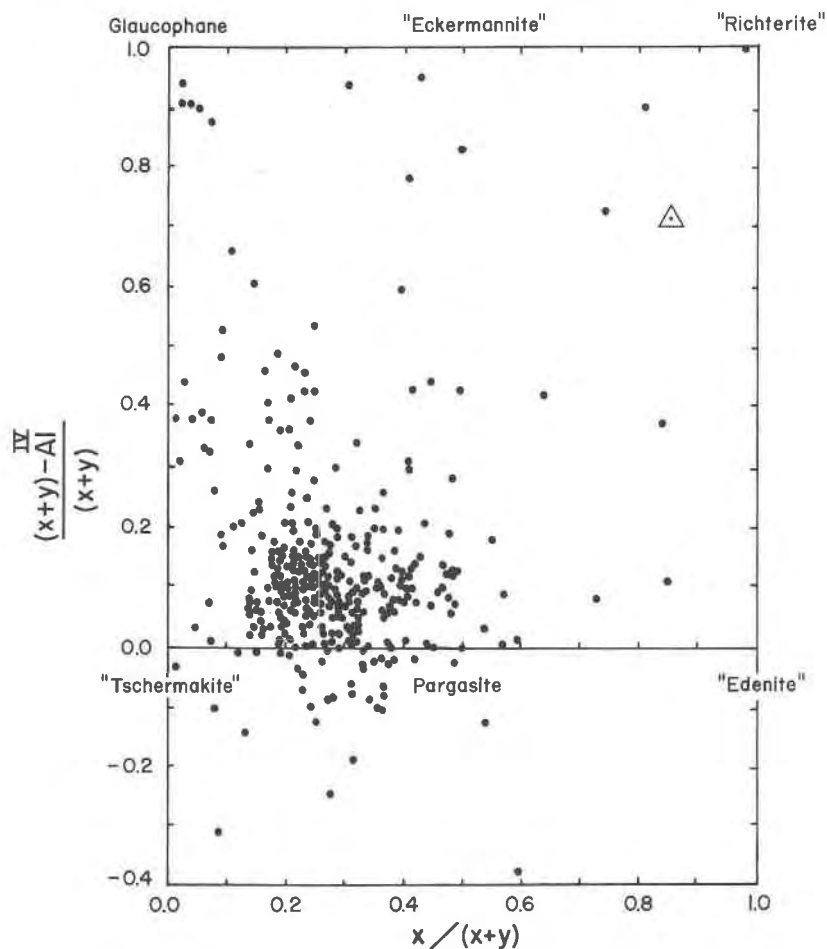


FIG. 1. Projection of the amphibole composition polyhedron from the tremolite apex onto the glaucophane-tschermakite-edenite-richterite plane showing projected composition of over 300 clinoamphiboles (modified after Robinson *et al.*, 1971, figure 7). The triangle represents the amphibole from Buell Park, Arizona. Explanation: $x = A$ -site occupancy, $y = \text{sum of } Al^{VI} + Fe^{3+} + Cr^{3+} + 2Ti^{4+}$ (atomic proportions).

to brown hornblende, indicating that the tremolite with high richterite content is not a xenocryst derived from lithic inclusions. It is therefore concluded that, although more detailed experimental evidence is needed, the tremolite with high richterite content described here appears to have formed as a primary phase, together with coexisting

nonhydrous phases, from an Al_2O_3 -CaO-alkali poor and volatile rich kimberlite magma under upper mantle conditions.

ACKNOWLEDGMENTS

We wish to acknowledge support from the NSF Senior Foreign Scientist Fellowship given to K. Aoki for a six-month tenure at the University of New Mexico. This work was supported in part by the National Aeronautics and Space Administration, Grants NGL 32-004-063 and NGL 32-004-064 (Klaus Keil, Principal Investigator).

REFERENCES

- ALLEN, J. E., AND R. BALK (1954) Mineral resources of Fort Defiance and Tohatchi quadrangles, Arizona and New Mexico. *N. Mex. Bur. Mines Miner. Resour. Bull.* 36, 192 p.
- ERLANK, A. J., AND L. W. FINGER (1970) The occurrence of potassic richterite in a mica nodule from the Wesselton kimberlite, South Africa. *Carnegie Inst. Washington Year Book*, 68, 320-324.
- EVANS, H. T. JR., D. E. APPLEMAN, AND D. S. HANDWERKER (1963) The least squares refinement of crystal unit cells with powder diffraction data by an automatic computer indexing method [abstr.]. *Amer. Crystallogr. Assoc. Cambridge, Mass., Ann. Meet. Program*, 42-43.
- GREEN, D. H., AND A. E. RINGWOOD (1967) The genesis of basaltic magmas. *Contrib. Mineral. Petrology*, 15, 103-190.
- KUSHIRO, I. (1970) Stability of amphibole and phlogopite in the upper mantle. *Carnegie Inst. Washington Year Book*, 68, 245-247.
- , AND A. J. ERLANK (1970) Stability of potassic richterite. *Carnegie Inst. Washington Year Book*, 68, 231-233.
- LEAKE, B. E. (1968) A catalog of analyzed calciferous and subcalciferous amphiboles together with their nomenclature and associated minerals. *Geol. Soc. Amer. Spec. Pap.* 98, 210 p.
- NAESER, C. W. (1971) Geochronology of the Navajo-Hopi diatremes, Four Corners area. *J. Geophys. Res.* 76, 4978-4985.
- OXBURGH, E. R. (1964) Petrological evidence for the presence of amphibole in the upper mantle and its petrogenetic and geophysical implications. *Geol. Mag.* 101, 1-19.
- ROBINSON, P., M. ROSS, AND H. W. JAFFE (1971) Composition of the anthophyllite-gedrite series, comparisons of gedrite and hornblende, and the anthophyllite-gedrite solvus. *Amer. Mineral.* 56, 1005-1041.
- WADE, A., AND R. T. PRIDER (1940) The leucite-bearing rocks of the West Kimberly area, Western Australia. *Quart. J. Geol. Soc. London*, 96, 39-98.