SHORT COMMUNICATIONS

Amphibole in the Mayo Belwa meteorite: first occurrence in an enstatite achondrite

EXTRATERRESTRIAL examples of the amphibole richterite [$Na_2CaMg_5Si_8O_{22}(OH,F)_2$] have previously been reported from two chemical group IA iron meteorites, Wichita County (Olsen, 1967) and Cañon Diablo (Olsen et al., 1973), and from the enstatite chondrite, Abee (Douglas and Plant, 1968). This paper reports an occurrence of richterite in an enstatite achondrite.

On 3 August 1974 a meteorite fell at Mayo Belwa (8° 58' N., 12° 5' E.) in the Adamawa district of Nigeria, and was quickly recovered. An examination of the mineralogy and chemistry revealed it to be an enstatite achondrite which had been heavily shocked (Graham et al., 1977). The 4·85 kg stone is an imperfect ovoid (24 cm × 13 cm) with a thin transparent fusion crust. On the surface, and throughout the body of the stone, are numerous irregular vugs up to 1 cm in diameter in which richterite occurs as bundles of radiating fibrous needles up to 3 mm long. The vugs are lined with a white, sugary crystalline crust of mainly enstatite and diopside with some cristobalite.

A few amphibole needles were isolated and a powder diffraction pattern obtained using a 114·6 mm diameter Debye-Scherrer camera. The results are shown in Table I compared with the data obtained by Olsen (1967) for Wichita County richterite. Using a refinement programme based on the method of Hess (1951), and developed by Dr. R. J. Davis (Min. Dept. BM(NH)), the following cell parameters were obtained: a 9·845 ± 0·01 Å, b 17·999 ± 0·02 Å, c 5·258 ± 0·01 Å, β 104·41 ± 0·005°, V 902·45 Å^3, and a.sinβ 9·535 ± 0·01 Å. These dimensions are very similar to those obtained by Huebner and Papike (1970) by refinement of Olsen's (1967) data, and suggest that the amphibole is fully fluorinated.

Four amphibole needles, some 1 mm in length, including a needle identified by X-ray diffraction as richterite (X-ray no. 18758), were analysed by electron-microprobe. The methods and results are given in Table II, together with analyses of the three previously known meteoritic amphiboles (Olsen et al., 1973). The Mayo Belwa amphibole shows both intra- and inter-grain homogeneity, and compositions (Table II) are closer to that of ideal richterite than any analyses of natural occurrences of this amphibole quoted in the literature (Deer, Howie, and Zussman, 1963). Grains from the white crystalline crust lining the vugs were also analysed and found to be two distinct pyroxenes, both near end-members, with sharp boundaries one against the other. Enstatite (96·4$_{en}$; 3·6$_{di}$) cores are surrounded by diopside (89·9$_{di}$; 8·2$_{en}$; 2·0$_{jd}$) rims in apparent structural continuity. Their compositions correspond with those expected for diopside and enstatite coexisting in equilibrium according to experimental data determined for the system $MgSiO_3$—$CaMgSi_2O_6$ (Boyd and Schairer, 1964). This sequence of crystallization is compatible with that found by Grigor'eva et al. (1971) in melting experiments in the system $Ca_2Mg_5Si_8O_{22}F_2$ — $Na_2Mg_6Si_8O_{22}F_2$. The observed order of formation and compositions of the pyroxenes lining the vugs thus suggest that they crystallized from a liquid melt rather than from the vapour phase.

TABLE I. *X-ray diffraction patterns of Mayo Belwa and Wichita County richterite*

Wichita County (Olsen, 1967)		Mayo Belwa (this study)			
I/Io (visual)	d_obs (Å)	I/Io (visual)	d_obs (Å)	d_calc (Å)	hkl
		20	9·03	9·000	020
70	8·605				
70	8·393	60	8·47	8·426	110
30	4·864	40	4·85	4·857	$11\bar{1}$
50	4·493	50	4·50	4·500	040
70	4·160				
30	4·004	30	4·00	4·015	$20\bar{1}$
				3·987	111
50	3·850	40	3·867	3·861	$13\bar{1}$
100	3·376	80	3·389	3·379	131
				3·372	041
				3·368	150
80	3·267	70	3·276	3·272	240
100	3·125	90	3·135	3·130	310
		20	3·026	3·017	$31\bar{1}$
80	2·944	60	2·948	2·944	221
40	2·800	30	2·808	2·809	330
100	2·709	100	2·706	2·702	151
70	2·581	50	2·587	2·585	061
90	2·522	70	2·527	2·522	$20\bar{2}$
20	2·382	30	2·389	2·384	400
				2·383	350
50	2·320	50	2·328	2·332	$35\bar{1}$
				2·319	$42\bar{1}$
50	2·286	40	2·290	2·291	$17\bar{1}$
40	2·258	40	2·266	2·266	$31\bar{2}$
20	2·203	20	2·205	2·200	$24\bar{2}$

Wichita County (Olsen, 1967)		Mayo Belwa (this study)			
I/Io (visual)	d_obs (Å)	I/Io (visual)	d_obs (Å)	d_calc (Å)	hkl
70	2·160	60	2·164	2·164	132
				2·161	261
		10	2·134	2·134	$33\bar{2}$
40	2·048	40	2·051	2·045	202
10	2·020	40	2·018	2·018	351
		40	2·004	2·001	$40\bar{2}$
				1·999	370
10	1·952	30	1·9580	1·9591	$42\bar{2}$
				1·9573	190
				1·9504	152
		30	1·9305	1·9320	421
				1·9305	$26\bar{2}$
				1·9286	$35\bar{2}$
20	1·893	40	1·8982	1·8964	510
10	1·857	40	1·8617	1·8614	242
				1·8591	$19\bar{1}$
		20	1·8328	1·8332	$44\bar{2}$
10	1·794	20	1·7965	1·7966	191
		20	1·7423	1·7422	$20\bar{3}$
				1·7414	$51\bar{2}$
				1·7399	$11\bar{3}$
30	1·676	40	1·6774	1·6789	$28\bar{2}$
				1·6783	$13\bar{3}$
				1·6741	$31\bar{3}$
				1·6741	$39\bar{1}$
60	1·650	60	1·6530	1·6514	461
				1·6487	511
Plus 27 additional spacings to 0·7882 Å		Plus 60 additional spacings to 0·7810 Å			

The three previously recorded occurrences of meteoritic richterite (Olsen *et al.*, 1973) are in association with metal: in the Type I enstatite chondrite, Abee, the amphibole occurs within 'podlike segregations of metal', and Wichita County and Cañon Diablo are both coarse octahedrites. The enstatite achondrites, however, contain little metal (< 0.2 wt %) suggesting that the Mayo Belwa richterite crystallized in a near metal-free environment. Its chemistry reflects this: Fe, Cr, and Mn are present in trace amounts, if at all, whereas the earlier described occurrences contain significant amounts of these elements. Furthermore, its composition is much closer to that of 'end-member' richterite than any of the other three examples.

This chemical 'purity' of the amphibole can be explained by the operation of a virtual distillation process within the meteorite. Fluor-richterite had presumably been formed as a residual phase during the meteorite's pre-shock history. Enstatite, plagioclase, and this existing fluor-compound were mobilized during shock melting, producing fluorine-filled vugs lined with a liquid melt. After crystallization of enstatite followed by diopside, reaction of the sodium-enriched melt with the fluorine vapour produced the radiating sodic amphibole needles, leaving a small amount of residual cristobalite. The bulk analysis of Mayo Belwa is typical of the

TABLE II. *Electron-microprobe analyses of meteoritic amphiboles*

	1	2	3	4	5	6		
SiO$_2$	58·23	58·09	57·2	57·9	57·8	Number of ions on the		
TiO$_2$	0·21	0·18	2·2	0·01	1·5	basis of 24 (O,F)		
Al$_2$O$_3$	0·15	0·17	0·38	0·15	0·4			
Cr$_2$O$_3$	0·07	0·06	3·5	0·00	0·7	Si	8·029 }	8·03
FeO	0·01	0·01	0·44	0·17	0·5	Al	— }	
MnO	0·02	0·00	0·05	0·00	0·00	Al	0·027 }	
MgO	24·20	24·34	20·9	26·1	22·4	Ti	0·019 }	5·05
CaO	6·69	6·73	3·7	5·5	5·8	Mg	5·009 }	
Na$_2$O	7·22	7·21	8·3	7·3	7·5	Ca	0·995	1·00
K$_2$O	0·48	0·47	1·2	0·36	0·6	Na	1·928 }	
Cl	0·02	0·03	n.f.	n.f.	n.f.	K	0·082 }	2·01
F	3·91	3·91	3·6	4·6	2·3	F	1·707	1·71*
Sum	101·21	101·20	101·5	102·1	99·5			
Less O ≡ F	1·61	1·61	1·5	1·9	0·9			
Total	99·60	99·59	100·0	100·2	98·6			

1. Mayo Belwa richterite; grain from X-ray mount no. 18758.
2. Mayo Belwa richterite; average of three other grains.
3. Cañon Diablo richterite ⎫
4. Abee richterite   ⎬ Analyses from Olsen *et al.* (1973).
5. Wichita County richterite ⎭
6. Molecular formula of Mayo Belwa amphibole 2.

Electron-microprobe analyses made in the Department of Mineralogy, BM(NH): using analysed minerals and pure metals as standards, and the results were corrected according to the method outlined by Sweatman and Long (1969) and Mason *et al.* (1969).
F by electron-microprobe in the Department of Geology and Mineralogy, University of Oxford, using a fluorite standard.
Total Fe expressed as FeO.
n.f. not found.
* It is assumed that the amphibole is completely fluorinated: this low figure is due to analytical constraints on accuracy for this element.

enstatite achondrites, which suggests that little or no partial melt has been lost due to the shock episode.

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Formation of analcime in the Dippin sill, Isle of Arran

THE Dippin sill is a Tertiary differentiated basic intrusion, 43 m thick, occurring in the SE. part of the Isle of Arran, Scotland. The sill is composed of different varieties of analcime olivine dolerite, particularly crinanite in which the analcime occurs most commonly as clear, wedge-shapes in the interstices between plagioclase laths. The interstitial analcime is characterized by low SiO_2 and Na_2O and high CaO (e.g. $Ne_{66.4}Ks_{0.2}Qz_{24.3}An_{9.1}$, wt%) and is occasionally associated with small ($<$ 0·1 mm) nepheline grains, which are comparatively SiO_2-rich (e.g. $Ne_{73.4}Ks_{8.1}Qz_{16.9}An_{1.6}$). Analcime also occurs along innumerable small cracks in plagioclase and as a major constituent of large patches, up to 1 cm across, in which it may be associated with brown fibrous natrolite and radiating aggregates of other zeolites. Rocks from the chilled margins of the sill are characteristically rich in lath-shaped analcime pseudomorphs (after plagioclase) and the analcime-bearing patches; the abundances of both decrease inwards from the contacts.

There can be little doubt that the analcime present as pseudomorphs and that in the patches was formed by the action of hydrothermal solutions at subsolidus temperatures. However, the origin of the wedge-shaped, interstitial analcime is more problematical. Many petrologists have interpreted the textural relations as being indicative of a late-stage 'primary' mineral, i.e. crystallized from the melt (e.g. Scott, 1916; Tyrrell, 1928; Harker, 1954, fig. 45b; Wilkinson, 1958). However, the analcime stability curve at low pressures in the system Ne-Ab-H_2O (Greenwood, 1961; Kim and Burley, 1971) lies well below the solidus for an alkaline olivine basalt and below the nepheline-alkali-feldspar minimum melting curve (fig. 1). Indeed, Roux and Hamilton (1976) showed that in the Ne-Ab-H_2O and Ne-Or-Ks-H_2O systems the assemblage analcime plus melt occurs only at pressures between 5 and 13 kb and between 640° and 600 °C. Geological evidence suggests that the Dippin sill is unlikely to have been emplaced at a depth of more than 3 km below the contemporary surface, in which case it is likely to have crystallized at a confining pressure of less than 1 kb. Thus the interstitial analcime must be secondary unless its comparatively high Ca content has substantially increased its thermal stability (Roux and Hamilton, 1976). We have tested this possibility by carrying out experiments on a fresh crinanite sample (AC 649) in which the bulk of the analcime is of the interstitial variety.

Rock powder and glass made from this by melting at 1200 °C for 15 hours at a log P_{O_2} of $-6·4$ and a pressure of 1 bar were used as starting materials in the experiments. Samples of each were sealed with excess water in separate gold capsules and were crystallized at pressures from 0·5 to 2·0 kb for 4-6 days; no attempt was made to buffer the P_{O_2}. The presence of analcime in the