MINERALOGICAL MAGAZINE, DECEMBER 1977, VOL. 41, PP. 487–92

The Mayo Belwa meteorite: a new enstatite achondrite fall

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SUMMARY. Mayo Belwa, a highly shocked enstatite achondrite, fell during the evening of 3 August 1974 in the Adamawa District, NE. Nigeria (8° 58′ N., 12° 05′ E.). The stone weighed 4·85 kg and was deposited in the Geological Survey of Nigeria and loaned for study to the British Museum (Natural History). It is composed principally of enstatite (0·02 FeO %), with some olivine (Fo_{100}), diopside, feldspar (An_9 Ab_{88} Or_3), and minor Fe-Ni metal and the sulphides oldhamite, daubréelite, ferroan alabandine, and troilite. The kamacite contains between 0·15 % and 1·2 % Si and the troilite contains 1·1 % Ti. The meteorite possesses vuggy cavities, which contain fluor-amphibole needles projecting from their walls, suggesting the presence at some time of a volatile-rich phase. The titanium-rich troilite, the nearly iron-free enstatite and the Mg/Si ratio are typical of the E-achondrites.

THE Mayo Belwa meteorite fell in the Adamawa district of north-eastern Nigeria (8° 58′ N., 12° 05′ E.) during the evening of 3 August 1974. A fireball was seen by herdsmen and sounds were heard over an area extending to 25 km from the impact site. Only one stone, weighing 4·85 kg, was reported to have fallen and this was taken to the Geological Survey of Nigeria; it was reported that the stone smelt strongly of sulphur when first received. Subsequently the stone was loaned to the British Museum (Natural History) for study. On arrival in London it weighed 4·272 kg and was partly covered by a thin translucent fusion crust. It was ellipsoidal in shape, with a maximum circumference of about 40 cm, and composed of angular fragments of a milky-white material set in a pale grey, sometimes glassy, matrix. The white fragments are of enstatite, and generally about 0·5 cm across though a few are much larger, up to 4 cm across. Also set in the microcrystalline matrix are rounded fragments of blackish, glassy material, up to 0·5 cm across, many of which are disordered enstatites but some are shock-blackened olivines. Like most other aubrites, Mayo Belwa is a breccia, but it differs in having a number of irregular and sometimes interconnecting vuggy cavities, generally about 1 cm across, and extending inwards from the surface for a centimetre or so. The interior surfaces of these vugs are coated with white, sugary enstatite and are in part formed of 'bundles' of clear acicular diopside crystals with a coating of enstatite. Projecting from the walls of the vugs are numerous acicular crystals up to 3 mm long and approximately 20 μm in cross-section; some have been identified as a fluor-amphibole by X-ray methods. The vugs and their minerals are described in detail by Bevan *et al.* (1977). The abundance of sulphide and metal phases is very low and these were not seen in the hand specimen.

Microscopic examination. In thin section the fine-grained nature of the matrix makes optical determinations difficult, but it is composed almost entirely of a cloudy mixture of enstatite and minor feldspar crystals, each about 2 μm across. Within this matrix are set large cloudy ortho-enstatites with a few clear crystals of clino-enstatite ($\sim$ 60 μm across), feldspar, olivine, and minor diopsidic pyroxene.

The usual texture of the enstatite achondrites is one of a matrix of angular enstatites enclosed in a breccia of much smaller enstatite crystals. This is well shown in the Norton County and Peña Blanca Spring aubrites. In Mayo Belwa the texture is somewhat different, there does not seem to be the same distribution in the size of enstatite crystals in the matrix. Compositions of the principal silicate phases are given (Table I). The iron content of the enstatite is similar to those found by Reid and Cohen (1967) and Wasson and Wai (1970) in their studies of enstatite achondrites.

The olivines are rounded and up to 2 mm across, larger than is usual in enstatite achondrites, where they are normally less than 0·5 mm across. They are forsterites (Table I) and many show a regular fracture pattern, enhanced in places as thin black veins (fig. 1). This pattern is uniform across each crystal regardless of its size, though a few olivines do not show this and are water-clear. Dispersed within most olivines are very small rounded individual grains of metal and sulphide, generally about 1 μm across but rarely up to 5 μm in diameter. The feldspar is sodic oligoclase (Table I) and is present in remarkably large aggregates, both rounded and sinuous in form, up to 1 mm across. These are radiating masses of undulatory-extinguishing feldspar, very like that seen in the lunar anorthosites, particularly in the breccia 61016, 22 (Stöffler *et al.*, 1975). The modal abundance of plagioclase is about 10 %, much higher than is general in the enstatite achondrites, where it is usually less than 1 %, and this is reflected in the high alkali content of the meteorite. The crystalline nature of the feldspar and the lack of feldspathic glass implies that post-shock cooling must have been slow enough to allow it to recrystallize. Diopsidic pyroxene is also present though much less abundant than the other silicates. It usually shows well-developed twin lamellae, which are bent and displaced in some cases. The twinned crystals contain a multitude of micron-sized rounded, black inclusions.

Opaque phases are not abundant in the enstatite achondrites and Mayo Belwa is no exception. Metal, both kamacite and taenite, occurs in small rounded grains generally less than 0·01 mm across though particles up to 0·5 mm are present. Kamacite, with an average of 7·5 % Ni, is the more common metal phase and contains variable amounts of silicon (0·5–1·2 %). Rarely kamacite grains with much lower contents of Ni (2·5 %) and Si (0·15 %) occur. Taenite has a more variable nickel content, 16–23 % Ni, but only three grains were found in the sections. Occasionally kamacite grains were encountered containing an apparent 2 % phosphorous (by microprobe), which may be caused by submicroscopic schreibersite. Perryite was looked for but not found. Sulphides are modally more abundant than metal and are of much the same grain size. Most commonly the sulphide is a composite of daubréelite and ferroan alabandine but troilite and oldhamite are also present. The compositions of the metal and sulphides are given in Table I.

Bulk chemistry. The bulk composition is given in Table II. The data were obtained using an improved version of the chlorination technique (Moss *et al.*, 1967), further modified to enable the small amount of metal to be analysed satisfactorily. It proved impossible to separate the low-Ni metal from the high-Ni metal and the total magnetic fraction was not chlorinated but was analysed directly. Of the ten known enstatite achondrites, the bulk composition is known for five; Bishopville (Merrill, 1916), Khor Temiki (Hey and Easton, 1967), Norton County (Wiik, 1956, and von Michaelis *et al.*, 1969), Peña Blanca Spring (Lonsdale, 1947), and Pesyanoe (D'yakonova and Kharitonova, 1960). A comparative table of atomic ratios for these and for Mayo Belwa is given in Table IV. The Mg/Si and the Ca/Al ratios are lower for Mayo Belwa than for the other enstatite achondrites and may reflect the abundance of plagioclase, which may also account for the sodium content. It is interesting to note that the sodium figure compares well with that for Bishopville, another aubrite with relatively abundant feldspar. The remarkable variation in the Ca/Al ratio should be treated with some caution, particularly the value for Peña Blanca Spring since in the analysis of this stone no alkalis were detected despite 0·5 % feldspar being reported in the mode (Lonsdale, 1947). It is possible that the variation in the Ca/Al ratio results from the inhomogeneous distribution of diopside and feldspar.

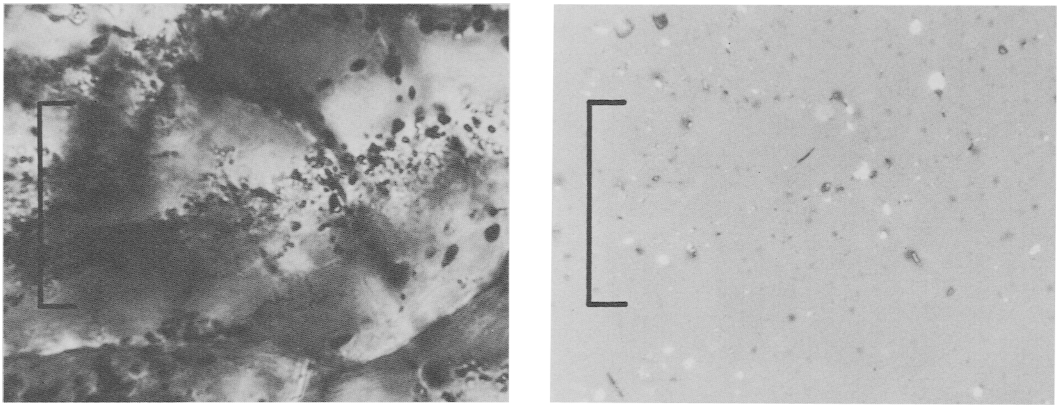

FIG. 1. *a* (left), photomicrograph of olivine in Mayo Belwa showing abundant opaque inclusions and shock fractures. Length of scale bar 50 μm. *b* (right), as fig. 1*a*, but in reflected light; the biggest metal particles shown are about 3 μm across.

TABLE I. *Silicate and opaque phases in Mayo Belwa*

Silicates

	Enstatite	Olivine	Diopside	Feldspar
SiO_2	59·0	42·7	55·3	65·5
Al_2O_3	0·07	n.d.	0·64	19·9
CaO	0·32	0·04	22·6	1·87
MgO	39·3	56·3	19·9	—
FeO*	0·02	0·06	0·69	—
Na_2O	—	—	—	10·4
K_2O	—	—	—	0·47
Cr_2O_3	< 0·01	0·02	0·03	—
Sum	98·71	99·12	99·16	98·14
	$Fs_{0\cdot028}$	$Fa_{0\cdot06}$	Wo_{44}	Ab_{88}
	$Wo_{0\cdot6}$		En_{55}	An_9
			Fs_1	Or_3

Sulphides

	Ferroan alabandine	Troilite	Daubréelite	Oldhamite
Ca	0·72	—	—	53·8
Fe	23·5	62·4	19·6	0·4
Mn	33·7	—	—	1·1
Cr	1·5	0·54	35·2	0·1
Ti	0·16	1·1	0·07	—
Zn	< 0·01	< 0·01	0·22	< 0·01
Mg	2·1	—	—	0·3
S	38·1	36·2	44·4	43·8
	99·78	100·24	99·49	99·5

Metal and schreibersite

	Ni-poor metal	Kamacite	Taenite	Schreibersite
Fe	94·9	89·7	78·7	69·75
Ni	2·5	7·6	20·7	13·33
Si	0·17	0·87	0·27	n.d.
P	0·12	0·03	0·03	15·01
Co	0·44	0·68	0·21	0·07
	98·13	98·88	99·91	98·16

FeO* = total iron as FeO. n.d. = not detected. — = not analysed for.

Analysts: A. L. G. and R. H.

Analytical conditions: Cambridge Instruments 'Geoscan' microprobe, accelerating voltage 15 kV, sample current 0·1 μA. Data for silicates have been corrected for matrix effects using the program Mk. 5 (Mason *et al.*, 1969).

TABLE II. *Bulk analysis and norm of the Mayo Belwa meteorite*

Non-magnetic, attacked (sulphides)		Non-magnetic, unattacked (silicates, phosphates, oxides)		Wahl norm	
Fe	0·17	SiO_2	59·31	Olivine	0·24
Mn	0·09	TiO_2	0·07	Enstatite	83·7
Ca	0·12	Al_2O_3	2·30	Ferrosilite	0·5
Cr	(65 ppm)	Cr_2O_3	0·06	Diopside	1·3
Ti	0·01	FeO	0·25	Orthoclase	0·72
Zn	(9·1 ppm)	MgO	34·18	Albite	10·1
Cu	(1·7 ppm)	MnO	0·09	Anorthite	0·6
S	0·38	CaO	0·75	Apatite	0·1
		Na_2O	1·19	Ilmenite	0·1
Magnetic fraction		K_2O	0·12	Chromite	0·1
(total metal)		P_2O_5	0·02	Sulphide	0·77
Fe	0·18	NiO	(60 ppm)	Metal	0·19
Ni	0·01	H_2O+	0·27		
Co	(7 ppm)	C	0·13		
Ge	(0·30 ppm)	Ge	(0·1 ppm)		
Ga	(0·44 ppm	Ga	(0·5 ppm		
Zn	(15·5 ppm)	Sum*	99·70		
Cu	(2·8 ppm)				

* Including 0·19% metal fraction and 0·77% sulphides.
Analyst: A. J. Easton. Weight taken for analysis 3·4 g.

TABLE III. *Comparative atomic ratios and total iron contents of some enstatite achondrites*

	Mg/Si	Ca/Al	Ca/Mg	Na/Si	Total Fe
1	0·86	0·29	$1{\cdot}6\times10^{-2}$	390×10^{-4}	0·55%
2	0·87	0·80	3·2	350*	1·16
3	0·96	1·02	2·8	100	0·47
4	1·12	1·45	1·7	43†	1·60
5	1·15	4·5	2·25	—	1·28
6	0·98	4·7	2·0	61‡	2·3
7	0·96	0·47	1·6	54‖	1·18

1. Mayo Belwa, this study.
2. Bishopville, Merrill (1916).
3. Khor Temiki, Hey and Easton (1967).
4. Norton County, Wiik (1956).
5. Norton County, von Michaelis *et al.* (1969).
6. Peña Blanca Spring, Lonsdale (1947). Total Fe a minimum value.
7. Pesyanoe, D'yakonova and Kharitonova (1960).

* Schmitt *et al.* (1972) found 370 and Easton (unpublished) 380.
† Schmitt *et al.* (1972) found 20.
‡ Schmitt *et al.* (1972). ‖ Schmitt *et al.* (1972) found 117.

Summary and discussion. Mayo Belwa is an enstatite achondrite with a number of unusual features, in particular the abundance of vugs and their associated amphibole is remarkable; as also is the abundance of highly shocked olivines, which are rarely seen in other enstatite achondrites. In addition the modal occurrence of oldhamite (CaS) appears to be new to the aubrites (see Keil, 1969) though normative oldhamite is not (Hey and Easton, 1967). Troilite contains 1·1 % Ti and an unidentified phase containing over 12 % Ti is also present, associated with the sulphides. The relatively high sodium content of Mayo Belwa coupled with the relatively low Mg/Si ratio suggests that this particular enstatite achondrite is related to the E chondrites, see Wasson and Wai (1970). Unfortunately the significance of the Mg/Si ratio is not clear; it could result from the process that produced the excess of Si over Mg, as in the E chondrites, or the overabundance of feldspar in the sample analysed. However, since 3·4 g of Mayo Belwa were used for analysis the amount of feldspar should be representative. It is plain (Table III) that the alkali contents of the enstatite achondrites are very variable and it is not possible to obtain a reliable mean value for the group as a whole from the present data. Even so Mayo Belwa does seem to be richer in sodium than the other listed achondrites except Bishopville, in which, although the bulk analysis is an early one, the modal abundance of feldspar is comparable to that in Mayo Belwa, and the alkali figures agree well with the average of Schmitt *et al.* (1972). The sodium abundance in enstatite achondrites could even be regarded as bi-modal with peaks at ~ 50 and ~ 380 (atoms/10^4 Si atoms) but the paucity of these meteorites precludes further speculation on the reasons for this, e.g. derivation from a layered noritic complex on the parent body. The metal fraction has 160 ppm Ge and 230 ppm Ga; this is unusual since most meteoritic Fe–Ni metal has less Ga than Ge (see, for example, Wasson, 1974). These figures do have a degree of uncertainty because of the very small quantity of metal, but the Ga/Ge ratio should be immune to slight variations in the amount of free metal. We believe that the high gallium content has resulted from the scavenging of the silicate by the metal. The high Zn and Cu contents of the metal (8100 ppm and 1450 ppm respectively) are compatible with this interpretation. The sulphide contains 1200 ppm Zn and 220 ppm Cu; the Zn is principally in daubréelite (0·22 %). However, the overabundance of Zn and Cu in the metal compared with the sulphide could imply either that the metal and sulphide are not in equilibrium and had different origins or that the 'metal' (Table II) includes another minor phase that has not yet been identified. Any possible scenario for the formation of the main features of the Mayo Belwa stone is required to incorporate a significant volatile, fluorine-containing component. The abundance of vugs and their associated minerals indicates not only that the volatile component had a significant vapour pressure but that it was also capable of depositing the vug lining (diopside, enstatite, and fluor-amphibole). This fluid phase could have been produced by a shock event (impact?) subsequent to the main crystallization but the necessary components must already have been present. In principle all the components of the vug lining are available from the refractory portion of the bulk meteorite but the fluorine, now present in the amphibole at about 3·8 % by weight, was probably initially dispersed in a water-free volatile fraction within the matrix. When the stone was shocked, irregular distribution of volatiles resulted in high F concentrations to form the vugs. Possibly the meteorite was formed under significant confining pressure some distance below the surface of its parent body. Rapid transport towards the surface, or disintegration of this body may have stimulated the release of the volatile fraction, which then formed the vugs. Whatever the sequence of shock events that produced the textures seen in Mayo Belwa, they must have terminated immediately prior to vug formation since the open vugs containing fine amphibole fibres would rapidly be destroyed by shock. The areas now occupied by feldspar may once have been vugs with a feldspathic lining and subsequent shock caused these to collapse and the filling material to recrystallize during slow cooling or annealing. Certainly the shock history of this meteorite is complex and an electron-microscope study of the structures of the component minerals should be enlightening.

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[*Manuscript received 17 November 1976, revised 6 January 1977*]