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The Molteno meteorite

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SUMMARY. The Molteno meteorite was seen to fall in South Africa in 1953. It is a howardite, with pyroxene varying from $En_{76}Fs_{22}Wo_2$ to $En_{38}Fs_{58}Wo_4$ and then to $En_{33}Fs_{26}Wo_{41}$. Also present are twinned plagioclase (An 84·4%) and small quantities of olivine (Fa 12%), troilite, nickel-iron (Ni 4%), ilmenite, and an aluminian chromite with 0·71% V_2O_3. A bulk analysis and analyses of the metal, troilite, and combined silicates and oxides are given.

THE Molteno meteorite fell about 21 km north-north-east of Molteno in Cape Province, Union of South Africa, at approximately 17.00 hours in April or May 1953. The approximate co-ordinates of the place of fall are thus 31° 15′ S., 26° 28′ E. It was seen to fall with detonations and recovered by Mr. R. E. Trembath who believes that at least one other mass fell but was not recovered. Through the kindness of the finder half of the stone was presented to the British Museum (Natural History) and is registered as BM 1966,287, the other half remaining in the finder's collection.

The original stone was about 60×50×35 mm in size. It had one large gently curved smooth surface, which may at one stage have been the frontal surface, and a number of smaller very irregular surfaces. All of these surfaces have a glossy dark brownish-black crust, which is fissured, and in the terminology of Krinov (1953) varies between knobbly and ribbed with small areas of striated crust. There are also some uncrusted broken surfaces. The weight in 1966 was about 148 g but the original weight of the fully crusted individual may have reached 200 g. A cut surface shows a light grey groundmass (Ridgeway 30''''f, near *pearl grey*) containing angular fragments varying from white through greenish white to almost black, up to a maximum diameter of 9 mm. The white fragments up to 2 mm long are mainly feldspar. Small specks of sulphide and metal may also be observed. The density of the crusted fragment, by suspension in carbon tetrachloride after evacuation to remove air, is 3·25±0·05.

In thin section Molteno is a complex breccia consisting of fragments, usually angular but sometimes rounded and commonly consisting themselves of microbreccia, set in a groundmass of microbreccia (fig. 1). Both the breccia fragments, which are up to 7 mm long, and the groundmass are composed mainly of monomineralic grains of pyroxene and plagioclase both of which show the effects of strain, being shattered, and showing undulatory extinction. Among the larger fragments are a few with similar mineralogy but showing other textures. Fig. 2 shows a fragment with an igneous granular texture, fig. 3 a subophitic–ophitic texture, and fig. 4 an intergranular texture. There are also a number of very fine grained almost opaque fragments. An X-ray

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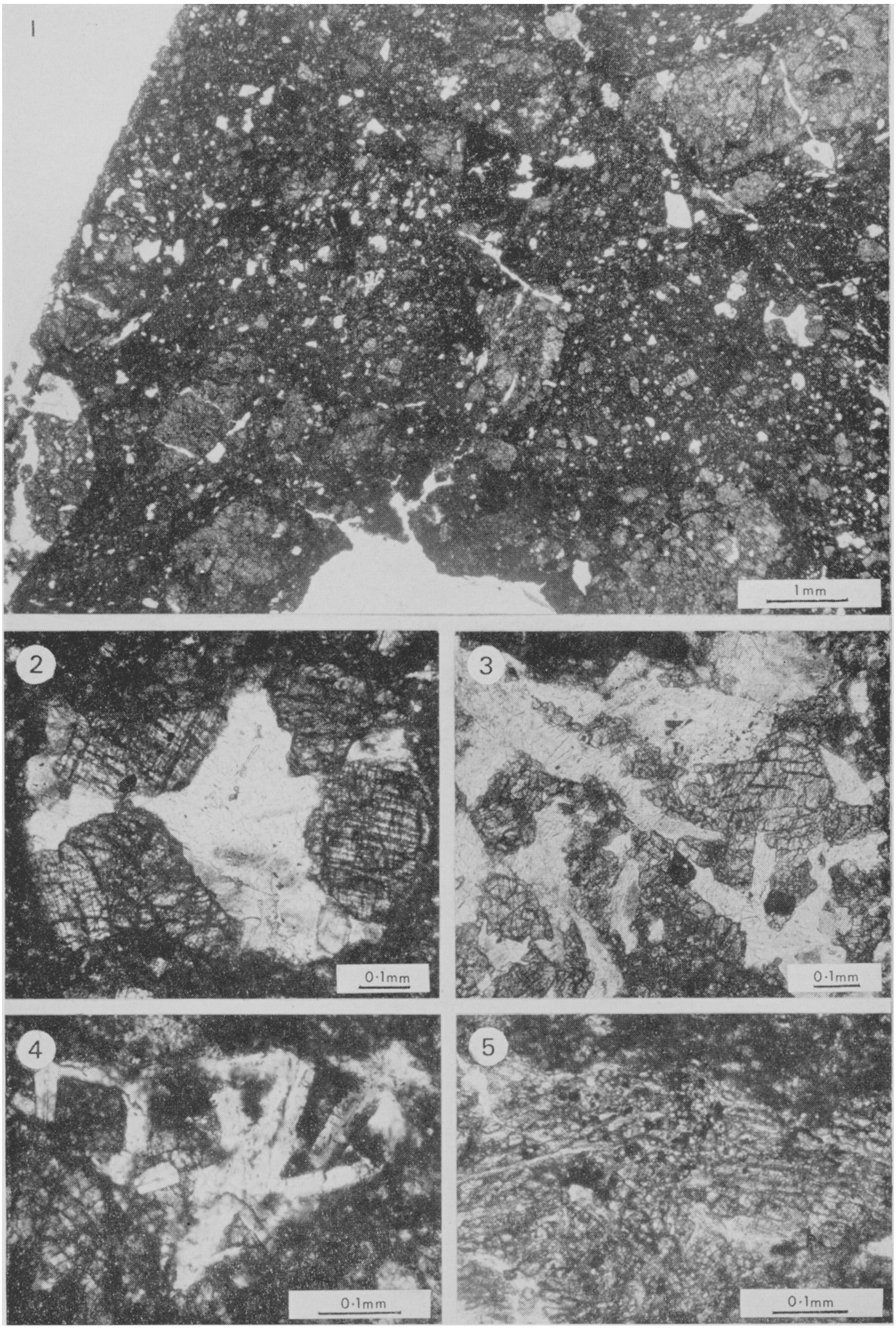

FIGS. 1–5. Photomicrographs of the Molteno howardite showing structure (parallel nicols). 1 (top). Low magnification photomicrograph showing over-all breccia texture. 2 (middle left). Fragment with granular texture. 3 (middle right). Detail of fragment showing sub-ophitic to ophitic texture with a small area of dark fine-grained texture at the top of the photograph. 4 (bottom left). Fragment showing intergranular texture. 5 (bottom right). Detail of a fragment of anomalous texture.

powder photograph has indicated that these are still composed of pyroxene and plagioclase and it is suggested that since some seem to have intruded coarser material they represent material that has suffered extreme shock and of which some may have become mobilized in a manner analogous to pseudotachylite. Some of these grains may be seen in fig. 1 and form the left-hand side of the top of fig. 3. Another fragment of some interest is shown in fig. 5. It consists of granular pyroxene filling the spaces between sets of sub-parallel irregular laths of dusty plagioclase. Although this texture could be interpreted as oriented intergranular texture it also bears, texturally only, a resemblance to that seen in some chondrules. A small fragment consisting of a myrmekitic intergrowth of troilite and pyroxene was also noted. Equidimensional grains of metal and probable ilmenite up to 0·1 mm in diameter, a sliver of metal 0·2 mm long, and an irregular sulphide grain 0·1 mm long could be interpreted either as being grains roughly original size from an original igneous-structured rock or as being fragments from a mass or masses of very different composition. For the ilmenite and sulphide, both of which occur mainly in the less crushed fragments, the former hypothesis seems preferable, but for the metal, which is common in the more crushed material and may thus be of later origin, the latter hypothesis is possible.

The composition of selected mineral grains was determined with a Cambridge Instrument Co. Geoscan electron microprobe. The usual corrections were applied and the accuracy for major elements is about $\pm 2\%$.

Pyroxene. Microprobe analysis of both representative and random grains, some possibly composite, gave the compositions plotted in fig. 6. The range of composition is very close to that recorded for Kapoeta by Fredriksson and Keil (1963) but somewhat different to that recorded for Petersburg by Duke and Silver (1967).

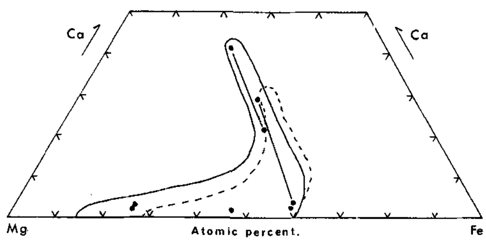

FIG. 6. Composition of pyroxenes in Molteno. Tie lines join exsolution and host pyroxene. Solid line indicates range of pyroxene compositions in Kapoeta and dashed line range in Petersburg.

Optically several distinct types of pyroxene may be distinguished. Most are clear colourless orthopyroxene. This has apparently inverted from pigeonite since occasional grains contain small patches of clear clinopyroxene in physical continuity with the main orthopyroxene grain, and others show narrow bands, having a slightly different orientation to that of the host, that may represent remnants of exsolution lamellae in the original clinopyroxene. Also present in smaller quantity is a clinopyroxene that varies from colourless, with few inclusions, to pale pink, commonly crowded with minute inclusions, the latter variety forming about one seventh of all the pyroxene present. This clinopyroxene often shows prominent exsolution lamellae, varying in width from 0·8 to 7·0 μm, of calcium-rich clinopyroxene. The refractive index γ reaches a maximum value of 1·747; assuming a Wo content of 10% this would correspond to 57 mol.% Fs.

Plagioclase. Microprobe analysis of a number of grains gave a fairly constant composition of An 84·4%. The refractive index α reaches a minimum value of 1·571±0·001 corresponding to 88·5±2% An (Chayes, 1952).

The plagioclase occurs in grains having the same size range as the pyroxene. The larger grains show complex twinning. Universal stage study of the plagioclase using the methods of Slemmons (1962) showed that the only four grains that were reasonably

TABLE I. *Chemical analysis and norm of the Molteno meteorite (anal. C. J. Elliott, on 6·7 g, by the chlorination technique). Percentage figures in roman type, parts per million in italic*

Bulk analysis				Composition of			
Non-magnetic, attacked		Non-magnetic, unattacked		Total metal			Norm
Fe	1·12	SiO_2	47·54	Fe	92·5%	Metal	4·06
Mn	*54*	TiO_2	0·41	Ni	7·0	Troilite†	1·77
Cu	*2·2*	Al_2O_3	8·83	Co	0·5	Chromite*	1·00
Ti	*40*	Cr_2O_3	0·53	Cu	*185*	Ilmenite	0·96
Cr	< *10*	V_2O_3	0·007*	Ge	*39*	Hydroxyapatite	0·08
S	0·64	FeO	15·94	Ga	*27*	Feldspar‡	25·05
		MnO	0·41			Pyroxene	65·84
Magnetic, attacked		MgO	13·15	Attacked metal (kamacite)		Quartz	1·12
		CaO	6·65			Water	0·07
Fe	3·17	Na_2O	0·29	Fe	94·5%		99·95
Ni	0·17	K_2O	0·028	Ni	5·0		
Co	0·016	P_2O_5	0·038	Co	0·5		
Ge	*1·3*	H_2O-	0·07	Cu	tr.		
Ga	*0·8*	Sum	99·63	Ge	*39*		
				Ga	*24*		
Magnetic, unattacked				Unattacked metal (taenite)			
Fe	0·59			Fe	83·1%		
Ni	0·116			Ni	16·4		
Co	*29*			Co	0·4		
Cu	*7·5*			Cu	*1060*		
Ge	*0·3*			Ge	*42*		
Ga	*0·3*			Ga	*42*		

* Assuming that all Cr and V are present as chromite of the composition found by the electron probe.

† Containing 0.5% MnS and 0.4% TiS.

‡ $An_{89}Ab_{10\cdot2}Or_{0\cdot7}$.

unstrained and had lamellae wide enough for study were twinned on the pericline or acline, the albite and Carlsbad-albite, the albite, Manebach, and either Ala-A or Manebach-acline, and the albite and Carlsbad laws respectively. The twin frequency is comparable with the twin frequency recorded for the plagioclase of Juvinas (Game, 1957) and igneous rocks (Slemmons, 1962) but differs in the lower percentage of pericline and the presence of Carlsbad and Carlsbad-albite from that of Moore County (Hess and Henderson, 1949).

Olivine. Only one large grain of olivine about 1 mm in length was positively identified. Microprobe analysis gave a composition of 12·1% Fa.

Opaques. At least 80% of the opaque mineral in the section studied is troilite, which occurs as subhedral and anhedral grains up to 0·26 mm in diameter and as fine intergrowths with pyroxene. Kamacite, with 4·0% Ni by microprobe, occurs as irregular grains up to 0·03 mm in diameter. Small single grains of ilmenite and chromite were also detected. Microprobe analysis of the chromite gave: total iron (as FeO) 29.1%, MgO 1·85, MnO 0·5, Cr_2O_3 53·0, Al_2O_3 9·9, V_2O_3 0·71, TiO_2 0·67, Total 95·73%. If an $RO:R_2O_3$ ratio of 1·0 is assumed this gives the formula based on O = 32 of $(Fe^{2+}_{7\cdot07}Mg_{0\cdot81}Mn_{0\cdot12})(Cr_{12\cdot25}Al_{3\cdot40}V_{0\cdot16}Ti_{0\cdot15}Fe^{3+}_{0\cdot04})O_{32}$. The chromite shows a general resemblance in composition to the chromites from chondrites (Bunch *et al.*, 1967) having high vanadium and low magnesium. It differs however in having higher aluminium and in this it resembles the chromite reported from the Mount Vernon pallasite (Tassin, 1908).

A modal analysis, by point counting of a 160 mm^2 area, gave: pyroxene 92 vol.%, olivine 1 vol.% (one large grain), plagioclase 5½ vol.%, opaques 1½ vol.%, of which at least 80% was troilite. This is in marked contrast to the chemical analysis (table I), and it is evident that the meteorite is inhomogeneous in composition. Since the relatively large sample used for the chemical analysis should be more representative, the Wahl norm is probably a better picture of the composition than the modal data.

In all respects Molteno is a typical howardite.

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