Studies of Brazilian Meteorites IX. Mineralogy, Petrology and Chemistry of the Macau, Rio Grande do Norte, Chondrite*

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(With 2 text-figures)

INTRODUCTION

The Macau (synonyms Macao; Macayo) chondrite fell on November 11, 1836, at 5.00 P.M. (local time), near the city of Macau, State of Rio Grande do Norte, Brazil (approximate coordinates 5° 12′ S, 36° 40′ W). A shower of stones fell, with most of them approximating the size of a dove's egg, but the largest one ranging up to 40 kg. The meteorite fall was accompanied by a brilliant fireball, visible up to 600 km away from the place of fall, followed by detonations, and it is said that several cattle were killed by the fall. The largest concentration of stones was reported from the mouth of the river Assu, but material was scattered over an area extending 150 km. However, apparently only four stones were recovered, weighing 2047 grams.

Although the meteorite has been listed by Derby (1888), Oliveira (1931), Vidal (1936), and Hey (1966), no comprehensive study of the chondrite has as yet been carried out. The only quantitative data on Macau were reported by Mason (1963), who determined the composition of its olivine by optical methods (Fa_{19}) and by van Schmus and Wood (1967) who, on the basis of optical and X-ray microscopy, classified the meteorite as an H5 chondrite. It is therefore the main purpose of the present paper to provide a detailed description of the meteorite on the basis of optical microscopy, electron microprobe and bulk chemical analyses, and to verify the classification of the stone by as many parameters as possible.

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ANALYTICAL PROCEDURES

Polished thin sections of the meteorite were studied microscopically in transmitted and reflected light, and constituent phases were analyzed with an ARLEMX-SM electron microprobe X-ray analyzer. The bulk composition of the stone was determined using the procedures described by Jarosewich (1966). Electron microprobe analyses were carried out using an accelerating potential of 15 keV, a sample current of ~0.02 μAmp, and an electron bean spot size of ⩽1 μm. Corrections were made according to the method of Bence and Albee (1968), and natural minerals of well-known composition (olivine Marjalahti; augite A-209; andesine AC-362; and chromite C53IN8) were used as standards.

TEXTURE, MINERALOGY AND PETROLOGY

The texture of the Macau stone is clearly chondritic, although recrystallization has caused chondrule-matrix boundaries to be diffuse (Fig. 1A). In one thin section, 30 relict chondrules were counted, ranging in apparent size from 0.2-2.4 mm (mean 0.6 mm). They are rounded and occasionally elongated in shape and have variable internal textures. Barred, porphyritic, and excentro-radial chondrules were noted, with the barred ones being the most common (Figs. 1B-D). The chondrules are either monosomatic (i.e. consist of either olivine or pyroxene) or polysomatic (i.e. contain both these phases). Metallic nickel-iron and troilite are rare constituents of the chondrules, but are common in the matrix. The major minerals of the stone are olivine, orthopyroxene, and metallic nickel-iron with minor amounts of plagioclase, and troilite, and accessory amounts of calcium-rich clinopyroxene, chromite, and a hydrous ferric oxide of terrestrial origin.

Olivine is homogeneous and uniform in composition, both within and outside chondrules, and its composition ($Fa_{19.0}$; TABLE I; Fig. 2) is well within the ranges for olivine of H-group chondrites (Keil and Fredriksson, 1964, as modified by Fodor *et al.*, 1976) Similarly, orthopyroxene ($Fs_{17.4}$) is homogeneous, uniform, and conforms to H-group classification (TABLE I, Fig. 2). The few data points that are somewhat outside the tight clusters exhibited in Figure 2 and are probably the result of minor overlap of some terrestrial hydrous ferric oxides by the electron beam during analysis and, thus, are artifacts. Plagioclase is oligoclase ($Or_{5.4}Ab_{82.1}$

Fig. 1 — A: Poorly defined chondritic texture in the H5 Macau, Rio Grande do Norte, meteorite. Ferromagnesian silicates (olivine and orthopyroxene) are gray in color, metallic nickel-iron is white. Reflected light. 31 ×. B: Relict chondrule of olivine surrounded by an irregularly shaped metallic phase. Reflected light. 75 ×. C: Relict chondrule of orthopyroxene, partially rounded and containing tiny grains of metal. Reflected light. 75 ×. D: Same as Fig. 1C, transmitted plane polarized light. 75 ×.

$An_{12.5}$) in composition, homogeneous, and is typical for plagioclase from H-group chondrites (van Schmus and Ribbe, 1968). Chromite is homogeneous, commonly shows irregular cracks and, compositionally, is similar to chromite from other H-group chondrites (Bunch *et al.*, 1967). Metallic nickel-iron is predominantly kamacite, with minor taenite, and the metal is often surrounded by a thin layer of a gray phase (reflected light), apparently a hydrous ferric oxide of terrestrial origin. Troilite is usually associated with metallic nickel-iron, and metal and troilite are usually of irregular shape, filling the space between chondrules and matrix silicates.

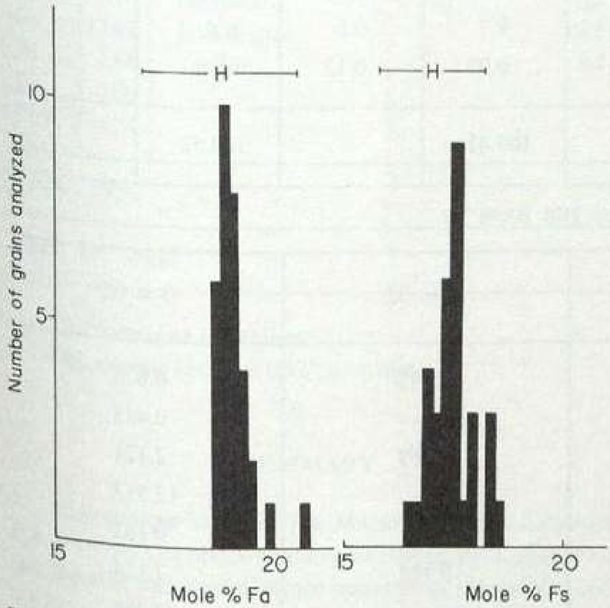

Fig. 2 — Histograms showing the compositions of olivine (Fa; Fe_2SiO_4) and orthopyroxene (Fs; $FeSiO_3$) in Macau as compared to the ranges for H-group chondrites as given by Keil and Fredriksson (1964; as revised by Fodor *et al.*, 1976).

BULK CHEMICAL ANALYSIS

The bulk chemical analysis and the CIPW molecular norm of the Macau chondrite are listed in TABLE II. Although the meteorite is somewhat oxidized by terrestrial weathering (i.e. some metallic nickel-iron was converted into hydrous ferric oxide), the meteorite clearly belongs to the H-group on the basis of its bulk chemical composition. Note that the Fe^{3+} was calculated by difference using the compositions of olivine and orthopyroxene as obtained by electron microprobe analysis and assuming these to be the sole Fe^{2+}– bearing phases. Thus, because of terrestrial weathering, the metallic nickel-iron content (13.81%) is somewhat low but still only very little outside the range for metallic nickel-iron contents of H-group chondrites (14.17 – 19.81%, mean 16.72% Keil, 1962a, b). Analogously, the ratios of Fe^o Ni^o (7.19; average H-group 10.90; Craig, 1964) and of Fe^o/Fe_{total}(0.46; average H-group 0.63; van Schmus and Wood, 1967) are slightly low but still within the ranges for H-group chondrites. The Fe_{total} (26.27%; average H-group 27.52%; Craig, 1964) and the ratios of Fe_{total}/SiO_2 (0.73; average H-group 0.77; Van Schmus and Wood, 1967) are typical for H-group chondrites.

CONCLUSIONS

On the basis of its minaral compositions, particularly of olivine ($Fa_{19.0}$), orthopyroxene ($Fs_{17.4}$), and chromite, it is concluded that Macau belongs to the H-group. This conclusion is also supported by the bulk chemical analysis, particularly the ratios of Fe^o/Ni^o (7,19), Fe_{total}/SiO_2 (0.73), and Fe^o/Fe_{total} (0.46), and the contents of Fe_{total} (26.27%) and metallic nickel-iron (13.81%). The uniformity and homogeneity of its constituent minerals, particularly olivine, orthopyroxene, chromite, and plagioclase, as well the only poorly-developed chondritic texture and the recrystallized matrix suggest that the chondrite belongs to the petrologic class H-5, thus confirming the earlier results of Van Schmus and Wood (1967).

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TABLE I

Average Compositions, as Obtained by Electron Microprobe Techniques, and Structural Formulae of Olivine, Bronzite, Plagioclase, and Chromite from the Macau, Brazil, Chondrite. All Data are in Weight per Cent. Number of Grains Analyzed are shown in Parentheses

	OLIVINE		BRONZITE		PLAGIOCLASSE		CHROMITE	
	(32)	S.D.	(32)	S.D.	(5)	S.D.	(21)	S.D.
SiO_2	39.4	0.4	56.6	0.5	64.2	0.4	0.10	0.02
TiO_2	n.d.	—	n.d.	—	n.d.	—	2.15	0.17
Al_2O_3	0.10	0.04	0.25	0.09	21.4	0.2	6.4	0.4
Cr_2O_3	n.d.	—	n.d.	—	n.d.	—	56.3	0.8
V_2O_3	n.d.	—	n.d.	—	n.d.	—	0.72	0.06
FeO	18.0	0.4	11.8	0.3	1.09	0.13	30.3	0.6
MnO	0.47	0.04	0.48	0.02	n.d.	—	1.05	0.06
MgO	42.9	0.4	31.0	0.4	0.39	0.14	3.5	0.4
CaO	< 0.02	0.02	0.73	0.20	2.66	0.09	n.d.	—
Na_2O	n.d.	—	0.06	0.04	9.7	0.6	n.d.	—
K_2O	n.d.	—	n.d.	—	0.97	0.12	n.d.	—
TOTAL	100.87		100.92		100.41		100.52	

NUMBER OF IONS ON THE BASIS OF

	O = 4	O = 6	O = 32		O = 32
Si	0.995	1.986	11.377		0.028
Ti	—	—	—		0.455
Al	0.003	0.010	4.469		2.121
Cr	—	—	—		12.513
V	—	—	—		0.162
Fe	0.380	0.346	0.162		7.124
Mn	0.010	0.014	—		0.250
Mg	1.615	1.622	0.103		1.467
Ca	—	0.027	0.505		—
Na	—	0.004	3.326		—
K	—	—	0.219		—
Z	0.995	1.996	15.846	SUM^{+3}	15.279
X	2.008	2.013	4.315	SUM^{+2}	8.841
SUM	3.003	4.009	20.161		24.120
	Fo 81.0	En 81.2	Or 5.4		Uv 5.8
	Fa 19.0	Fs 17.4	Ab 82.1		Cm 77.3
		Wo 1.4	An 12.5		PCm 3.9
					Sp 12.9

S.D. — Standard deviation; n.d. — not determined.

TABLE II

Bulk Chemical Analysis and CIPW Molecular Norm of the Macau Meteorite

SiO_2	36.26	Olivine	Fo	23.8
TiO_2	0.11		Fa	7.5
Al_2O_3	2.02	Hypersthene	En	23.2
Cr_2O_3	0.52		Fs	6.6
Fe_2O_3	6.19*			
FeO	8.83	Diopside	Wo	2.2
MnO	0.32		En	1.5
MgO	22.74		Fs	0.4
CaO	1.65	Plagioclase	Ab	7.4
Na_2O	0.84		An	1.5
K_2O	0.09		Or	0.6
P_2O_5	0.26	Apatite		0.6
H_2O^+	1.42	Chromite		0.8
H_2O^-	0.10	Ilmenite		0.2
Fe	12.07	Nickel-iron		18.8
Ni	1.68	Troilite		4.9
Co	0.06			
FeS	4.74			
Total	99.90			
Total Fe	26.27			

* This meteorite is weathered.
This sample contains 0.12% carbon.

SUMMARY

Microscopic study of the Macau chondrite indicates that it consists of major amounts of olivine, orthopyroxene, and metallic nickel-iron, minor amounts of plagioclase and troilite, and accessory amounts of calcium-rich clinopyroxene, chromite, and a hydrous ferric oxide of terrestrial origin. The composition of olivine ($Fa_{19.0}$), orthopyroxene ($Fs_{17.4}$), and chromite as well as the bulk composition, particularly the ratios Fe^o/Ni^o(7,19), Fe_{total}/SiO_2 (0,73), and Fe^o/Fe_{total} (0,46) and the contents of Fe_{total} (26,27%) and metallic nickel-iron (13.81%), indicate that Macau belongs to the H-group. Mineralogical and textural evidence suggests that Macau is a member of the H5 petrographic class.

RESUMO

O estudo microscópico do meteorito Macau indica que o mesmo tem como principais constituintes olivina, ortopiroxênio e ferro-níquel, aparecendo subordinadamente plagioclásio e troilita, além de clinopiroxênio, cromita e óxido de ferro hidratado de origem terrestre como acessórios. A composição da olivina ($Fa_{19,0}$), ortopiroxênio ($Fs_{17,4}$) e cromita, bem como a química global, particularmente as razões Fe^o/Ni^o (7,19), Fe_{total}/SiO_2 (0,73) e Fe^o/Fe_{total}(0,46), além dos teores de Fe_{total} (26,27%) e ferro-níquel (13,81%), indicam que o condrito Macau pertence ao Grupo H. Evidências mineralógicas e texturais sugerem que o meteorito Macau é um membro da classe petrográfica H5.

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