STUDIES OF BRAZILIAN METEORITES XIII. MINERALOGY, PETROLOGY, AND CHEMISTRY OF THE PUTINGA, RIO GRANDE DO SUL, CHONDRITE

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*The Putinga, Rio Grande do Sul, chondrite (fall, August 16, 1937), consists of major olivine ($Fa_{24.8}$), orthopyroxene ($Fs_{21.3}$), and metallic nickel-iron (kamacite, taenite, and plessite); minor maskelynite ($Ab_{81.0}An_{12.4}Or_{6.6}$) and troilite; and accessory chromite ($Cm_{79.0}Uv_{8.2}Pc_{1.8}Sp_{11.0}$) and whitlockite. Mineral compositions, particularly of olivine and orthorhombic pyroxene, as well as the bulk chemical composition, particularly the ratios of Fe°/Ni° (5.24), Fe_{total}/SiO_2 (0.58), and Fe°/Fe_{total} (0.27), and the contents of Fe_{total} (22.42%) and total metallic nickel-iron (7.25%) classify the meteorite as an L-group chondrite. The highly recrystallized texture of the stone, with well-indurated, poorly discernible chondrules; xenomorphic, well-crystallized groundmass olivine and pyroxene; and the occurrence of poikilitic intergrowth of olivine in orthopyroxene suggest that Putinga belongs to petrologic type 6. Maskelynite of oligoclase composition was formed by solid state shock transformation of previously existing well-crystallized plagioclase at estimated shock pressures of about 250-350 kbar. Thus, recrystallization (*i.e.*, formation of well-crystallized oligoclase) must have preceded shock transformation into maskelynite.*

INTRODUCTION

The Putinga, Rio Grande do Sul, chondrite fell at 4:30 p.m. on August 16, 1937, in Encantada County, about 2 km from Putinga (29°2′S, 53°3′W). The meteorite is also known under the synonym Encantada. The day after the bolide was observed, two big masses weighing 57 and 45 kg, respectively, as well as several smaller masses up to 10 kg, were recovered. The specimens were found buried at depths up to 2-3 m (Roisenberg, 1970). A specimen weighing approximately 45 kg (in 1970) is preserved in the Museu Luiz Englert, Universidade Federal do Rio Grande do Sul, Porto Alegre. In addition, 967.9 grams are in the U.S. National Museum (Natural History), Washington, D.C., 284 grams in the Vatican Collection, 254 grams in the American Museum of Natural History, New York, and several other small pieces are in other collections.

The meteorite Putinga is listed in Hey (1966) as an olivine-hypersthene (*i.e.*, L-group) chondrite, and a preliminary description was first given by Roisenberg (1970). Mason (1967) determined the composition of the olivine as Fa_{24} using optical and X-ray diffraction techniques. A brief description of the texture of the meteorite, including some electron microprobe and a bulk chemical analysis, were presented by Symes and Hutchison (1970), who classified the meteorite as an L-6 chondrite.

METHODS OF STUDY

Polished thin sections of the meteorite were studied in transmitted and reflected light, and olivine, orthopyroxene, maskelynite and chromite were analyzed quantitatively with an ARL EMX-SM electron microprobe, using procedures and standards previously described (Keil *et al.*, 1978). Special precautions had to be taken to analyze the maskelynite. This phase decays easily during bombardment with an electron beam, yielding erroneous counting rates and analyses. Therefore, for the analysis of maskelynite, a sample current of only ~ 0.01 μAmp and a beam size of about 10 μm were employed, and the beam was left on any one point for only 1 second. Using this procedure, a good analysis yielding a stoichiometric structural formula was obtained (Table 1). A bulk chemical analysis was performed according to modified methods described by Jarosewich (1966).

MORPHOLOGY AND TEXTURE

The 45 kg stone in the Museu Luiz Englert, Universidade Federal do Rio Grande do Sul, Porto Alegre (Fig. 1a), is irregular to polyhedral in shape. It is partly covered by a black fusion crust up to 0.2 mm thick and has regmaglypts in places. The interior of the stone is light gray and dense, with the chondritic texture only poorly visible in hand specimen. Brown spots are

Table 1
Electron microprobe analyses (in weight percent) of olivine, bronzite, plagioclase (maskelynite), and chromite from the Putinga, Brazil, chondrite. Number of grains analyzed by us is shown in parentheses.

	Olivine (20) (1)	Olivine (20) (2)	Pyroxene (20) (1)	Pyroxene (20) (2)	Maskelynite (30) (1)	Maskelynite (30) (2)	Chromite (22) (1)
SiO_2	38.4	38.5	55.8	54.5	65.5	n.d.	0.09
TiO_2	n.d.	–	0.25	–	n.d.	–	3.02
Al_2O_3	0.05	n.d.	0.21	n.d.	21.0	23.5	5.4
Cr_2O_3	n.d.	–	n.d.	–	n.d.	–	55.9
V_2O_3	n.d.	–	n.d.	–	n.d.	–	0.80
FeO	22.7	22.6	14.1	14.0	0.53	–	32.6
MnO	0.44	n.d.	0.52	n.d.	n.d.	–	0.37
MgO	38.7	39.1	28.6	28.5	n.d.	–	2.6
CaO	0.02	n.d.	0.84	0.67	2.57	2.3	n.d.
Na_2O	n.d.	–	< 0.02	n.d.	9.3	10.3	n.d.
K_2O	n.d.	–	n.d.	n.d.	1.14	1.4	n.d.
Total	100.31	100.2	100.32	97.6	100.04		100.78

End-members (%)

	(1)	(2)		(1)	(2)		(1)	(2)		(1)
Fo	75.2	75.7	En	77.1	77.5	Ab	81.0	82.4	Cm	79.0
Fa	24.8	24.3	Fs	21.3	21.2	An	12.4	10.2	Uv	8.2
			Wo	1.6	1.3	Or	6.6	7.4	Pc	1.8
									Sp	11.0

n.d. – not determined
References: (1) This work; (2) Symes and Hutchison (1970).

distributed irregularly over the light gray, broken surfaces of the stone, apparently due to mild terrestrial weathering. However, metallic nickel-iron in the microscope is very fresh and does not show signs of significant terrestrial weathering.

In thin section, Putinga displays a highly recrystallized, dense texture, with common poikilitic intergrowth of olivine in pyroxene (Fig. 1b). Chondrules are poorly defined and often intergrown with the matrix (Fig. 1c), a fine-grained groundmass averaging 0.15 mm in grain size. The chondrules range in apparent size from 0.2 up to 4.0 mm, with the apparent mean diameter being about 0.8 mm, and also vary in shape from round to

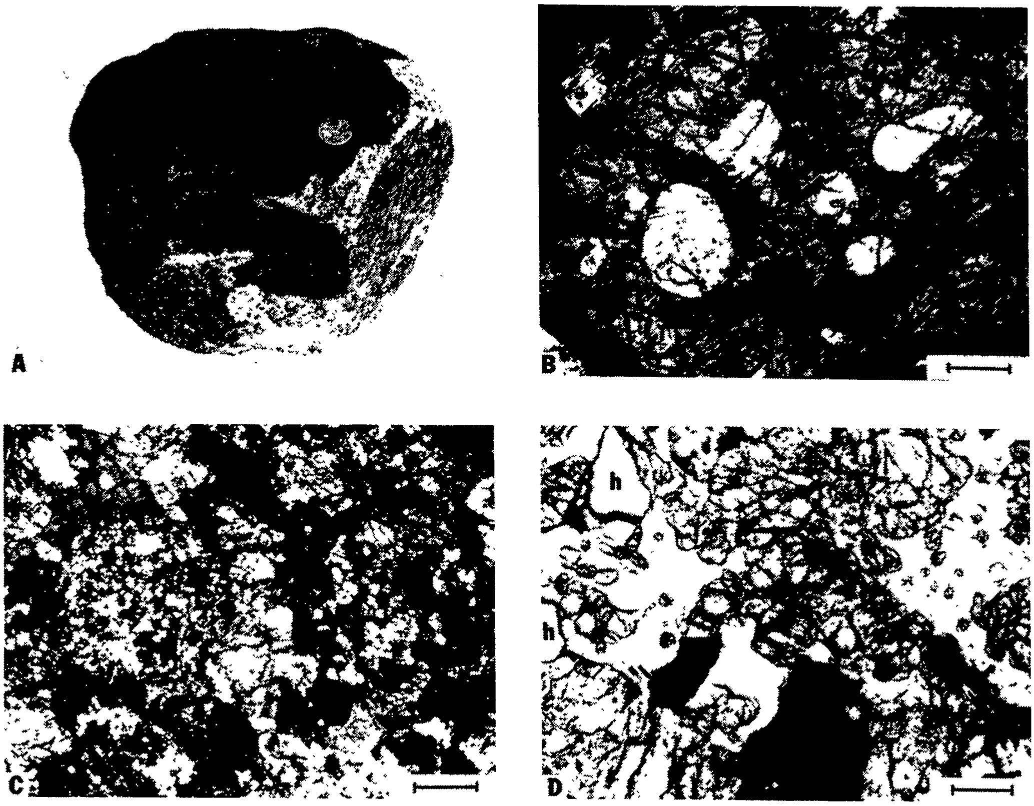

Fig. 1A One specimen, weighing approximately 45 kg, of the L6 Putinga chondrite showing a black fusion crust and regmaglypts in some places. Coin is about 25 mm in diameter.
B Poikilitic olivine (white) in pyroxene (gray). Transmitted light, crossed nicols. Scale bar equals 0.60 mm.
C General texture of Putinga, exhibiting poorly defined chondrules and large matrix grains. Transmitted light, crossed nicols. Scale bar equals 2 mm.
D Maskelynite (clear) with inclusions of mafic minerals. Transmitted, plane polarized light. Scale bar equals 0.5 mm (h = hole in section).

mainly elliptic or elongate. Their internal textures vary, and excentro-radial, porphyritic, barred, and granular types were observed. Symes and Hutchison (1970) reported a single chondrule approximately 7 mm in diameter that consists of a reticulate mass of minute olivine grains showing hour-glass type extinction. This feature they interpret as possibly being due to shock. No other indications of shock of Putinga were reported by them and no shock veins were observed. This is surprising because in our thin section, plagioclase occurs as clear maskelynite, *i.e.*, a shock-transformed feldspar, involving solid state conversion of the crystalline feldspar to a feldspar glass. The maskelynite is either perfectly isotropic, even at high magnification, or slightly anisotropic and contains small inclusions of mafic minerals (Fig. 1d). We also note that many mafic mineral grains show wavy extinction, a feature which we also interpret as being the result of shock. A reinvestigation of the original sections studied by Symes and Hutchison (1970) showed all plagioclase to be transformed to maskelynite, in agreement with our results (Hutchison, pers. comm., Oct. 13, 1977).

MINERALOGY

The meteorite Putinga consists of major olivine, orthopyroxene, and metallic nickel-iron (kamacite, taenite, and plessite); minor amounts of maskelynite and troilite; and accessory amounts of chromite and whitlockite.

Olivine is a major phase of the chondrules and the matrix. It occurs with plagioclase in barred chondrules, with plagioclase and pyroxene in porphyritic chondrules, and rarely with plagioclase in excentro-radial chondrules. Olivine is anhedral to subhedral in shape and is homogeneous in composition (average $Fa_{24.8}$, Table 1, Fig. 2, this work; $Fa_{24.3}$, Symes and Hutchison, 1970).

Pyroxene is also a major constituent of chondrules and of the matrix and, in general, occurs in grains smaller than those of olivine. The crystals are anhedral to subhedral and are homogeneous, averaging $Fs_{21.3}$ (Table 1, Fig. 2). Symes and Hutchison (1970) report $Fs_{21.2}$.

Maskelynite is isotropic to weakly anisotropic and occurs as clear, anhedral grains in the matrix and in chondrules. In the matrix, maskelynite grains are up to several hundred μm in size and often have minute inclusions of mafic minerals (Fig. 1d). There are no indications of fusion (*i.e.*, no schlieren, flow structures, vesicles, non-stoichiometry) and, thus, the phase formed from plagioclase by solid state shock transformation and not by fusion. Maskelynite is oligoclase in composition ($Ab_{81.0}An_{12.4}Or_{6.6}$) and is stoichiometric (Table 1); thus, during the shock transformation, melting and associated vapor fractionation apparently did not take place. Symes and Hutchison (1970) give the composition $Ab_{82.4}An_{10.2}Or_{7.4}$ for plagioclase.

Chromite occurs as irregular grains varying in size from 50-500 μm throughout the matrix of the meteorite. Most chromite is of the coarse type of Ramdohr (1973), and the aggregate type is rare. The mineral is homogeneous in composition and averages $Cm_{79.0}Uv_{8.2}Pc_{1.8}Sp_{11.0}$.

Metallic nickel-iron occurs as kamacite, taenite, and plessite, with kamacite being the most abundant phase. Grain sizes vary considerably, with the largest grains approaching 1.2 mm. Symes and Hutchison (1970) report 7.1% Ni for kamacite and 29% Ni for the average of the centers of the three taenite grains.

Troilite occurs in irregular, isolated grains up to 1.1 mm in size (mean about 300 μm) or as granular, usually monomineralic aggregates.

BULK CHEMICAL COMPOSITION

The two recent bulk chemical analyses by Symes and Hutchison (1970) and by us are listed in Table 2, together with the CIPW norms. The analyses

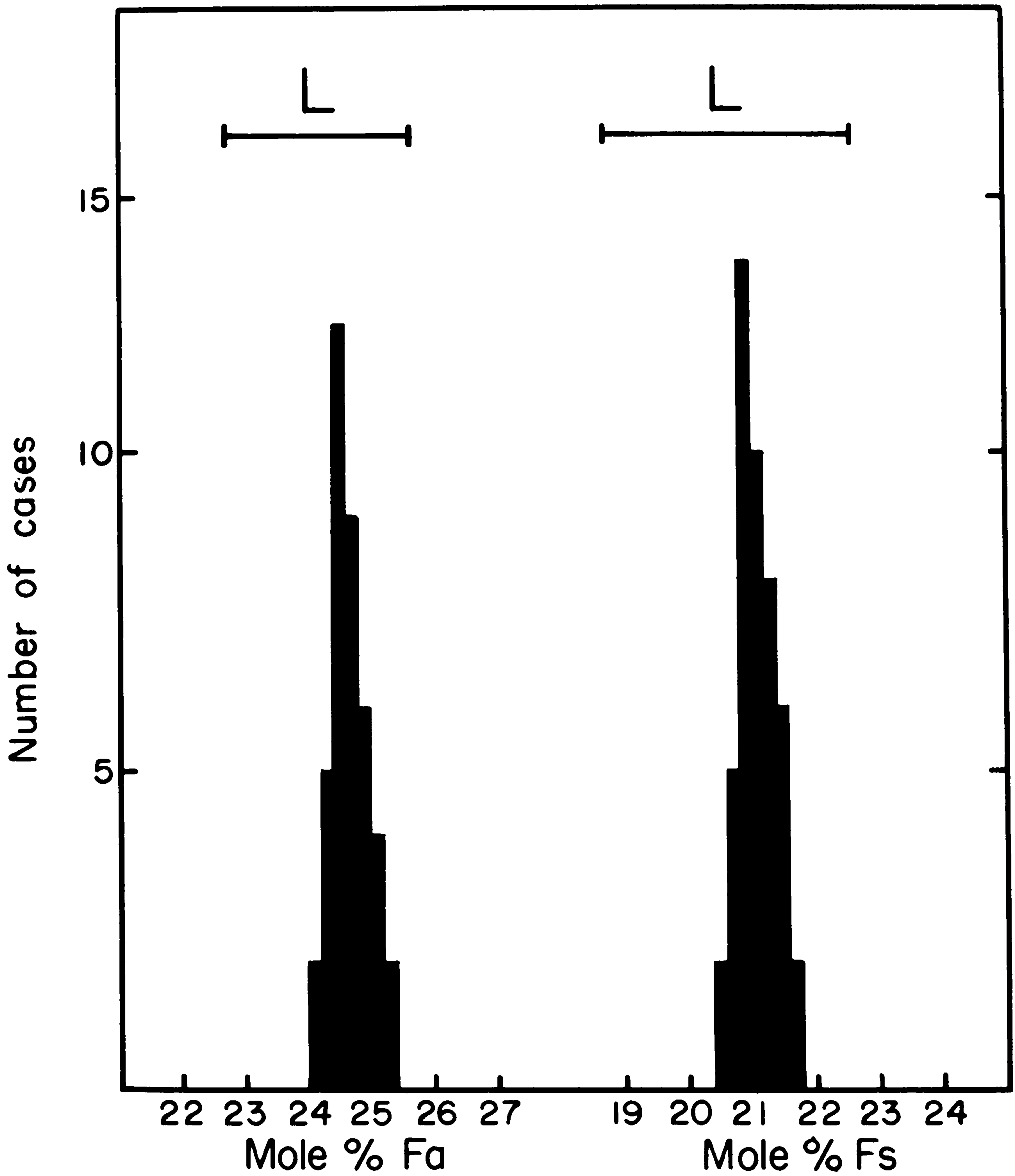

Fig. 2 **Histogram illustrating the compositions of olivine and low-Ca pyroxene in the Putinga meteorite, as expressed as mole % end-members fayalite (Fa; Fe_2SiO_4) and ferrosilite (Fs; $FeSiO_3$). The compositional ranges are from Keil and Fredriksson (1964), as revised by Fodor *et al.* (1976).**

agree well with each other, and the CIPW norms show olivine, hypersthene, and metallic nickel-iron as major constituents; plagioclase, diopside and troilite as minor constituents; and apatite, chromite, and ilmenite as accessory constituents, in good agreement with the modal abundances of these phases (except that we did not observe ilmenite).

Table 2
Bulk-chemical analysis (in weight percent) and the CIPW norms of the Putinga chondrite

	(1)	(2)			(1)	(2)
SiO_2	38.95	40.4	Olivine	Fo	33.0	29.9
TiO_2	0.13	0.1		Fa	18.7	16.2
Al_2O_3	2.35	2.1	Hypersthene	En	12.7	16.1
Cr_2O_3	0.52	0.5		Fs	6.6	7.9
FeO	17.03	16.3	Diopside	En	1.4	1.7
MnO	0.34	0.3		Fs	0.7	0.9
MgO	24.32	24.4		Wo	2.3	2.8
CaO	1.80	1.8	Plagioclase	Ab	8.1	8.4
Na_2O	0.95	1.0		An	1.8	0.9
K_2O	0.11	0.1		Or	0.7	0.6
P_2O_5	0.27	0.2	Apatite		0.6	0.5
H_2O^+	0.81	–	Chromite		0.8	0.7
H_2O^-	0.06	–	Ilmenite		0.2	0.2
Fe	6.03	6.6	Nickel-iron		7.3	7.8
Ni	1.15	1.2	Troilite		5.0	5.4
Co	0.07	0.06				
FeS	4.96	5.4				
C	0.20	–				
Total	100.05	100.5				
Fe_T	22.42	23.3				

(1) This work; (2) Symes and Hutchison (1970).

DISCUSSION AND CONCLUSIONS

Classification

Our data confirm the earlier conclusions by Mason (1967), Roisenberg (1970), and Symes and Hutchison (1970) that the meteorite Putinga belongs to the L-group of chondrites. This classification is indicated by the compositions of olivine ($Fa_{24.8}$, Table 1, Fig. 2, this work; Fs_{24}, Mason, 1967; $Fa_{24.3}$, Symes and Hutchison, 1970) and orthopyroxene ($Fs_{21.3}$, Table 1, Fig. 2, this work; $Fa_{21.2}$, Symes and Hutchison, 1970), which are within the ranges for the average olivine ($Fa_{22.7-25.6}$) and orthopyroxene ($Fs_{18.7-22.6}$) compositions of L-group chondrites (Keil and Fredriksson, 1964, as modified by Fodor *et al.*, 1976). Chromite ($Cm_{79.0}Uv_{8.2}Pc_{1.8}Sp_{11.0}$) and maskelynite ($Ab_{81.0}An_{12.4}Or_{6.6}$) compositions are only approximately consistent with L-group classification (Bunch *et al.*, 1967; Van Schmus and Ribbe, 1968). L-group classification is also indicated by the bulk chemical analyses, particularly the ratios of Fe°/Ni° (5.24, this work; 5.50, Symes and Hutchison, 1970; average L-group 6.87, Craig, 1964); Fe_{total}/SiO_2 (0.58, this work; 0.58, Symes and Hutchison, 1970; average L-group 0.55, Van Schmus and Wood, 1967); and Fe°/Fe_{total} (0.27, this work; 0.28, Symes and Hutchison, 1970; average L-group 0.33, Van Schmus and Wood, 1967), as well as the contents of Fe_{total} (22.42%, this work; 23.3%, Symes and Hutchison, 1970; average L-group 21.82%, Craig, 1964) and total metallic nickel-iron (7.25%, this work; 7.86%, Symes and Hutchison, 1970; average L-group 6.85%, Keil, 1962a,b).

The highly recrystallized texture of Putinga, consisting of poorly defined chondrules and the usually xenomorphic appearance of well-crystallized groundmass olivine and pyroxene, as well as the common poikilitic intergrowths of olivine in orthopyroxene, suggest that the meteorite belongs to petrologic type 6 of Van Schmus and Wood (1967). This finding is in agreement with the work of Symes and Hutchison (1970), who also classified Putinga as a type 6 chondrite.

Origin of maskelynite

Maskelynite, first discovered in achondrites and chondrites by Tschermak (1872, 1883), is defined as the isotropic glass of plagioclase composition that formed by solid state shock transformation of plagioclase and not by fusion (Milton and De Carli, 1963). The abundant isotropic glass of oligoclase composition in Putinga is stoichiometric in composition and, thus, in the glass-forming process, volatile elements such as Na and K did not escape. Furthermore, the glass does not contain vesicles, flow structures, schlieren, or other indications of fusion, and there are no indications of eutectic melting of metallic nickel-iron and troilite, a process that would take place at about 950 °C (Kullerud *et al.*, 1969). Since formation of oligoclase glass by fusion in vacuum would probably result in the loss of some volatile elements and since shock melting of plagioclase requires temperatures of about 1500-1700 °C (Stöffler and Hornemann, 1972) and would probably result in the formation of vesicles, flow structures, etc., we conclude that the oligoclase glass in Putinga formed by solid state shock transformation rather than by fusion and, thus, the material is properly referred to as maskelynite. That shock was the cause of the transformation is further indicated by the presence in the meteorite of olivine with hour-glass type extinction (Symes and Hutchison, 1970) and common wavy extinction in mafic mineral grains, although the typical black shock veins are not observed. Such veins consist of fused olivine, pyroxene, plagioclase, metallic nickel-iron, troilite, etc. (*e.g.*, Keil *et al.*, 1977), and their absence in Putinga is further evidence for low temperatures and no fusion. We also concur with Binns (1967) and Van Schmus and Ribbe (1968) that the size of the maskelynite grains and their habit suggest that maskelynite must have formed from previously-existing, well-crystallized plagioclase and not from fine-grained, interstitial, feldspathic material. Thus, recrystallization of Putinga (*i.e.*, formation of well-crystallized oligoclase) must have preceded shock-transformation into maskelynite.

Experiments in the laboratory allow estimates to be placed on the shock pressures that may have been responsible for the formation of maskelynite in Putinga. Milton and De Carli (1963) produced maskelynite by explosion shock and solid state transformation as pseudomorphs of plagioclase in the pressure range of 250-300 kbar. At higher pressures of about 600-800 kbar, the temperature was raised considerably above the melting point of plagioclase and a glass formed by fusion. Stöffler (1972) and Stöffler and Hornemann (1972) indicate that the plagioclase solid state conversion takes place at about 300-450 kbar. In view of the apparently low temperatures (<950 °C in case of Putinga), we conclude that the maskelynite probably formed at pressures in the lower ranges of these estimates, say, between 250-350 kbar.

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