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W. R. VAN SCHMUS*

Lunar-Planetary Research Branch, Air Force Cambridge Research
Laboratories, Bedford, Massachusetts 01730

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Department of Geology

University of Kansas

Lawrence, Kansas 66045



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Abstract—Most of the Mezö-Madaras chondrite is similar to other “unequilibrated ordinary chondrites” in that the chondritic texture is excellently preserved, the olivine and pyroxene are of very heterogeneous compositions, and several of the chondrules contain primary sodium–aluminum–silicate glasses. In addition to the normal chondritic material, several fragmental inclusions of other types of chondritic material occur in Mezö-Madaras. One type, which consists of very small chondrules and silicates, sulfide, and metal in a black, opaque, carbonaceous matrix, is similar in texture to some of the Type 2 carbonaceous chondrites, although apparently not chemically equivalent. Other inclusions more closely resemble ordinary chondritic material, but the silicates show a range of equilibration and are more homogeneous than in most of Mezö-Madaras. One inclusion of this type also contains abundant secondary glass interstitial to the olivine, pyroxene and other grains.

The polymict structure in Mezö-Madaras is unlike the structure in light-dark meteorites (e.g. Pantar) and is interpreted as the result of catastrophic mixing of surface and near-surface material on the chondritic parent body during or after its formation. This mixing may have originated through either impact or volcanic processes.

INTRODUCTION

AN IMPORTANT phase in the evolution of meteorites was that of brecciation. In many instances this brecciation was followed by reaggregation of the material, so that many of the meteorites preserved in collections exhibit *monomict* or *polymict* brecciated structures (WAHL, 1952).† A detailed knowledge of the mineralogy, petrology and chemistry of such meteorites is necessary before one can begin to understand the processes that led to their formation.

WAHL (1952) presents an excellent summary of his own and earlier observations of brecciated stony meteorites. However, most of his descriptions lack the detail required for genetic interpretation of the phenomena. Recently the brecciated meteorites Pantar and Kapoeta (chondrite and achondrite, respectively) were studied in detail by FREDRIKSSON and KEIL (1963), who concluded that they were monomict breccias. SUESS, WÄNKE and WLOTZKA (1964) have disputed the validity of the term “monomict” for these stones on the basis of slight chemical differences between the light fragments and the dark matrix, and WOOD (1967) found distinct differences in the cooling rates deduced from metal particles in the light and dark portions of light-dark structured chondrites.

Several meteorites exist with very dissimilar component fragments. An excellent example is Cumberland Falls (MERRILL, 1920), which is a brecciated mixture of

* Present address: Department of Geology, University of Kansas, Lawrence, Kansas 66044.

† According to WAHL, monomict breccias are those in which the clasts are of the same material as the surrounding principal mass of the meteorite; polymict breccias are those in which the clasts or fragments are unlike the principal mass and may be unlike one another.

enstatite achondritic material with black chondritic fragments. Some meteorites also consist of chondritic fragments in a chondritic matrix, and one of these is the chondrite Mezö-Madaras.

Mezö-Madaras fell in 1852 with a total recovered weight of 22.7 kg (KNÖPFLE, 1853). Chemical analyses of Mezö-Madaras (RAMMELSBERG, 1871; JAROSEWICH, 1967; BINNS, 1967) show that this meteorite belongs to the L-Group chondrites as defined by UREY and CRAIG (1953). MEUNIER (1871) earlier noted the polymict nature of Mezö-Madaras.

KEIL and FREDRIKSSON (1964) determined that the olivine and pyroxene compositions in this chondrite are extremely variable. DODD and VAN SCHMUS (1965) further noted that Mezö-Madaras, together with several other chondrites that have variable mineral compositions, contains primary glass in several of its chondrules (TSCHERMAK, 1885). This, plus the excellent preservation of the chondritic texture, led them to conclude that Mezö-Madaras has experienced only slight metamorphism. More recently, DODD, VAN SCHMUS and KOFFMAN (1967) have performed a detailed analysis of the variability of mineral compositions in several unequilibrated ordinary chondrites, including Mezö-Madaras.

DODD, VAN SCHMUS and MARVIN (1965, 1966) discovered the new mineral merrihueite $[(K, Na)_2(Fe, Mg)_5Si_{12}O_{30}]$ in Mezö-Madaras, where it co-exists with iron-poor enstatite and fayalitic olivine. The latter two minerals are a distinctly non-equilibrium assemblage according to the data of BOWEN and SCHAIRER (1935).

EBERHARDT, EUGSTER, GEISS and MARTI (1966) and MARTI, EBERHARDT and GEISS (1966) have studied rare gases in Mezö-Madaras and report large abundances of primordial Ne, Ar, Kr and Xe relative to more recrystallized ordinary chondrites.

WOOD (1967) has studied the metal and sulfide phases in Mezö-Madaras and reports that the sulfide is nickel-free ($<0.2\%$ Ni) and that the Ni-Fe has partitioned into both kamacite ($\sim 5\%$ Ni) and taenite ($50-60\%$ Ni). WOOD interprets these data as evidence for mild, low temperature metamorphism ($300-500^\circ\text{C}$) of Mezö-Madaras.

On the basis of the general petrologic properties and lack of equilibrium, VAN SCHMUS and WOOD (1967) have placed Mezö-Madaras in their petrologic Type 3 category, and would thus refer to Mezö-Madaras as a Type 3, L-Group chondrite (L3 for short).

In the present paper are presented the results of a detailed study of the various components of Mezö-Madaras: the host or "normal" Mezö-Madaras, and three types of chondritic inclusions encountered (Figs. 1-3). The various components of Mezö-Madaras were examined petrographically and with the electron microprobe. In the course of the work several microprobe thin-sections were used and these will be referred to as No. 2, 3, 4 or 5 in the text, tables and figures. "Normal" Mezö-Madaras is considered to be the host material as shown in parts of Figs. 1 and 3: chondrules and silicates, nickel-iron, troilite, and matrix, without any inclusions of chondritic fragments.

ANALYTICAL TECHNIQUES

Unless otherwise noted, all data reported or referred to were taken by the author using an Applied Research Laboratories (ARL) Model EMX microprobe at the Department of Geology, University of California, Los Angeles. The microprobe was operated with a 15 kV accelerating

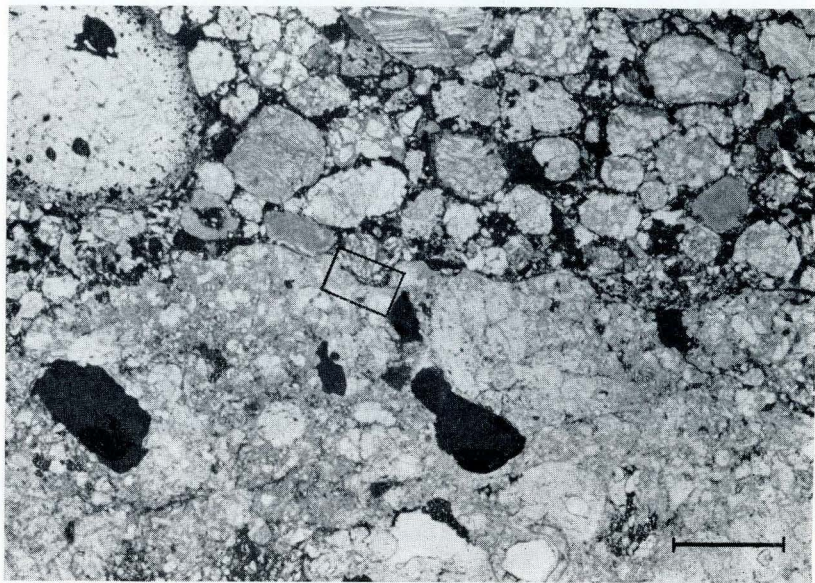


Fig. 3. A photograph of part of section No. 5. The lower part of the picture shows inclusion C, which is imbedded in chondrules of "normal" Mezö-Madaras (upper). Note the rounded geometry of the metal-troilite masses (black) in the inclusion. Scale bar 1.0 mm. The small rectangle outlines Fig. 6.

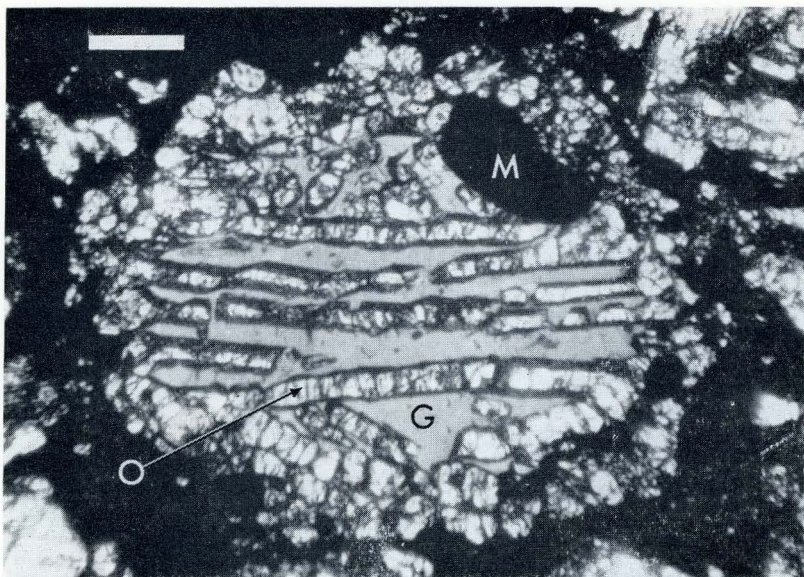
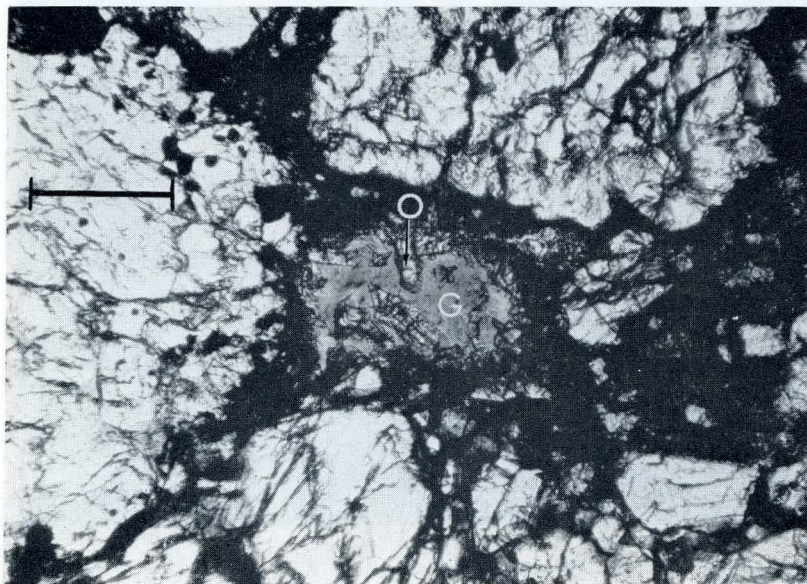
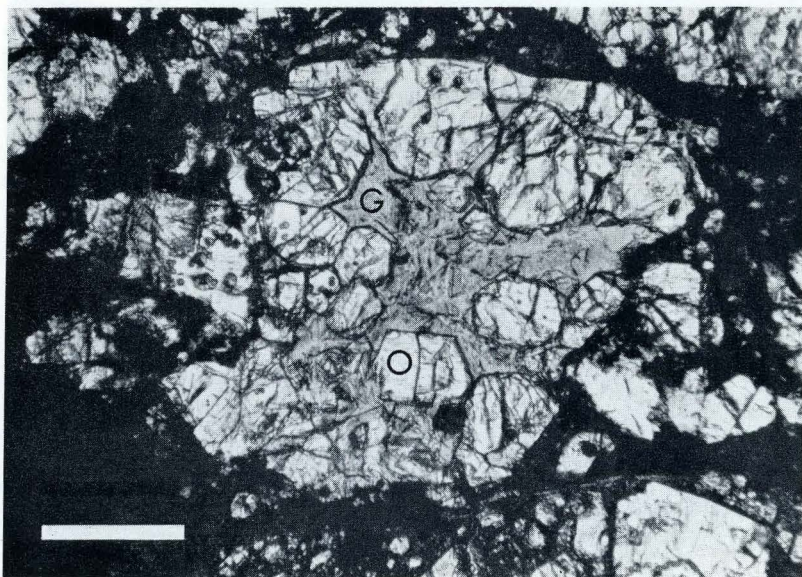


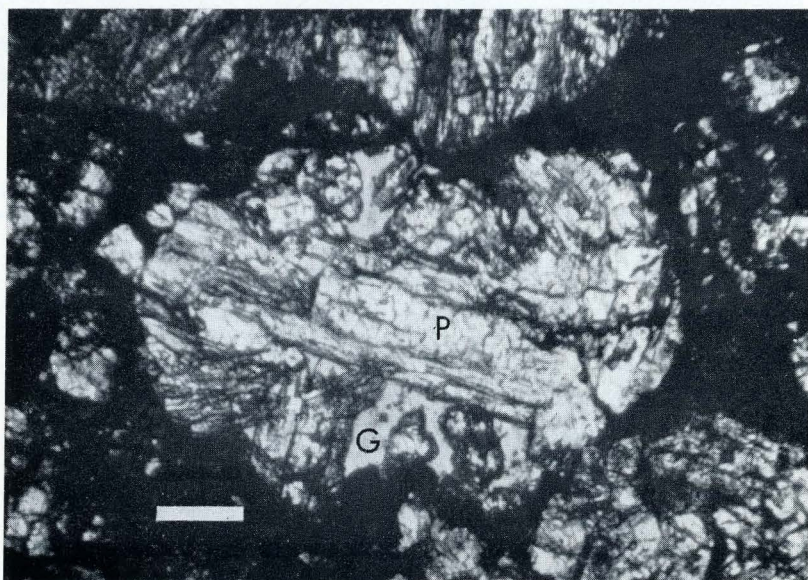
Fig. 4. Photographs of four glass-bearing chondrules.
 (a) Chondrule No. 4/1. The olivine is low in iron (1-2 mole % Fe_2SiO_4) and the glass is rich in sodium and aluminum (Table 4).



(b) Chondrule No. 4/4. The olivine crystals contain 28-30 mole % Fe_2SiO_4 ; crystallites of Fe-poor (<1% Fe) diopside also occur in the chondrule.



(c) Chondrule No. 4/8. The olivine ranges from 4–8 mole % Fe_2SiO_4 .



(d) Chondrule No. 5/7. Monoclinic low-calcium pyroxene predominates in this chondrule. The pyroxene contains 12–20 mole % FeSiO_3 and 1–10 mole % CaSiO_3 . The glass composition is given in Table 4.
 O = olivine; P = pyroxene; G = glass; M = metal. Scale bars are 0.1 mm long.

voltage and a specimen current of 0.03 μ A was used. All data were corrected for back-ground and instrument dead-time.

The iron concentrations reported for olivine and pyroxene were calculated using an empirical calibration curve determined from chemically analysed natural olivines and pyroxenes. The corresponding mole per cent fayalite (Fe_2SiO_4) or ferrosilite (FeSiO_3) values reported were calculated from the wt. % iron in the olivine or pyroxene, respectively, by assuming the difference to be the magnesium end members (i.e. forsterite— Mg_2SiO_4 ; enstatite— MgSiO_3). The small amount of other cations (e.g. Mn, Ca, Cr, Ti), which are usually less than 2% of the total, introduce little significant error for the purposes of this paper.

Analyses of the glass phases presented special problems due to the loss of sodium from the analysed spots during analyses. In the case of only Fe–Mg–Ca values reported for glasses (Table 3), simple spot analyses were made. The error introduced in these values due to the loss of sodium during the analysis is small ($\sim 10\%$ or less) and in view of the low concentrations of these elements, considered negligible.

For the more complete analyses (Table 4) other methods were used. The spot size of the electron beam was enlarged to $\sim 5 \mu$ in order to minimize heating effects at the analyzed point, and the sample was moved under the beam, in order to further minimize the effect of heating at the analyzed point.

Both natural albite and synthetic albite glass were used as standards for sodium. Under comparable conditions, both the meteoritic glass and the albite glass exhibited similar instabilities during analysis, but natural crystalline albite was stable. Consequently, the sodium concentrations in the meteoritic glass were calculated from intensity ratios determined using the albite glass as the reference standard rather than using crystalline albite as the reference standard (the data indicated that sodium K_{α} X-ray intensities obtained from glasses were diminished by 15–20% due to the volatility of sodium).

The data were corrected using the formula of PHILBERT (1963) as modified by DUNCOMB and SHIELDS (1964), and the mass absorption coefficients of HEINRICH (1964) to correct for mass absorption effects. Based on the fluorescence correction formulas of WITTRY (1962), this effect is negligible for the silicates analyzed. Since silicate standards were used for analysis of silicate phases, the "atomic number effect" was also considered negligible. In the case of the glasses, an uncertainty is introduced into the correction factors due to other elements present (e.g. K, Cr, Ti, Mn). However, these elements account for less than 10% (usually less than 5%) of the total. As a result, the error introduced into the correction factors by the incomplete analyses is considered negligible compared to other uncertainties in theoretical microprobe corrections and errors introduced due to the instability of the glasses.

Probable errors in the analyses are estimated to be no greater than 10% of the amount present for all elements.

"NORMAL" MEZÖ-MADARAS

A. Petrologic and mineralogic description

A wide variety of chondrules occur in Mezö-Madaras, and all the common types (porphyritic, radiating, barred, glassy) are represented. Subhedral to euhedral olivine and pyroxene predominate in the chondrules. The pyroxene is typically a low-calcium, polysynthetically twinned clinoenstatite to clino-hypersthene. Normal igneous zoning (Fe-poor centers and Mg-poor edges) is common in the olivine and pyroxene crystals and undoubtedly represents non-equilibrium crystallization of these minerals during their crystallization from the chondrule melts.

The material interstitial to the olivine and pyroxene in most of the chondrules consists of very fine grained or fibrous crystals, presumably olivine, pyroxene, or plagioclase; this material probably represents the devitrification or fibrous crystallization of the residual melts that resulted within the chondrules during their cooling and crystallization. In several chondrules of this chondrite, however, the interstitial

melt did not crystallize nor did it subsequently devitrify so that it is still preserved as an isotropic glass. Examples of four glass-bearing chondrules are shown in Figs 4a-d. This glass is a "primary igneous glass" as opposed to glasses which may have been formed by later shock processes ("shock glasses").

Most of the metal and sulfide in this chondrite occur outside the silicate chondrules as particles in the matrix or as metal-sulfide droplets; the metal and sulfide are usually intermixed with one another. Some of the metal and sulfide occur within chondrules, either as spheroidal droplets that suggest solidification of the metal before the silicates or as interstitial networks that suggest solidification of the metal after the silicates, so that at least part of the metal and sulfide in Mezö-Madaras are co-genetic with the silicates. This is in accordance with recent conclusions by other workers (e.g. KEIL and FREDRIKSSON, (1964); WOOD, 1967; REID and FREDRIKSSON, 1967).

The matrix of Mezö-Madaras includes fine grained ($<10\mu$ dia.) silicates, metal and sulfide. This chondrite has a significant carbon content (0.46%, MOORE and LEWIS, 1967) and it is assumed that this carbon is predominately in the matrix.

B. Microprobe data on "normal" Mezö-Madaras

DODD, VAN SCHMUS and KOFFMAN (1967) performed two surveys of the olivine and pyroxene compositions in Mezö-Madaras. For reasons given below, only the second survey (their analysis "Mezö-Madaras B") may be considered representative of "normal" Mezö-Madaras; their data from this survey are shown in Fig. 5 and listed in Table 1. As can be seen from these data, Mezö-Madaras has definite modes in both the olivine and pyroxene distributions, and their respective mean deviations

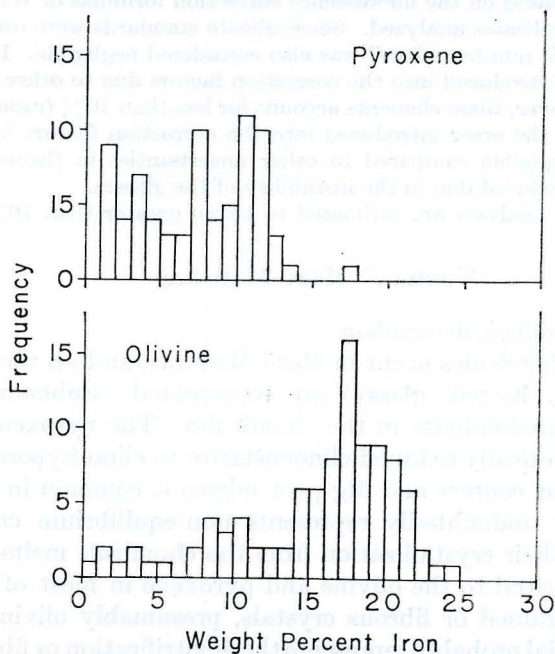


Fig. 5. Histogram (in number of grains analyzed) of olivine and pyroxene in a sample of "normal" Mezö-Madaras. Unpublished data from the work of DODD, VAN SCHMUS and KOFFMAN (1967; their Mezö-Madaras "B" data).

Table 1. Comparison of microprobe data on Mezö-Madaras components

	Olivine				Pyroxene			
	No.(1)	%MD(2)	$\overline{\text{Fe}}^{(3)}$	$\overline{\text{Fa}}^{(4)}$	No.(1)	%MD(2)	$\overline{\text{Fe}}^{(5)}$	$\overline{\text{Fs}}^{(6)}$
1. "Normal" Mezö-Madaras ⁽⁷⁾ (Section No. 2)	99	28	15.7	21.7	75	44	7.5	14.1
2. Section No. 3 ⁽⁷⁾ (Total)	97	15	17.5	24.5	70	26	8.6	16.3
3. "Normal" Mezö-Madaras ⁽⁸⁾ (Section No. 3)	48	23	16.8	23.3	35	38	8.6	16.2
4. Inclusion B ⁽⁸⁾ (Section No. 3)	38	5.3	18.0	25.1	21	12	10.1	19.3
5. Inclusion C (Section No. 5)	18	2.6	17.4	24.3	5	4.8	10.1	19.3

(1) No. = number of grains analyzed.

(2) %MD = per cent Mean Deviation (DODD, VAN SCHMUS and KOFFMAN, 1967).

(3) $\overline{\text{Fe}}$ = average wt. % iron in olivine.

(4) $\overline{\text{Fa}}$ = average mole % fayalite (Fe_2SiO_4).

(5) $\overline{\text{Fe}}$ = average wt. % iron in low-Ca pyroxene.

(6) $\overline{\text{Fs}}$ = average mole % ferrosilite (FeSiO_3).

(7) From DODD, VAN SCHMUS and KOFFMAN (1967).

(8) See text.

(28 and 40%) are somewhat less than those found by DODD *et al.* for the most heterogeneous chondrites. A possible conclusion from this is that Mezö-Madaras is slightly more metamorphosed than chondrites such as Bishunpur and Hallingeborg. However, these differences could also reflect primary differences in unaltered chondritic material that formed these chondrites.

Because of the manner in which the survey data of DODD *et al.* were obtained, little information was available on olivine and pyroxene compositions in relation to chondrule types. In order to fill this gap olivine and pyroxene were analyzed in thirty-seven random chondrules from thin section No. 2, and twenty-three selected glass-bearing chondrules from sections Nos. 2, 4 and 5. The data are presented in Tables 2 and 3 respectively. For many of the chondrules in Tables 2 and 3 the data on the olivine and pyroxene are only approximate (only $\pm 20\%$ accuracy) because of zoning in individual crystals and variations from one crystal to another within many chondrules. Such uncertainties will not, however, affect the conclusions based on these data.

In general there appears to be little connection between chondrule type (barred porphyritic, etc.) or size and the olivine composition for the chondrules studied (Table 2), although the olivine and pyroxene in the glass-bearing chondrules (Table 3) are on the average less ferrous. The glass-bearing chondrules analyzed in this study average 7.9% Fe in their olivine whereas the chondrite ("normal") as a whole averages 16% Fe in the olivine (Table 1). Furthermore, the olivine compositions in the glass-bearing chondrules do not yield the mode present in the overall chondrite analysis (Fig. 5).

Table 2. Data on random chondrules; section No. 2

Chondrule	Type ⁽¹⁾	Size ⁽²⁾ (mm)	Olivine		Pyroxene		Assemblage ⁽³⁾
			$\overline{\text{Fe}}$	$\overline{\text{Fa}}$	$\overline{\text{Fe}}$	$\overline{\text{Fs}}$	
A	XLN	2.6	17.6	24.6	11.2	21.4	CPX, OL, MT, MXL
B	POR	0.9	7.8	10.3	5.5	10.1	OL, CPX, MXL, DI?
C	AGG	0.7	5.1	6.6	3.0	5.5	OL, PX, MT
D	POR	0.2	17.5	24.4	4.7	8.7	CPX, OL*, MXL
E	POR	0.9	14.5	19.9	—	—	OL, PX?, MXL
F	IXL	(0.2)	0.4	0.5	—	—	OL
G	POR	(0.4)	15.9	22.1	—	—	OL, MXL
H	POR	0.3	17.3	24.2	6.8	12.8	CPX, OL*, MXL
J	XLN	0.9	16.5	22.8	—	—	OL, MXL, MT
K	XLN	0.2	19.8	28.0	4.4	8.1	OL, CPX, G, MT
L	POR	0.4	10.1	13.5	2.0	3.5	OL, CPX, MXL, MT
M	POR	0.7	9.2	12.2	2.0	3.5	CPX, OL*, MXL
N	BAR	1.1	1.0	1.3	—	—	OL, G
P	POR	0.5	17.6	24.6	10.7	20.4	OL, CPX, MXL
Q	POR	0.4	1.9	2.4	1.0	1.9	CPX, OL*, MT, G
R	POR	(0.3)	9.4	12.4	2.0	3.5	CPX, OL*
S	POR	(0.3)	15.9	22.1	—	—	OL, MXL
T	POR	(0.2)	—	—	3.3	6.0	CPX, OL, MXL
U	POR	0.3	18.7	26.5	—	—	OL, MLX, MT
V	RAD	(0.5)	—	—	8.1	15.2	PX, MXL
W	POR	0.4	8.6	11.6	—	—	OL, MXL, MT
X	—	—	15.1	20.7	3.9	7.2	—
Y	POR	0.6	20.7	29.5	—	—	OL, MXL, MT
Z	POR	0.9	4.2	5.5	—	—	OL, MXL
AA	POR	0.5	18.7	26.5	10.1	19.2	OL, PX, MXL
AB	AGG	0.6	7.5	9.8	1.8	3.2	OL, PX, DI?, MXL
AC	POR	0.2	7.1	9.2	3.3	6.1	CPX, OL*, MXL
AD	XLN	0.9	—	—	2.4	4.3	CPX, OL*, MXL
AE	POR	0.7	8.7	11.7	—	—	OL, G, MXL, MT
AF	XLN	0.8	10.0	13.4	5.7	10.5	OL, PX, MXL
AG	XLN	(0.9)	18.6	26.2	10.7	20.4	OL, PX, MXL
AH	XLN	0.4	16.7	23.2	10.4	19.8	OL, PX, MXL
AJ	XLN	(0.3)	16.8	23.4	—	—	OL, MXL
AK	POR	0.4	17.1	24.1	—	—	OL, MXL, MT
AL	POR	0.6	2.4	3.1	—	—	OL, G, MT
AM	POR	(1.0)	16.9	23.4	—	—	OL, MXL
AN	XLN	1.1	10.7	14.3	—	—	OL, MXL

(1) AGG: Aggregate of small grains; apparently never molten.

BAR: Barred olivine chondrule.

POR: Porphyritic; grossly dissimilar crystal sizes.

RAD: Radiating pyroxene.

XLN: Crystalline; most crystals of comparable sizes.

IXL: Single crystal.

(2) Size in mm as observed in thin section; only a minimum size. Parentheses mean that the "chondrule" is actually a fragment of a larger chondrule.

(3) OL: Olivine; OL*: Olivine poikililitically enclosed in pyroxene.

PX: Pyroxene.

CPX: Polysynthetically twinned pyroxene (low-Ca, monoclinic).

DI: Diopside; (Fe, Mg) Ca Si₂O₆.

MXL: Microcrystalline.

MT: Metal-Troilite present within chondrule.

G: Glass (isotropic).

Table 3. Average phase compositions in glass-bearing chondrules

Chondrule	Olivine		Pyroxene		Glass		
	%Fe ⁽¹⁾	Fa ⁽²⁾	%Fe ⁽¹⁾	Fs ⁽³⁾	%Fe ⁽¹⁾	%Mg ⁽¹⁾	%Ca ⁽¹⁾
2/1	1.0	1.3	—	—	1.4	0.0	0.0
2/2	—	—	0.9	1.7	0.6	0.1	0.0
2/4	18.9	26.9	—	—	nd	nd	nd
2/5	8.1	10.8	—	—	6.0	4.9	3.4
2/6	2.9	3.8	—	—	1.8	1.5	1.6
2/7	18.6	26.1	2.5	4.7	nd	nd	nd
2/8	2.1	2.7	—	—	0.9	0.1	0.0
4/1	1.5	2.0	—	—	2.0	0.5	0.1
4/2	15.9	21.9	—	—	nd	nd	nd
4/4	20.6	29.3	—	—	1.8	1.2	1.3
4/5	12.8	17.3	—	—	nd	nd	nd
4/6	1.6	2.1	—	—	0.8	0.0	0.0
4/7	2.7	3.5	—	—	0.5	1.0	0.7
4/8	3.6	4.7	—	—	2.4	3.1	2.7
4/9	—	—	17.6	35.0	1.8	0.3	0.6
4/10	4.1	5.3	—	—	2.1	2.3	1.9
4/11	2.4	3.1	—	—	nd	nd	nd
5/3	—	—	4.7	8.7	1.0	0.9	1.6
5/4	18.1	25.3	—	—	1.9	0.6	0.6
5/5	2.4	3.1	—	—	0.8	0.1	0.1
5/6	5.9	7.7	—	—	1.1	0.0	0.0
5/7	—	—	6.4	11.0	0.7	0.6	0.1
5/8	6.7	8.8	4.2	7.8	0.6	0.0	0.0

⁽¹⁾ Weight per cent, nd = not determined.

⁽²⁾ Fa = mole % fayalite = Fe/(Fe + Mg).

⁽³⁾ Fs = mole % ferrosilite = Fe/(Fe + Mg).

One important result from the data in Table 3 is that real glasses do not occur only in reduced chondrules as has been suggested by FREDRIKSSON and REID (1965) and REID and FREDRIKSSON (1967). Several of the chondrules listed in Table 3 contain up to 30 mole% Fe₂SiO₄ in the olivine, yet they also contain water-clear, pink to purple, fully isotropic glass. Furthermore, it would appear that these glasses are generally iron-poor, although insufficient data are available to make this conclusion firm.

A qualitative check was made on apparent grain size vs. composition for individual olivine and pyroxene crystals and this showed that, *within a single chondrule*, the smaller grains are more iron-rich than the larger grains. However, since some of the small grains may represent sections of edges of larger crystals, and crystal edges are usually more iron-rich, part of this correlation may be artificial. This relative relationship only holds when comparing grains from the same chondrule, because some chondrules have only iron-poor crystals (all sizes) and others only iron-rich crystals (all sizes).

The lack of a correlation between olivine composition and chondrule size as noted above is in contrast to the results obtained by KEIL *et al.* (1964) on the Chainpur meteorite. They found that the smaller chondrules contained, on the average, olivine poorer in iron than in the larger chondrules. The difference between their results and these on Mezö-Madaras could be the result of the fact that KEIL *et al.* measured the chondrule sizes on disaggregated chondrules, whereas I used a thin section and am not recording true chondrule size. On the other hand, this difference could reflect real variations in the type of accreting material.

Also presented in Table 3 are partial analyses (Fe–Mg–Ca) of the glass in many of the glass-bearing chondrules. From these data it may be seen that these three elements are quite low in concentration in the glasses. In Table 4 are presented the

Table 4. Partial analyses of glasses in Mezö-Madaras

	Mezö-Madaras ⁽¹⁾				Chainpur ⁽²⁾
	A	B	C	D	
SiO ₂	50.4	63.0	72.3	63.9	64.0
MgO	0.0	0.1	1.0	3.9	5.4
FeO	1.8	1.0	0.9	2.2	2.7
Al ₂ O ₃	25.7	20.9	14.4	14.5	15.7
CaO	0.0	0.1	0.2	5.5	1.7
Na ₂ O	15.7	10.5	7.6	7.4	8.0
Total	93.6	95.6	96.4	97.4	97.5

⁽¹⁾ Glass A from a barred olivine chondrule (Fig. 4a, and No. 2/1, Table 3).

Glass B from a barred olivine chondrule (No. 5/5, Table 3).

Glass C from a porphyritic pyroxene chondrule (Fig. 4d, and No. 5/7, Table 3).

Glass D from Inclusion C (Fig. 6).

⁽²⁾ FREDRIKSSON and REID (1965); also contains K₂O = 1.0, TiO₂ = 0.8, CoO = 0.3, Cr₂O₃ = 0.5, MnO = 0.2.

results of more complete analyses of the glass in three of the chondrules from Table 3, a fourth glass to be discussed later, and the composition of a glass from the Chainpur chondrite as reported by FREDRIKSSON and REID (1965). From the data in Tables 3 and 4 it is apparent that the primary glasses in chondrules are usually, if not always Fe–Mg–Ca-poor sodium–aluminum–silicate glasses. Sodium and aluminum appear always to occur in nearly equal amounts (atomic), but the (Na + Al) to Si ratio may vary considerably, with the result that normative compositions of the glasses range from greatly undersaturated (~60% normative nepheline in glass A) to oversaturated (~20% normative quartz in glass C). Such glasses are not “mafic” or “basaltic” as has been assumed by some authors (e.g. WOOD, 1963a; DODD and VAN SCHMUS, 1965).

From published data on the system forsterite–silica–nepheline (SCHAIRER and YODER, 1961) and the system fayalite–albite (BOWEN and SCHAIRER, 1936) it can be seen that the compositions of the glasses found in the chondrules are appropriate to residual melts in these systems, indicating that essentially all the normative olivine and/or pyroxene crystallized, but that the chondrules cooled rapidly enough to

prevent crystallization of the residual melts into their normative components (nepheline + albite or albite + silica, depending on the bulk composition of the chondrules). Since such soda-alumina-silica melts are very viscous, they crystallize very slowly in a dry system at low pressure (SCHAIRER and BOWEN, 1956). The previously used argument that the presence of glass in chondrules indicates very rapid (seconds or minutes) quenching of the once molten chondrules (e.g. WOOD, 1963a) seems no longer valid; the glasses alone could be consistent with longer cooling times. Therefore, REID and FREDRIKSSON (1967) were partially correct in stating that composition of chondrules determines whether glass forms in chondrules. The critical parameter appears to be the amount of sodium and aluminum present in the chondrule however, rather than the absence of oxidized iron. Even if oxidized iron is present, glass will still form: the FeO combines with SiO₂ to form olivine or pyroxene, leaving behind a residual melt rich in sodium and aluminum and which is easily solidified to a glass.

CHONDRITIC INCLUSIONS

A. *Inclusion A (black inclusion)*

The first of the chondritic inclusions is shown in Fig. 1, which is a photomicrograph of part of section No. 4 used in this study. The inclusion is about 4 mm long and consists of small, fine-grained chondrules and fragmental silicates, nickel-iron particles and droplets, troilite, and a very fine-grained, unresolvable matrix. The overall appearance of this inclusion in transmitted light resembles that of Murray, a Type 2 carbonaceous chondrite (WOOD, 1963b, Plate 6a).

Microprobe analyses by the author show that the silicate phases in inclusion A are fine-grained olivine and pyroxene having variable compositions (4–20 mol. % iron-silicates). Qualitative analysis on the matrix yields definite presence of carbon in the range of 1–4%. * Spot analyses on the metal and sulfide show that the kamacite contains ~4.5% Ni, the taenite contains 40–50% Ni, and that the sulfide is Ni-free (<0.1% FeS).

SCHMITT, SMITH and GOLES (1965) have presented data which show that the carbonaceous chondrites (Types 2 and 3) are depleted by about a factor of 2 in Na and Mn relative to ordinary chondrites. Furthermore, it has long been recognized (UREY, 1961; DU FRESNE and ANDERS, 1962) that the carbonaceous chondrites have higher Mg:Si ratios than the ordinary chondrites. In view of these observations, semi-quantitative microprobe analyses were made for Fe, Si, Mg, Na and Mn in the black inclusion relative to ordinary chondrites and carbonaceous (Type 3) chondrites. This was done by using an expanded electron beam (100–150 μ dia.) and by continuously moving the sample under the beam in order to obtain integrated data on these elements. The analyses were of 100-sec duration and several analyses were taken on each sample as required to get representative data. Such data are certainly subject to numerous errors and can only yield semi-quantitative results at best.

* The carbon analysis was made on an ARL-EMX microprobe at the Division of Meteorites, U.S. National Museum, through the courtesy of K. FREDRIKSSON and with the assistance of C. FIORI.

By using other meteorite samples as "standards",* some meaningful comparisons can be made: (1) The Mn abundance in the black inclusion of Mezö-Madaras is comparable to that in ordinary chondrites and about 50% greater than that in carbonaceous chondrites. (2) Na appears depleted (by ~30%) relative to ordinary chondrites but more abundant (by ~50%) than in Types 2 and 3 carbonaceous chondrites. (3) Fe appears to be present in amounts comparable to that in the carbonaceous chondrites (Fe:Si ~20% greater than in ordinary low-iron chondrites). (4) The Mg:Si relationships appear to be more similar to the carbonaceous chondrites than the ordinary chondrites, but the diagnostic difference is only 5-10%, relative, and the data are not good enough to make this conclusion firm. All of these conclusions need to be checked with analyses of other inclusions of this type. On the basis of the available data, however, this inclusion appears to have a greater chemical similarity to carbonaceous chondrites than to ordinary chondrites, although it cannot be definitely placed with either.

FREDRIKSSON and his co-workers (personal communication) are doing a more exhaustive investigation on a similar, but larger, inclusion from Sharps, which is a Type H3 chondrite. Similar inclusions have also been observed by the author in samples of several other chondrites, including Tensasilm (L4)†, Bremervörde (H3)†, and Cynthiana (L4)†. Clearly this type of inclusion is not unique and contains valuable clues to the origin and evolution of chondrites.

B. Inclusion B

A second, more common type of inclusion is shown in Fig. 2; illustrated is one of the two pieces of Mezö-Madaras on the microprobe section (Section No. 3) used by DODD, VAN SCHMUS and KOFFMAN (1967) for their first survey analysis of Mezö-Madaras (their "Mezö-Madaras A" data). The aggregate data for "Mezö-Madaras A" are also listed in Table 1; from comparison with the "Mezö-Madaras B" data it can be seen that the former has considerably less variability in its olivine and pyroxene than does the latter. Petrographic examination of the microprobe section shows a subtle, but real, difference in the character of part of one of the two meteorite chips used to make the slide. Part of that chip has less matrix, and a sharp contact may be observed within it (Fig. 2).

The co-ordinates of the original data points for section No. 3 were plotted and superimposed on a photo of the sample. As a result, it was possible to separate those points due to the inclusion and those due to the "normal" Mezö-Madaras. The mean deviations for the olivine and pyroxene were then recomputed separately for "normal" Mezö-Madaras and for the inclusion: the results are presented in Table 1. It is readily apparent that the lower per cent mean deviations reported for "Mezö-Madaras A" by DODD, VAN SCHMUS and KOFFMAN (1967) are the result of the composite nature of the section used.

* H-Group: Estacado; L-Group: Carraweena, Cynthiana, Mezö-Madaras, Tensasilm; LL-Group: Varvik; C-Group: Vigarano, Karoonda, Mokoia. Unfortunately I did not have access to a section of Murray, so the best comparison is not available at this time.

† Classified according to VAN SCHMUS and WOOD (1967).

Petrographically, inclusion B is very similar to the chondrites studied by DODD, VAN SCHMUS and KOFFMAN (1967) which have relatively lower mean deviations (3–6%) for olivine (e.g. Carraweena). The chondrules are all very well preserved and show only slight evidence of recrystallization (though more than in “normal” Mezö-Madaras). The pyroxene is mostly clino-bronzite, and turbid, partially devitrified glass is occasionally found. The opaque matrix material appears less abundant and the matrix appears slightly coarser-grained than in “normal” Mezö-Madaras.

A similar inclusion also comprises the bulk of one of the samples of Mezö-Madaras in the collection of the British Museum of Natural History (No. 33909). G. KURAT (personal communication) states that the olivine and pyroxene in this inclusion are almost uniform in composition: the olivine averages 17.7 wt.% Fe (~ 25 mol.% Fe_2SiO_4) and the pyroxene averages 10.3 wt.% Fe (~ 20 mol.% FeSiO_3). Descriptions of this material are in preparation by KURAT and also by R. A. BINNS (personal communication).

C. Inclusion C

The third type of inclusion encountered in this study is shown in Fig. 3; the inclusion is the lower portion of this figure and is distinguished from “normal” Mezö-Madaras by its much less distinct chondritic texture. The individual chondrules within the inclusion have reacted considerably with the surrounding material, although they are still easily recognized, and within the inclusion there is no black, opaque matrix between chondrules. Microprobe data on olivine and pyroxene within the inclusion (Table 1) show that these minerals are nearly uniform in composition, although small variations are present. The average values of 24.3 and 19.3 mole% $\text{FeO}:(\text{FeO} + \text{MgO})$ for olivine and pyroxene respectively are quite appropriate for crystallized L-Group chondrites.

Other characteristics of this inclusion are not in accord with simple recrystallization, however. Throughout this inclusion the silicate material interstitial to the olivine and pyroxene grains is not well-developed plagioclase (or maskelynite) or microcrystalline material as is the case in chondrites with true recrystallization textures. In this inclusion the interstitial material is slightly turbid but nonetheless isotropic glass. This interstitial glass is shown in Fig. 6 and its composition is given in Table 4. The composition of this glass is not unlike the primary glass found in some unaltered chondrules (above) and it is probably also representative of the composition of the early appearing liquid resulting from partial fusion of silicate assemblages of chondritic composition. This latter remains to be verified experimentally, but the available relevant phase equilibria data (SCHRAIRER and YODER, 1961; above) support this possibility.

The morphology of the metal-sulfide particles is quite unlike that in either Mezö-Madaras as a whole or in truly recrystallized material. In the former case the metal and sulfide occur in smaller particles or grains resembling ragged droplets; in the latter case the metal and sulfide are interstitial to the silicate grains. In inclusion C the metal-sulfide phases occur as relatively large ovoid masses (Fig. 6), such as one might expect to prevail in two immiscible liquids (e.g. metal in silicate). The Fe-Ni is differentiated into both the α (kamacite) and γ (taenite) phases.

In view of the overall characteristics of inclusion C, a reasonable interpretation of the data is that this fragment is a quenched portion (fragment) of chondritic material which was partially molten at the time of its disruption, and which was later subjected to metamorphism or annealing. The significant FeO, MgO and CaO content of the glass (Table 4) would indicate temperatures somewhat above the olivine-pyroxene-albite eutectic ($\sim 1100^{\circ}\text{C}$ in a dry system at low pressure). The globular shapes of the metal and sulfide would also be in accord with this high temperature since the Fe-Ni-S eutectic occurs about 950°C (KULLERUD, 1963) with the result that these phases could easily coalesce. The quench is necessary to preserve both the metal-sulfide segregation morphologies and the glass. The fact that the Fe-Ni is now in two phases requires that the fragment has been subjected to mild metamorphism ($300\text{--}500^{\circ}\text{C}$) subsequent to the quenching of the fragment (the quenching alone would have produced a more homogenous Fe-Ni phase).

An alternative possibility is that the partial fusion into glass was produced by shock, and that the inclusion represents a fragment of shocked chondritic material. Although shock cannot be ruled out, the morphology of the metal and sulfide phases do not seem to be in accord with this; shock usually produces veining. Furthermore, the textures in the inclusion do not appear to be those of shock (blackening, brecciation) but rather, more like those of thermal alteration (recrystallization).

In either case the interstitial glass is considered to be a *secondary* glass, i.e. one which formed after accretion of the primary chondrules and chondritic debris.

If it is assumed that this chondritic material was initially similar to unmetamorphosed chondritic material in general (e.g. "normal" Mezö-Madaras), then the near-homogenous olivine and pyroxene compositions in inclusion C are due to approaching equilibration at high temperatures.

D. *Pseudo-polymict features*

In addition to true polymict structure such as described above, there are also some features in Mezö-Madaras which look like polymict structure but, in fact are not.

The most obvious "pseudo-polymict structure" I have observed is exhibited by the specimen in the Ninger Collection, Arizona State University (Fig. 7). Upon close inspection, the two-toned nature of this sample proved to be nothing more than differential iron staining. No difference was detected in the petrologic character of the lighter and darker portions, and in many instances the light-dark boundary crossed individual chondrules. Whether this is a pre-terrestrial effect or not is unknown. Professor J. GEISS (personal communication) has observed similar features on samples of Mezö-Madaras he has studied for their rare gas contents, but reports that the primordial gas abundances are the same (i.e. very abundant, EBERHARDT *et al.*, 1966) in both types of material, thus confirming the above observation.

DISCUSSION

The data presented above indicate that the formation of Mezö-Madaras was more complex than simple deposition of chondrules onto the surface of a parent body. No mechanism is proposed for chondrule formation but subsequent to production of chondrules, the following sequence of events could have produced Mezö-Madaras:

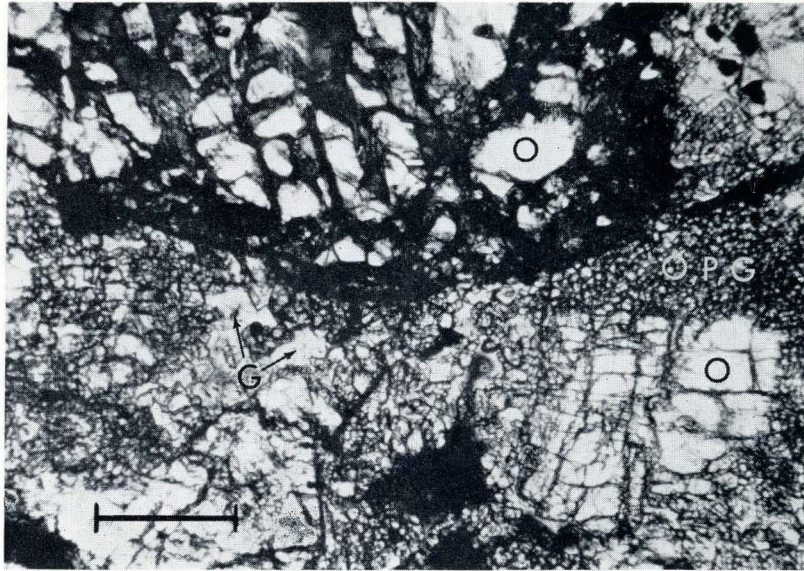


Fig. 6. High magnification photo of part of section No. 5 (see Fig. 3). The lower part of the photo shows the crystals of olivine (O) and pyroxene (P) with interstitial glass (G) in inclusion C. The upper part of the photo is part of a barred-olivine chondrule from "normal" Mezö-Madaras. Scale bar 0.1 mm.

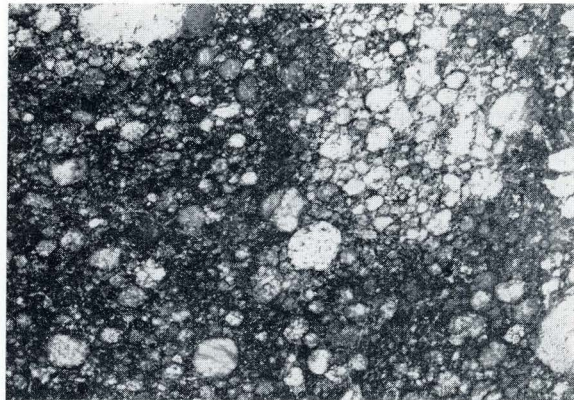


Fig. 7. Photograph of the Arizona State University (Nininger Collection) sample of Mezö-Madaras showing a two-toned coloring due to differential iron staining. This is not a true polymict structure. Illustration is approximately 3 cm long.

1. The chondritic portion of the parent body of Mezö-Madaras formed by deposition of chondrules and their fragments, metal-sulfide droplets and fragments, and "dust". The chondrules immediately upon deposition probably resembled these found today in the most unequilibrated ordinary chondrites such as Tieschitz or Bisunpur (DODD, VAN SCHMUS and KOFFMAN, 1967) with extremely variable olivine and pyroxene compositions and primary glass in many chondrules.

2. As a result of local and/or regional heat sources large regions of the parent body approached temperatures on the order of 800–1200°C. This resulted in local and/or regional metamorphism of the primary chondritic debris with consequent homogenization of olivine and pyroxene, recrystallization, and in the regions of higher temperatures, partial melting of the silicates. The heat within the parent body for this step could have come from uniformly distributed short-lived radio-nuclides in the case of regional heating (as proposed by FISH, GOLES and ANDERS, 1960), from the gravitational energy released during the accretion process (UREY, 1964) or subsequent collisions, or residual heat from the processes of chondrule formation.

3. During or shortly after the development of the hot regions, and before equilibrium cooling had occurred, portions of the surface of the parent body were subjected to major disruptions which mixed chondritic material from various initial depths in the body. These disruptions could have been caused by either (a) impact of other meteoritic or cosmic debris upon the newly formed parent body, or (b) internally generated explosive processes, due to the release of high volatile pressures.

4. After re-accumulation of the chondritic debris, enough heat was available to continue mild metamorphism, followed by full cooling of the body and the breakup of the parent body.

The various characteristics of Mezö-Madaras described above may be readily accounted for by this model.

Inclusion C may be considered to be a sample of indigenous chondritic material from a hot region in which partial melting had occurred. The interstitial, secondary glass in this fragment represents the molten part of the silicate at the time of disruption and was preserved because of quenching during ejection from the hot environment. Similarly, the ovoid geometry of the metal-sulfide masses represents quenching of their form, that form being the result of their immiscibility in the partially molten silicate. The near uniformity of the olivine and pyroxene could be the result of equilibration under high temperature prior to disruption.

Inclusion B also represents chondritic material that was subjected to thermal metamorphism prior to disruption. It was not heated to the degree that inclusion C was, as shown by the lack of extensive recrystallization or partial melting in inclusion B. The greater uniformity of the olivine and pyroxene compositions in this inclusion relative to "normal" Mezö-Madaras was the result of partial metamorphism.

Inclusion A is so unlike the rest of Mezö-Madaras that no firm conclusion can be made on its origin. If the parent body had a surficial layer composed primarily of dust, such as proposed by FISH, GOLES, and ANDERS (1960) or RINGWOOD (1966), then Inclusion A might represent a fragment of this material that fell back into the other debris. Or, it could be a fragment of unlike chondritic material from an impacting body.

The fact that most of Mezö-Madaras is composed of individual chondrules indicates that the bulk of the material was individual chondrules at the time the inclusions were incorporated. The individual chondrules could easily be of at least three types in this model:

(i) Primary, unaltered chondrules. Glass has been preserved and no olivine-pyroxene compositional homogenization has occurred.

(ii) Primary, but altered, chondrules. This could account for the fact that some chondrules (e.g. merrihueite-fayalite-enstatite chondrules; DODD, VAN SCHMUS and MARVIN, 1966) show definite evidence for reaction and alteration prior to final agglomeration. Such chondrules could have come from "warm" regions or could be the result of alteration in the solar nebula prior to accretion (e.g. LARIMER and ANDERS, 1967).

(iii) Secondary chondrules. Inclusions B and C represent aggregates of chondrules. However, if some of the partially molten material from the source of inclusion C were ejected in much smaller form (sizes on the scale of 1 mm or less) it would be difficult to distinguish these "droplets" from primary chondrules. One possible distinction: the olivine and pyroxene compositions within such chondrules would be similar to those from equilibrated chondrites or from inclusion C. Chondrules 2/A, 2/P, 2/AA, 2/AG, and 2/AH in Table 2 do in fact show this relationship.

The postulated continuing mild metamorphism after final accretion would explain the fact that the kamacite and taenite compositions in all the different components, especially inclusions A and C, are very similar. All the metal has undergone equilibration during cooling at low temperatures (300–500°C) as suggested by WOOD (1967) for "normal" Mezö-Madaras.

The brecciation and re-mixing are considered to have happened early in the history of this chondrite in order (1) to have residual heat left in the parent body for induration and mild metamorphism of the re-aggregated material, and (2) to have had most of the chondritic debris available as individual chondrules and chondrule fragments at the time of brecciation and mixing.

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