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The Renazzo Meteorite

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INTRODUCTION

The Renazzo meteorite fell near Ferrara, Italy, on January 15, 1824. A number of stones fell, the largest weighing about 5 kilograms. It was described by Cordier (1827), with an analysis by Laugier, and there are numerous references to it in the nineteenth-century literature, which is enumerated by Wülfing (1897). Wülfing was able to account for some 1083 grams in collections, the largest amount (441 grams) being in the Mineralogical Institute of the University of Bologna. The fate of the major portion of this meteorite remains unknown, which is unfortunate, because the Renazzo meteorite is unique in several respects, as can be seen from the following description.

MINERALOGICAL COMPOSITION

In hand specimen the Renazzo meteorite has a striking appearance, consisting of comparatively large white chondrules, up to 3 mm. in diameter, in a black structureless groundmass. In thin section (fig. 1) the chondrules are seen to consist for the most part of granular olivine. Occasional chondrules are made up of clinoenstatite (showing well-developed polysynthetic twinning) and enstatite, and others consist of a

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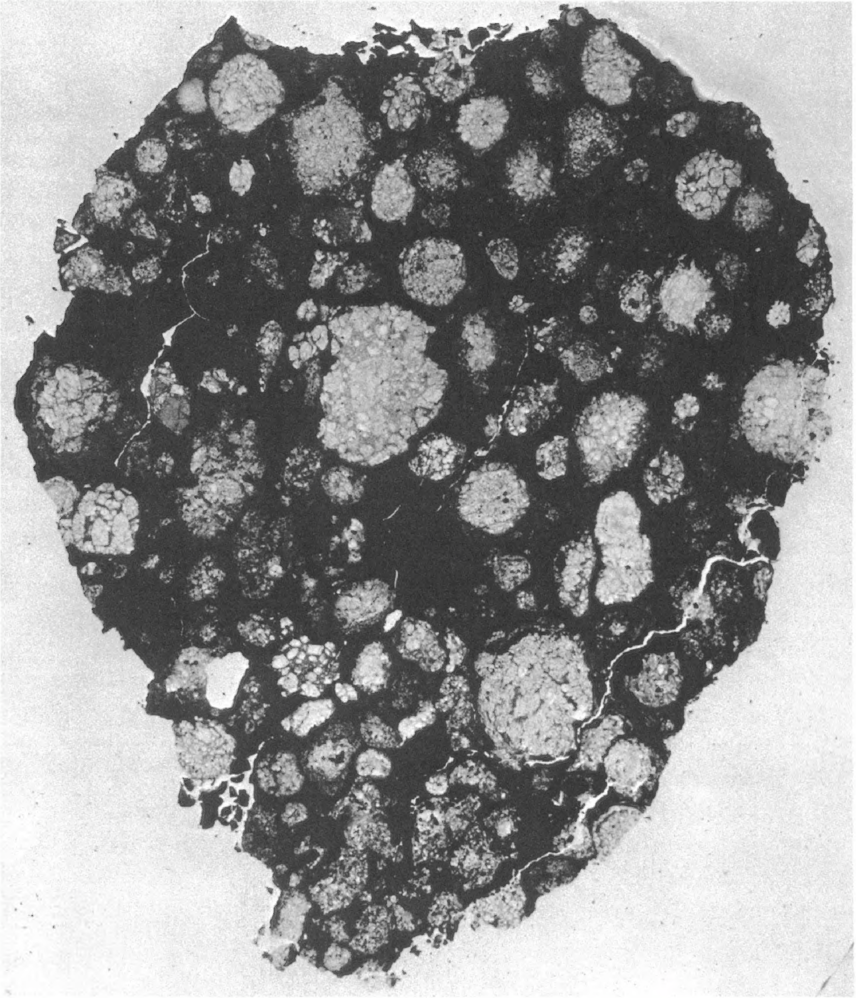

Fig. 1. Thin section of the Renazzo meteorite, showing chondrules of olivine and pyroxene in opaque groundmass of carbonaceous serpentine. Photograph by G. R. Adlington. × 6.

mixture of grains of clinoenstatite, enstatite, and olivine. The chondrules are frequently bordered by a rim of granules of nickel-iron (fig. 2). One olivine chondrule is completely mantled by a border of nickel-iron about 0.3 mm. thick (fig. 3). Another chondrule has an iron core 0.5 mm. in diameter and a rim, 1 mm. thick, of granular olivine (fig. 4). The groundmass is black and opaque; an X-ray powder photograph of this material shows lines of serpentine and magnetite. Notes on the individual minerals follow.

OLIVINE: The refractive indices are: $\alpha = 1.638$, $\gamma = 1.670$, indicating that the olivine is almost iron-free and close to Mg_2SiO_4 (forsterite) in composition. This was confirmed by the X-ray technique of Yoder and Sahama (1957); the diffraction pattern showed sharp peaks, indicating olivine of uniform composition, and the positions of the peaks corresponded to 96 mol per cent Mg_2SiO_4.

CLINOENSTATITE: This mineral is prominent in some of the chondrules by its low birefringence and the presence of polysynthetic twinning; the individual twin lamellae are very thin. The refractive indices could not be precisely determined because of the closely spaced twinning lamellae, but are close to those of pure $MgSiO_3$.

ENSTATITE: This mineral is difficult to identify in thin section, but was readily detected in the acid-insoluble fraction of the meteorite, along with the clinoenstatite. It is untwinned, with extinction parallel to the cleavage traces. The refractive indices are: $\alpha = 1.653$, $\gamma = 1.661$, indicating that it is nearly pure $MgSiO_3$, with little or no iron content.

DIOPSIDE: Crushed fragments of the meteorite show rare grains with higher indices than the olivine, enstatite, or clinoenstatite, oblique extinction, and birefringence about 0.03. The refractive indices are: $\alpha = 1.674$, $\gamma = 1.704$, and the mineral is almost certainly diopside.

SERPENTINE: As mentioned above, this mineral has been identified by X-ray powder photographs as a principal phase in the opaque groundmass. Its identification as serpentine rather than chlorite rests on (a) the absence of a 14 Å reflection; and (b) the low Al_2O_3 content of the meteorite, as shown by the analysis (table 1). From the analysis it appears that the serpentine must have a considerable iron content.

NICKEL-IRON: This is present almost or entirely as kamacite. It commonly occurs as rims of small granules around the individual chondrules, and the interior of such chondrules is usually free from nickel-iron. Other chondrules do not have nickel-iron rims, but then show numerous small kamacite particles throughout (these may be chondrules that have been cut tangentially). Sometimes the nickel-iron forms large round grains—in effect, metal chondrules. Nickel-iron is notably absent from the groundmass between the chondrules.

TROILITE: This mineral is present in lesser amount than is usual in chondrites. It occurs principally as small grains in association with nickel-iron, and as dust-like particles in the groundmass between the chondrules.

PENTLANDITE: This mineral occurs in small amount in association with

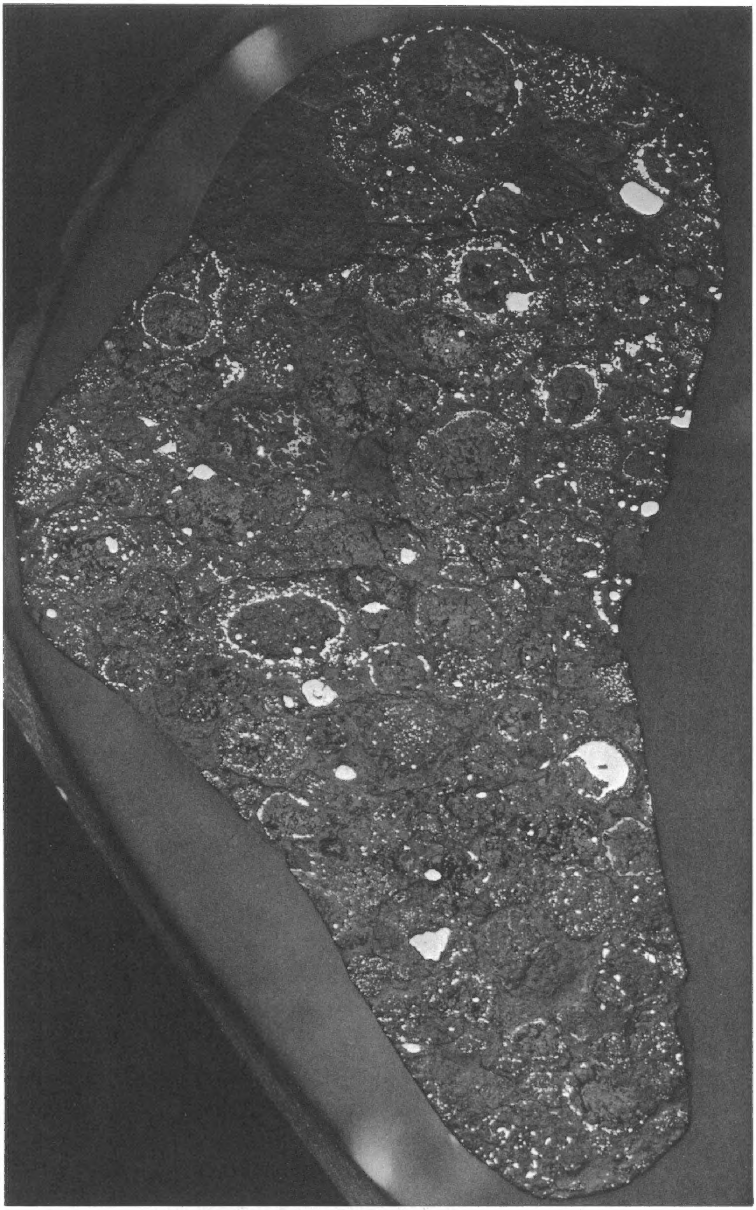

FIG. 2. Polished surface of the Renazzo meteorite; the chondrules are prominent, and are frequently mantled by grains (white) of nickel-iron. Photograph by Battelle Memorial Institute. × 7.

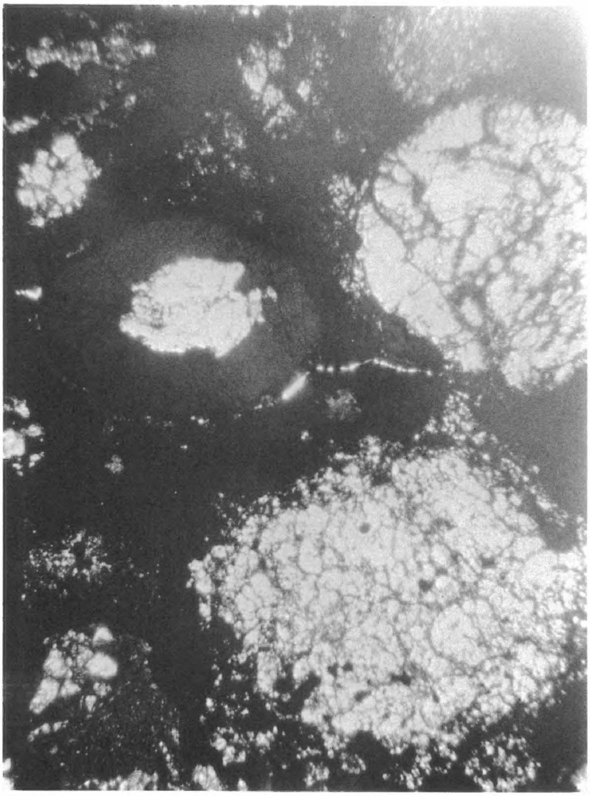

FIG. 3. A chondrule in the Renazzo meteorite, consisting of a core of olivine (white), 0.6 mm. in diameter, mantled by a rim of nickel-iron (gray), 0.3 mm. thick. Photograph by J. Weber.

troilite. Its presence is surprising, in view of the considerable excess of free iron; under these circumstances the nickel would normally alloy with the metal, rather than forming a sulphide.

MAGNETITE: This mineral is evidently present in considerable amount in the opaque groundmass, to judge from the X-ray powder photographs. The cell dimension is $a = 8.44$ A, considerably higher than that of pure Fe_3O_4 and close to that of trevorite, $NiFe_2O_4$ ($a = 8.43$ A), which suggests that some of the nickel in the meteorite is present in the magnetite phase.

CHROMITE: Occurs in small amount, in idiomorphic crystals.

GRAPHITE: This mineral appears to be abundant in the groundmass, in minute, almost submicroscopic grains.

A notable feature of the Renazzo meteorite is the apparent absence of

TABLE 1

CHEMICAL COMPOSITION OF THE RENAZZO METEORITE

A		B		C	
Fe	10.72	H	0.63	Mg	33.94
Ni	1.35	C	1.44	Si	32.32
Co	0.114	N	0.06	Fe	25.71
Cu	0.0145	Na	0.41	Al	2.66
FeS	3.59	Mg	14.33	Ca	1.85
SiO_2	33.83	Al	1.25	Ni	1.32
TiO_2	0.186	Si	15.805	Na	1.02
Al_2O_3	2.36	P	0.122	Cr	0.43
FeO	15.35	S	1.31	P	0.23
MnO	0.24	K	0.034	Mn	0.20
MgO	23.76	Ca	1.272	Ti	0.13
CaO	1.78	Ti	0.111	Co	0.10
Na_2O	0.55	V	0.027	K	0.05
K_2O	0.042	Cr	0.383	V	0.03
P_2O_5	0.28	Mn	0.186	Cu	0.01
H_2O	5.67	Fe	24.93		
Cr_2O_3	0.56	Co	0.114		100.00
V_2O_5	0.048	Ni	1.35		
C	1.44	Cu	0.0145		
N	0.06	(O	36.22)		
	101.94		100.00		

A Chemical analysis expressed as nickel-iron, troilite, and oxides

B Chemical analysis expressed as elements, with oxygen added to make 100 per cent

C Chemical analysis expressed as atom percentages with the elimination of H, O, C, and S

plagioclase. This mineral, which is almost universally present in chondritic meteorites in amounts of from 5 to 10 per cent, could not be detected either in thin sections or in the acid-insoluble residues.

The density of the meteorite was determined by measuring the apparent loss of weight on suspension in carbon tetrachloride and found to be 3.29.

CHEMICAL COMPOSITION

The chemical analysis is given in table 1, in the conventional form expressed as oxides, troilite, and metal; in terms of the individual elements as determined by analysis, with oxygen to bring the total to 100; and recalculated as atom percentages with the elimination of H, O, S, and C. The conventional form of presenting meteorite analyses involves

FIG. 4. A chondrule in the Renazzo meteorite, consisting of a core of nickel-iron (black), 0.5 mm. in diameter, mantled by granular olivine (white). Photograph by J. Weber.

certain assumptions, for example, that all S is present as FeS, that Fe in excess of free metal and FeS is present as FeO, and that the H_2O given by the analysis is present as free or combined H_2O. These assumptions are probably valid for most chondritic meteorites, but are certainly not for Renazzo. Much of the S is present as FeS, but some is in pentlandite, and some may be present as complex organic compounds. Some Fe is certainly present as ferric iron in magnetite, and the serpentine phase may well contain ferric iron. The H_2O given by the analysis is in part combined in serpentine, but some of it is probably present in combination with carbon as organic compounds (the high summation of the conventional form of the analysis can be ascribed to hydrogen combined with carbon rather than oxygen). Under these circumstances the form of presentation in column B in table 1 is preferable, since it gives the results actually obtained by the analysis. In effect, the chemical analysis determines the amounts of the different elements, except the amount of oxygen, no readily applicable method for this element being available.

The expression of the analysis as atomic percentages after eliminating H, O, S, and C was used by one of us (Wiik, 1956) for comparing analyses of the different types of chondrites. Such a procedure in effect distinguishes non-volatile elements from those likely to be lost or gained during heating in extra-terrestrial environments. The figures for the Renazzo meteorite show that its elemental composition is closely similar to that of Murray, a Type II carbonaceous chondrite.

DISCUSSION

The well-developed chondrules in the Renazzo meteorite show that it belongs beyond doubt in the group of the chondritic meteorites. However, it is not readily placed in any of the five classes of chondrites commonly recognized—enstatite, olivine-bronzite, olivine-hypersthene, olivine-pigeonite, or carbonaceous chondrites (Mason, 1962). In mineralogy and elemental composition it resembles the Type II carbonaceous chondrites of Wiik (1956), except that these contain little or no free metal, and the chondrules are normally small and sparse. The abundant free metal and the iron-free pyroxenes and olivine in Renazzo are properties analogous to those of the enstatite chondrites. In fact, the Renazzo meteorite appears to be intermediate between a carbonaceous chondrite and an enstatite chondrite.

The nature of the Renazzo meteorite poses some significant questions. Some of its remarkable features are: (a) the occurrence of chondrules of essentially iron-free anhydrous magnesium silicates in an iron-rich groundmass of hydrated silicate; (b) the mantling of many chondrules by a sheath of nickel-iron granules, whereas the interior of the chondrules are free from nickel-iron; (c) the constant association of nickel-iron with the chondrules and its absence from the groundmass.

Several hypotheses can be formulated to explain the genesis of the Renazzo meteorite. The most likely possibilities seem to be:

1. The chondrules were formed in one environment, the groundmass

in a different environment, and the meteorite is a chance accumulation of these two materials with different genetic histories.

2. The meteorite is the product of a single process, the chondrules and the groundmass being genetically related, in which case there are the following alternatives: (a) the groundmass has been formed from the materials of the chondrules; (b) the chondrules have been formed from the material of the groundmass.

The first possibility is consistent with the theory of Urey (1959), according to which the chondritic meteorites are agglomerates of debris resulting from collisions between pre-existing bodies. However, there are weighty arguments against this in the case of Renazzo. Its elemental composition as expressed in C in table 1 is similar to that of other carbonaceous chondrites, and to the H-group olivine-pyroxene chondrites studied by Urey and Craig (1953). Chance accumulation of debris from different objects would hardly result in such uniformity of chemical composition. An additional argument against Renazzo's representing a chance accumulation is the uniformity of composition of the chondrules; they consist of $MgSiO_3$ or Mg_2SiO_4 or mixtures of these. Such chondrules are rare in meteorites, being found only in some of the carbonaceous chondrites and in the small group of enstatite chondrites. On the evidence the first possibility must be rejected as an explanation for the origin of the Renazzo meteorite.

The second possibility now requires consideration: that chondrules and groundmass are genetically related, which raises the question as to whether the chondrules formed from the groundmass, or vice versa. One of us (Mason, 1960a, 1960b) has argued as a general postulate that chondrules are the product of a solid-state recrystallization of carbonaceous hydrated silicates, similar in composition to the groundmass of Renazzo and the carbonaceous chondrites. These views have been strongly opposed by Urey (1961), who suggests . . . "that some water-carrying organic compounds, hydrogen sulphide, etc., infiltrated some high-iron-group chondritic material, oxidized the metallic iron to magnetite or the sulphide, deposited carbon compounds, sulphate, sulphur, etc., and removed some sodium and potassium, and partly destroyed the chondrules."

The Renazzo meteorite may well be a critical object in a decision between these two contrasted hypotheses. The evidence from this meteorite seems to favor the hypothesis that the chondrules formed from the groundmass. The following formula shows a perfectly feasible chemical reaction:

$$Mg_6Si_4O_{10}(OH)_8 + Fe_3O_4 + 2C = 2Mg_2SiO_4 + 2MgSiO_3 + 3Fe + 4H_2O + 2CO_2$$

$$\underbrace{\text{serpentine} + \text{magnetite} + \text{carbon}}_{\text{groundmass}} = \underbrace{\text{olivine} + \text{pyroxene} + \text{iron}}_{\text{chondrules}}$$

However, the reaction is presumably reversible, proceeding to the left at low temperatures and to the right at high temperatures. Bowen and Tuttle (1949), who studied the phase relations in the system MgO-SiO_2-H_2O, showed that serpentine can decompose to give Mg_2SiO_4 at temperatures as low as 400° C.

In view of the presumed reversibility of the chemical reaction it is not possible to decide on this basis alone whether the chondrules formed from the groundmass or vice versa. However, the structural relations between the minerals in the chondrules and the groundmass indicate that the chondrules have formed from the groundmass, and not that the groundmass is the product of partial replacement of the chondrules. Several features support this view. Most of the chondrules are above average diameter for chondritic meteorites. Chondrules average about 1 mm. in diameter in most meteorites, whereas those in Renazzo are frequently larger, which is inconsistent with the belief that they were being destroyed with the formation of groundmass serpentine. The concentration of metallic nickel-iron marginally to the chondrules indicates that the chondrules were probably in the process of growth rather than of destruction, the crystallization of the pure magnesium silicates as chondrules concurrently with the formation of the metal resulting in the concentration of the latter on the margins of the chondrules. The distribution and form of the nickel-iron suggest that it has formed from the groundmass, not that it is in the process of being converted into magnetite. It is noteworthy that no free metal is visible in the groundmass itself. One might expect to see occasional vestigial remains were the iron a primary phase from which the groundmass was formed. Other features of the mineralogy are inconsistent with a derivation from high-iron-group chondritic material. Such material never contains chondrules of iron-free olivine, which are the commonest type in Renazzo; such material always contains plagioclase feldspar or its glassy equivalent, and this is absent from Renazzo.

Considering all the evidence, we conclude that the Renazzo meteorite represents an arrested stage in the conversion of a carbonaceous chondrite into an enstatite chondrite. The chondrules of iron-free olivine and pyroxene with the associated nickel-iron appear to have formed at the expense of the carbonaceous serpentine groundmass, which is presumably the result of a thermal metamorphism that failed to proceed to completion.

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