The mineralogical composition and structure of the Assisi meteorite

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Summary. The principal data about the fall and the distribution of the fragments of the Assisi (Perugia, Italy) meteorite are collected. A fragment of the stone, weighing 146·5 g, preserved in the British Museum (Natural History) (B.M. 63621), is described in some detail. Crust morphology, mineralogical composition, and structure are studied. Optical data are established by microscopical analysis of five thin sections and two polished surfaces. Compared with electron-probe analysis, they are found in good agreement. Assisi is an olivine-bronzite chondrite, H group, with characteristic features of metamorphism.

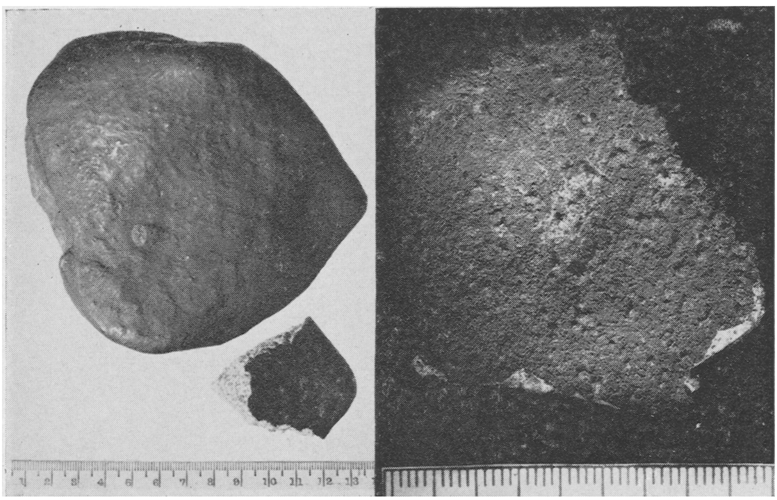
On 24 May 1886, at 7 a.m., the sky being clear, a single stone weighing 1795 g fell in a cornfield in Tordandrea, 7·5 Km south-west of Assisi (Perugia, Italy). Three peasants were present and immediately unearthed the small meteorite. It was at a depth of about 60 cm, in an apparently vertical hole about 25 cm in diameter. The stone was 13·8 cm long, 12·8 cm wide.

The fall was first described by Bellucci (1887), who submitted the individual specimen to a macroscopic examination. In the same year the complete meteorite was sent by Bellucci to Vienna, where Eger made a cast of the stone and sawed the meteorite in several pieces.[1] Museums and collections later purchased the fragments, which (1967) are now widely distributed (B. Baldanza, 1965; in addition to the fragments there recorded, there are 5·5 g at the University of Southern Arizona, Tempe, 44·3+70·0 g at the Field Mus. Nat. Hist., Chicago, 27·0 g in Dresden, Univ. Min. Mus., 4·5 g at the Amer. Mus. Nat. Hist., New York, 127·0+32·0 g in Milan Nat. Hist. Mus., and 29·0 g in Washington, U.S. Nat. Mus.; total, 1563 g). During the last war 3 g in Bonn (Univ. Min. Dept.) were lost and small fragments (Chicago, Field Mus. Nat. Hist.: 15·7 g; Dresden, Univ. Min. Mus.: 13·6 g; London, British Mus. Nat. Hist.: 6·5 g) were used for thin sections and studies.

[1] Unpublished correspondence between G. Bellucci and L. Eger (1886–7).

No published account of the mineralogical composition and structure of the Assisi meteorite has been traced.

Morphological and macroscopic description. The British Museum (Natural History) preserves two fragments of the stone, weighing 146·5 g (B.M. 63621) and 3 g (B.M. 92565), and a cast of the Assisi meteorite, presented in 1887 by Dr. J. Hector (fig. 1).



FIGS. 1 and 2: FIG. 1 (*left*). The fragment (B.M. 63621, 146·5 g) and the cast of the Assisi meteorite in the British Museum (Natural History). Scale in cm. FIG. 2 (*right*). The crust of the fragment shown in fig. 1. Scale in mm.

A general inspection of the form of the Assisi meteorite, made on the cast of the stone, shows very clearly one side whose corners and edges are convexly rounded and smoother than others. The frontal surface (apex) of the stone is particularly well identifiable, while the lateral sides are formed by flat surfaces. Such peculiarities of form lead to the conclusion that, following Krinov (1960), Assisi may be considered a 'semi-oriented' meteorite. The characteristic dark crust ('blackish' in Bellucci's (1887) description), which originally covered the stone, almost completely is in this fragment about 1 mm thick. These data should be connected with the mineralogical composition and structure of the stone (Krinov, 1960): in our particular case the colour could be related with the inclusions of nickeliferous-iron; the relatively thick crust could be connected with the friable mass of the meteorite and with the long trajectory in the lower parts of the retardation region, as observed by the people present.

A more detailed examination of the crust (fig. 2) shows rather small protuberances scattered upon a close-textured granulitic surface. The geometrical distribution of protuberances and irregularities on the surface appears to be not completely random, having some sort of preferred orientation. They may be attributed to fused inclusions of nickel-iron. Very fine fissures, well developed in the same direction, are notable on the same fragment. Regmaglypts are not clearly visible.

The broken surface of the Assisi meteorite is light grey, fine-grained, not very compact. It shows numerous bright particles of nickel-iron and spherical chondrules. Small patches of limonitic material of various diameters and colour intensity may be found in proximity of metallic grains.

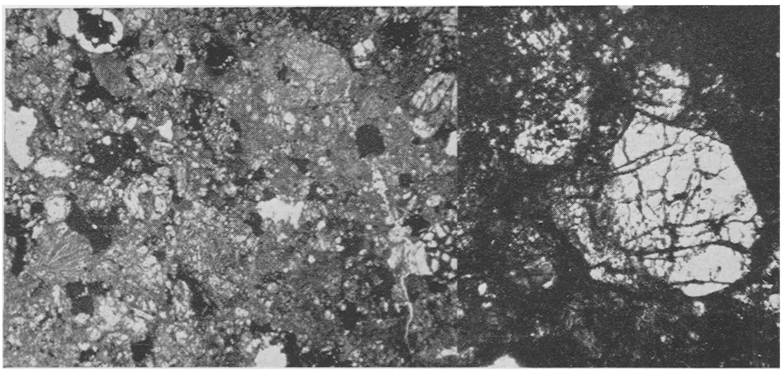
Mineralogical composition. The following notes on mineralogy and structure are based on the study of five thin sections and two polished surfaces cut from the British Museum fragment, B.M. 63621.

The principal minerals in the Assisi meteorite (as in all olivine–bronzite and olivine–hypersthene chondrites) are olivine and orthopyroxene. Nickel-iron, troilite, and chromite were also identified (fig. 3). Yellowish brown limonitic stains surrounding some of the opaque grains may represent trace amounts of lawrencite, presumably produced after the fall. At high magnification ($\times$200–400) a large proportion of micro-grained materials or turbid aggregates may be noted in the matrix, in chondrules, as well as in cracks of single grains; the composition of this mass is in several cases lithoidic, in others ferrous.

Olivine, by far the most abundant constituent of the meteorite, occurs as different-sized grains in both matrix and chondrules. Frequently we found idiomorphic olivine crystals (see fig. 4) in which it is possible to observe cracks, inclusions, and unusually good cleavage. We must, however, consider this cleavage only apparent, as often it appears slightly sinuous. Olivine grains were also observed as inclusions in nickel-iron granules, forming a sort of micro-pallasitic structure, not often mentioned in chondritic stones.

Stains of limonitic material often preclude accurate investigations; however several measurements of optic axial angles, based on curvature of isogyres in interference figures, give $2V_\gamma$ $87^\circ \pm 2^\circ$; $\beta = 1{\cdot}696 \pm 0{\cdot}001$, indicating a content of 18 to 20 mol. % fayalite using the tables of Winchell and Winchell (1961). X-ray diffractometer analysis, utilizing the method of Yoder and Sahama (1957), gave 19 mol. % fayalite

(Mason, 1963). Electron-probe measurements indicate a content of 17·9±0·3 mol. % Fa (Keil and Fredricksson, 1964). These data are in good agreement with the optical properties. A determination of the content of Ni, made by Fredricksson on the olivine, gave approximately 100 ppm (Keil and Fredriksson, 1964).



FIGS. 3 and 4: FIG. 3 (*left*). Thin section of the Assisi meteorite (×10); nickel-iron and troilite are black, olivine and bronzite white to grey. FIG. 4 (*right*). A large idiomorphic olivine crystal in the micro-grained matrix rich in opaque components (black). Cracks and nickel-iron inclusions are visible. (Crossed nicols.)

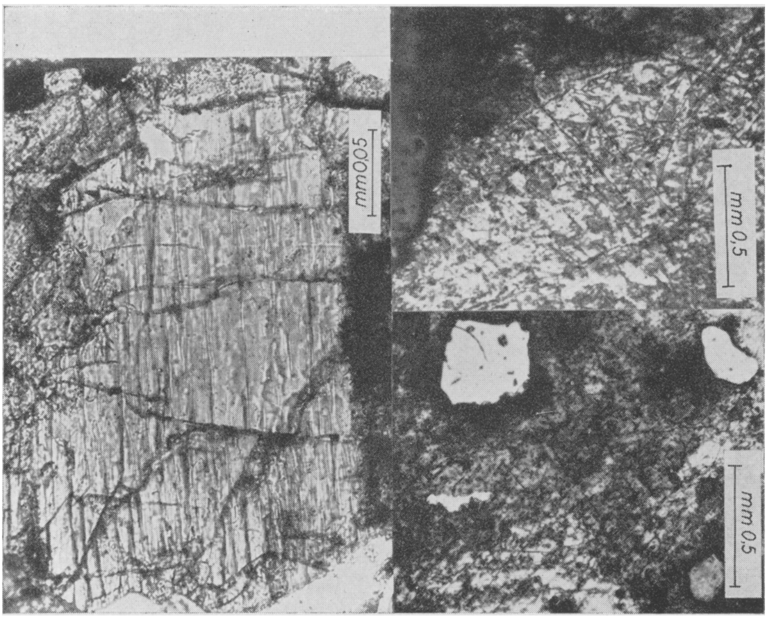
Pyroxene occurs as rhombic prismatic grains. It is characterized by grey interference colours and by finely striated or lamellar twinning structure. Cleavage of the pyroxene is essentially and more perfectly 'ruled' than that of olivine (fig. 5). Interference figures are poor and preclude accurate measurements of optic axial angle. $2V_\gamma$ determined on several crystals, using the curvature of isogyres, was constantly positive. Under high magnification inclusions are frequent. The mineral is not pleochroic.

Electron-probe analysis indicates a content of 16·0±0·3 mol. % of ferrosilite; calcium was found present (0·42 %) (Keil and Fredriksson, 1964).

A few minute grains of a mineral with low interference colours and β 1·623±0·002 were noted in the Assisi meteorite. They were tentatively identified as *apatite* or *merrillite*: electron-probe or chemical analysis could confirm our observations if phosphorus and calcium were found.

Two polished sections were studied in reflected light; they were etched for various times (from 15 to 30 sec) using a mixture of 5 % picral and 5 % nital in the proportions 7:3.

In unetched sections *troilite* was easily recognized by the characteristic dark grey colour and the distinct anisotropy. It occurs in comparatively large nodules, very irregularly distributed, with smooth convex surfaces. This mineral was also observed in sinuous aggregates around the nickeliferous-iron compounds. Inclusions of troilite are randomly present in small granules.



FIGS. 5 to 7: FIG. 5 (*left*). A large idiomorphic pyroxene crystal in micro-grained matrix; cleavage is highly evident. (Crossed nicols.) FIG. 6 (*top right*). Polished and etched surface of the Assisi meteorite, photographed in reflected light. Troilite appears in the lower parts of the photomicrographs. FIG. 7 (*bottom right*). Some grains of taenite (white) included in plessite and micro-plessite. The etched surface shows a very fine octahedral structure.

Chromite was noted as a minor opaque component in small grains, ranging up to 5 μ across, in certain chondrules and in the matrix.

Kamacite occurs in large variously sized grains (figs. 6 and 7), which present an amoeboid form and are distributed in all the interchondritic matrix. It shows a granulitic structure and often it contains small irregular or wedge-shaped inclusions.

Taenite appears clearly whiter in colour and considerably more acid-resistant. Its grains usually have regular cuspate margins, but it occurs also in form of oblong bands or spotted granules. Taenite inclusions within kamacite are frequent (fig. 7).

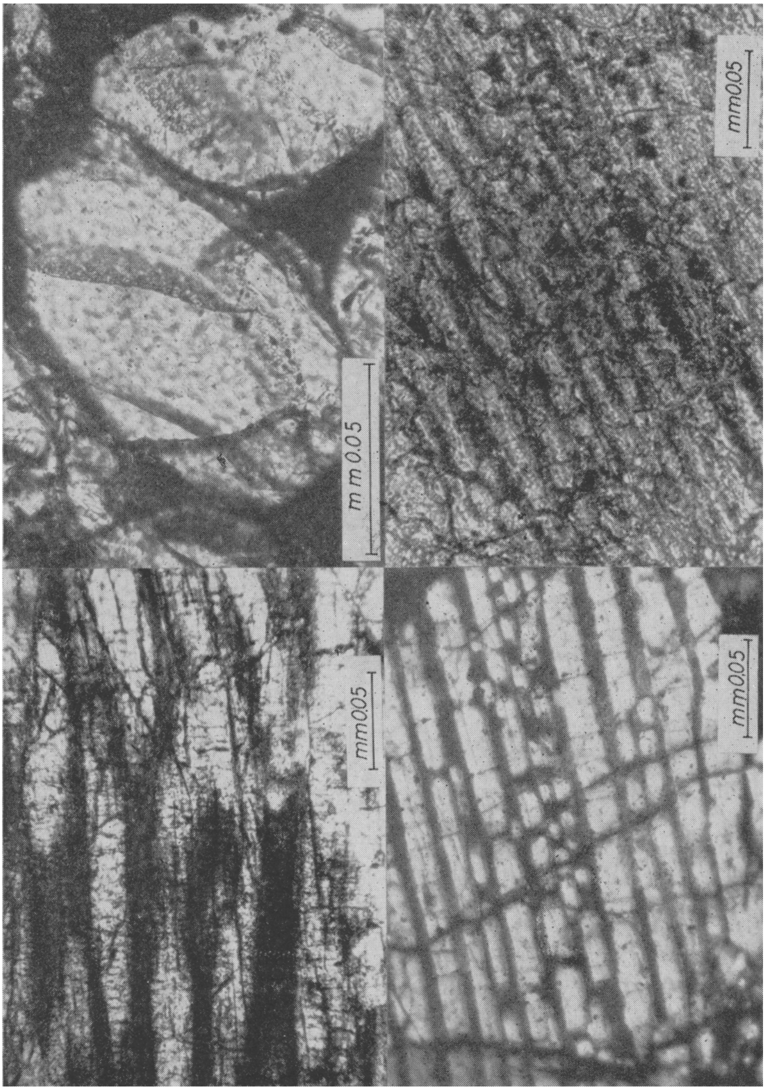
Plessite was observed by etching with mixtures whose concentrations were lower or higher than usual. Both light or normal plessite and dark or micro-plessite were observed. Dark plessite is very fine grained, sometimes to the limit of resolution of the microscope.

Structure. The Assisi meteorite was first classified by Bellucci (1887) as a chondrite. Brezina (1895) in a more detailed classification placed it among the spherical chondrites (Cc) characterized by 'friable mass with firm chondrules of radial structure, which do not break with it. Black or metallic veins', and Mason (1963) as an olivine–bronzite chondrite (Cb), in the H (high-iron) group of Urey and Craig (1953).

The chondritic structure of this meteorite is extremely well developed: the proportion of chondrules in the five thin sections was determined by planimetric integration as 29·50 %. Assisi contains not only chondrules of radial structure, but most of the common kinds of chondrules found in stony meteorites. Spherical, ovoid, or polyhedral in shape, these chondrules are about 1 mm or less in diameter, and present different types of structure: porphyritic, microporphyritic, barred, excentro-radial, and granular (fig. 3). Their mineralogical composition is usually monosomatic, more rarely polysomatic.

Porphyritic and microporphyritic olivine and pyroxene chondrules are abundant: under high magnification the first present euhedral crystals (fig. 8), up to 50 by 100 μ, which show cracks with frequent inclusions of crushed material of the same nature as the turbid silicate groundmass in which the crystals are dispersed. Some small grains, less than 5 μ diameter, are present. The microporphyritic chondrules are formed mainly by olivine, with iron and troilite grains concentrated near the surface.

Three types of barred chondrules were noted: monosomatic singly oriented fibrous barred chondrules, with an interior consisting of slightly distorted plates of olivine, between which lies a fine turbid silicate groundmass (fig. 9); monosomatic singly oriented barred chondrules, in which the small olivine (fig. 10) or pyroxene (fig. 11) plates and shells present rounded margins and continuous structure, forming a single crystal; and mono- and poly-somatic bioriented barred chondrules,



FIGS. 8 to 11: FIG. 8 (*top left*). Crystals of olivine in a porphyritic chondrule. Cracks, lithoidic and opaque inclusions are visible (crossed nicols). FIG. 9 (*bottom left*). Fibrous olivine in a monosomatic singly oriented barred chondrule (ordinary light). FIG. 10 (*top right*). The core of an olivine barred chondrule, the bars consisting of turbid material showing a greenish colour in strong unpolarized illumination (ordinary light). FIG. 11 (*bottom right*). The core of an orthopyroxene chondrule consisting of a single crystal of bronzite (crossed nicols).

which are very uncommon, with the interior consisting of two systems of almost-parallel grains oriented to the right and left of an axial line. Each set shows uniform extinction, and they form a peculiar twinned assemblage (fig. 12).

Excentro-radial chondrules are rarer and may be formed by olivine (fig. 13) or pyroxene (fig. 14). Figs. 13 and 15 show characteristic olivine radiating chondrules in which, under high magnification, may be noted numerous opaque inclusions and nickel-iron veinlets. In fig. 14 the radial pyroxene chondrule presents abundant opaque inclusions. In general the margins are not well defined.

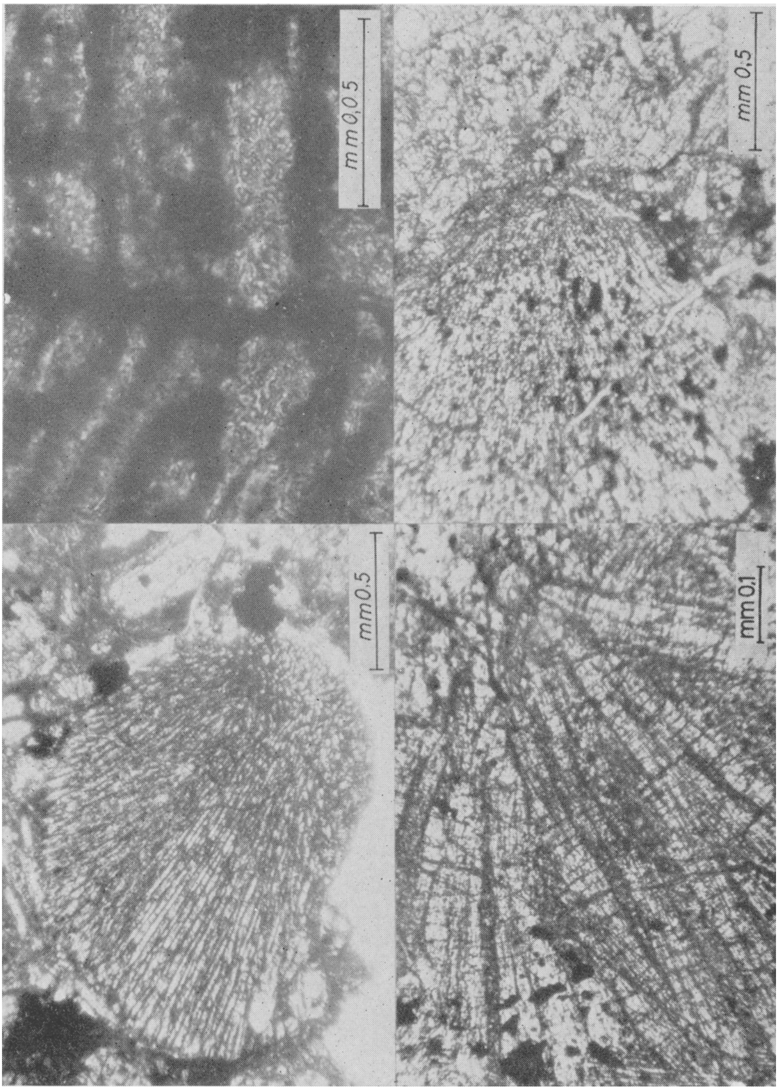
Granular chondrules are variously distributed in thin sections: in fig. 3 it is possible to observe several granular arrangements containing chondrules of different structure.

The interchondrule matrix of Assisi contains olivine and orthopyroxene grains, whose details and varieties of texture have been described above under individual minerals. A large amount of micrograined and turbid lithoidic material is present within chondrules, between them, and as inclusions in cracks of single crystals (fig. 8); it was inspected under high magnification using both ordinary light and crossed nicols. The mass revealed in strong unpolarized illumination an interesting greenish colour, characteristic of some olivine metamorphic products.

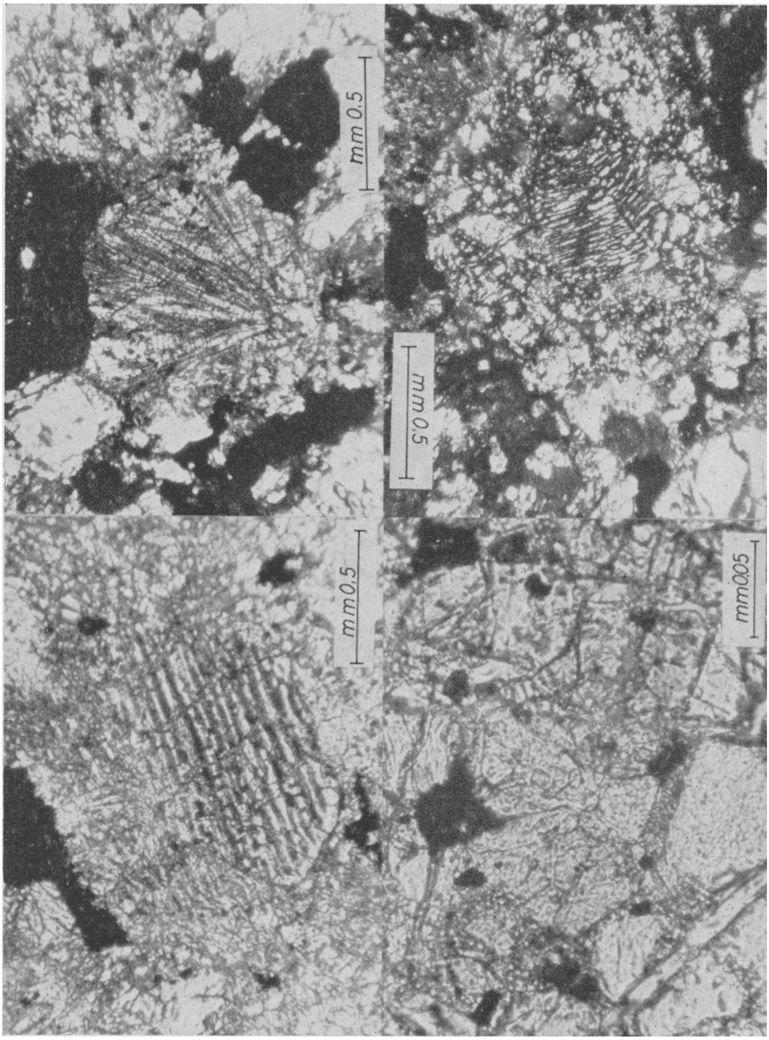
Opaque components are variously distributed. They occur: In *large grains*, up to 1 mm across, in the matrix (fig. 3); a determination of the approximate percentage of these opaque particles was made by microscopical measurements, using planimetric integration, under low magnification; over the five thin sections we found a result of 11·58 %. In *droplets*, less than 5 μ in diameter, included in olivine and pyroxene grains, present in the matrix as well as in chondrules (figs. 8, 10, and 11). The average percentage of small metallic grains and nickel-iron inclusions in the matrix was determined on several high magnification photographs. As for the chondrules, we agree with Fredriksson (1963), who showed that 'certain chondrules contain as much nickel-iron as the matrix'. In *veinlets* crossing some chondrules (fig. 15).

Summing up, the total content of opaque components in the Assisi meteorite may be estimated as between 17·80 and 19·58 %.

The etched surfaces of opaque mineral grains showed a very fine octahedral structure (figs. 6 and 7), similar to that observed in iron meteorites.



FIGS. 12 to 15: FIG. 12 (*top left*). Uncommon variety of chondrule showing olivine crystals in a polysomatic bioriented barred chondrule (crossed nicols). FIG. 13 (*bottom left*). Excentric-radiating structure in an olivine chondrule (crossed nicols). FIG. 14 (*top right*). Excentric-radiating structure in an orthopyroxene chondrule, with not well defined contours and many opaque inclusions (ordinary light). FIG. 15 (*bottom right*). Chondrule consisting of prismatic grains of olivine in different orientations. Opaque components in veinlets and in small grains are concentrated near the surface (crossed nicols).



FIGS. 16 to 19: FIG. 16 (*top left*). Quite distinct olivine chondrule. The outlines (smooth or amoeboid) of the opaque grains are notable (ordinary light). FIG. 17 (*bottom left*). Not very distinct chondrule in a micro-grained matrix (ordinary light). FIG. 18 (*top right*). A chondrule that has lost the contours and blends into the surrounding mass (ordinary light). FIG. 19 (*bottom right*). Centric texture in the Assisi meteorite. Radial distribution of irregular grains of olivine can be seen around the grains of troilite and nickel-iron (ordinary light).

Discussion

The effects of a period of high-temperature recrystallization may be recognized in the Assisi meteorite by several indications:

The complete absence of glass in the composition of the stone; Assisi is a holocrystalline chondrite.

Considering the structure of the meteorite, some of the chondrules are still quite distinct (figs. 13, 16), while others (figs. 14, 17, and 18) have lost their contours and blend imperceptibly into the surrounding mass. Many meteorite petrographers (Merrill, 1921; Ringwood, 1961; Wood, 1962, 1963) attribute this texture to a process of thermal metamorphism or recrystallization.

The radial distribution of irregular grains of olivine around the opaque granules (fig. 19) is one of the most characteristic features of a recrystallized chondrite (Krinov, 1960), while the outlines (smooth or amoeboid) of the opaque grains in Assisi are peculiar, in Kvasha's (1961) opinion, to a crystalline altered chondrite.

From a different point of view we may observe: cracks present in single crystals; micro-grained crushed materials, forming part of the interchondrule matrix as well as of the structure present within cracks; and the deformed polyhedral shape (often very closely hexagonal), characteristic of several chondritic aggregates. All these may be considered results of metamorphic structural transformation: in this case a probable agent responsible could be found in the prolonged pressure conditions, present in the meteorite during the cosmic journey. The changes of pressure, due to temperature variations and gradients, especially significant in the lower layers of the atmosphere, may have variously contributed.

An estimate of temperatures and pressures in the Assisi meteorite during the metamorphism appears to be highly interesting, but this evaluation is part of a major problem beyond the field of our research.

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