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The Siena meteorite: Mineralogy and Chemistry

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SUMMARY. The principal data are collected about the fall and the distribution of the fragments of the Siena, Italy, meteorite (11·6° E., 43·1° N.). A complete individual, weighing 110·55 g, is described in some detail. Crust morphology, mineralogical composition, and structure were studied. Optical data were established by microscopical analysis and both thin and polished sections were observed. Compared with available electron-probe analysis they are found in good agreement. The chemical analysis is Fe 12·93, Ni 1·39, Co 0·09, FeS 5·46, SiO_2 37·10, TiO_2 0·14, Al_2O_3 3·91, FeO 11·46, MnO 0·35, MgO 23·81, CaO 1·63, Na_2O 0·90, K_2O 0·16, P_2O_5 0·44, H_2O^+ 0·10, H_2O^- 0·00, Cr_2O_3 0·56, total 100·43. Siena is an ordinary chondrite, with relatively ambiguous characteristics and evident features of recrystallization and metamorphism.

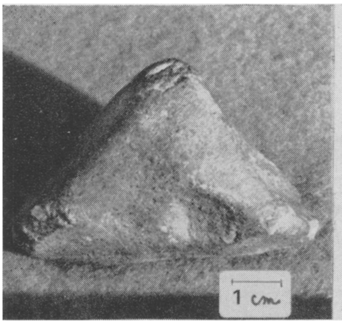
ON 16 June 1794 at about 7 p.m. a large number of stones fell after detonations and the appearance of a fireball over an area centred between Lucignano d'Asso and Cosona (11° 35′ E., 43° 7′ N.), small villages 47 km SE. of Siena, Italy. A few days later, on 13 July 1794 Father Domenico Soldani, in Siena, described the phenomenon (Soldani, 1794) and gave a particular account of five of the fallen pieces. In the same year a dissertation on the Siena meteoritic shower appeared in Naples (Tata, 1794); in London, Hamilton (1795, 1796) mentioned the fall, while other descriptions are due to Tata (1800) and Howard (1803). In 1880 Hahn published five microphotographs of the chondritic structure and more recently Salomon (1930) collected some historical notes.

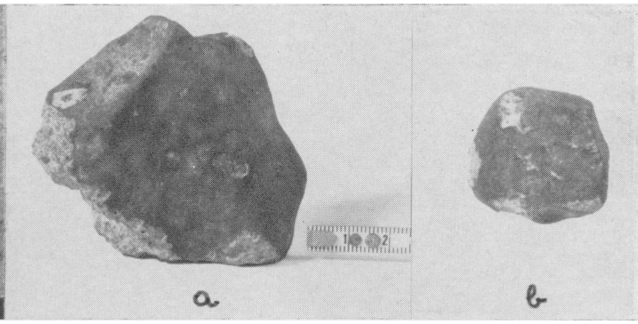
The total weight of the stones fallen in the Siena showers was never known. The fragments are now (1968) widely distributed in museums and collections (Baldanza, 1965; in addition to the fragments there recorded, there are 0·5 g at the University of Southern Arizona, Tempe, 65 g at the Field Museum of Natural History, Chicago, 44 g at the American Museum of Natural History, New York, 4·68 g at the U.S. National Museum, Washington; total 3674·45 g).

Mineralogically the Siena meteorite was never exhaustively studied: some fragments were submitted to a macroscopic examination by Capellini (1915), and in 1962 Keil made a planimetric study of an area of 11·5 cm² of the stone. No published account on the optical data and structure of the Siena stones has been traced; the chemical analyses are incomplete and unreliable (Howard, 1803; Klaproth, 1803; John, 1821), and the classification still presents some discrepancies. Krinov (1960) catalogued the Siena in the list of the meteorites of rare type, which might be of special interest to research workers. Therefore we decided to re-examine this meteorite in order to establish, from the complete mineralogical and chemical composition, a more exhaustive classification.

General description and crust morphology

A complete individual of the Siena meteoritic shower is preserved in the private collection of Professor B. Baldanza in the Mineralogical Institute, Facoltà di Scienze, University of Perugia, Italy (fig. 1). The stone exhibits a rather clearly defined form of trilateral pyramid, characteristic of a semi-orientated sample (Krinov, 1960); this shape shows that after the fragmentation of the original body, which may have happened at considerable altitude, our stone probably continued to move at cosmic speed





FIGS. 1 and 2: FIG. 1 (left). The complete individual (110·55 g) of the Siena meteoritic shower preserved in the private collection of Professor B. Baldanza in the Mineralogical Institute, Facoltà di Scienze, University of Perugia. FIG. 2 (right). Complete individuals of the Siena meteoritic shower: *a*, in the University Mineralogical Museum, Florence (172·5 g); *b*, in the Accademia dei Fisiocritici, Siena (42·16 g). Scale in cm.

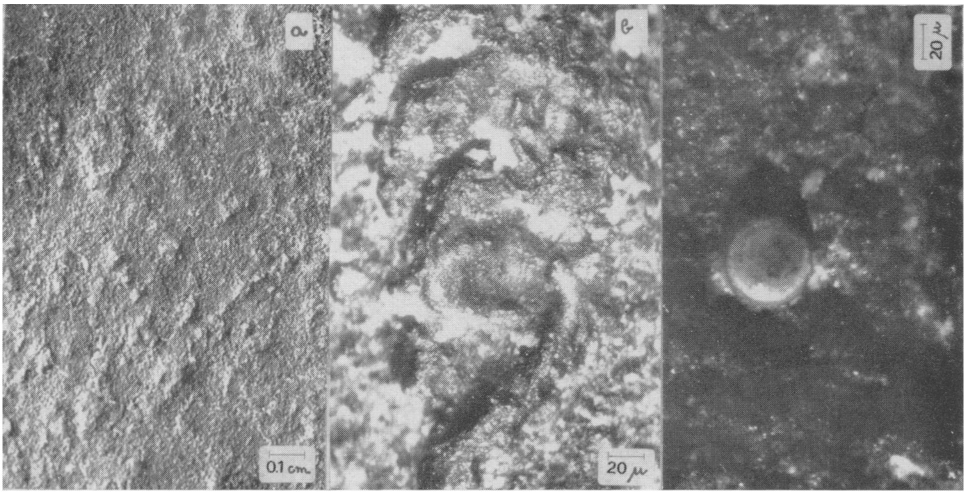
and maintained the same direction during the rest of the journey, while other individual samples, contemporaneously fallen, were subjected to a different atmospheric action (see fragments C and E of Soldani, 1794, with the form of a brick; figs. 2*a* and 2*b* with a more rounded shape).

The crust is brownish in colour and covers almost completely the lateral surfaces of the well-preserved specimen: it has an average thickness of less than 0·3 mm, which could be connected, following Krinov (1960), with the dense mass of the meteorite. The rear surface presents a rough fracture surface that was not severely subjected to atmospheric influence and became irregularly covered with a fusion crust.

A more detailed examination shows typical flow lines (fig. 3 *a* and *b*) with rather small distributed protuberances. Thus the 'knobby' structure of the crust surface predominates on the front of the stone. At high magnification, on the lateral surfaces, streams were observed, formed by involuted striae. Regmaglypts are evident and well developed with rounded forms; occasionally tiny colourless droplets of glassy material were noted (fig. 4).

The uncut Siena fragment weighed approximately 110·55 g; it did not exhibit any evidence of weathering.

The interior of the stone was found to be quite uniformly fine grained (fig. 5), and impregnated with metallic granules ranging in size from the finest metallic dust to amoeboid individuals having a maximum dimension of as much as 1 mm. Our observations are in agreement with the description made by Soldani (1794) on several specimens of the shower: 'La parte interna [he wrote] è durissima e composta da materiali cristallizzati. . . .'



FIGS. 3 and 4: FIG. 3 (left). The crust of the Siena stone shown in fig. 1: *a*, protuberances in the 'knobby' structure of the surface; *b*, streams formed by involuted striae. FIG. 4 (right). A droplet of glassy material observed at high magnification on the crust of the Siena stone.

Mineralogical composition

The following notes on mineralogy and structure are based on the study of two thin sections and two polished surfaces cut from the Siena complete individual of the Baldanza Collection in the Mineralogical Institute of the University of Perugia, Italy. For comparison and more exhaustive investigation we used a thin section cut from the British Museum (Natural History) fragment BM 33990.

The principal minerals in the Siena meteorite are olivine and orthopyroxene. Nickel–iron alloys, troilite, and chromite are also easily identifiable (figs. 6, 7, 8). Minor constituents including ilmenite and copper are present and microscopically distinguishable (figs. 8, 9, 10).

Olivine occurs as different-sized grains in both matrix and chondrules; it is frequently found in idiomorphic subhedral and euhedral crystals, which often present cracks with metallic inclusions (fig. 13). Micrograined olivine or turbid aggregates or both are present between the crystallized individuals, forming a continuous texture. The refractive indices, measured in Na light by the immersion method, are $\alpha = 1{\cdot}689$, $\gamma = 1{\cdot}727$, indicating a content of 27–9 mol. % of the Fe_2SiO_4 (Fa) component, according to the determination tables of Winchell and Winchell (1961). X-ray diffractometer analysis gave 28 mol. % fayalite (Mason, 1963).

Pyroxene occurs as rhombic prismatic grains, characterized by finely striated or lamellar structure and by grey interference colours. The mineral is not pleochroic; under high magnification inclusions are frequently observed. The refractive indices were determined by the immersion method, Na light. They are $\alpha = 1{\cdot}680$, $\gamma = 1{\cdot}690$, indicating an average content of 24 mol. % of ferrosilite (Fs), according to the determinative curve of Kuno (1954).

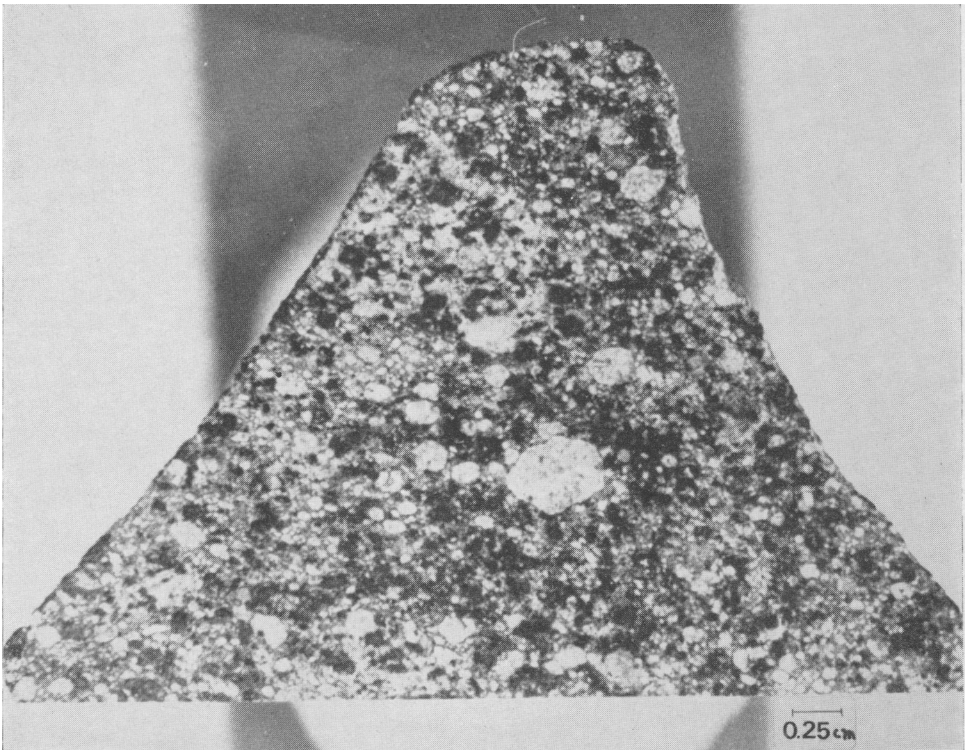
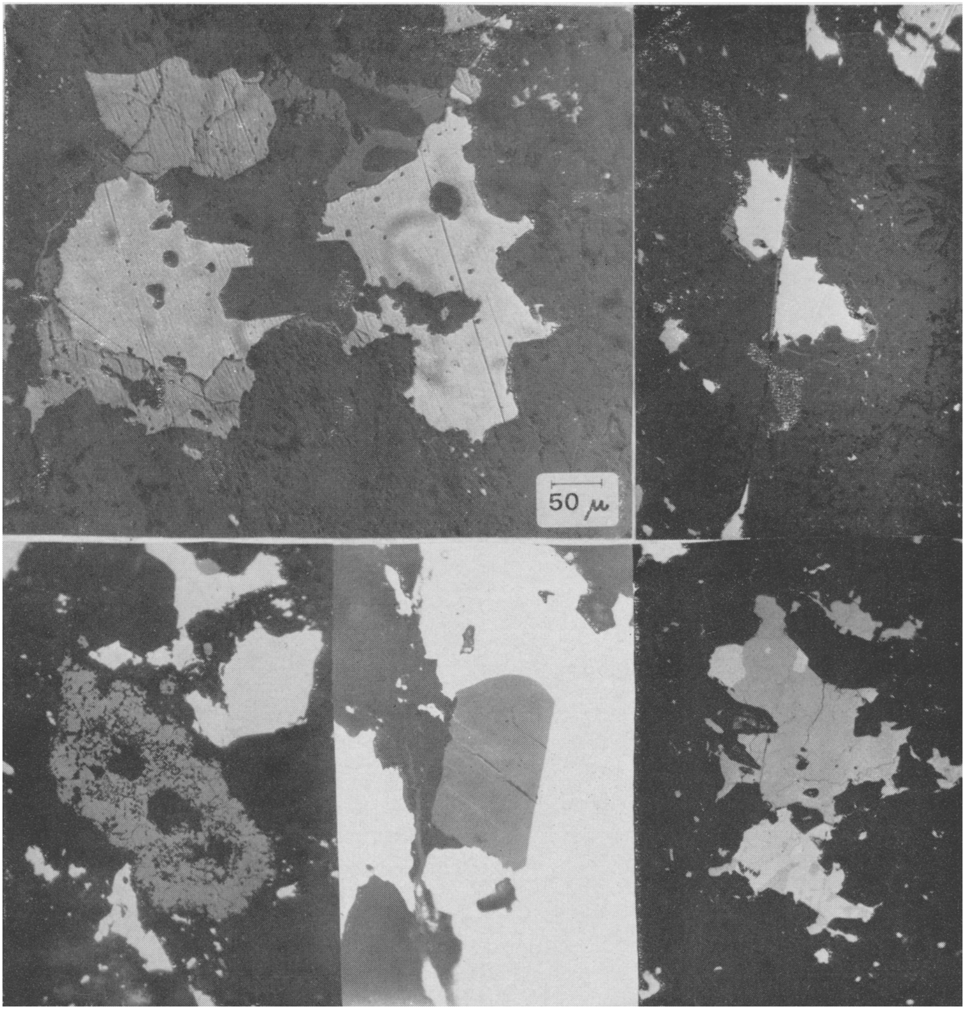


FIG. 5. Polished section of the Siena meteorite, showing light–dark structure.

The determination of the refractive indices in the *feldspar* proved impracticable but by the general aspect it was tentatively identified as sodic plagioclase, in agreement with Ramdohr (private communication, 1968). Minute grains of a mineral with low interference colours and an approximate refractive index $1{\cdot}623 \pm 0{\cdot}002$ were noted in Siena. They are probably identifiable as *apatite* or *merrillite*.

Two polished sections were studied in reflected light in order to observe and distinguish different aspects in opaque constituents. They were etched for various times (from 15 to 60 s) using a mixture of 5 % picral and 5 % nital in the proportion 7:3.

Troilite was easily recognized in unetched sections by the characteristic bronze-yellow colour (figs. 6, 7). It is common in rounded or sharply angular, shard-like grains scattered throughout the metal, as well as in veinlets, lamellae, and globules



FIGS. 6–10: FIG. 6 (top left). Nickel–iron alloys (light grey), troilite (medium grey), and chromite (dark grey) photographed in reflected light. FIG. 7 (top right). A faulted nickel–iron grain (×100; P. Ramdohr photo.). FIG. 8 (bottom left). Chondrules of chromite (×325; P. Ramdohr photo.). FIG. 9 (bottom middle). An idiomorphic crystal of ilmenite (×520; P. Ramdohr photo.). FIG. 10 (bottom right). Native copper; the flame-like form of the small crystals is characteristic (×225; P. Ramdohr photo.).

with smooth convex surfaces. In the sulphide mineral nodules cracks are often present with lithoidic local flowage.

Nickel–iron alloys are widely distributed in the Siena meteorite. After etching, kamacite, taenite, and the eutectoid intergrowth, plessite, were recognized. Kamacite is the most abundant iron constituent and it occurs in large, variously sized grains, with amoeboid form. Taenite is considerably whiter in colour and more acid resistant;

it occurs in the form of small oblong bands or spotted granules. Rims of plessite were often noted on the borders of the nickel–iron fragments.

Minor opaque components are chromite, ilmenite, native copper, and spinel (Ramdohr, private communication, 1968). *Chromite* was observed in coarse xenomorphic grains against the silicate; in rounded or idiomorphic forms towards iron and troilite. Several aggregates of chromite were noted, with different interesting aspects. The mineral was also found forming almost entirely some small chondrules (fig. 8). *Ilmenite* occurs in a few xenomorphic twinned grains or idiomorphic crystals (fig. 9). *Copper* was microscopically detected and recognized (fig. 10); it is present in very small crystals, characterized by flame-like form. *Spinel*, although several times mentioned as a meteorite component, appears to be very rare here.

Chemical composition

The chemical analysis gave: Fe 12·93 %, Ni 1·39, Co 0·09, FeS 5·46, SiO_2 37·10, TiO_2 0·14, Al_2O_3 3·91, FeO 11·46, MnO 0·35, MgO 23·81, CaO 1·63, Na_2O 0·90, K_2O 0·16, P_2O_5 0·44, H_2O^+ 0·10, H_2O^- 0·00, Cr_2O_3 0·56, sum 100·43 %. Expressed in terms of elements this becomes: Fe 25·31 %, Ni 1·39, Co 0·09, S 1·99, Si 17·33, Ti 0·08, Al 2·07, Mn 0·27, Mg 14·36, Ca 1·16, Na 0·67, K 0·13, P 0·19, H 0·01, Cr 0·39, O 34·99. The possible error in the metallic and total iron determinations is estimated at not more than 0·5 %.

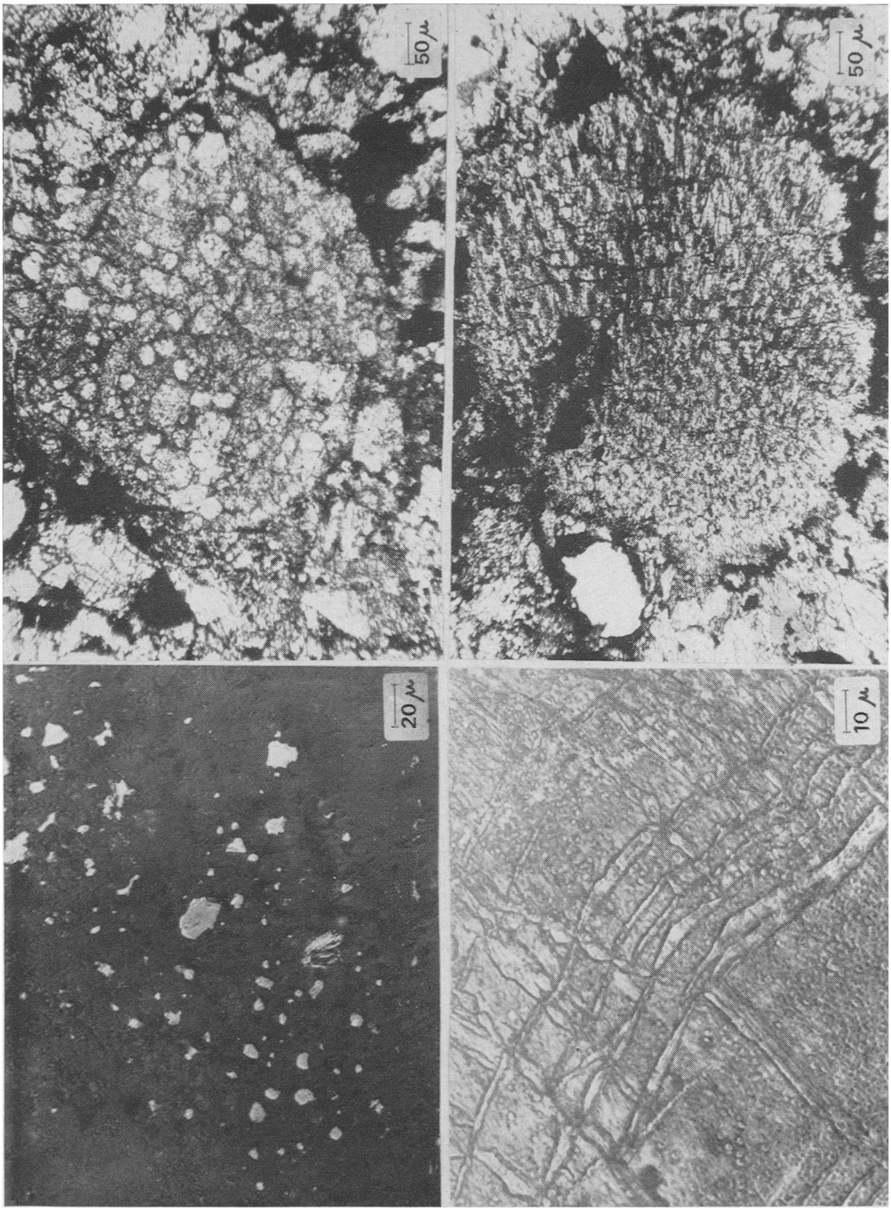
The presence of P_2O_5 confirms the presence of merrilite (about 1 %); TiO_2 may be connected with the observation of ilmenite (0·3 %).

Structure

The structure of the Siena meteorite was first studied by Reichenbach (1860), who described the 'light–dark' parts of the Siena stone as present in few meteorites. In 1952 Wahl observed that up to 20 % of chondrites are brecciated and he calls 'polymict' those chondrites with light–dark structure.

The macroscopically visible differences between the light and the dark material are not so evident in the Siena meteorite as in the Pantar chondrite (Fredriksson and Keil, 1963) or Mezö-Madaras (Van Schmus, 1967). Nevertheless we notice (fig. 5) that the light and the dark materials appear quite in equal proportion; that the largest light bodies are usually angular in shape, while the smallest are roundish or oval; and that the boundaries between the light and the dark portions are often sharp, but sometimes diffuse.

Microscopic examinations of both portions in transmitted and reflected light reveal that the grain size is smaller in the dark portions than in the light ones. However, the optical data of the components strongly indicate mineralogical identity of both portions of the meteorite. These results could indicate, in accordance with some observations made by Fredriksson *et al.* (1962) on Chantonnay and Ställdalen and by Fredriksson and Keil (1963) on Pantar and Kapoeta, that perhaps the characteristic light–dark structure in the Siena meteorite may be originated 'by way of a secondary partial transformation of primary light colored parent rocks'. However, we should mention



FIGS. 11–14. FIG. 11 (top left). A microporphyritic olivine chondrule that imperceptibly blends into the surrounding mass; a fault is clearly visible (ordinary light). FIG. 12 (top right). Metallic ring and veinlets around and in an olivine chondrule (ordinary light). FIG. 13 (bottom left). Metallic droplets in lithoidal matrix (reflected light). FIG. 14 (bottom right). Highly distorted Neumann bands in the nickel-iron alloys of the Siena meteorite; polished and etched section in reflected light.

a more recent hypothesis by Mazor and Anders (1967), who reached the conclusion that the dark portions in the light–dark meteoritic structure represent a possible mixture of the light portion with carbonaceous matter (not revealed by our chemical analysis). Avoiding any possible speculation about the origin of the Siena meteorite, we think that from the mineralogical point of view it would perhaps be more correct to classify our stone with the *monomict*, rather than with the *polymict* meteorites.

In 1862 Rose classed Siena as a chondrite and in 1895 Brezina, in a more detailed classification, placed this stone among the howarditic chondrites (Cho), characterized by 'polyhedral fragments; spherical rare chondrules; crust partly bright'. In Prior's classification (1920) Siena was placed in the 'intermediate chondrites' group (Ci), having 'firm polishable mass, with white and grey chondrules, which break together with the main mass'. The chondritic structure of this meteorite is in effect well developed and distinguishable, although some chondrules have lost their contours and blend into the surrounding mass (fig. 11). Observing this particular texture, we may consider Siena as a stone with advanced 'integration' (Dodd *et al.*, 1967): many chondrule–chondrule boundaries are indistinct or wholly obliterated; the matrix is granular and chondrule–matrix intergrowth is common.

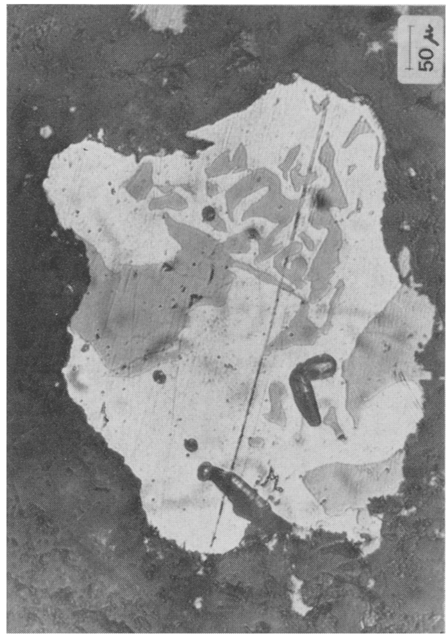


FIG. 15. Myrmekitic inclusions of troilite in nickel-iron (reflected light).

The microscopic examination shows a wide variety of chondrules (cryptocrystalline, granular, microporphyritic, porphyritic, excentroradial, and barred). Spherical, ovoid, or polyhedral in shape, these chondrules have different dimensions, ranging from 0·1 to 0·8 mm and are often surrounded by metallic rings (fig. 12). Most of the metal and sulphide in this chondrite occur outside the silicate chondrules as particles in the matrix or as fine-grained metal–sulphide droplets ($<5\ \mu$ dia.). Opaque components often cross the field as veinlets, which suggests solidification of the metal after the silicates, while elsewhere spheroidal droplets ($<5\ \mu$ dia.) of metal and sulphide (fig. 13) occur within chondrules, and suggest solidification of the metal before the silicates. So one might consider the possibility that at least part of the metal and sulphide in the Siena meteorite should be cogenetic with the silicates, in agreement with recent conclusions by other authors (Keil and Fredriksson, 1964; Van Schmus, 1967).

The structure of the nickel–iron alloys was inspected after etching at low and high magnification: highly distorted Neumann bands were observed and photographed (fig. 14). Myrmekitic inclusions are present (fig. 15). Coarse cracks are visible in the Siena stone sections; some interesting faults were noted crossing the opaque components (fig. 7) and the chondrules (figs. 11 and 16).

Recrystallization and metamorphism

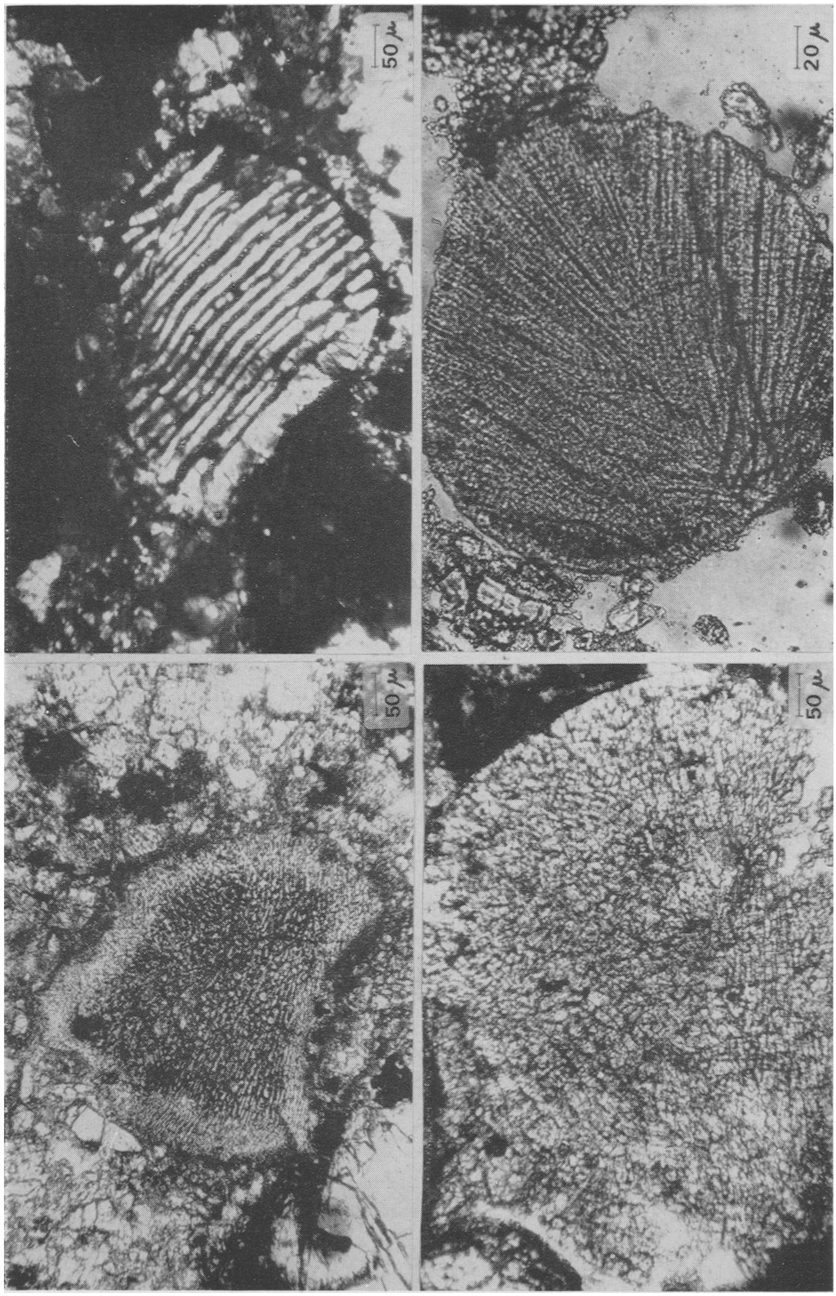
'There are so many metamorphic events in meteorites', writes P. Ramdohr (1967), 'that it seems urgent to limit the term "metamorphism" only to demonstrable cases.' Actually we distinguished in the Siena meteorite different features that may be ascribed to phenomena of recrystallization, which many meteorite petrographers regard as typical manifestations of thermal metamorphism (Merrill, 1921; Ringwood, 1961; Wood, 1963; Van Schmus and Wood, 1967) or to different inequivocal processes of metamorphism, such as the break-up caused by shock waves, particularly noticeable in our stone.

The Siena meteorite shows undoubted evidence of recrystallization and the presence of feldspar is highly significant: Mason (1965) noted that only the well-crystallized chondrites contain feldspar grains readily visible in thin section; in our case we found that the mineral is rare and the grains are small and not well developed, but on the other hand we should not forget the presence of a large number of cryptocrystalline chondrules; in Wood's (1963) opinion, in this type of orthopyroxene chondrule the fibres are so fine that a substantial amount of glass could lie between them and not be observed (fig. 17). In the light material, coarse-grained lithoidic minerals are often cracked and areas within idiomorphic crystals are frequently transformed into a large number of small grains with different optical orientation. This seems to be typical for shock transformation (Fredriksson *et al.*, 1962). In some cases we observed interesting structures (i.e. mylonitization) (figs. 18 and 19) that may easily be connected with deformation events. Wavy extinction is observable in several chondrules and it is now agreed that this is produced by dynamic metamorphism.

Some other indications of mechanical transformation processes may be found by inspection of the opaque components. Neumann bands, highly distorted and curved, are often present (fig. 14): similar effects have been observed in artificially shocked kamacite (Smith, 1958). Moreover, some kamacite shows flowage along zones of weakness: the flow-like structure is frequent also in troilite and some connecting traces of metal are noticeable. In the interior of the meteorite globules of nickel–iron and sulphide (fig. 13) occur within well-defined regions between the silicate chondrules: similar globules have been produced experimentally by Fredriksson *et al.* (1962), with shock pressures ranging from 150 to 800 kb.

Conclusions

From a general point of view the Siena meteorite may be considered an ordinary chondrite with relatively ambiguous characteristics. The mineralogy of this stone suggested to the petrographers (Prior, 1920; Keil, 1962; Mason, 1963; Hey, 1966) a hypersthene chondrite or amphoterite, while the chemical analysis revealed a high total iron (25·31 %). This is not the only case mentioned in the meteoritical literature: the Chainpur meteorite is a similar example and it was defined by Keil *et al.* (1964) as



FIGS. 16–19. FIG. 16 (top left). A barred olivine chondrule; faults are evident; wavy extinction (crossed nicols). FIG. 17 (top right). A cryptocrystalline hypersthene chondrule (BM 33990, ordinary light). FIG. 18 (bottom left). Mylonitization in a distorted olivine chondrule (BM 33990, ordinary light). FIG. 19 (bottom right). The core of a reticulated monosomatic olivine chondrule (BM 33990, ordinary light).

an 'olivine–hypersthene chondrite in chemical composition and an olivine–pigeonite in mineralogy (and structure)'. So the Siena meteorite may be defined as *an olivine–bronzite chondrite in chemical composition and an olivine–hypersthene chondrite in mineralogy*: our study could demonstrate again that it is not enough to do only the mineralogical investigation or only the chemical analysis, but that both have to be considered in order to get more complete information on the nature of meteoritic stones.

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