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## THE PROBLEMS OF THE ORIGIN AND STRUCTURE OF CHONDRULES IN STONY METEORITES

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Chondrules are spheroidal aggregates of one or more silicates, which occur in about 90 per cent of all stony meteorites. In form, manner of crystallization, texture and structure, they are like no other spheroidal bodies observed in terrestrial rocks.

The study of chondrules—how they were formed and the alterations they have undergone subsequent to their formation—is not an end in itself; it has significant bearing on related problems. As a constituent part of chondritic meteorites, chondrules reflect the conditions under which the chondritic meteorites themselves were formed, and, by extension, the conditions under which meteorites of all types were formed. Chondrules bring to notice a type of rock which exists in the solar system and which, it may be presumed, has the sort of composition likely to be found in the substances in the interior of the earth. No discussion that relates to the origin of meteorites or to the material constituting the interior of the earth can be complete that does not take into account the nature and origin of chondrules. This matter has not received the attention it deserves.

### MINERALOGY OF CHONDRULES

The general mineralogy of the chondrules is fairly well established. It is essentially the same as the matrix in which it occurs. In order of their relative abundance the constituent minerals forming chondrules are: olivine; pyroxene; plagioclase feldspar, ranging from anorthite to oligoclase; glass; nickel-iron; iron sulphides, both pyrrhotite and the variety troilite; and chromite. There are others, commonly referred to as "minor constituents," such as apatite (merrillite) and manganapatite. Because of their minute size and

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because they occur co-mixed with dust-like aggregations of other minerals, it is often well nigh impossible to isolate or identify most of these with any degree of certainty, optically or otherwise.

Olivine and pyroxene are the principal constituents. Feldspar occurs rarely, but there is maskelynite, a mineral, the exact nature of which is yet to be determined. Some regard it as a metamorphosed product resulting from re-fusion of feldspar; others as a distinct mineral allied to leucite. Chondrules containing plagioclase in excess of olivine and manifesting alternating barred structures are best seen in the Dharamshala meteorite. A high temperature feldspar (probably a variety of albite) has been seen in the Walters meteorite (Walters: Glass, Roy and Henderson, MS.). The mineral shows considerable optical abnormality. Biaxial negative,  $2V = 40^\circ$  to  $60^\circ$ . Birefringence = 0.007. Glass, clear or stained or clouded with inclusions, is a common constituent of chondrules. Glass containing microlites of enstatite also occurs.

Nickel-iron occurs as blebs, as small interstitial grains, and as rims surrounding some chondrules. Rounded bodies resembling chondrules and composed wholly of nickel-iron are uncommon, but they do occur. Such bodies may or may not contain grains of iron sulphide. The latter mineral, however, occurs in chondrules composed chiefly of silicates. Chromite in microscopic grains occurs as inclusions usually near the surface of the chondrules. The presence of inclusions of iron, iron sulphide, and chromite in large quantities may render the chondrules completely opaque. On the whole, the constituent minerals of the chondrules are often the same as those of the ground mass in which they are embedded. This may be considered as a significant factor in the conditions which have brought about the formation of the chondrules.

The metalliferous portions—the iron-nickel and the iron sulphide of the chondrules and of the ground mass of the stony meteorites—are the same as those of the iron meteorites. This may be regarded as another significant feature.

#### OCCURRENCE, TEXTURE AND STRUCTURE OF CHONDRULES

The silicate content of the stony meteorites diminishes from the silicate phase toward the iron phase; thus, I favor the interpretation that the meteorites, whether iron, iron-stone, or stone, were derived from a mass that had density stratification and a metallic core surrounded by silicate shells of decreasing density. Even if the meteorites are fragments of more than one cosmic mass, it would

still seem from the meteorites known to us that those separate masses had similar structure, therefore the same cooling history and the same mode of crystallization and crystal settling. That the iron and stone meteorites exhibit, respectively, well-formed and hasty crystallization, further indicates that the iron was covered by the silicates. In the cooling of such a mass under a silicate mantle, the temperature of the interior would remain sufficiently high to keep the iron viscous long enough to favor slow cooling and the growth of well-formed crystals; the silicate exterior, being exposed, would naturally cool more rapidly and thus crystallize more rapidly. Thus, it would seem that the stone and iron meteorites were born of the same parent, rather than of different ones.

Texturally and structurally the chondrules in the same meteorite show great variations in shape, size, and manner of crystallization. The last may vary from densely crypto-crystalline through a great many intermediate forms to holo-crystalline. The center of crystallization also varies; it may be eccentric or multiple. The variations of these features are so great that no attempt here has been made to describe each individually. Instead, a few representative photomicrographs (figs. 164–175) have been selected to illustrate some of the diversities and attending complexities that are presented.

#### PREVIOUS WORK AND PRESENT STATUS

In 1915, my predecessor in this Museum, the late Dr. O. C. Farrington, stated: "The conditions which have brought about the formation of chondri are not well understood, though the question has been much discussed and various hypotheses have been suggested." (Farrington, 1915, p. 108.) The substance of this statement is still materially correct.

Soon after the introduction of the petrographic microscope, Reichenbach (1860) announced that chondrules are older small meteorites enclosed in younger and bigger ones, "Meteoriten en Meteoriten." A number of investigators since then have expressed widely different views. To summarize briefly: (1) chondrules are fused drops of "fiery rain" (Sorby, 1864, 1877); (2) chondrules are fragments of pre-existing meteorites, which have become rounded by oscillation and attrition (Tschermak, 1895); (3) chondrules are products of a special phase of magmatic segregation, formed in place as a result of rapid, arrested crystallization in a molten mass (Brezina, 1885); (4) chondrules originated from dispersal of a silicate

melt in a hot atmosphere, the resultant drops crystallizing from the outside inward (Wahl, 1911); (5) chondrules are metamorphosed garnets—garnets converted to enstatite (Fermor, 1938); and (6) chondrules were produced by the cooling of liquid silicates, which fell as a molten rain during a collision of a small asteroid with a larger one (Urey and Craig, 1953).

The diverse and conflicting views cited here indicate that the problem is still an obscure one. The principal reason seems to be that many of the hypotheses proposed were based upon examination of a limited number of chondrites—access to a greater number was obviously difficult or impossible. Another reason is that little or no attention was paid to the importance of the order of crystallization of minerals from solution. Some of the views presented were inferences drawn from chemical analyses or from literature that itself contained no concrete information. *In a field of inquiry of this sort, where direct contact with the objects of research is possible and essential, inferential hypotheses are not likely to meet the requirements of acceptance.*

My own tentative view is one that, in some respects, reflects the concepts of Brezina (1885) and Wahl (1911). The occurrences of pyroxene chondrules enclosed by olivine *in situ*, seem to me irrefutable evidence that they were formed in place, as products of magmatic separation. The anomalous relationships of various components, so marked in chondritic meteorites, can be the result of subsequent deformation and metamorphism. Practically all chondritic meteorites—if not all—have undergone a certain degree of metamorphism, and some have undergone repeated metamorphism (Paragould: Roy and Wyant, 1955; Walters: Glass, Roy and Henderson, MS; see also Wahl, 1952). I have no definite explanation of the eccentric or multiple centers of crystallization or the occurrence of astonishing variations in texture in chondrules of identical composition, often within the narrow space of a fraction of a square centimeter.

#### SUGGESTED GENERAL PLAN OF STUDY AND PROCEDURE

Chondrules are of igneous origin; they were subjected to laws similar to those which govern the formation of terrestrial igneous rocks. With this in mind, and recalling that the relationships between components of a rock cannot be divorced from its physical history, studies should begin with thin sections, and in some cases, polished surfaces. The features to be noted in order of importance



are: *the order in which the different minerals have appeared; the degrees of metamorphism; textural and structural variations; and the distribution and interrelationships of the various components of the chondrules.* Detailed knowledge of these features is indispensable; it may reveal the original environment of the chondrules and provide the information necessary for building an acceptable theory. Thermometamorphism and brecciation have played an important role in producing the deviations in chondrules from the norm, but these later changes and adjustments can be traced, once the original environment has been established. Color microphotographs of thin sections, in ordinary light and between crossed nicols, and black and white photographs of some of the polished surfaces, are of the utmost importance in this study, both for the interpretation of the features observed under the microscope and as a permanent reference for comparison and discussion of controversial points.

The problem is more one of petrology than one of analytical chemistry. It deals with forms and features, the mode of formation of which cannot be satisfactorily interpreted alone in the light of elements and compounds present. Their distribution and interrelationships should be seen and examined in polished and thin sections and the necessary interpretations should then be made.

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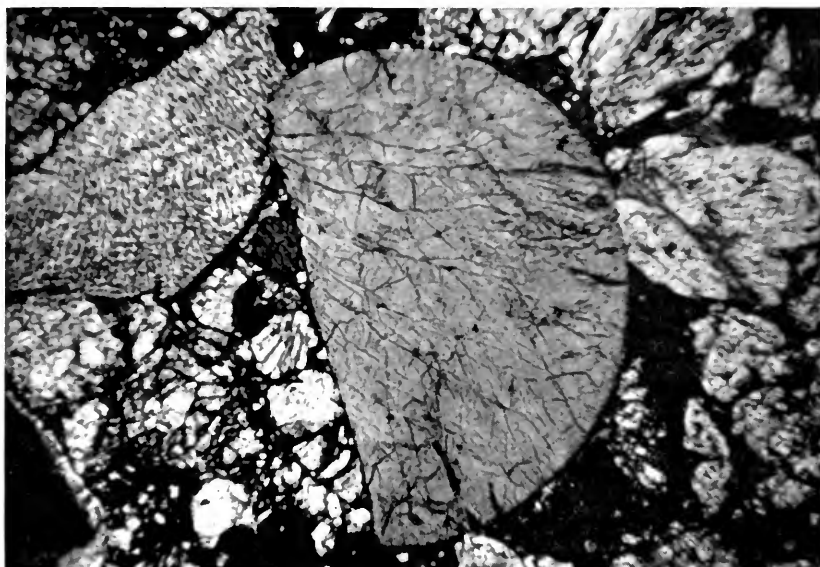


FIG. 164. Mezö-Madaras meteorite; Transylvania. Polymict brecciated gray hypersthene-chondrite;  $\times 40$ .

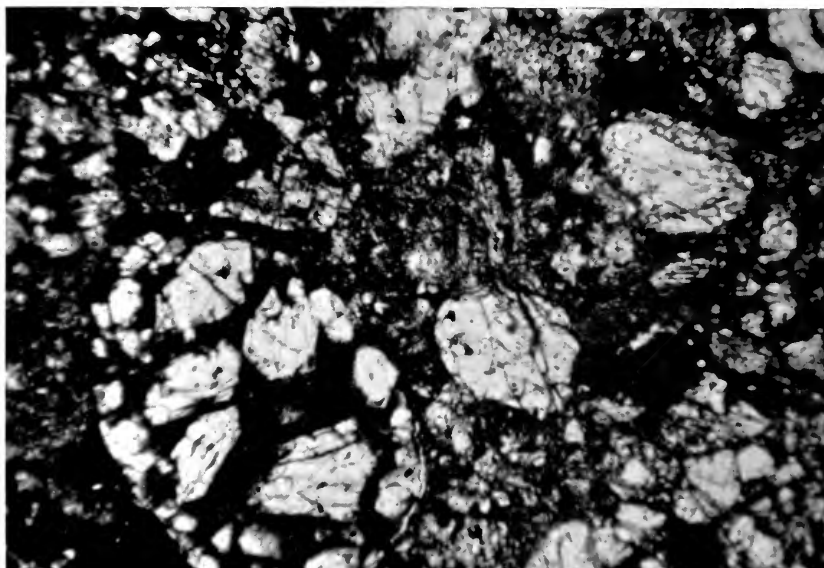


FIG. 165. Allegan meteorite; Allegan County, Michigan. Spherical bronzite-chondrite;  $\times 40$ .

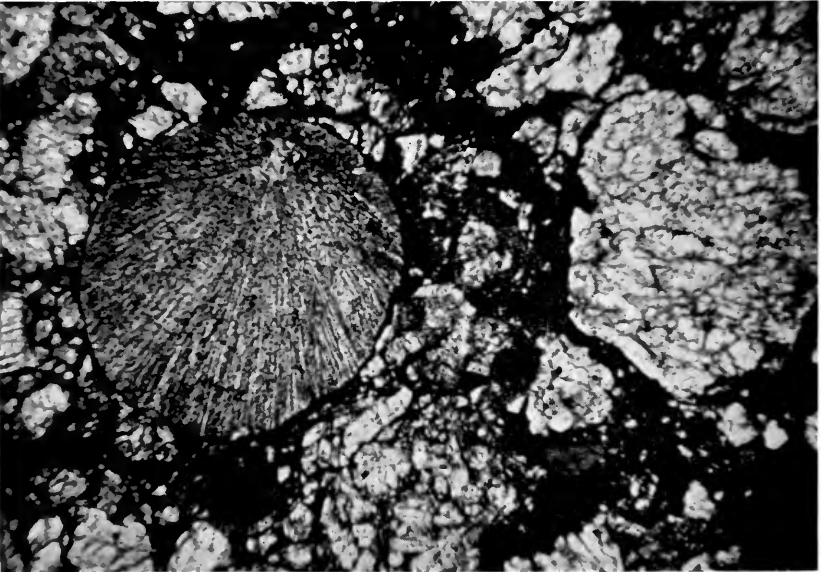
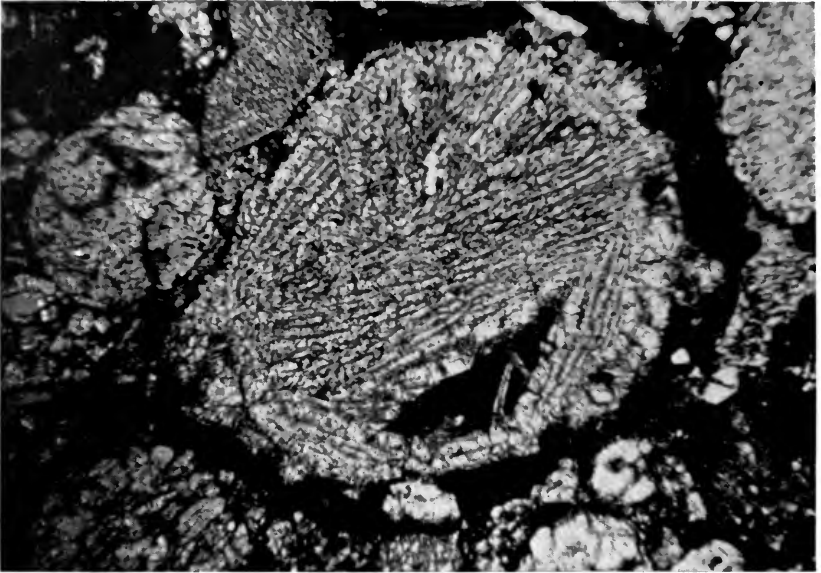


FIG. 166. Mezö-Madaras meteorite; Transylvania. Polymict brecciated gray hypersthene-chondrite;  $\times 40$ .

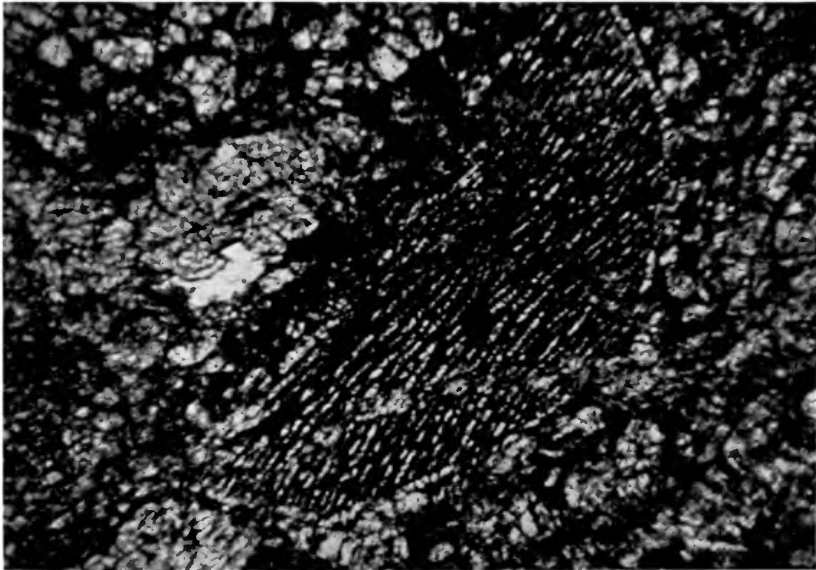
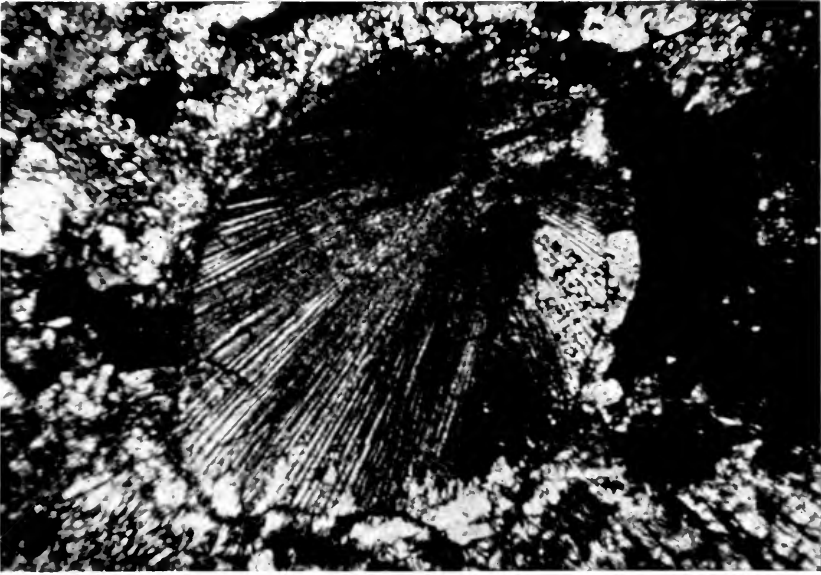


FIG. 167. Dharamshala meteorite; Kangra District, Punjab, India. Intermediate hypersthene-chondrite;  $\times 40$ .

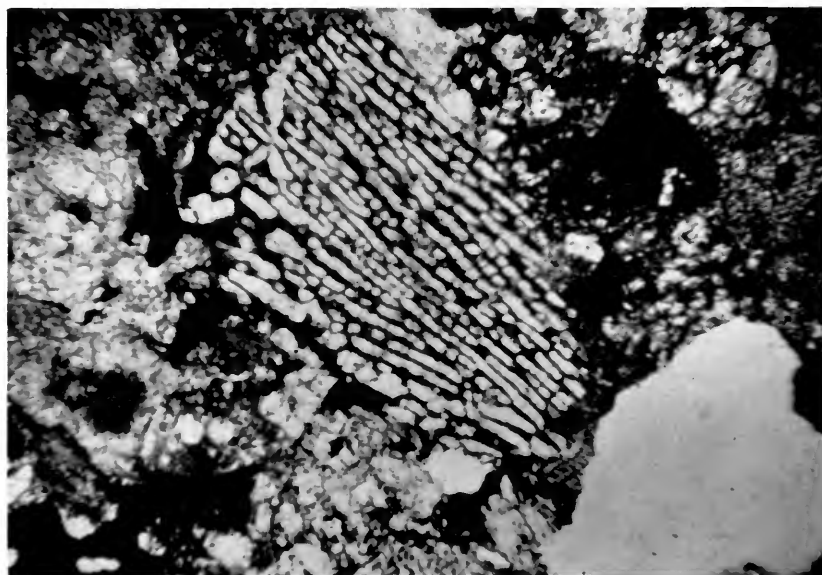


FIG. 168. Kesen meteorite; Iwate, Honshū, Japan. Spherical hypersthene-chondrite;  $\times 40$ .

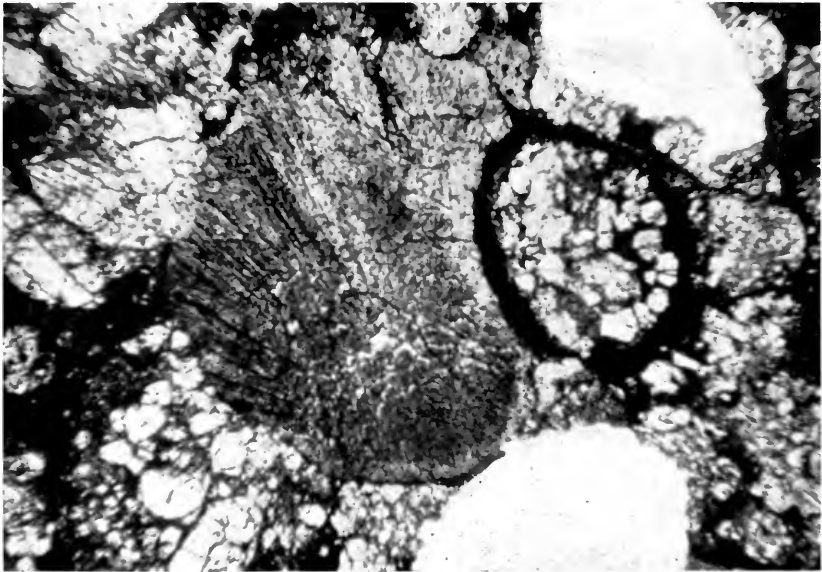
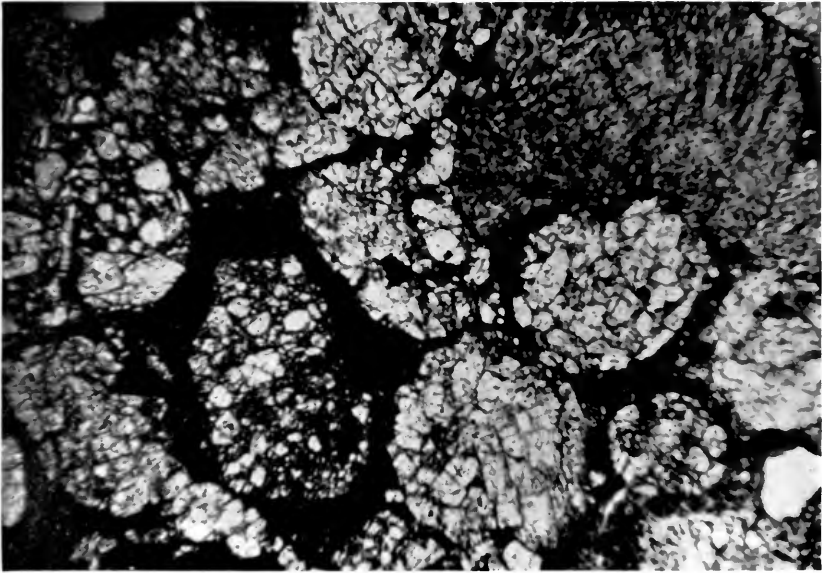


FIG. 169. Parnallee meteorite; Madura District, Madras, India. Polymict brecciated veined gray hypersthene-chondrite;  $\times 40$ .

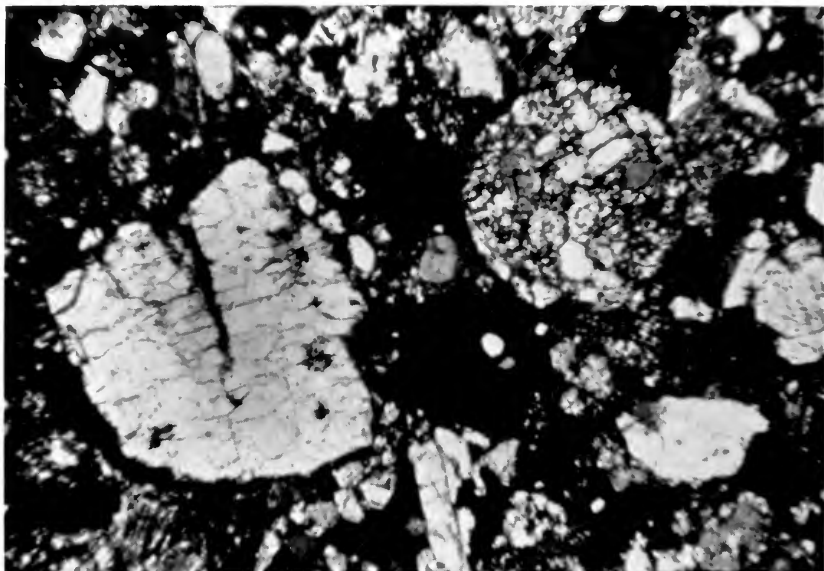


FIG. 170. Beaver Creek meteorite; West Kootenay District, British Columbia. Crystalline spherical bronzite-chondrite;  $\times 40$ .

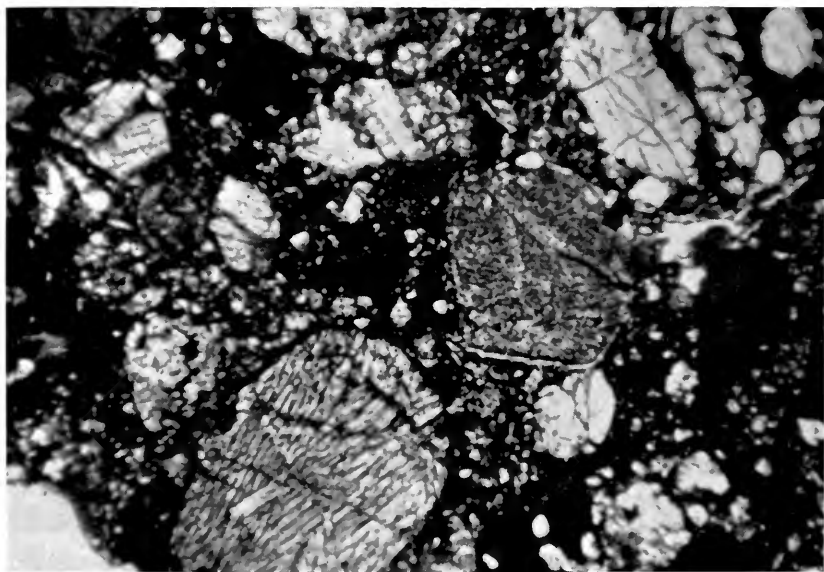


FIG. 171. Weston meteorite; Fairfield County, Connecticut. Polymict brecciated spherical chondrite;  $\times 40$ .



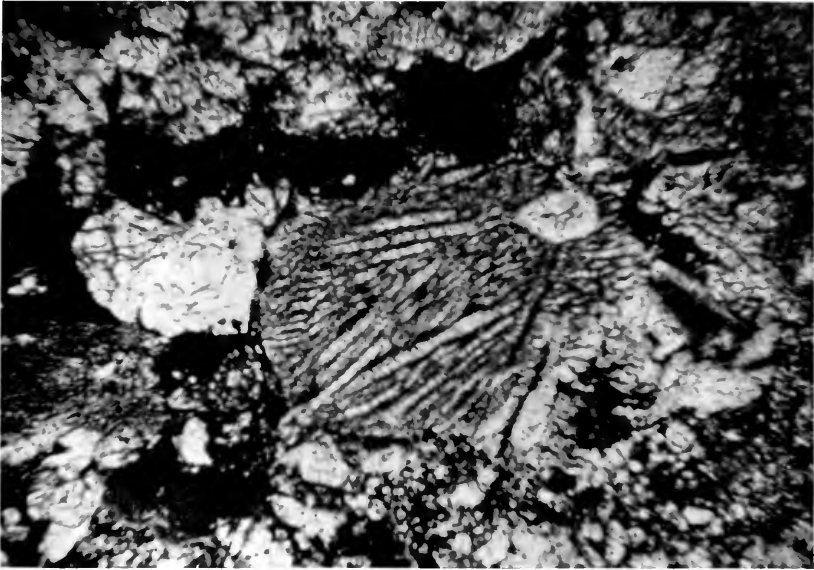


FIG. 172. Knyahinya meteorite; Nagy-Bereszna, Czechoslovakia. Polymict brecciated gray hypersthene-chondrite;  $\times 40$ .

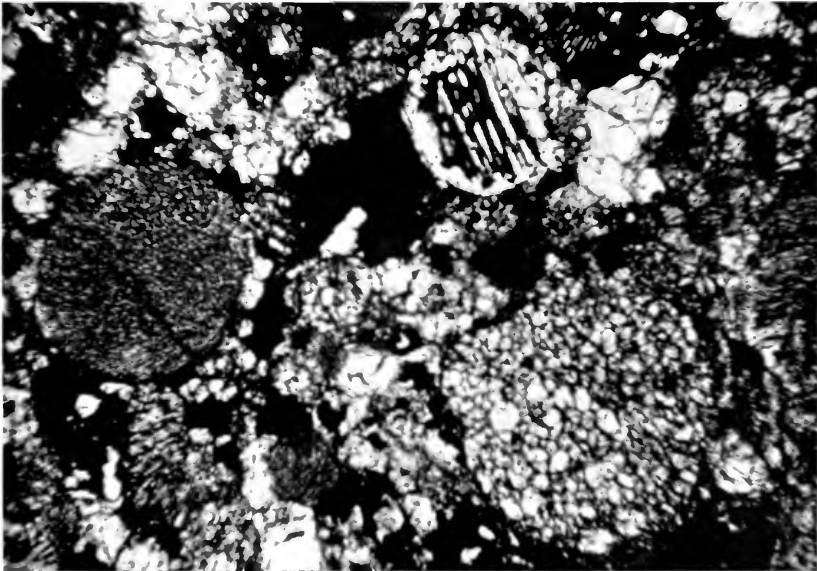


FIG. 173. Pultusk meteorite; Warsaw, Poland. Veined gray bronzite-chondrite;  $\times 40$ .



FIG. 174. Ensisheim meteorite; Alsace, France. Polymict brecciated crystalline hypersthene-chondrite;  $\times 40$ .

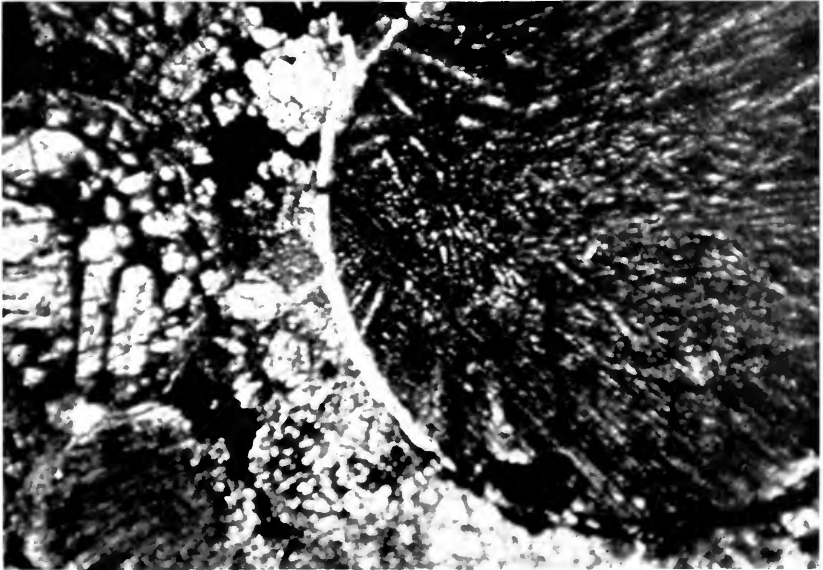
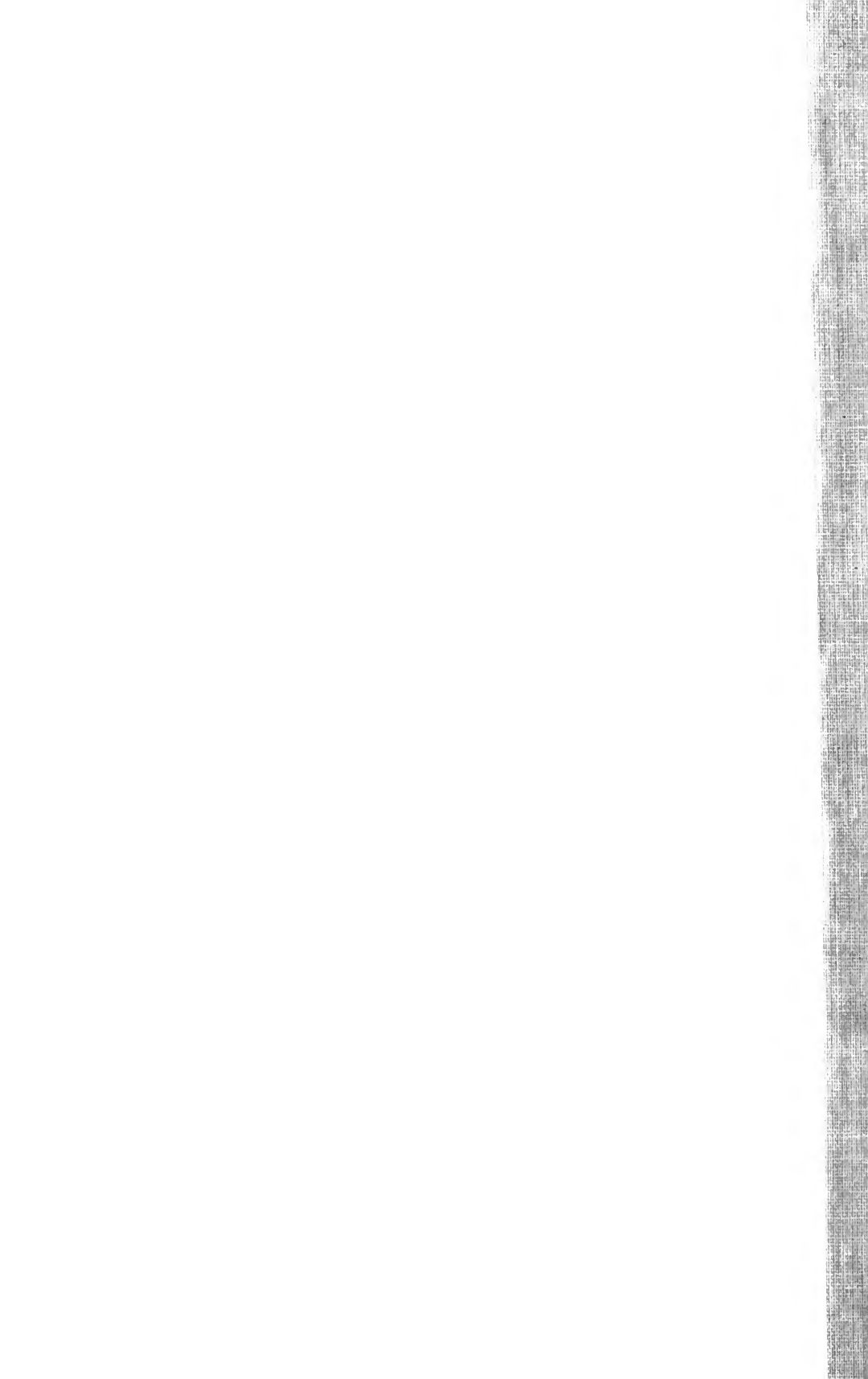


FIG. 175. Ausson meteorite; Haute Garonne, France. Spherical hypersthene-chondrite;  $\times 40$ .











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