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A Study of the Lalande, New Mexico, Yonōzu, Japan, and Glorieta Mountain, New Mexico Meteorites

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STEVENSON

A STUDY
OF
METEORITES

D.F.

A STUDY OF THE LALANDE, NEW MEXICO, YONŌZU, JAPAN, AND GLORIETA MOUNTAIN, NEW MEXICO METEORITES

By

Ralph G. Stevenson, Jr.

A Thesis
In partial fulfillment of the
Requirements for the Degree of
Master of Science in Geology,
prepared under a cooperative
arrangement between
The Department of Geology
and
The Institute of Meteoritics

The University of New Mexico
1950

This thesis, directed and approved by the candidate's committee, has been accepted by the Graduate Committee of the University of New Mexico in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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DATE May 16, 1950

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Thesis committee

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ABSTRACT

This thesis presents details relating to the discovery of three meteorites, as well as information concerning their acquisition, description, and mineralogy. These three meteorites are the Lalande, New Mexico chondrite (E.C.N. = 1047,343), the Yonōzu, Japan chondrite (E.C.N. = *1394*,380)*, and the Glorieta Mountain, New Mexico siderite (E.C.N. = 1058,356).

The Lalande, New Mexico meteorite is composed of olivine and enstatite (var. hypersthene), with small percentages of enstatite-clinoenstatite intergrowths, secondary hematite, and dispersed metallic grains. Alteration to iron oxide has produced a strong stain over most of the component grains. The meteorite is classified as a hypersthene-olivine chondrite (Chy).

The Yonōzu, Japan meteorite is composed of olivine and enstatite (var. hypersthene), with small percentages of enstatite-clinoenstatite intergrowths, secondary hematite, possible diopside and anorthite, and metallic grains. A very strong coating of iron oxide has been produced on many of the non-metallic grains by alteration of the olivine and hypersthene. The meteorite is classified as a hypersthene-olivine chondrite (Chy).

The Glorieta Mountain meteorite is a siderite composed

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* Underlining indicates italics.

of kamacite, taenite, and plessite, with a small percentage of schreibersite scattered throughout the kamacite. This specimen shows none of the pallasitic areas which have been reported in some other members of this fall. The meteorite is classified a medium octahedrite (Om).

INTRODUCTION

Purpose of Study

The principal purpose of this study is to make useful contributions to the present knowledge of mineralogy with relation to meteorites. The question most likely to arise in many minds at this point is "Why study meteorites at all?" At least two answers to this question can be easily brought forth.

Primarily, it should be evident to all scientists at this time that pure research is valuable. In this sense, the study of meteoritics is strongly woven into the science of astronomy. Since the beginnings of conscious thought mankind has gazed at, and speculated about, the heavenly bodies. Meteorites represent the only tangible, material link between our limited terrestrial environment and the apparently limitless reaches of "Outer Space". The study of meteorites, and even the realization of their extra-terrestrial origin, was long retarded by religious tabus and superstitions.

It is apparent at the present time that more and more people are becoming more and more interested in what lies beyond the boundaries of the sphere to which mankind has always been inexcapably imprisoned. This interest is partially due to the human tendency to explore and study

the unknown, a tendency which has been instrumental in advancing the human race to the position it now occupies. This interest is intensified by the increasing possibility of bursting the bonds which have fettered man to his terrestrial habitat.

This thought leads directly to a part of the second reason for the study of meteorites. This reason follows a more immediate and practical vein. The study of meteorites has given invaluable aid to the growing science of rocketry, indirectly by furthering astronomical knowledge, and directly by furnishing design data which could only be obtained otherwise by expensive and time-comsuming trial-and-error experimentation. Meteorites are the only solid objects mankind possesses which have traveled in the regions under consideration and at velocities of the same order as those now attained by rockets. Their study supplies data relating to the conditions to be expected in the areas to be traversed in rocket flight. Their study indicates the shapes best fitted for flight in these areas, and provides information relating to paths and trajectories of objects at relatively great distances from the center of the earth.

The remainder of the second reason lies in various military and industrial applications of meteorite studies. As examples, consider the origin of nickel-iron armor plate and stainless steels. Perhaps a more important application

was initiated during the First World War and continues at the present time. This is the computation of trajectories for high-altitude and non-conventional artillery projectiles. Much important information concerning the upper atmosphere has been contributed by the study of meteors and meteorites.

It can be further demonstrated that the study of meteorites links astronomy and geology in philosophical as well as practical aspects. It furnishes data relating to the composition and structure of the interior regions of the earth. Substantiation of these data by other means then indicates similarity of the overall structure of the earth and at least some of the other members of the solar system. This in turn provides some reason for postulating a common origin, and thereby furnishes information useful in formulating hypotheses relating to formation of the earth and of the solar system as a unit.

Method of Study

The method employed in this study is fourfold, consisting of thin-section, oil-immersion, polished section, and chemical analyses. Each of these phases of the study is briefly described below.

To appreciate thin-section analysis, one must first know what a thin-section is. A thin-section consists of a thin slice of the specimen, ground to a thickness of was [illegible]

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approximately 0.03 mm, and mounted on a glass slide with Canada balsam. Thin-section analysis consists of identification of the non-opaque mineral components and of determination of some of their optical constants. Grain counts and statistical estimation provide rough percentages of the various constituents. Structures and textures, or the relationships of the component minerals to each other, can be ascertained with a high degree of accuracy. Thin-section studies are carried out through the use of a petrographic microscope with a sub-stage light source.

Oil-immersion analyses are useful in providing detailed optical data on the minerals. The first step in the procedure is to grind a small quantity of the specimen to a relatively small grain diameter. Some of these grains are then immersed in a drop of an oil of known refractive index on a glass slide. A cover glass is placed over the oil and grains. By use of a petrographic microscope the refractive indices of the minerals are compared to the known index of the oil. Preparation and study of other immersions in oils of different indices provides a means of ascertaining the indices of the minerals to within 0.003 units, or to within 0.001 units if extreme care is exercised. If the grains are randomly oriented, as they usually are, other optical data, such as the relation of the vibration directions to the crystallographic axes, can easily be obtained.

If the grains show a preferred orientation, due to parting or cleavage, it may be necessary in extreme cases to resort to methematical formulas to obtain these data. Proper usage of this procedure can provide much valuable data, including a fairly accurate chemical composition.

Polished sections are used for the acquisition of data on opaque substances. A polished section consists of a small piece of the specimen mounted in bakelite,or some similar substance,and polished to a mirror surface. Study is accomplished by use of a metallographic microscope, or a petrographic microscope equipped with a vertical illuminator. This phase of the study is followed in an effort to determine the composition and structure of the metallic phase of each meteorite.

Quantitative chemical analyses were made from small samples of each meteorite by Dr. E. L. Martin of the Chemistry Department of The University of New Mexico. From these chemical analyses normative compositions have been calculated by the writer for each meteorite.

For clarification of certain aspects of the study 40 photographs and microphotographs are included.

Meteorite-Planet Hypothesis

Study of the meteorites supports the currently most acceptable hypothesis for the origin of meteorites, the

meteorite-planet hypothesis. This was first suggested by Boisse and Meunier and was later worked out independently by Farrington. Recently it has been given further support by Brown (1948) of the University of Chicago. Boisse and Meunier arrived at this hypothesis as a result of cogitation on the density spectrum of meteorites, from the heaviest siderites to the lightest aerolites. Farrington based his conclusions on studies of the structural pattern of meteorites. Each party independently theorized that all meteorites had their origin in the disruption of a single celestial body of subplanetary size constituted much like the earth. Brown (1948) has applied thermodynamics to the study of meteorite composition. His investigations support the meteorite-planet hypothesis but indicate a body with dimensions about equal to those of Mars. Its orbit lay between the orbits of Mars and Jupiter. Disruption of this planet was accomplished in an unknown manner; perhaps by tidal forces, by internal explosion, or by collision with another planet. The meteorite planet is thought to have had a core of nickel-iron and a silicate mantle with dispersed nickel-iron decreasing in amounts as the surface is approached. Therefore, the less metallic phase in a meteorite the closer to the surface of the planet it had its origin.

Acknowledgments

This thesis was written under a cooperative arrangement between the Department of Geology and the Institute of Meteoritics of The University of New Mexico. The writer is indebted to Dr. Carl W. Beck of the Geology Department, at whose suggestion this study was undertaken, for guidance and aid in its prosecution. For meteoritical background, as well as for pertinent suggestions regarding the investigation reported on in this thesis, the writer wishes to thank Dr. Lincoln LaPaz, Director of the Institute of Meteoritics at The University of New Mexico. The writer is indebted to Dr. J. Paul Fitzsimmons of the Geology Department for critical reading of the manuscript. Finally, the author is indebted to the Department of Geology for provision of the specimens of the Glorieta Mountain and Lalande, New Mexico meteorites studied in this investigation; to the Institute of Meteoritics for providing the specimen of the Yonōzu, Japan chondrite; and to both the Department of Geology and the Institute of Meteoritics for making available equipment and supplies.

THE LALANDE, NEW MEXICO CHONDRITE (E.C.N. = 1047,343)

Introduction

The Lalande meteorite was found in 1933 near the Lalande postoffice in De Baca County, New Mexico. A single mass weighing seventy-seven pounds was discovered. Although less than 15 percent of the thin-section studied consisted of chondrules, the stone has been classified as a chondrite. The specimen studied is a three-pound-twelve-ounce piece cut from the original mass. This specimen is part of the Joe R. Heaston collection of New Mexico meteorites at The University of New Mexico, and is catalogued as Specimen N. 464.50. It also carries the designation of IOM-6 under the Institute of Meteoritics classification.

The above represents essentially all the information that has previously been available on the Lalande meteorite. Mention of it was made by Nininger (1934) in his paper on the nearby Melrose meteorite. Due to the extreme similarity of the two above-mentioned specimens the possibility has been recognized that they may actually belong to the same fall. If this can be proved a fact, the name Melrose should probably take precedence by reason of priority.

Specimens of both stones are seen to possess an essentially identical overall color on cut surfaces, a deep brownish-green. The mineral composition of the non-metallic

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phase of both stones shows extreme similarity. The amount and distribution of the metallic phase of both specimens, as shown on cut surfaces, reveal close similarity. Both meteorites exhibit the relatively unusual feature of megascopically observable troilite nodules surrounded by kamacite.

The only observable difference in the two meteorites consists of a difference in surface coloration, which might easily have arisen from dissimilar environmental circumstances after arrival on the earth. The one distinct difference should have been the presence of gold in the Melrose, called "the only gold-bearing meteorite in America." (Ninger, 1934). Recent analyses of four fragments of the Melrose meteorite, utilizing the Purple of Cassius and the Phenylhydrazine Acetate methods of testing for gold, have failed to show any gold content. Analyses of Lalande have also failed to indicate any gold.

This paper represents a part of a careful study of the possibility of these stones belonging to the same fall being carried out by Dr. Carl W. Beck of the Department of Geology at The University of New Mexico, Dr. Lincoln LaPaz, Director of Meteoritics at the same institution, and the writer. On the basis of the complete Lalande study and the studies already made on the Melrose, it is believed at the present time that Lalande is not a distinct fall, but is simply a member of the widely scattered Melrose shower.

Since the longitude of the Melrose find, according to Leonard, is, to the nearest tenth of a degree, 103.6° West, while the longitude of the postoffice at Lalande, New Mexico, near which the Lalande specimen was found, is approximately 104.7° West, it follows that the linear dimension of the Melrose strewn-field considerably exceeds 50 miles and hence is the most extensive of the recognized showers.

Megascopic Examination

The specimen of the Lalande, New Mexico meteorite, which constitutes a part of the Joe R. Heaston collection of New Mexico meteorites at The University of New Mexico, weighs three pounds and twelve ounces. It is catalogued as Specimen N. 464.50 and IOM-6, and apparently represents a small end portion of the seventy-seven pound mass which was discovered near Lalande postoffice in De Baca County, New Mexico, in 1933.

In shape this specimen closely resembles a crude oblique pyramid with a rounded apex when it is set on the sawed base (Fig. 1). Approximately half of the lateral area is occupied by a gently rounded surface; the remaining half is divided between two smaller faces containing angular pits and projections. These latter two faces meet at an angle roughly equal to 65°. The entire basal area is composed of the flat surface left by the saw when the specimen

Figure 1

Exterior Surface. Lalande Meteorite.


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was cut from the large mass (Fig. 2).

The area of the base is approximately 100 square centimeters. The altitude of the pyramid is 11 centimeters. The slant height of the large rounded surface is slightly under 18 centimeters.

The appearance of the large rounded surface differs somewhat from that of the more angular surfaces, and the basal face, being an interior face, naturally differs radically from all the others, since they have been exposed to conditions inducing alteration while the base has been protected.

The large rounded surface is red-brown or brown-red. It has the general appearance of an unsorted ferruginous sandstone. The surface is covered with fine pits and an occasional large one. A rather granular appearance with some observable chondrules is presented over this entire surface. Apparently this is a portion of the surface which was most exposed to the rigors of high-velocity flight through the outer atmosphere.

The other exterior surfaces exhibit a mottled red-brown color similar to the large one, but they have a much less eroded appearance. No chondrules were noted. The difference in surface texture between the gently rounded surface and the more angular ones may be due to either of two reasons. It may possibly be a result of the shattering,

Figure 2

Cut Surface. Lalande Meteorite. x 1

Showing Dispersal of Metallic Phase


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or explosion, of a larger mass in the atmosphere. This would offer fresh surfaces to erosion but would not halt erosion on the older surfaces. The new surfaces would thus suffer much less alteration than the older ones. A similar alternative lies in the possibility of explosion or shattering on contact with the ground. This would leave fresh surfaces exposed to weathering forces, which would produce alteration differing from that on the pre-shattering exterior surfaces.

The interior of the stone, as exposed on the cut, is deep brownish-green, with scattered metallic nodules ranging from microscopic to 6 mm in diameter. A few of these nodules show troilite surrounded by kamacite. Individual minerals are not generally distinguishable. An iron oxide stain is seen to cause the reddish color of the exterior surfaces. This color extends only a very slight distance into the body of the stone. It is generally vanishingly small as viewed in cross-section, being at most only a few tenths of a millimeter thick. This iron oxide follows a few cracks into the interior of the stone to the full depth of the cracks. Within the oxidized portion of one small crack near the surface of the stone, there appears to be a local concentration of extremely fine metallic particles. This is thought to be a "residual concentration" indicating a profusion of fine metallic particles evenly distributed throughout the body of the stone.

No fusion rind was visible in megascopic examination. Because it is not known how long this specimen had lain in the earth prior to its discovery in 1933 it seems entirely possible that such a feature may have weathered away. However, there is no evident reason for postulating that such a thing has happened.

Because the writer has been unable to accumulate any data pertaining to the discovery of the meteorite, and has not been able to locate a picture of the entire stone, all observations have been restricted to the specimen described above.

Microscopic Examination

Thin-section analysis

Thin-section analysis of the Lalande aerolite shows it to be composed of olivine and enstatite (var. hypersthene), with a small percentage of enstatite-clinoenstatite intergrowths, secondary hematite, and opaque metallic grains. Under plane light the minerals are seen to be strongly stained with an iron oxide. As olivine is readily altered to hematite it is felt that it, rather than the metallic phase or external sources, is the source of most of the iron oxide (Fig. 3). Alteration of hypersthene to iron oxide along cleavage planes is also evident (Fig. 4).

an infalling and visible to persons in [illegible]. Because it is not known how long this meteorite had lain on the earth prior to its discovery in 1936, it seems entirely possible that such a feature may have been destroyed. However, there is no evident reason for postulating that such a thing has happened.

Because the writer has been unable to secure any data pertaining to the discovery of the meteorite, and has not been able to locate a picture of the entire mass, all observations have been based upon the specimen described above.

Microscopic Examination

Thin-section analysis

Thin-section analysis of the Lincoln meteorite shows it to be composed of olivine and enstatite (var. hypersthene), with a small percentage of crystals of [illegible] quartz, secondary hematite, and opaque metallic grains. Under plane light the minerals are seen to be heavily stained with an iron oxide. The olivine is readily altered to hematite in this that is, rather than the metallic phase or external sources, is the source of most of the iron oxide (Fig. 3). Alteration of hypersthene to iron oxide along cleavage planes is also evident (Fig. 4).

Figure 3

Olivine Grain. Lalande Meteorite. x250:

Black Areas are Iron Oxide

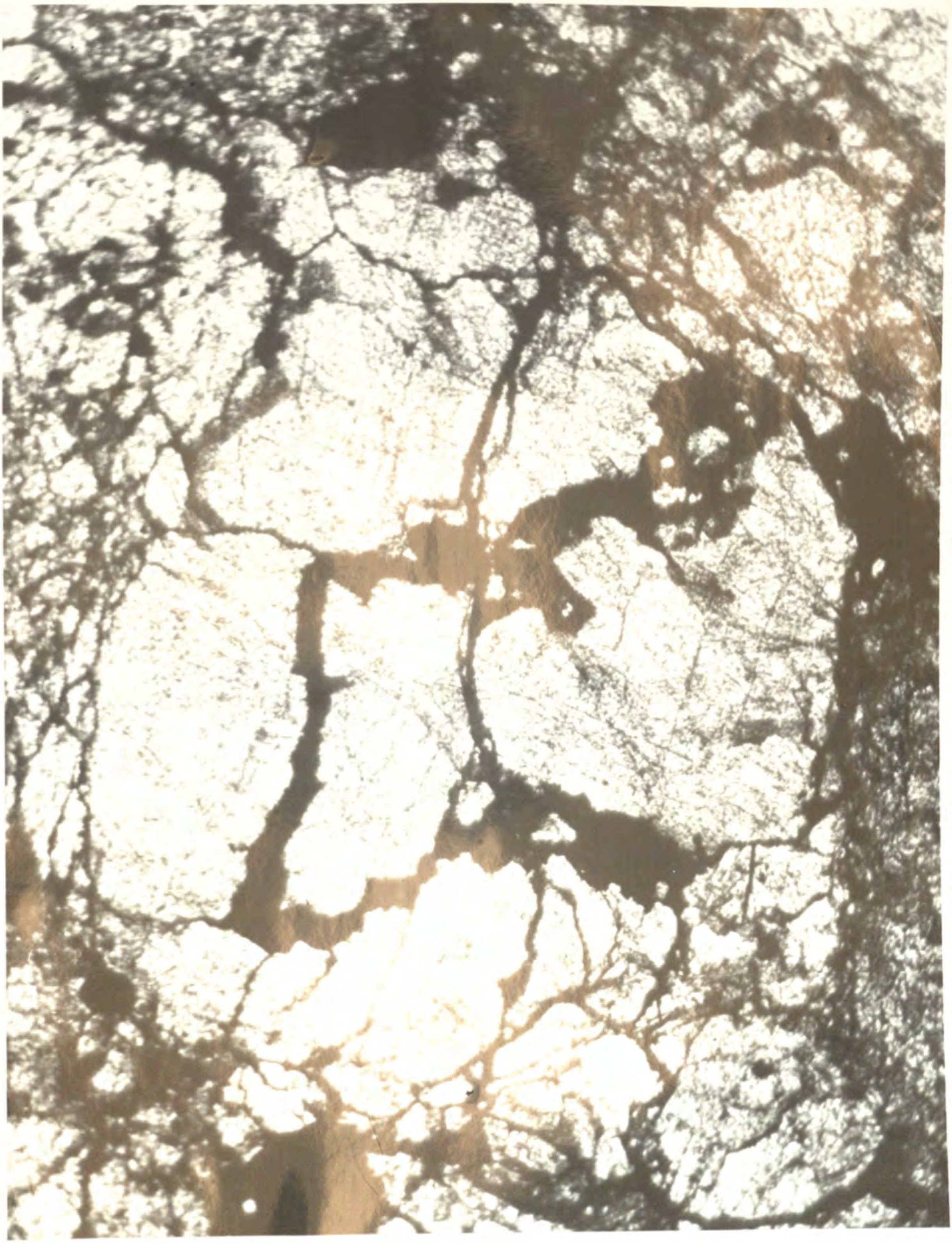
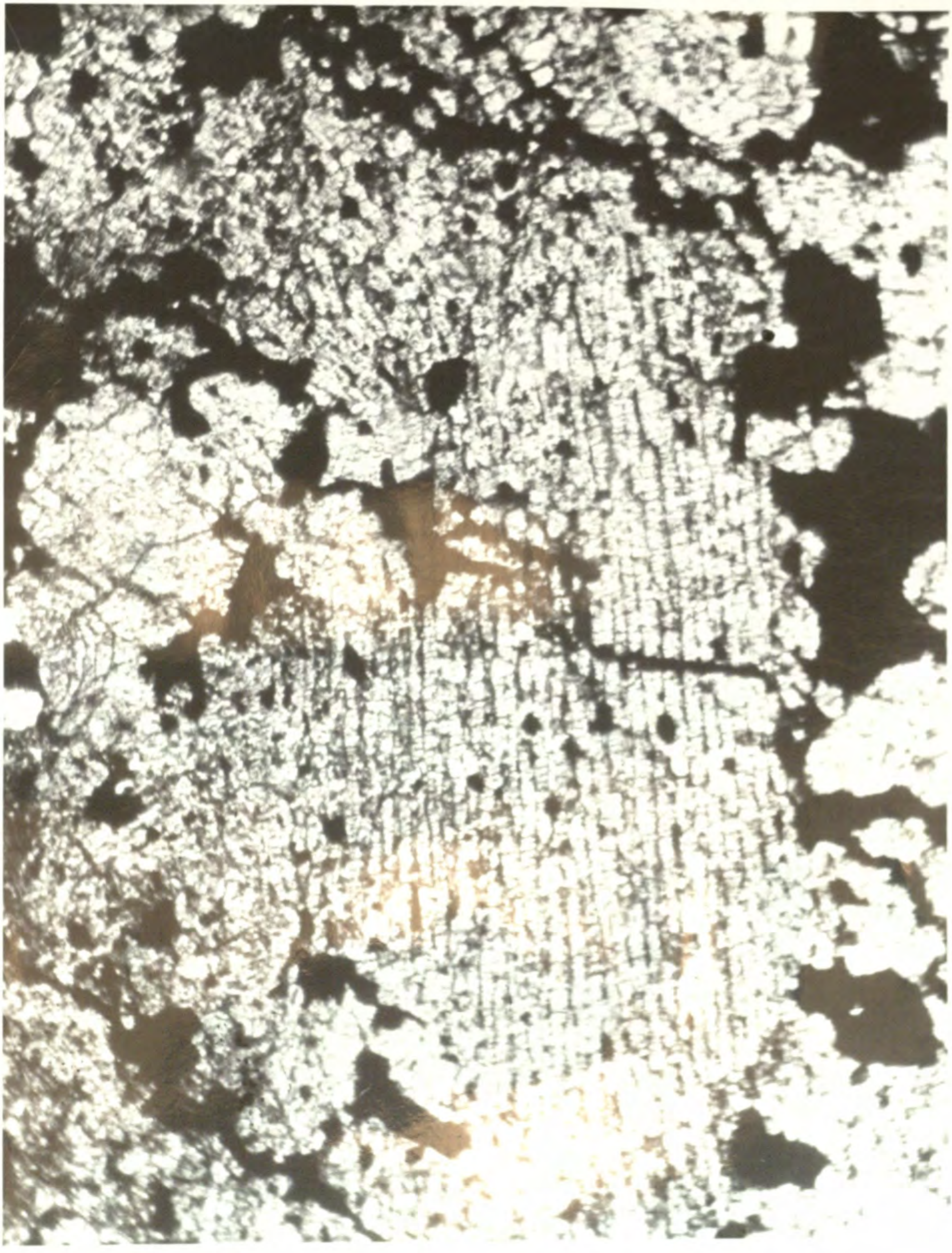


Figure 4

Hypersthene Grain. Lalande Meteorite. x250:

Black Areas are Iron Oxide



Olivine is the common name applied to members of the isomorphous series between forsterite, Mg_2SiO_4, and fayalite, Fe_2SiO_4. The general formula for olivine is $(Mg,Fe)_2SiO_4$. The crystal system is orthorhombic with a distinct $\{010\}$ cleavage and less distinct $\{100\}$ cleavage. Olivine is an essential constituent of many meteorites, of which it constitutes, with enstatite, the stony portion of the mass.

Enstatite is an orthorhombic pyroxene with a composition of $MgSiO_3$. However, natural enstatite free from iron is very rare. By some writers varieties containing less than 5 percent FeO are called enstatite; from 5 to 14 percent, bronzite; and more than 14 percent, hypersthene. As indicated above, enstatite is an important constituent of many meteorites.

Clinoenstatite is a mineral rare in igneous rocks (found in a few diabases), but not rare in meteorites. It is the same as enstatite save for the crystallography, which is monoclinic instead of orthorhombic.

Examination of the thin-section under crossed nicols shows that the above two minerals are present in a proportion of about 40 percent olivine and 60 percent hypersthene. Normal interference colors are exhibited, high blues and reds for the olivine and yellow to buff for the hypersthene. The grains of both minerals are generally fragmental (Fig. 5), although some subhedral and euhedral

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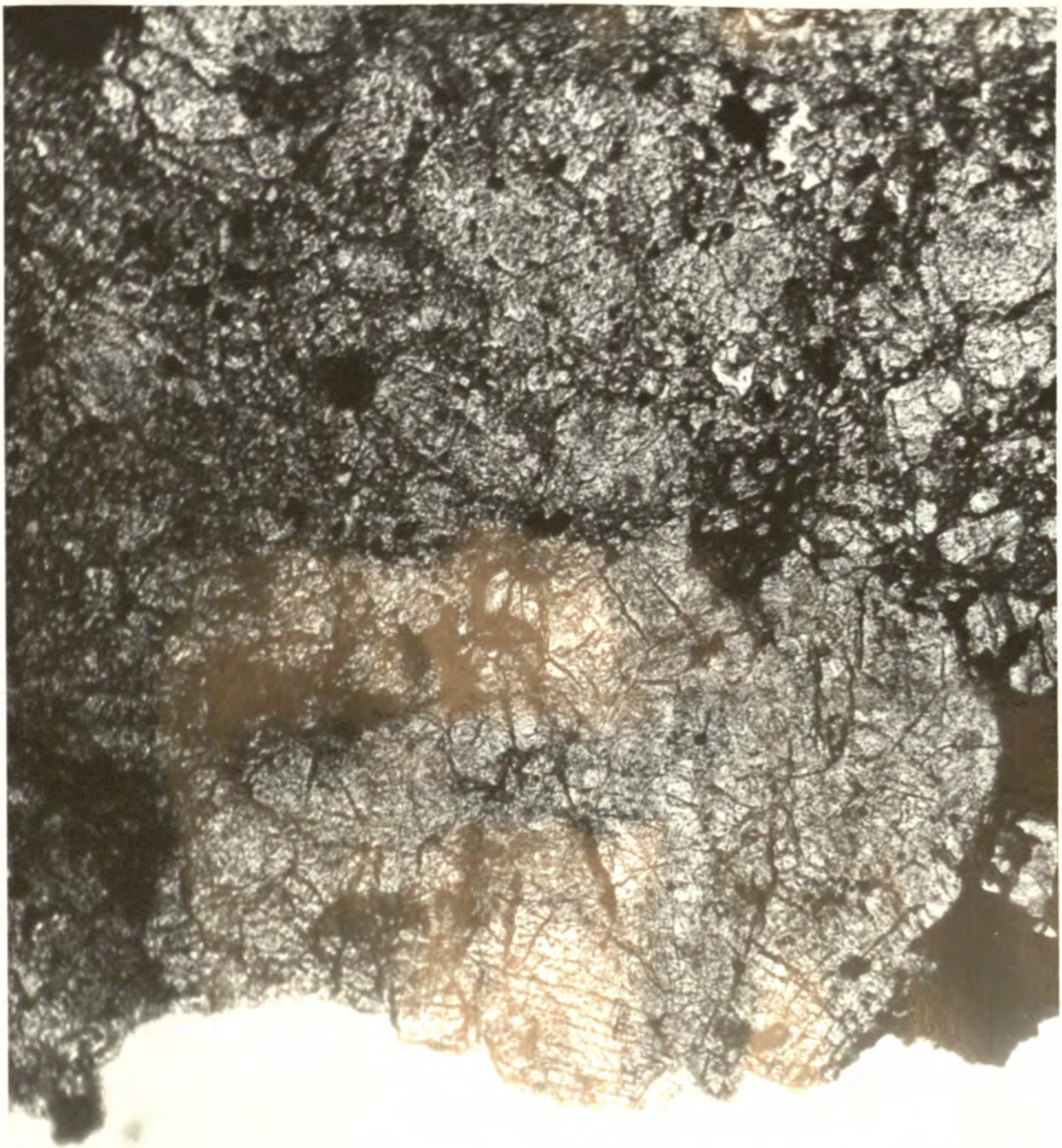
Figure 5

Fragmental Hypersthene Grain. Lalande Meteorite. x250:



olivine grains were noted (Fig. 6). At one place several olivine grains appear to be set in a matrix of randomly oriented fibrous hypersthene (Fig. 7). Several distinct chondrules were noted, comprising from 10 to 15 percent of the section. The term chondrule is derived from the Greek χονδρος , meaning a grain, and refers to the spherical granules in meteorites. These are generally composed of globular aggregations of mineral particles, and may consist of one or several minerals. There is a wide range of internal structure. The majority of the chondrules noted in this section are composed primarily of small olivine fragments, generally with a small amount of hypersthene, and are mostly imperfectly developed (Fig. 8). However, examples of well-formed chondrules were noted. These are composed of a fibrous intergrowth of hypersthene and clinohypersthene with a well-displayed radiate structure (Figs. 9 and 10). The different character of the constituent minerals is shown by the inclined extinction of some of the radiating fibers, as contrasted to the parallel extinction of normal hypersthene displayed by the rest of the fibers. A barred chondrule is illustrated in Figure 11. According to Merrill (1930, p. 32) the barred forms are limited mainly, if not wholly, to monosomatic forms composed of olivine. This chondrule is composed of hypersthene with alternating bars of iron oxide.

Figure 6

Euhedral Olivine Crystals. Lalande Meteorite. x250:

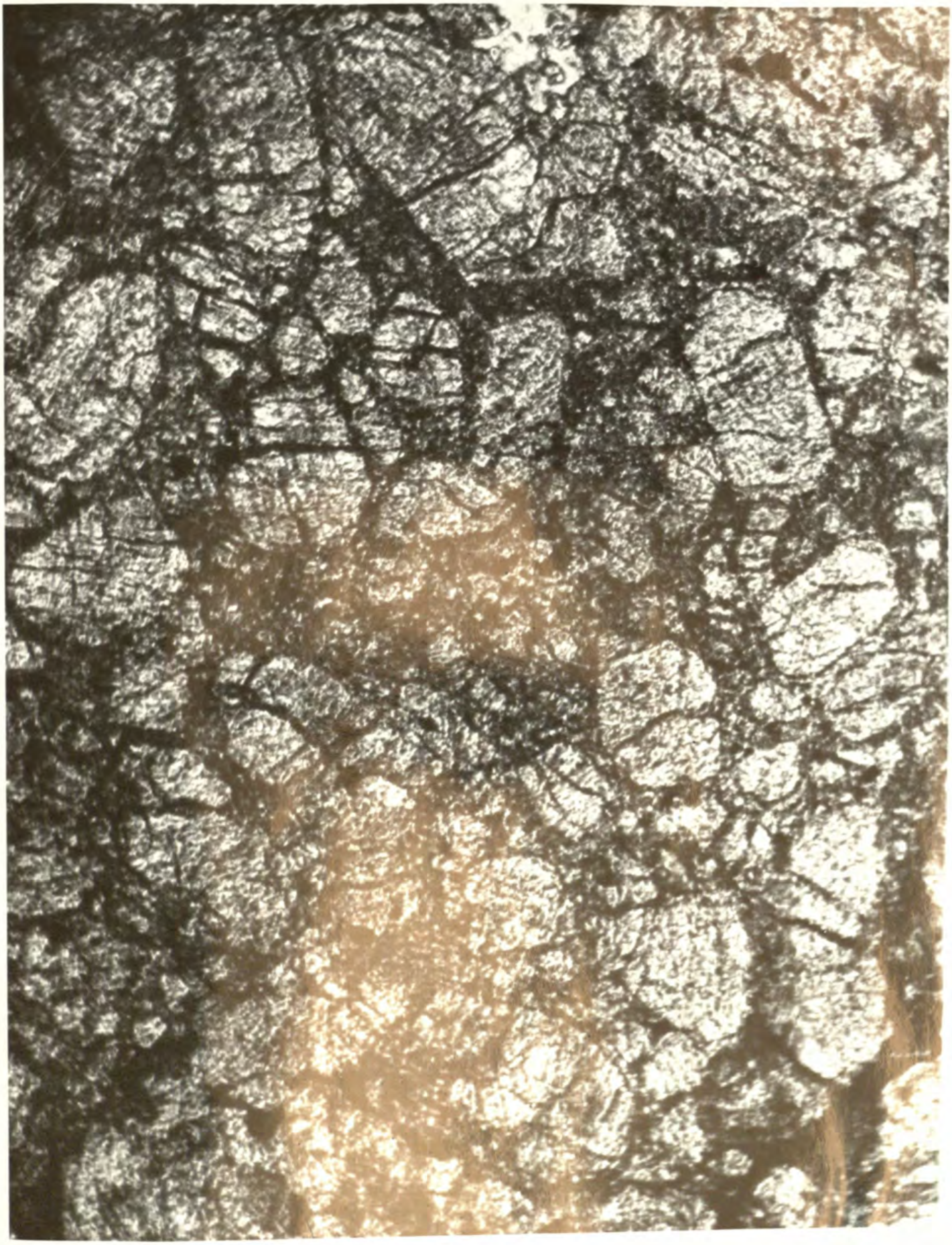


Figure 7

Olivine Grains in Matrix of Fibrous Hypersthene.

Lalande Meteorite. x250:

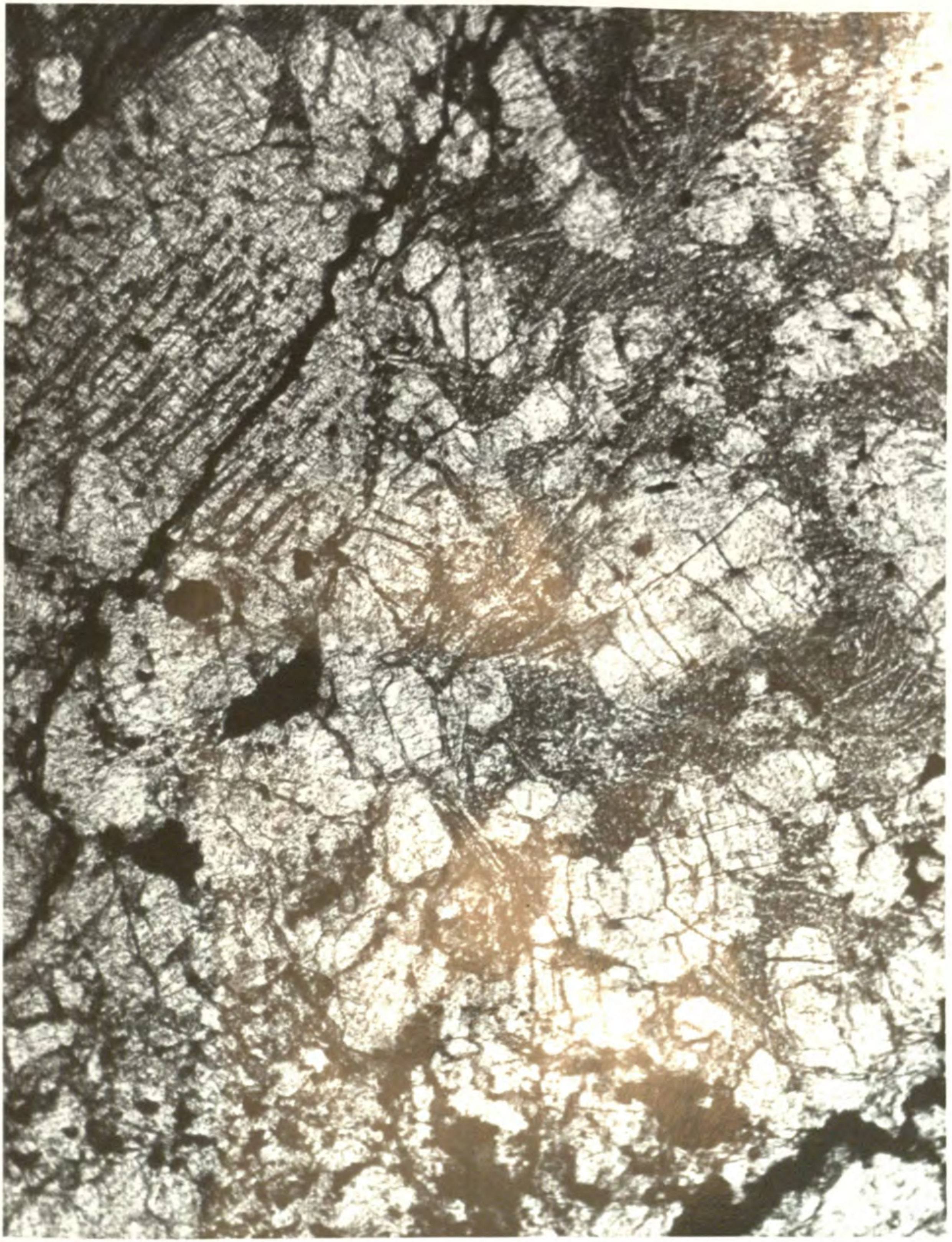


Figure 8

Imperfectly Formed Chondrule Composed of Olivine Grains.

Lalande Meteorite. x250:

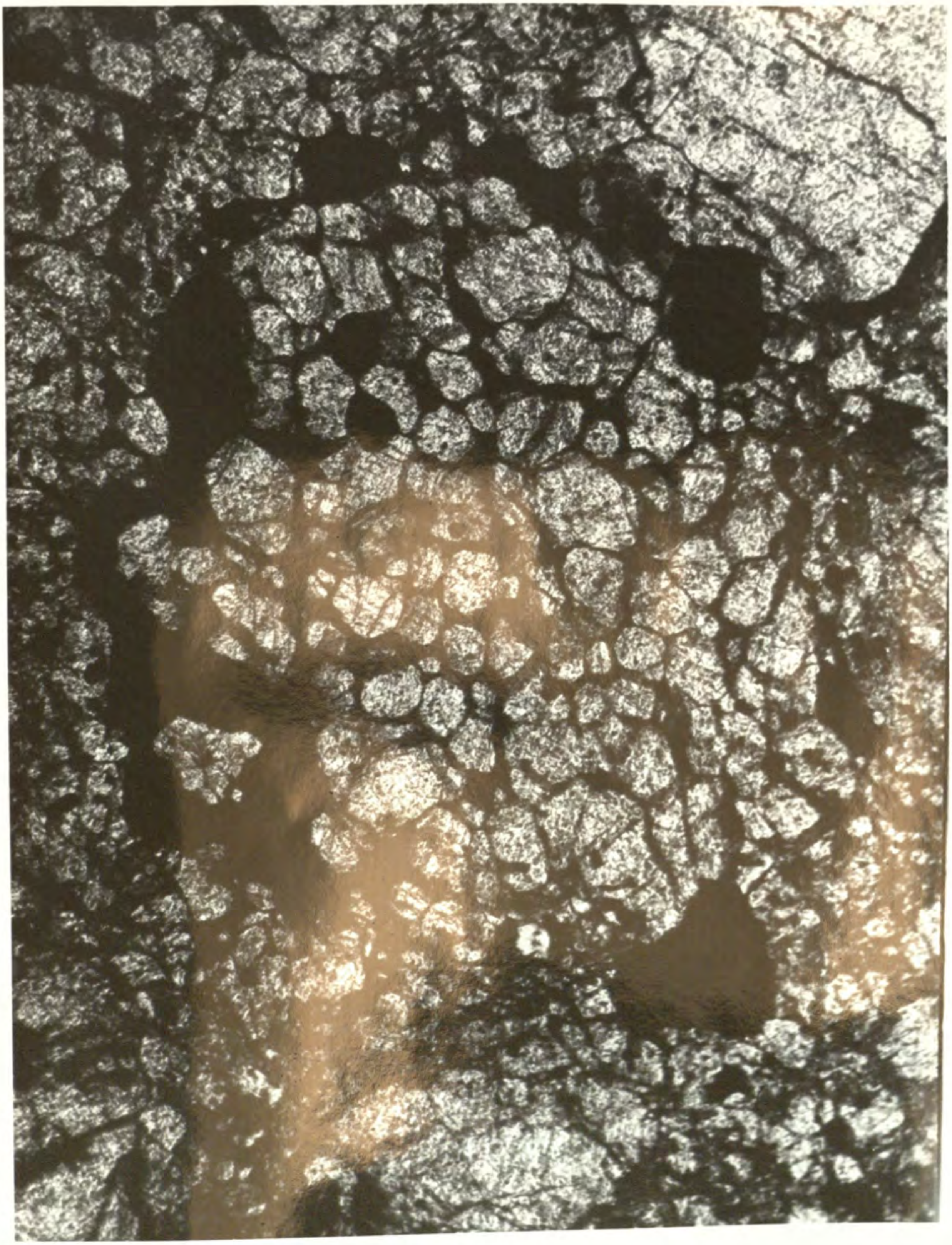


Figure 9

Radiating Chondrule of Fibrous Hypersthene-Clinohypersthene Intergrowth. Lalande Meteorite. x250:

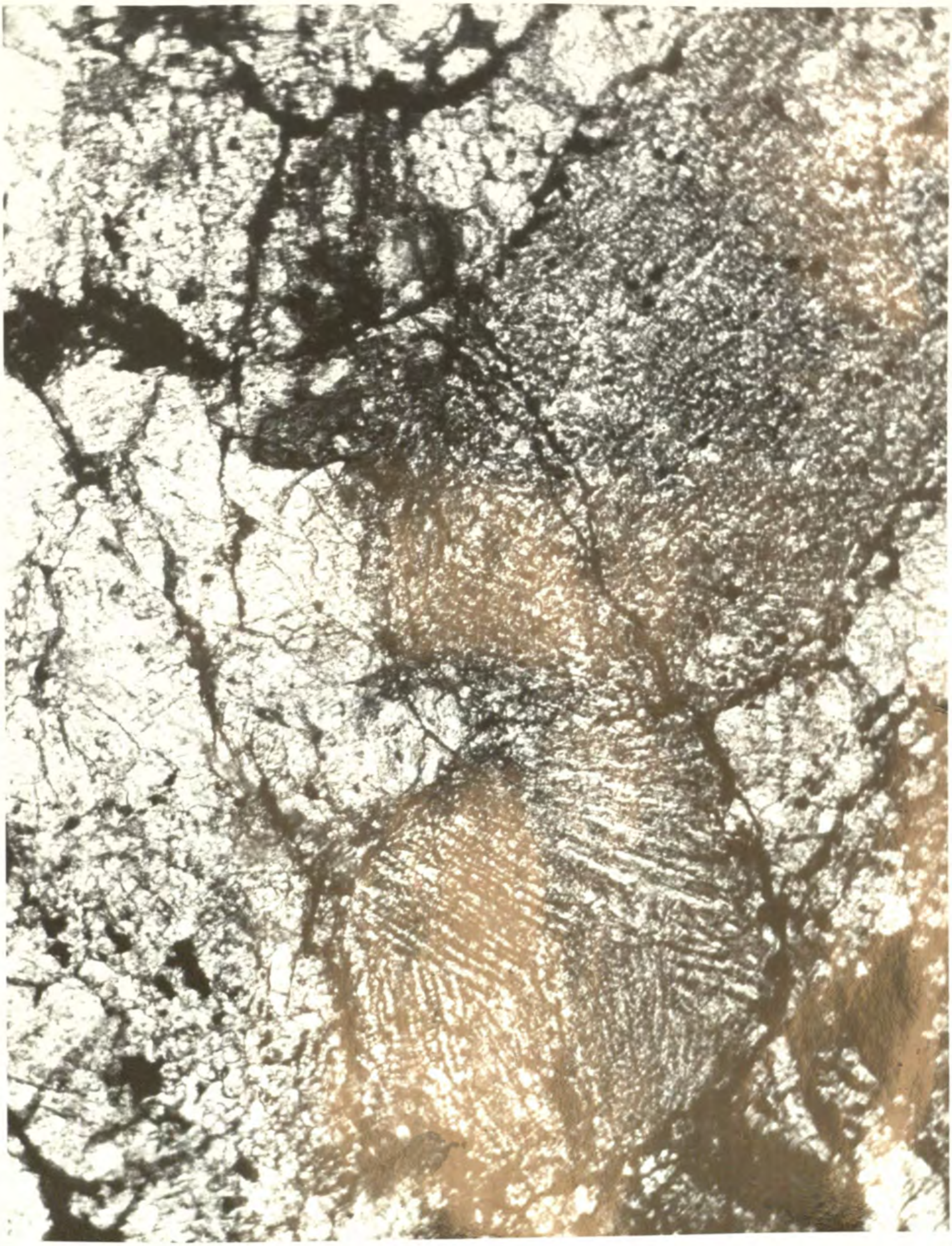


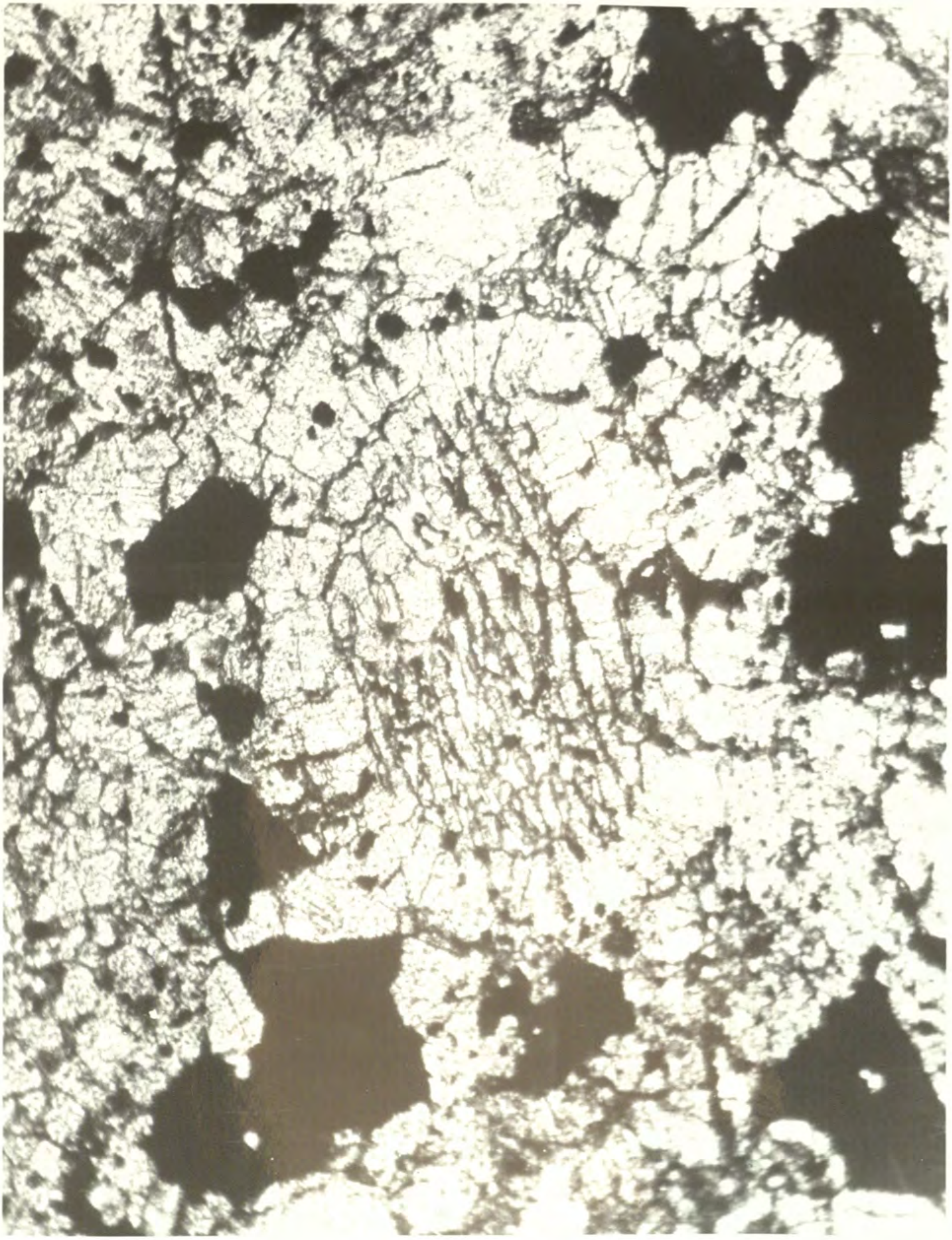
Figure 10

Radiating Chondrule of Fibrous Hypersthene-Clinohypersthene Intergrowth. Lalande Meteorite. x250:

Figure 11

Barred Chondrule Composed of Hypersthene

Lalande Meteorite. x250:



Oil-Immersion Analysis

Although the oil-immersion analysis was rendered more difficult than usual by the masking effect of the abundant iron oxide, it was possible to obtain detailed optical constants for the non-opaque minerals.

The olivine gave the following optical constants: $\alpha = 1.683$, $\beta = 1.702$, $\gamma = 1.721$; optical character, negative; birefringence, 0.038; axial angle $= 85^\circ$; dispersion, $r < v$, weak; optical orientation, $X = b$, $Y = c$, $Z = a$; axial plane, $\{001\}$.

These constants indicate a molecular percentage of Fe_2SiO_4 equal to 24.2 percent, and a specific gravity of 3.65. The corresponding percentage by weight of FeO is 22 percent and of MgO is 39 percent. These data place the olivine in the class called chrysolite by Winchell (1947, p. 191).

The hypersthene gave the following optical constants: $\alpha = 1.704$, $\beta = 1.713$, $\gamma = 1.718$; optical character, negative; birefringence = 0.014; axial angle = 70°; dispersion, $r < v$, weak; optical orientation, $X = a$, $Y = b$, $Z = c$; the axial plane is $\{010\}$. The usual prismatic cleavage $\{110\}$ was very seldom evident. The lower interference colors of the hypersthene provided the only easily discernible distinguishing feature for differentiation between olivine and hypersthene under crossed nicols. It was noted that some of the hypersthene exhibited undulatory extinction, both under oil and in thin-section. This is probably an indication that these grains

are under some strain. No pleochroism, so characteristic of hypersthene, was noted, although this may well have been present but masked by the omnipresent iron oxide stain.

The above constants indicate hypersthene with a molecular percentage of $FeSiO_3$ equal to 32.5 percent and a specific gravity of 3.45. The corresponding percentage by weight of FeO is 21 percent, and that of MgO is 24 percent.

Also noted in the oil-immersion analysis were some shards of glass. These had not been discovered in thin-section study. The refractive index of this glass was found to be 1.551. Some evidence of probable strain was a lack of complete extinction under crossed nicols. As the glass could not be distinguished in thin-section the relationship it bears to the other minerals of the meteorite could not be ascertained. According to Farrington (1915, p. 32) meteoritic glass chiefly abounds as inclusions and intergrowths in chrysolite (olivine), taking, in this association, a great variety of forms. This association is not, of course, universally true. The occurrence of glass is generally taken as an indication of a rapid crystallization or cooling of the meteorite substance (Farrington, 1915, p. 32).

Polished Section Analysis

A polished section of the Lalande meteorite was prepared and studied in an effort to ascertain information relating to the metallic phase of the specimen. The section was etched with Nital, 5 percent HNO_3 in 95 percent alcohol, for fifteen seconds to bring out the relations of the components. Kamacite is more soluble than taenite, and the etching is most vigorous along grain boundaries. Thus the structure is easily seen following etching for an appropriate time. A photomicrograph of a portion of this section is shown in Figure 12 to demonstrate the relationship of kamacite, taenite, and plessite.

Kamacite is the alpha phase of the iron-nickel equilibrium system. It is body-centered cubic in structure. The composition is approximately 94 percent iron and 6 percent nickel. Taenite is the gamma phase of the nickel-iron equilibrium system, and is face-centered cubic in structure. It is a nickel-rich alloy with the percentage of nickel ranging from 18 to 48, corresponding to formulas ranging from Fe_7Ni to FeNi. Plessite is a more or less fine mixture of kamacite and taenite. It may be regarded as a supersaturated solid solution of taenite with respect to kamacite, its forms depending upon the conditions of temperature and rate of cooling (Perry, 1944, p. 65). Plessite is probably

Polished section analysis

A polished section of [illegible] prepared and studied [illegible] relating to the [illegible] was etched with [illegible] for fifteen seconds to [illegible] ponents. [illegible] etching [illegible] structure is [illegible] [illegible] time. A [illegible] is shown in Figure [illegible] kamacite, taenite, and plessite.

Kamacite is the alpha phase of the iron-nickel equilibrium system. [illegible] The composition is approximately [illegible] cent nickel. Taenite is the gamma [illegible] equilibrium system. [illegible] It is a nickel-rich [illegible] ranging from 15 to [illegible] from [illegible] of kamacite and [illegible] saturated solid solution [illegible] its forms depending upon the [illegible] rate of cooling [illegible]

Figure 12

Kamacite, gray; taenite, white; and plessite, black among white taenite. Lalande Meteorite. x80:

an indication of incomplete gamma-alpha transformation, the kamacite growing at the expense of the taenite.

The majority of the metallic nodules in the section consist entirely of kamacite (Fig. 13). Very few show any taenite and even fewer exhibit plessite. No troilite (FeS) was noted in the section, although it can occasionally be seen, enclosed in kamacite, on megascopic examination of the sawed surface of the large specimen. The metallic nodules can be seen to have a random distribution throughout the specimen.

Chemical Analyses

Quantitative chemical analyses of the metallic phase, the non-metallic phase, and the undifferentiated entirety of the meteorite were made, and are appended as Table I. Molecular proportions of the metallic phase and a normative calculation of the non-metallic phase were computed from these (Table II). It will be noted that the lime has been placed in the mineral diopside. This mineral was not ascertained in the microscopic examination but is assumed to be present to explain the chemical analyses, or the calcium and other constituents are present as substitutes in the hypersthene and olivine. This is not an unreasonable assumption as diopside has optical constants quite similar to those of olivine and might easily have been overlooked.

an indication of incomplete [illegible] the [illegible] the kamacite growing at the expense [illegible]

The majority of the metallic nodules in the [illegible] consist entirely of kamacite (Fig. [illegible]). [illegible] taenite and even fewer exhibit [illegible]. [illegible] was noted in the section, although it [illegible] seen, enclosed in kamacite, [illegible] the sawed surface of the large specimen. [illegible] nodules can be seen to have [illegible] the specimen.

Chemical Analyses

Quantitative chemical analyses of the [illegible], the non-metallic phase, and the [illegible] of the meteorite were made, and are [illegible]. Molecular proportions of the [illegible] calculation of the non-metallic [illegible] these (Table II). It will be [illegible] placed in the mineral diopside. [illegible] ascertained in the microscopic examination [illegible] to be present to explain the chemical [illegible] calcium and other constituents are present [illegible] in the hypersthene and olivine. [illegible] assumption as diopside has [illegible] to those of olivine and [illegible]

Figure 13

Kamacite, white. Lalande Meteorite. x250

TABLE I

Chemical Analysis of the Lalande, New Mexico Chondrite.

	Percent
Silica, SiO_2	28.33
Iron Oxide, Fe_2O_3	31.20
Aluminum Oxide, Al_2O_3	6.05
Calcium Oxide, CaO	2.53
Magnesium Oxide, MgO	24.81
Potassium Oxide, K_2O	0.21
Sodium Oxide, Na_2O	1.81
Nickel, Ni	1.42
Cobalt, Co	0.62
Manganese, Mn	1.01
Sulfur, S	1.21
Chlorine, Cl	1.23
Titanium, Ti	0.00
Phosphorus, P	0.45
Carbon, C	None detected
	100.88%

TABLE II

Lalande

Metallic phase

Fe	88.08
Ni	7.89
Co	0.64
P	0.47
S	1.22
Cl	1.34
C	0.00
	99.62

Molecular proportion $\frac{Fe}{Ni} = 11.73$

Molecular proportion $\frac{Fe}{Ni + Co} = 10.86$

Non-metallic phase

SiO_2	32.01
Fe_2O_3	27.81
Al_2O_3	6.34
CaO	2.86
MgO	28.04
K_2O	0.20
Na_2O	2.05
MnO	1.14
TiO_2	0.00
C	0.00
	100.45

Normative calculation

Hypersthene	42.17%
Olivine	41.20
Diopside	9.86
Hematite	6.77

Metallic phase. . . . . 17.98% by weight
Non-metallic phase. . . . . . 82.02% by weight.

This assumption is made all the more plausible by the masking effects of the iron oxide.

Conclusion

It is the conclusion of the author that the Lalande, New Mexico meteorite be classified as (Chy), a hypersthene-olivine chondrite, following the Leonard modification of the Rose-Tschermak-Brezina system (Leonard, 1948). The strong alteration of olivine to iron oxide is taken to indicate that the stone fell a considerable time prior to its discovery in 1933. In accordance with the "meteorite-planet" hypothesis originated in 1850 by Boisse and advanced independently by Farrington in 1901, and recently strongly supported by Brown from thermodynamic consideration, this stone must have come from the exterior mantle of the hypothetical planet. This is thought true because the planet has been stated to have had a core of nickel-iron with a gradation to an exterior mantle of enstatite and olivine. Therefore, the less metallic phase present the farther from the center of the planet this meteorite had its origin.

THE YONŌZU, JAPAN AEROLITE (E.C.N. = *1394*,380)*

Introduction

Although the Yonōzu (Yonōzu-mura, Nishikambara-gun, Niigata, prefecture) aerolite is the second oldest of the recognized meteorites of Japan, being outranked only by the Ogi stone of 1741, there is, nevertheless, but little in the literature of meteoritics concerning it. According to Kotora Jimbo (1906), the Yonōzu aerolite fell into a paddy-field of "of Tominaga in Yonōzu-Murs, Nishinkambara-gori, Echingo province" on the 12th day of the 6th month (old style) of the 8th year of Tempo (i.e., on July 14, 1837). The fall occurred at approximately 4 o'clock in the afternoon and the meteorite was observed in the lowest portion of its trajectory as a black object flying in from the southwest accompanied by a noise like thunder. The stone is stated to have penetrated 10 feet deep into the field, this extraordinary penetration for a mass of at most 31.65 kg (Murayama) probably being attributable to the plasticity of the terrain into which the meteorite fell.

The stone which was recovered from the paddy-field was irregular in shape with six nearly plane surfaces showing the characteristic flight pittings of meteorites and bounded

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* Underlining indicates italics

THE YONOZU, [illegible] METEORITE [illegible]

Introduction

Although the Yonozu (Yonozu-mura, [illegible], Niigata prefecture) appears to be the second oldest of the recognized meteorites of Japan, being outranked only by the Ogi stone of 1741, there is, nevertheless, but little in the literature of meteoritics concerning it. According to Kotora Jimbo (1906) the Yonozu meteorite fell into a paddy-field of "of [illegible] in [illegible], [illegible] province" on the 14th, of the [illegible] (old style) of the 8th year of Tempo (i.e., on [illegible]). The fall occurred at approximately 4 o'clock [illegible] and the meteorite was observed by the [illegible] saw a black object flying [illegible] accompanied by a noise like thunder. The stone is stated to have penetrated 10 feet deep into the [illegible] penetration for a mass of at most [illegible] kg. [illegible] probably being attributable to the [illegible] of the [illegible] into which the meteorite fell.

The stone which was recovered from the paddy-field was irregular in shape with [illegible] plane surfaces showing the characteristic [illegible] of [illegible]

* Underlining indicates italics

by smoothly rounded edges. The maximum dimensions of the aerolite are given by Jimbo (1906) as 41 by 33 by 31 cm and its present weight as 30,310 grams. The thin crust which covered the mass at the time of recovery has weathered to a chocolate-gray on the specimen of the Institute of Meteoritics of the University of New Mexico, and in a few small areas has flaked off the stone. Examination of the cut faces on this specimen, which weighs 63.5 grams, about double the weight of the specimen in the British Museum, discloses that weathering has penetrated rather deeply into the stone.

Apparently the only previous investigation of the meteorite consists of a chemical analysis (given below), by M. Kodera of the Imperial Geological Survey of Japan, and a general microscopic study by Y. Otsuki leading to classification of the aerolite as a crystalline chondrite.

Megascopic Examination

A general megascopic description of the entire Yonozu stone is given in the introduction and is not repeated here. Instead, a megascopic description of the 63.5 gram specimen borrowed for study from the Institute of Meteoritics at The University of New Mexico is given in this section.

The shape of this specimen might be described roughly as half a rectangular solid, the division being made by a by [illegible] rounded edges. [illegible] particular [illegible] of the meteorite are given by [illegible] (1936) and [illegible] and its present weight as [illegible] which covered the [illegible] of the [illegible] to a chocolate-gray [illegible] surface [illegible] of the [illegible] small areas has [illegible] faces on this [illegible] double the weight of the specimen in the [illegible] that [illegible] from the crust.

Apparently, the only previous [illegible] of the meteorite consists of a chemical analysis [illegible] of the [illegible] and a general microscopic [illegible] of the [illegible]

[illegible]

A general macroscopic description of the entire [illegible] stone is given in the [illegible] and is not repeated here. Instead, a [illegible] of the [illegible] specimen for [illegible] at the University of New Mexico [illegible]

The shape of this specimen [illegible] as [illegible] a rectangular [illegible] curved line across the diagonal. This leaves the specimen with a volume slightly more than half that of the rectangular solid. The edges of the rectangular solid measure approximately 40 by 28 by 20 mm and the volume of the specimen is on the order of 22.5 cm^3, or at most 25 cm^3. The curved surface represents a part of the original exterior of the meteorite. The other surfaces were produced during the sawing of the specimen from the main mass described in the introduction. Figure 14A represents the curved exterior face and Figure 14B illustrates two of the sawed faces.

The face comprised of a portion of the natural exterior of the specimen is of a medium-brown color, and exhibits chondritic structure to a high and varied degree, with numerous irregular fragments or grains of the metallic phase being visible in completely random arrangement. The surface is rather rough, although all edges are well-rounded.

Two of the sawed faces have been cut much more recently than the other two, as evidenced by the shining faces of the metallic nodules on two faces and the lack of any shining faces on the other two. The color is somewhat darker on all four cut faces than on the rounded natural exterior face. A few large grains and chondrules can be easily ascertained on each of these faces. They are generally gray rather than brown. The largest grain measures 2.5 mm on each side and is somewhat square. Several of the extracted as across the [illegible] leaving the specimen with a volume slightly [illegible] than half [illegible] the specimen [illegible]. The edges of the [illegible] approximately 40 by 23 by 26 cm and the volume of the [illegible] is on the order of 22.1 cm^3, or [illegible]. The rough surface represents a part of the original exterior of the meteorite. The other surfaces [illegible] from [illegible] the figuring of the specimen [illegible] and [illegible] in the introduction. Figure 1-A [illegible] exterior face and Figure 1-B illustrates [illegible].

The face consisting of a portion of the original exterior of the specimen [illegible] and exhibits [illegible] with numerous [illegible] with [illegible] phase being visible [illegible]. The surface is rather rough, [illegible].

Two of the sawed faces have been cut much more recently than the other two, as [illegible] by the shining faces of the metallic nodules on the former and the lack of any shining faces on the other two. The sample is somewhat darker on all four cut faces than on the rounded natural exterior face. A few large metallic nodules are easily ascertained on each of these faces; however, generally they are [illegible] measures 2.5 mm on each side and it [illegible] several of the

Figure 14A

Exterior Face. Yonōzu Meteorite. x1½:

Figure 14B

Cut Faces. Yonōzu Meteorite. x1½


1
2
3
4
5

larger chondrules have a diameter of 2 mm. The metallic nodules range in diameter from microscopic to about 1 mm.

No rind or skin is megascopically visible on the sections cut through the exterior face. Oxidation extends to the interior limits of the specimen. There is no apparent gradation of oxidation from the exterior toward the interior.

Microscopic Examination

Thin-section Analysis

A cursory examination of a thin-section of this stone shows strikingly its strongly chondritic nature. The term chondrule, from the Greek χονδρος, a grain, is applied to the rounded and oval granules in meteorites. They present a considerable range in mineral composition and a still wider range of internal structure (Merrill, 1930). More detailed examination exposes an even more striking aspect of this meteorite. This aspect is the extreme range of the internal structure of the chondrules in one stone. This subject will be discussed more fully after a brief discussion of the mineral content.

Thin-section analysis shows the non-metallic portion of this stone to be composed primarily of the minerals olivine and hypersthene, with small percentages of hypersthene-clinohypersthene, secondary hematite, and metallic

larger chondrules are [illegible]
nodules range in diameter from [illegible]

No grid or [illegible] is [illegible] visible [illegible]
sections cut through the [illegible] [illegible]
in the interior [illegible] of the [illegible]
apparent gradation of [illegible] [illegible]
the interior.

[illegible]

Thin-section Analysis

A cursory examination of a [illegible]
stone shows strikingly the [illegible]
The term chondrule, from the Greek [illegible]
is applied to the rounded and [illegible]
They present a considerable range [illegible]
and a still wider range of internal [illegible]
More detailed examination [illegible]
of this meteorite. This [illegible]
internal structure of the chondrules [illegible]
subject will be discussed more fully [illegible]
of the mineral content.

Thin-section analysis shows [illegible]
of this stone to be composed [illegible]
olivine and hypersthene, [illegible]
stone-clinohypersthene, [illegible]

particles. The proportions of olivine and hypersthene are approximately half-and-half.

Olivine is the general name applied to the minerals of an isomorphous series between forsterite, Mg_2SiO_4, and fayalite, Fe_2SiO_4. The mineral crystallizes in the orthorhombic system and possesses distinct {010} and less distinct {100} cleavages. The hardness if 6.5 to 7 on Mohs scale of hardness. The specific gravity ranges from 3.2 to 4.3. Olivine is an essential constituent of many meteorites, of which it constitutes, with enstatite, the stony portion of the mass (Winchell, 1947, p. 10).

Hypersthene is an orthorhombic pyroxene, an iron-rich member of the enstatite family. Enstatite has the formula of $MgSiO_3$ but natural enstatite free from iron is very rare. By some writers varieties with less than 5 percent FeO are called enstatite, those containing from 5 to 14 percent FeO are called bronzite, and those with more than 14 percent FeO are designated hypersthene. In petrography enstatite is commonly used for varieties which are positive and hypersthene for those which are negative. Hypersthene has a general formula of $(Mg,Fe)SiO_3$. It has a distinct {110} cleavage. The hardness is 5 to 6 and the specific gravity ranges from 3.3 to 3.5. The mineral is an important constituent of many meteorites (Winchell, 1947).

Both olivine and hypersthene are present in many particles. The proportions of olivine and hypersthene are approximately half-and-half.

Olivine is the general name for the intermediate members of an isomorphous series between forsterite, Mg_2SiO_4, and fayalite, Fe_2SiO_4. The mineral crystallizes in the orthorhombic system and possesses [illegible] {010} and [illegible] {100} cleavages. The hardness is [illegible] on [illegible] scale of hardness. The specific gravity ranges from [illegible]. Olivine is an essential constituent of [illegible] of which it constitutes, with enstatite, the stony [illegible] of the mass (Winchell, 1948, p. [illegible]).

Hypersthene is an orthorhombic pyroxene, an iron-rich member of the enstatite family. [illegible] formula of $MgSiO_3$ but natural enstatite [illegible]. By some writers varieties with less than [illegible] percent [illegible] are called enstatite, those containing from [illegible] percent [illegible] are called bronzite, and those with [illegible] percent [illegible] are designated hypersthene. [illegible] is commonly used for varieties of [illegible] and hypersthene for those which are [illegible]. [illegible] has a general formula of $(Mg,Fe)SiO_3$. It has a distinct {210} cleavage. The hardness is [illegible] gravity ranges from [illegible]. [illegible] is an [illegible] constituent of many meteorites (Winchell, 1948).

Both olivine and hypersthene [illegible] forms, ranging from finely granular and fragmental to well-formed euhedral crystals (Figs. 15 and 16). Large fragmental grains of hypersthene are not rare (Fig. 17) and some show alteration to iron oxide along the cleavage traces (Fig. 18). The section is very strongly obscured by iron oxide, as can be seen in many of the included figures. The iron oxide is thought to be hematite, produced mainly from alteration of olivine and hypersthene.

This section shows fibrous and radiating hypersthene chondrules (Figs. 19 and 20), chondrules composed entirely of fragmental hypersthene (Fig. 21), some composed entirely of olivine grains (Fig. 22), and many "porphyritic" varieties. The latter are mainly composed of one or more fairly large euhedral olivine crystals in a matrix of fragmental hypersthene of small dimensions (Figs. 23 and 24). Occasionally there are euhedral grains of hypersthene included in a chondrule. A very interesting development is a chondrule of fine-grained hypersthene with a rim of coarse olivine. Unfortunately, half of this chondrule is obscured by iron oxide (Fig. 25). The olivine rim is apparently secondary and seems to indicate a fragmental origin for the chondrule. No glass was noted in any of these chondrules.

Oil-immersion Analysis

Although most of the grains are heavily coated with

Figure 15

Chondrule of Fine-grained Hypersthene (top center) and

Euhedral Hypersthene Crystal (lower right).

Yonōzu Meteorite. x250:

Figure 16

Euhedral Olivine Crystals. Yonōzu Meteorite. x250:

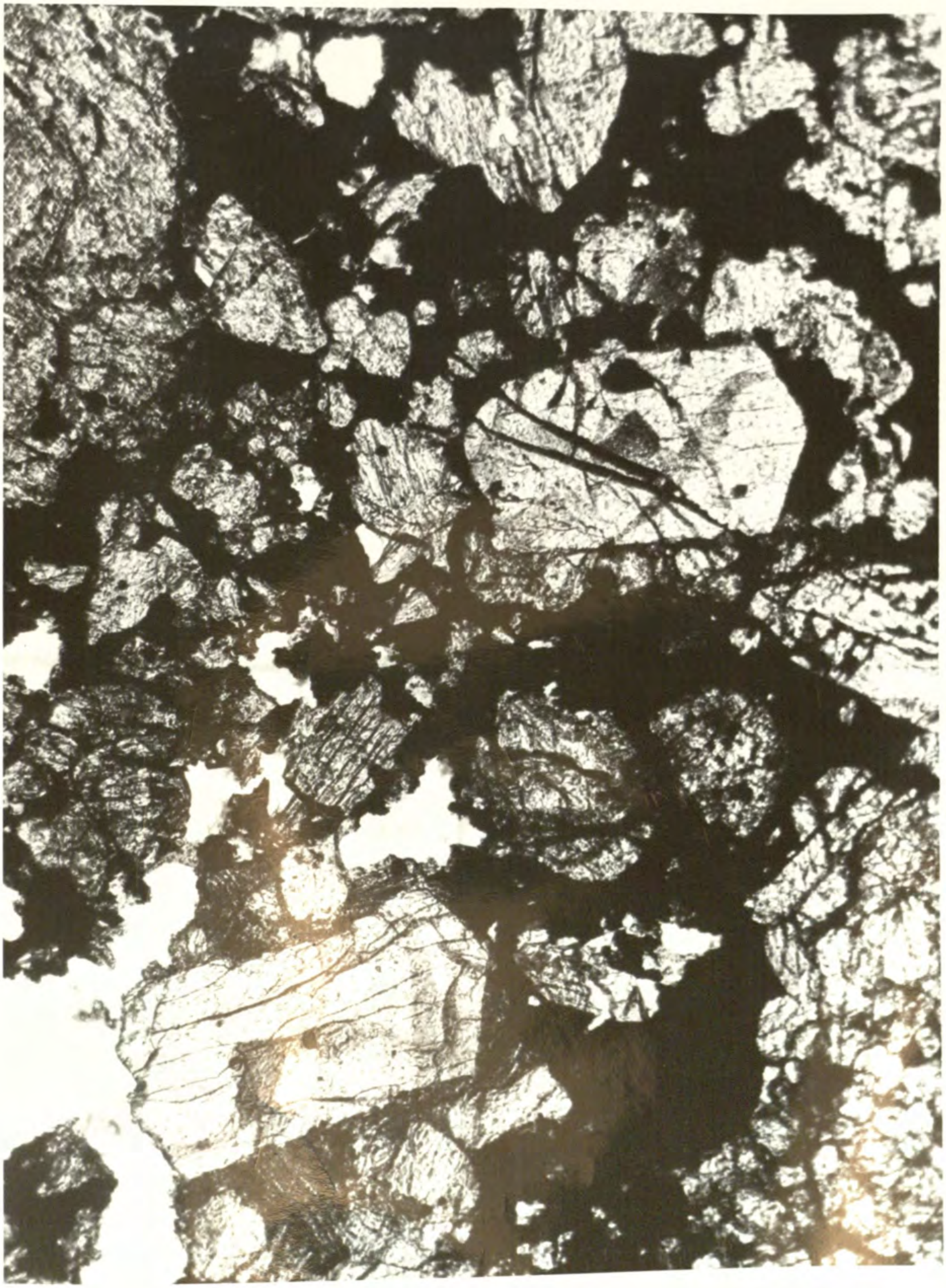


Figure 17

Large Fragmental Hypersthene Grain. Yonōzu Meteorite. x250:

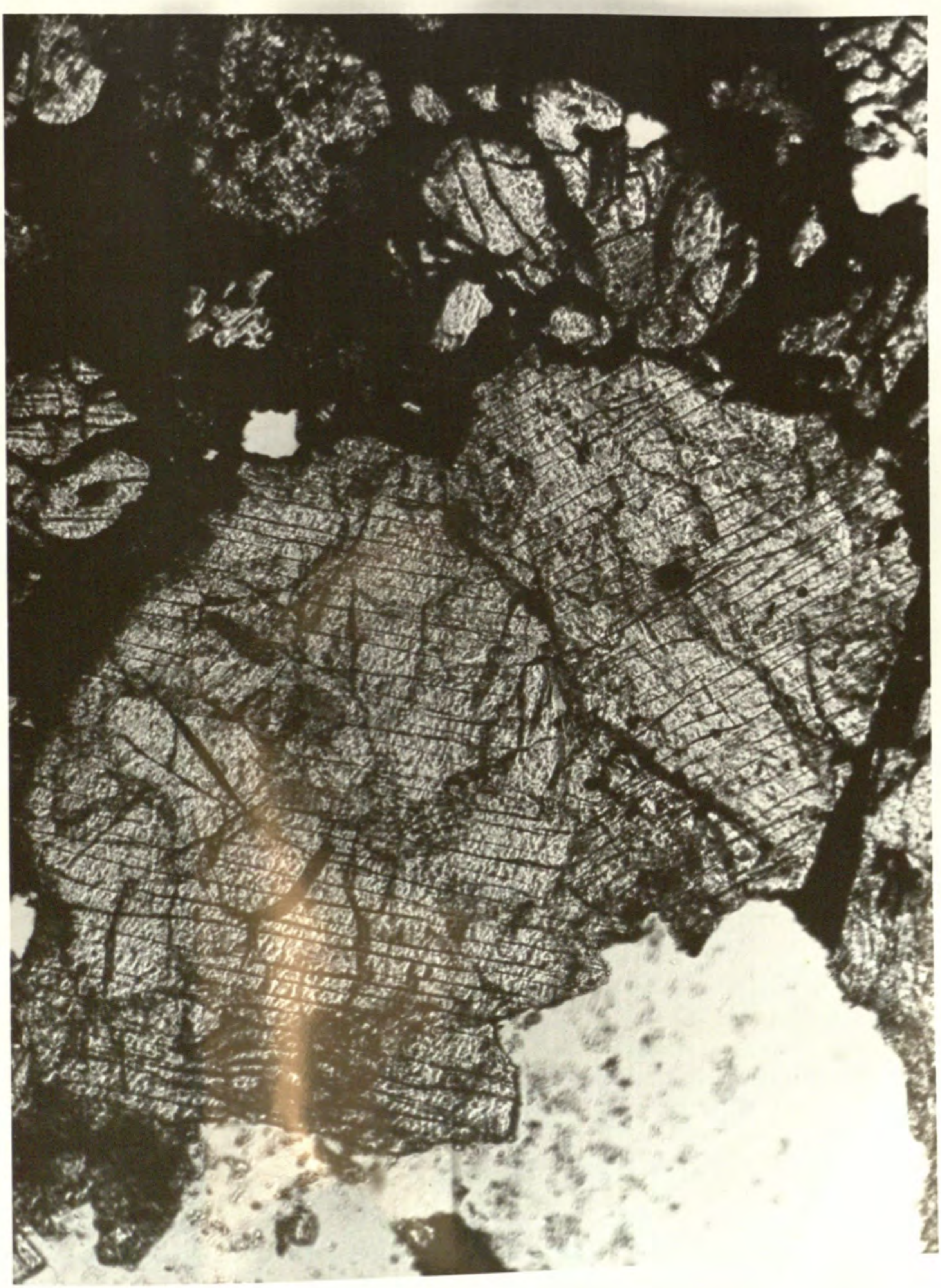


Figure 18

Hypersthene with Iron Oxide Alteration Along Cleavage Planes.

Yonōzu Meteorite. x250:

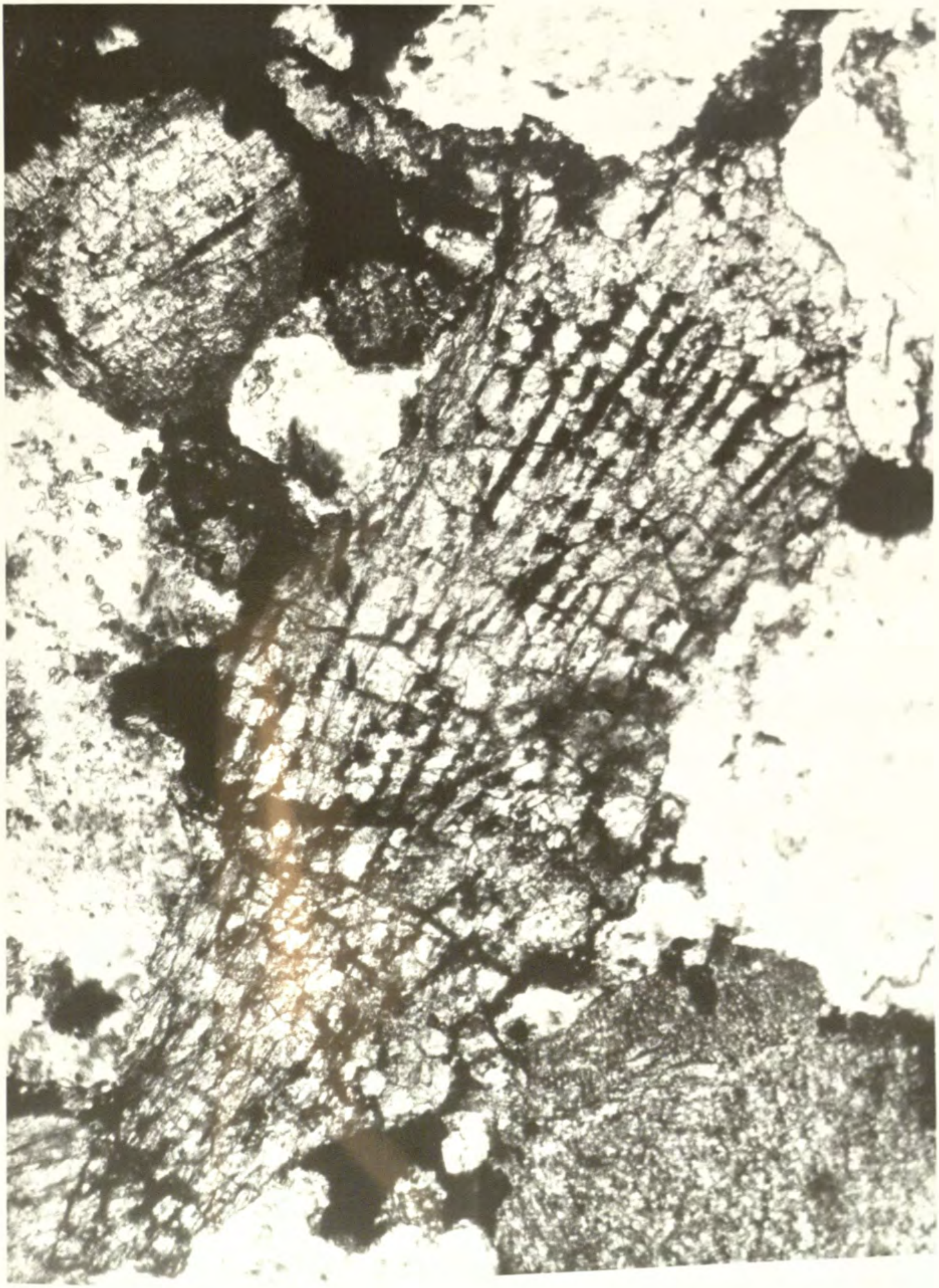


Figure 19

Chondrule of Radiating Fibrous Hypersthene.

Yonōzu Meteorite. x250:

Figure 20

Chondrule of Radiating Fibrous Hypersthene

Yonōzu Meteorite. x250;

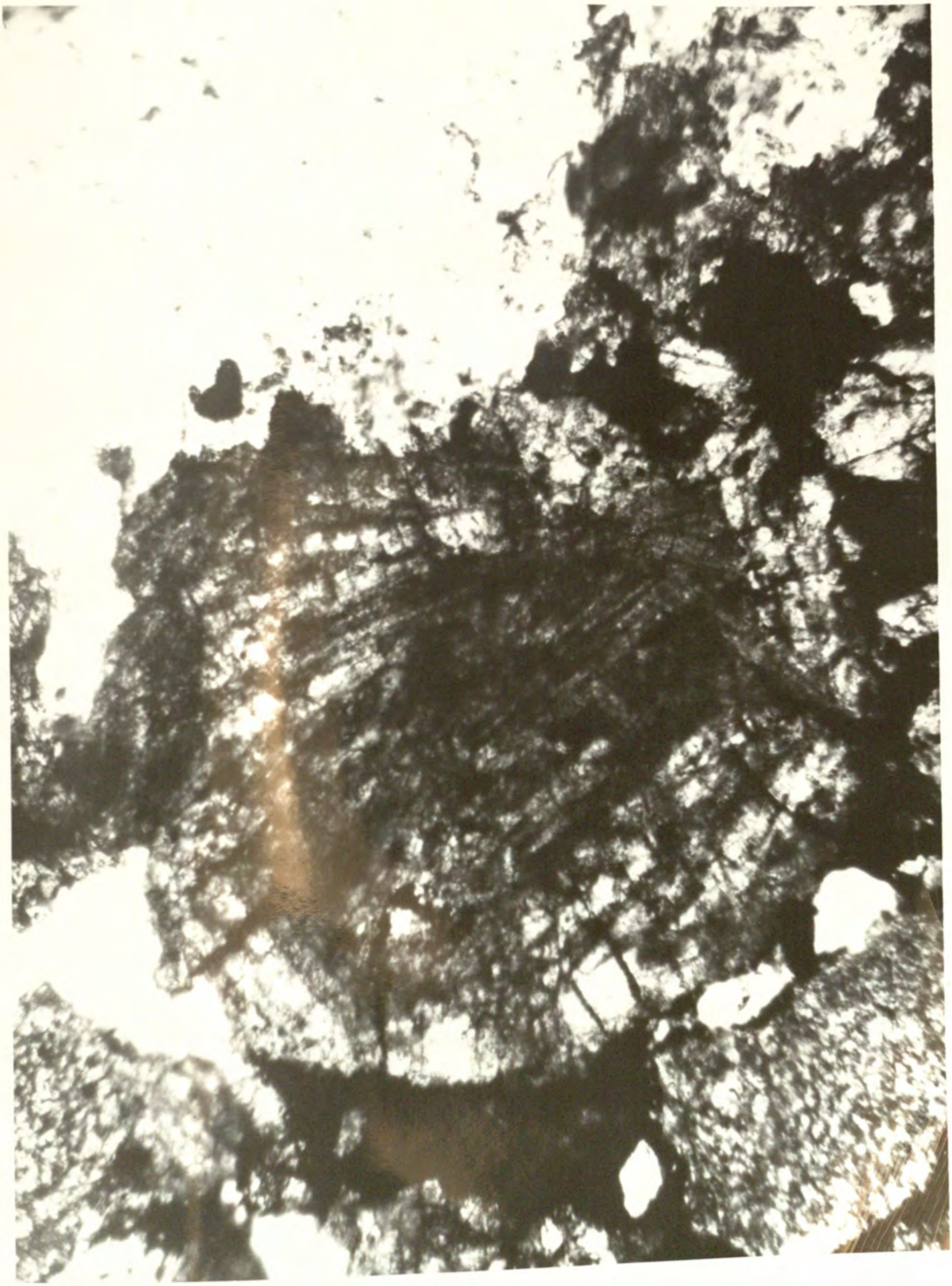


Figure 21

Chondrule Composed Entirely of Fragmental Hypersthene.

Yonōzu Meteorite. x250:

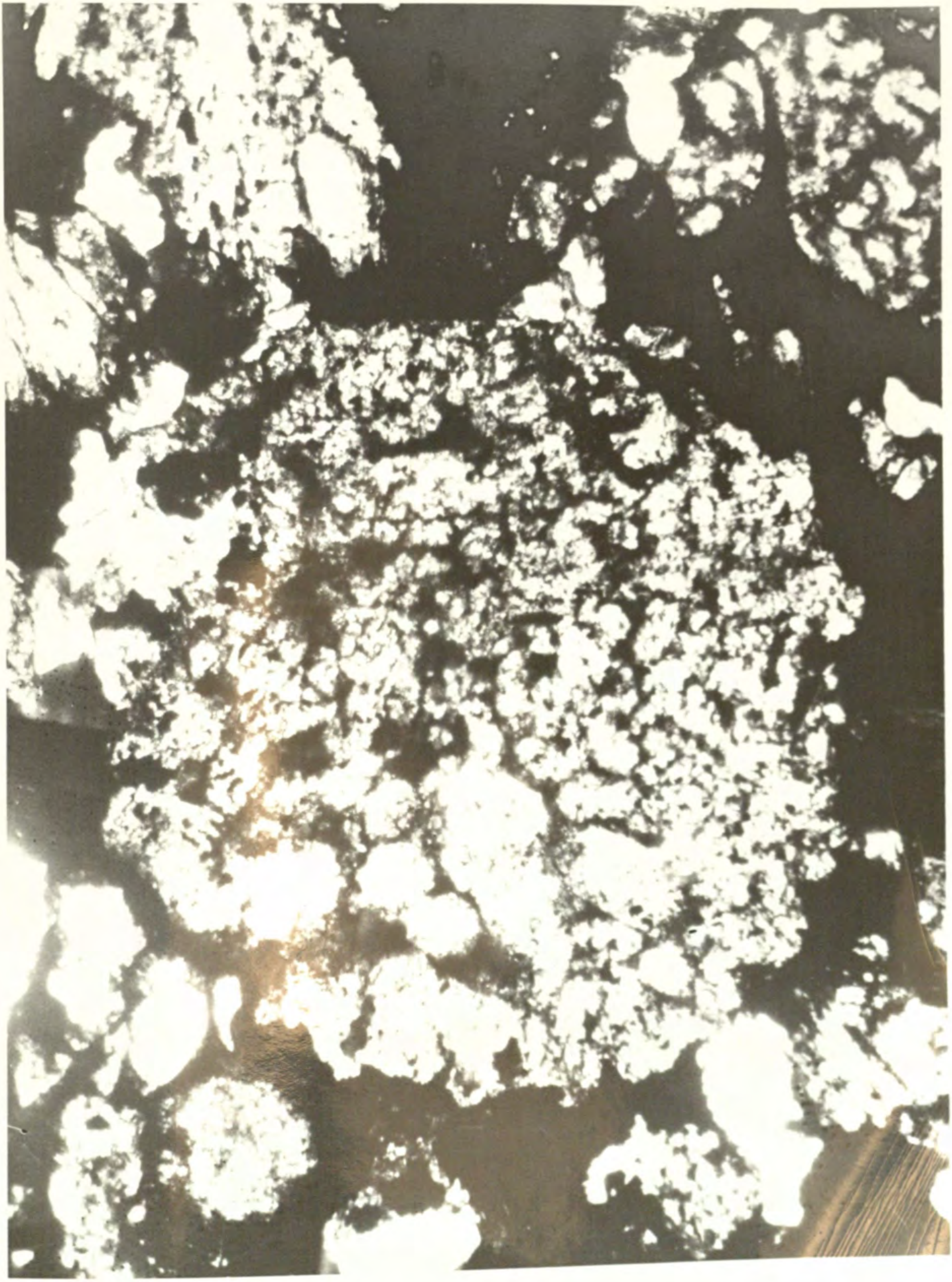


Figure 22

Chondrule Composed Entirely of Olivine Grains.

Yonōzu Meteorite. x250:

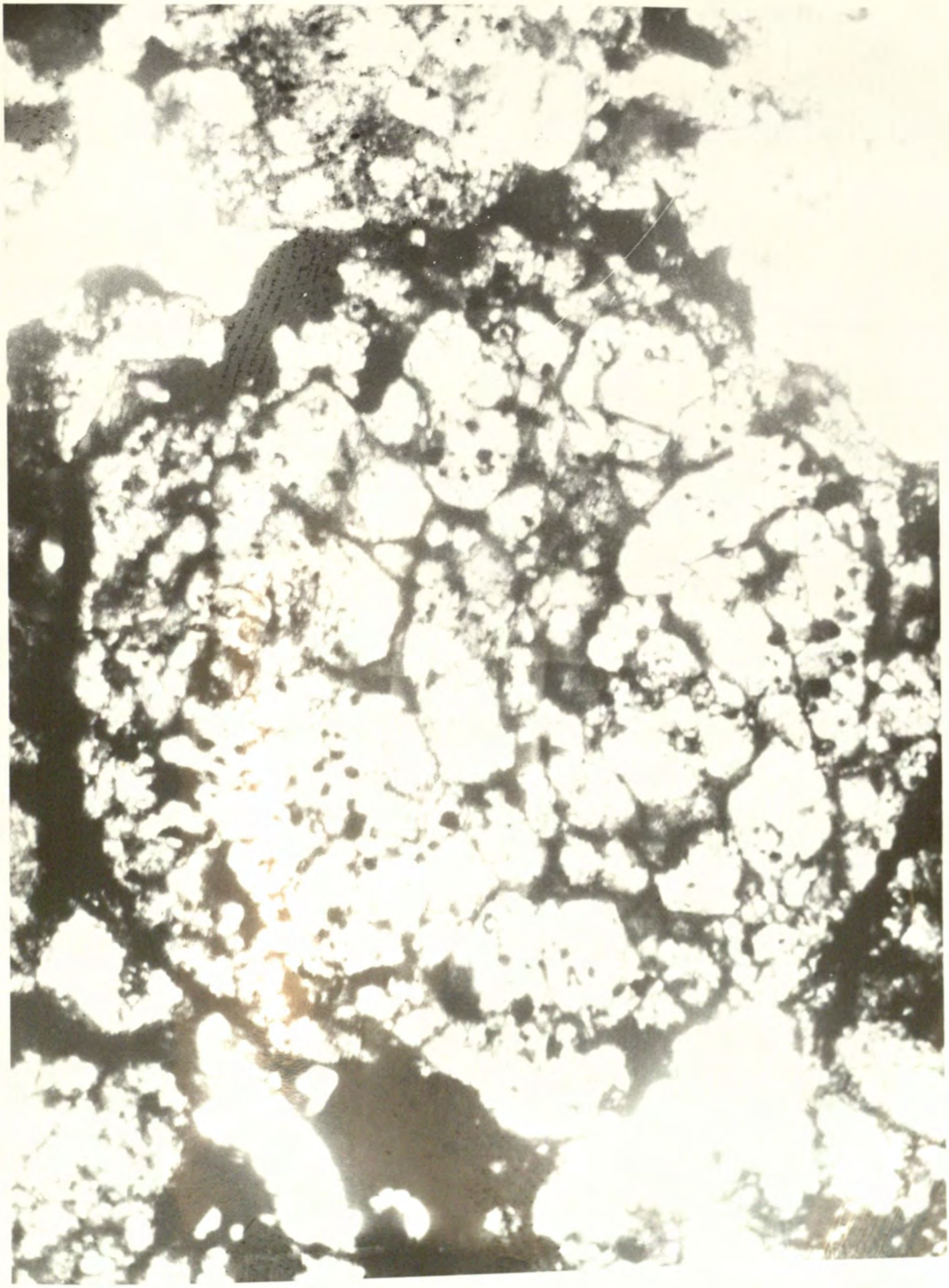


Figure 23

"Porphyritic" Chondrule. Euhedral Olivine Crystal in Matrix of Hypersthene. Yonōzu Meteorite. x250:

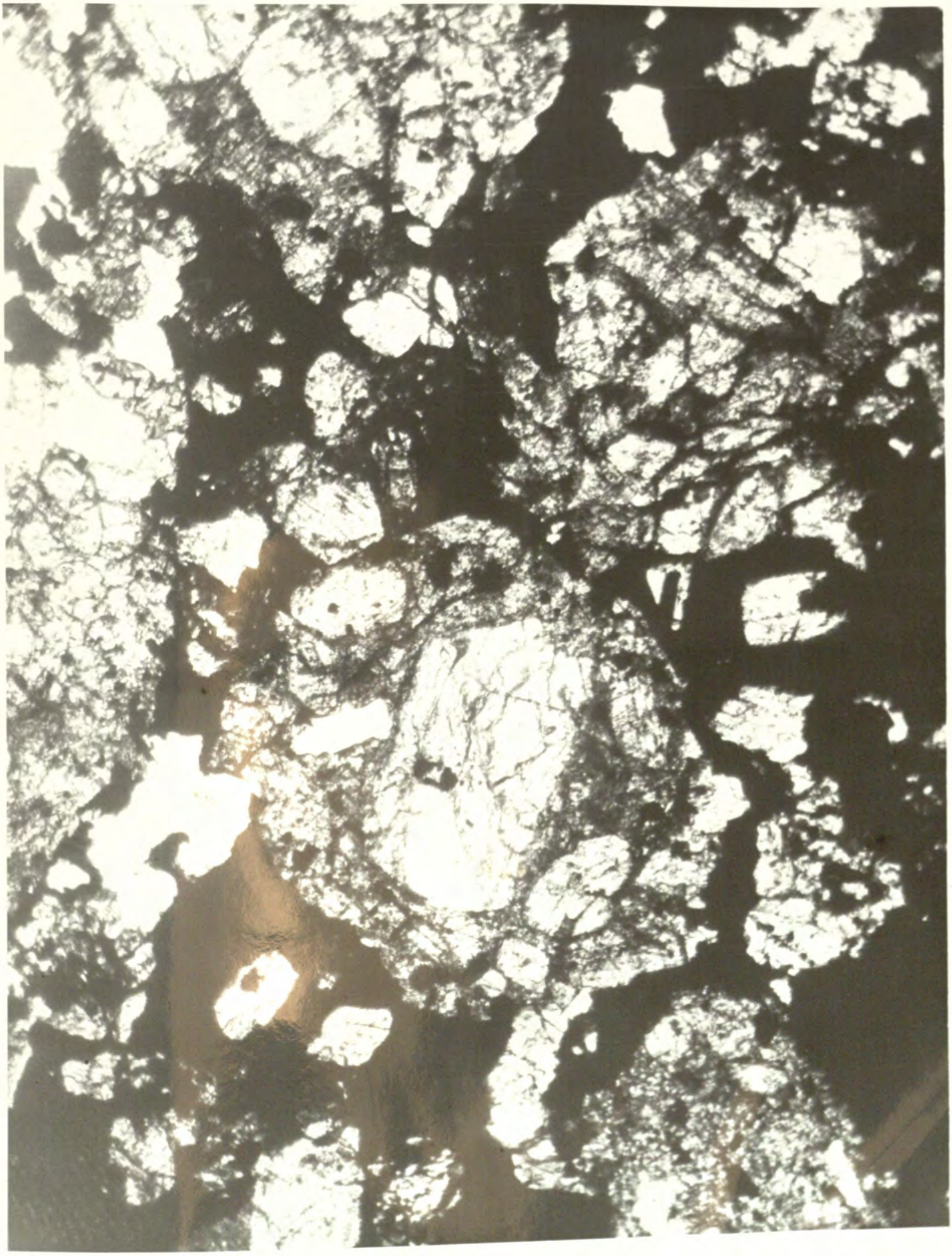


Figure 24

"Porphyritic" Chondrule. Euhedral Olivine Crystals in Matrix of Hypersthene. Yonōzu Meteorite. x250:

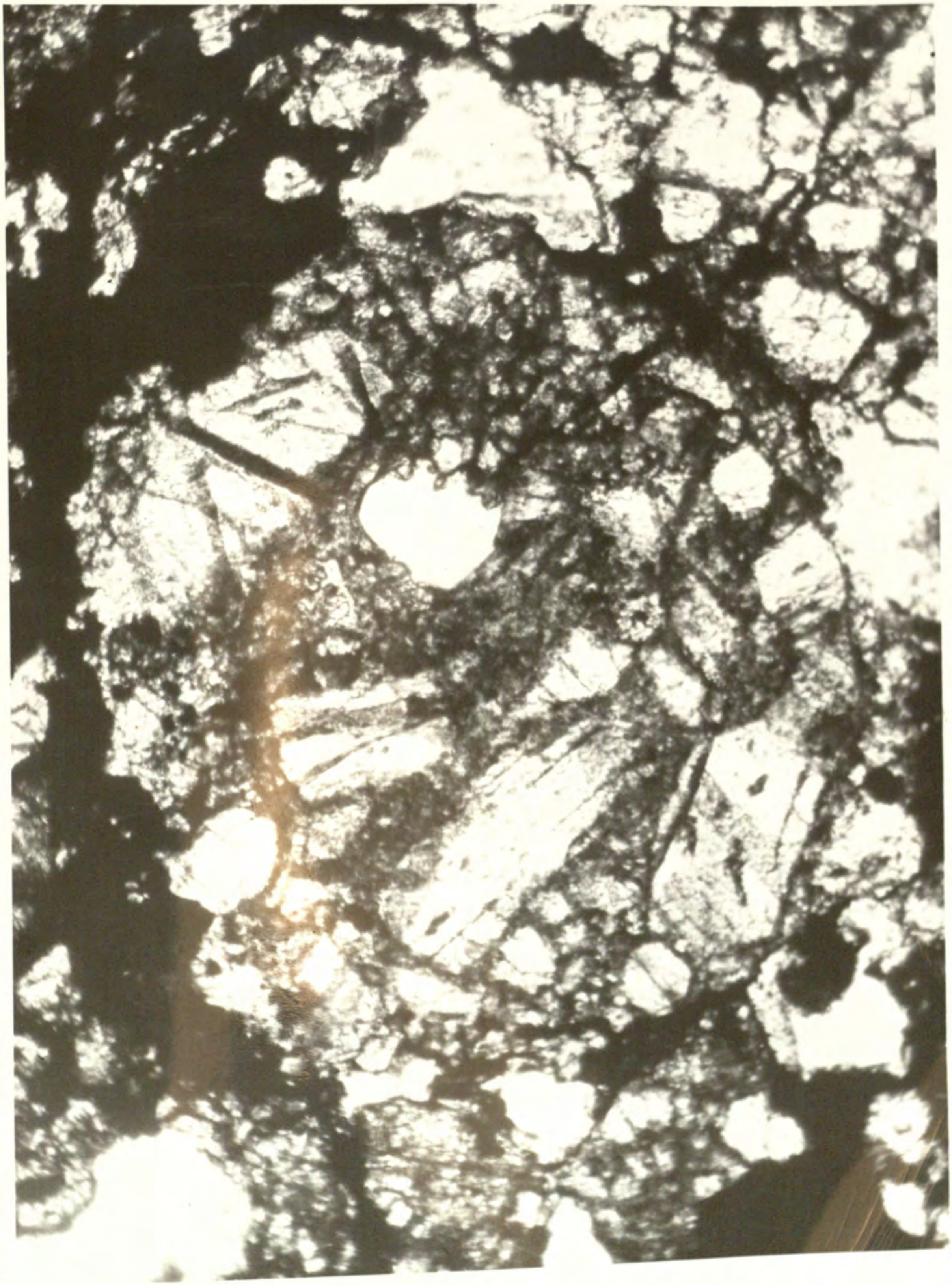
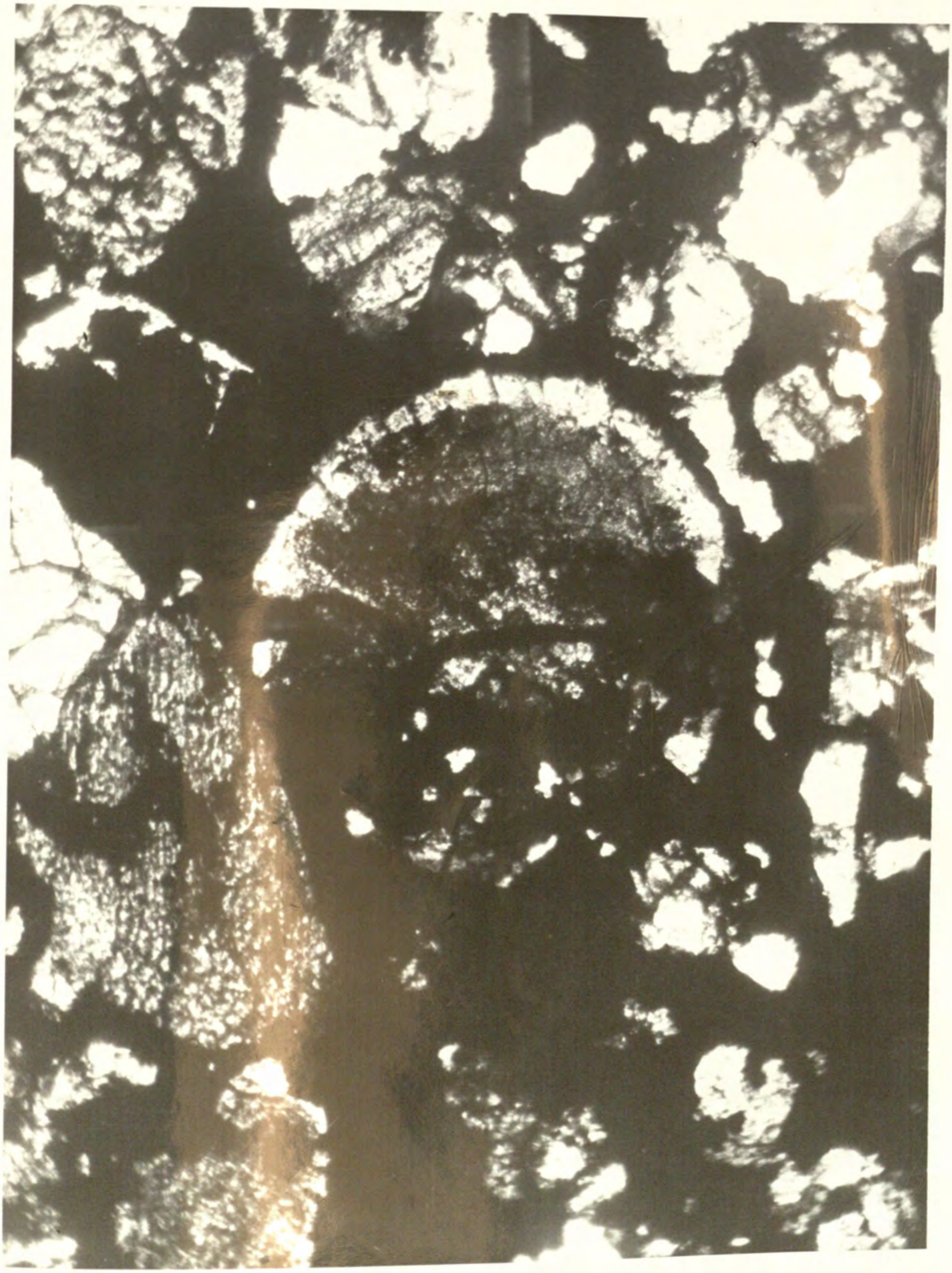


Figure 25

Chondrule of Fine-grained Hypersthene with

Rim of Coarse Olivine.

Yonōzu Meteorite. x250:



iron oxide, it was possible to arrive at the following optical constants for olivine, hypersthene, and the glass that was discovered in this analysis.

The olivine gave the following optical constants: $\alpha = 1.705$, $\beta = 1.728$, $\gamma = 1.745$; birefringence, 0.040; optical character, negative; axial angle = 80°; $r < v$, weak; optical orientation, $X = b$, $Y = c$, $Z = a$; axial plane $\{001\}$.

These constants indicate olivine with a molecular percentage of Fe_2SiO_4 of 36 percent and a specific gravity of 3.65. The percentage of FeO by weight is 32 percent, and the percentage of MgO is also 32 percent. These data place the olivine very near the border between chrysolite and hyalosiderite (Winchell, 1947, p. 191).

The hypersthene gave the following optical constants: $\alpha = 1.703$, $\beta = 1.713$, $\gamma = 1.718$; birefringence, 0.015; optical character, negative; axial angle = 70°; dispersion, $r < v$, weak; optical orientation, $X = a$, $Y = b$, $Z = c$; axial plane $\{010\}$.

These data are diagnostic of enstatite (var. hypersthene) with a molecular percentage of $FeSiO_3$ of 32 percent. A specific gravity of 3.45 is indicated. The corresponding weight percentages of FeO and MgO are 21 percent and 24 percent respectively (Winchell, 1947, p. 218).

The usual prismatic cleavage $\{110\}$ of 88° and 92° and the pleochroism so characteristic of hypersthene were

seldom evident. The latter phenomenon may have been present but masked by the iron oxide coating on the grains. The optical character providing easy distinction between olivine and hypersthene was the lower interference colors under crossed nicols of the hypersthene. Undulatory extinction was noticed in a few of the hypersthene grains. This is interpreted as an indication of strain.

A few shards of glass, making up less than one percent of the grains, were found in this oil-immersion analysis, although none was noted in the thin-section analysis. The refractive index of this glass was determined to be 1.588. This is a rather high index, at least among terrestrial glasses. As the glass was not noted in thin-section the relationship it bears to the other minerals of the meteorite could not be ascertained. According to Farrington (1915, p. 190) glass chiefly abounds as inclusions and intergrowths in olivine, taking in this association, a great variety of forms. The presence of glass in meteorites is generally taken as an indication of rapid cooling of the meteorite substances.

Polished-Section Analysis

A polished section of the Yonōzu meteorite was prepared and studied in order to ascertain the composition and structure of the metallic phase. The section was etched seldom evident. The latter phenomenon may have been present but masked by the iron oxide staining on the grains. The optical character providing easy distinction between olivine and hypersthene was the low birefringence and [illegible] crossed nicols of the hypersthene. Undulatory extinction was noticed in a few of the hypersthene grains. This is interpreted as an indication of strain.

A few shards of glass, showing [illegible] of the grains, were found in this [illegible] although none was noted in the thin-section analysis. The refractive index of this glass was determined to be [illegible] a rather high index, at least as compared to terrestrial glasses. As the glass was not found in thin-section the relationship it bears to the other minerals of the meteorite could not be ascertained. According to [illegible] p. 160) glass chiefly occurs as [illegible] in olivine, [illegible] in this association a great variety of forms. The presence of glass in meteorites is generally taken as an indication of rapid cooling of the meteoritic substances.

Polished Section Analysis

A polished section of the [illegible] meteorite was prepared and studied in order to ascertain the [illegible] and structure of the metallic phase. The section was etched for 10 seconds with Nital, 5 percent HNO_3 in 95 percent alcohol. Because solution is more active along grain boundaries and fractures, the structure of the metallic phase is brought out by this process. Due to differential solubility of the components, this process also aids in distinction between them. The majority of the nodules are found to be composed of kamacite only (Fig. 26), and about half of these show Neumann lines (Fig. 27). More than one set of these lines can be seen in this section. Since it has been established that the lines are developed parallel to the planes of the trapezohedron the lines might develop in any number of directions up to twelve (Perry, 1944, p. 89). It is assumed that in meteoritic irons Neumann lines may be the result either of stress or shock. The stress may have been induced by atmospheric resistance during flight. Some of the larger kamacite particles contain included taenite nodules, at the boundary of which the Neumann lines stop abruptly (Fig. 28). Also noted were some troilite (FeS) nodules surrounded by kamacite (Fig. 29). Numerous inclusions of the non-metallic phase in kamacite are noted. In these instances the Neumann lines do not cut the non-metallic particle but appear in perfect alignment on the opposite side. This alignment has been interpreted as a definite indication that the lines are Neumann lines and not merely striations left from the polishing operation.

Figure 26

Kamacite (white) in Silicate Matrix. Yonōzu Meteorite. x250:

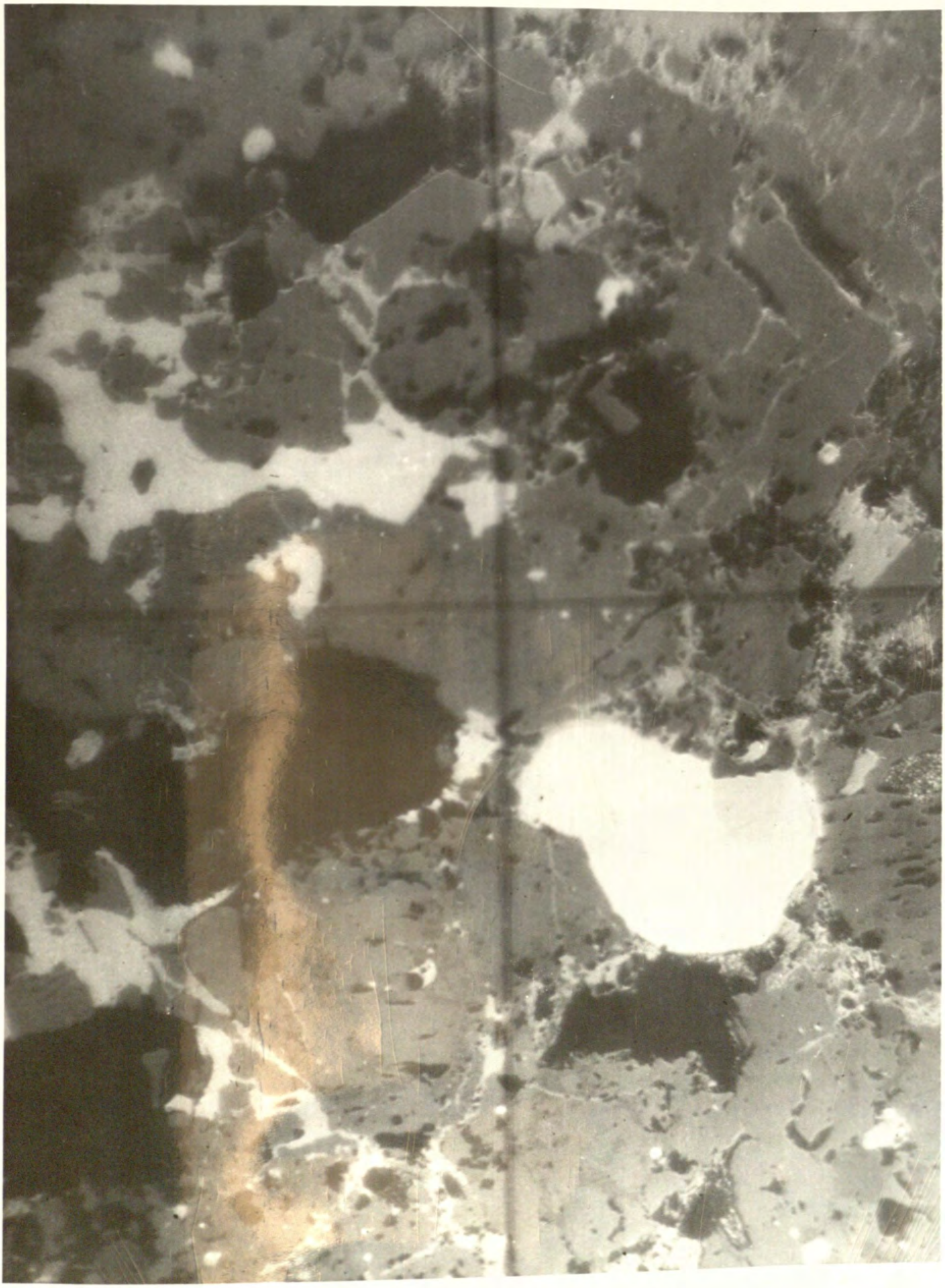


Figure 27

Kamacite (white) Nodules. The Nodule in the Upper Right Shows Several Sets of Neumann Lines.

Yonōzu Meteorite. x250:

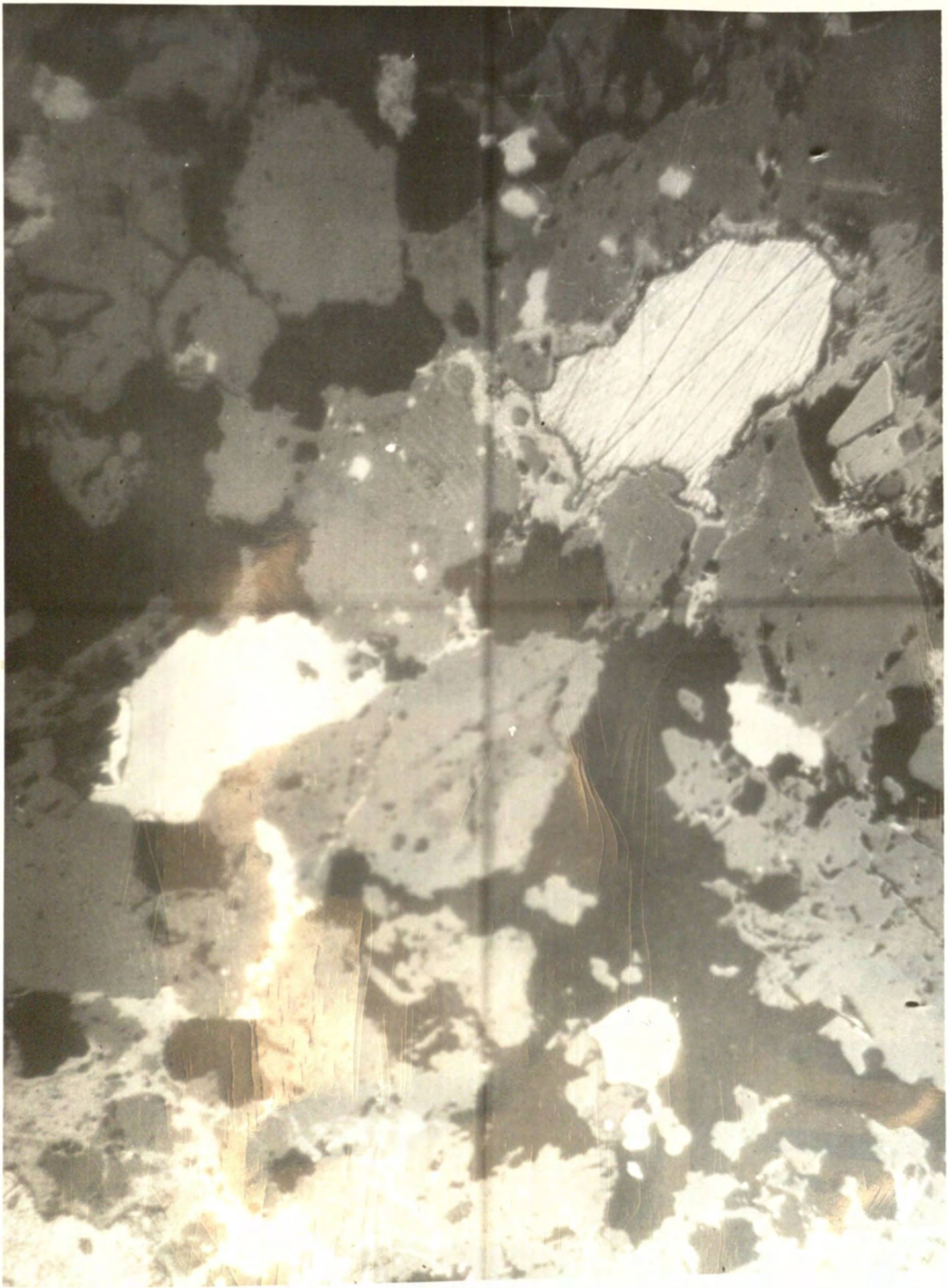


Figure 28

Taenite Included in Kamacite. Neumann Lines Stop Abruptly At Contact. Yonōzu Meteorite. x250:

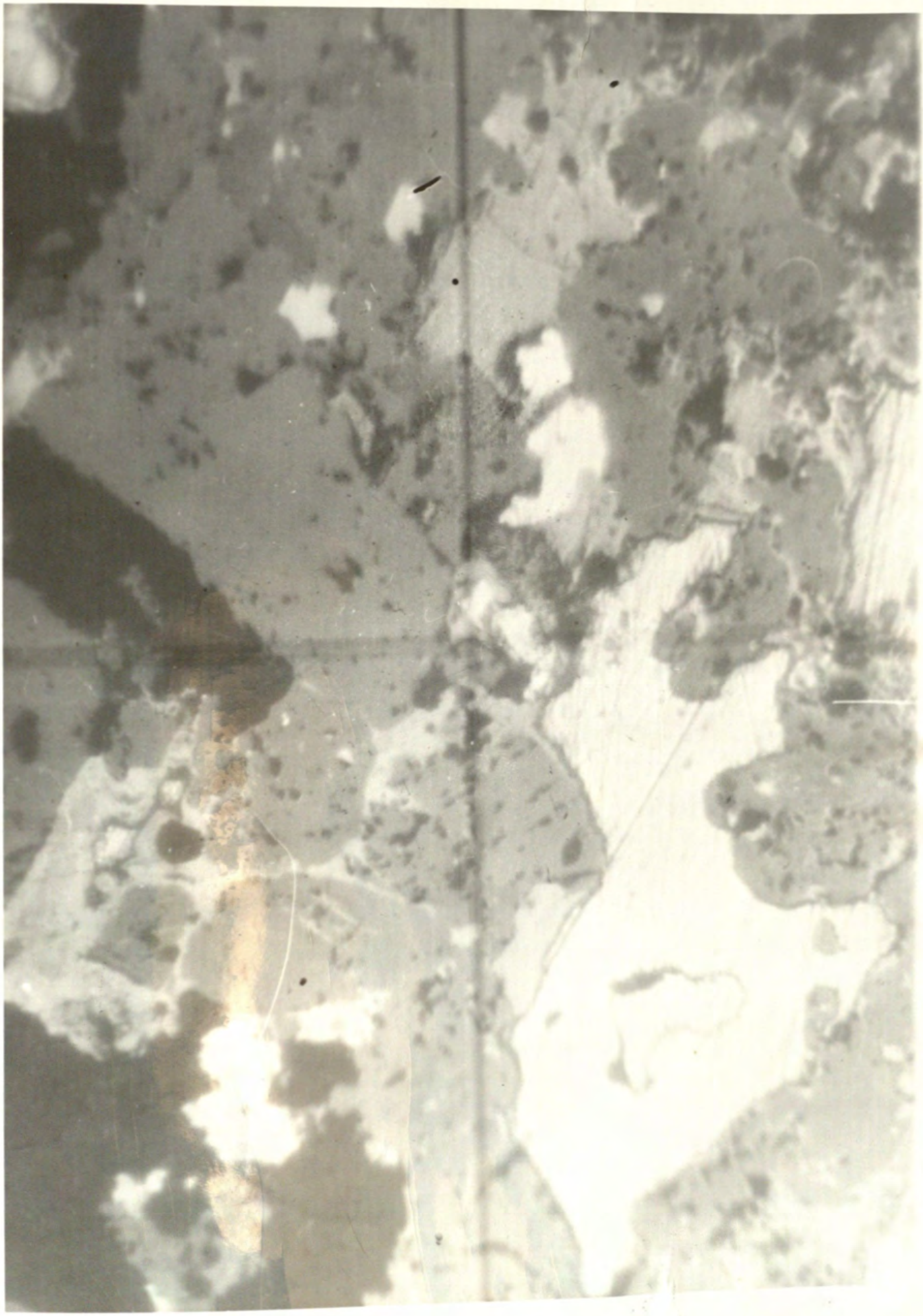
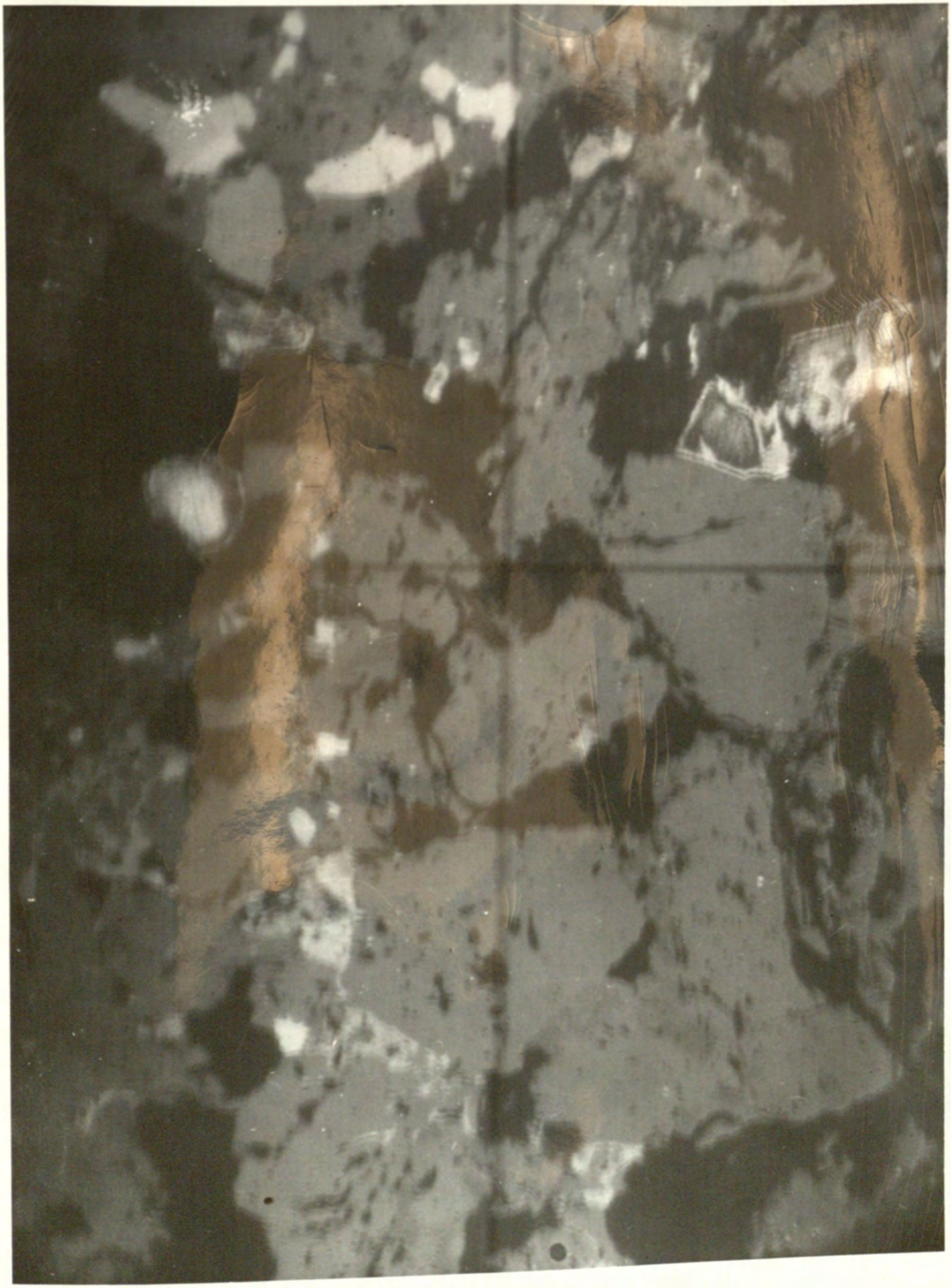


Figure 29

Troilite Nodules Surrounded By Kamacite.

Yonōzu Meteorite. x250:



Kamacite is the name applied to the body-centered cubic alpha phase of the iron-nickel equilibrium system. It generally has a composition of approximately 94 percent iron and 6 percent nickel. It is iron-gray, magnetic, and has a hardness between 3 and 4 on Mohs scale of hardness, being easily scratched with a needle. This is generally the principal component of meteoric irons (Perry, 1944, p. 10).

Taenite is the face-centered cubic gamma phase of the iron-nickel equilibrium system. The composition is variable, ranging from 18 to 48 percent nickel, corresponding to the formulas of Fe_7Ni to $FeNi$. The hardness is virtually identical with that of kamacite by ordinary hardness tests. However, taenite is resistant to etchants, being practically insoluble in dilute acids. This serves to distinguish it from kamacite, which is easily etched (Perry, 1944, p. 14). They also differ in color, the taenite being lighter than the kamacite.

No plessite was observed.

Chemical Analyses

Quantitative chemical analyses of the metallic phase, the non-metallic phase, and of the undifferentiated entirety of the meteorite were made. Molecular proportions of the metallic components were made from the analysis of the

Kamacite is the name [illegible] cubic alpha phase of [illegible] It generally has a[illegible] appearance of [illegible] iron and 6 percent nickel. It is [illegible] has a hardness between [illegible] being easily scratch[illegible] the principal component of [illegible] p. 10).

Taenite is the face-centered cubic [illegible] the iron-nickel equilibrium diagram. [illegible] variable, ranging from [illegible] ing to the [illegible] virtually identical [illegible] hardness tests. However, [illegible] being practically [illegible] to distinguish it from kamacite, [illegible] (Perry, 1944, p. 14). [illegible] taenite being [illegible]

No plessite was observed.

Chemical Analyses

Qualitative chemical [illegible] the non-metallic [illegible] of the meteorites were [illegible] metallic components were [illegible] metallic phase. A normative composition was calculated from the analysis of the non-metallic phase. These data are appended as Tables III and IV. M. Kodera's analysis is also included as Table V.

Conclusion

It is the conclusion of the writer that the Yonōzu, Japan meteorite be classified as (Chy), a hypersthene-olivine chondrite, following the Leonard classification of the Rose-Tschermak-Brezina system (Leonard, 1948). Because of the high percentage of silicate minerals it is thought that this meteorite must have had its origin in the exterior mantle of the meteorite-planet. This is in accordance with the meteorite-planet hypothesis originally suggested by Boisse in 1850 and independently formulated by Farrington in 1901, and recently strongly supported by Brown by reason of thermodynamic studies. This hypothetical planet is supposed to have been constituted much like the earth, having had a nickel-iron core and an exterior mantle of silicate minerals. It had dispersed nickel-iron in quantities decreasing from the interior outward. Therefore, meteorites with small percentages of nickel-iron scattered throughout a silicate phase must have come from relatively near the surface of the planet.

metallic phase. A quantitative [illegible]
from the analysis of [illegible]
are appended as Tables [illegible]
is also included as Table [illegible].

Conclusions

It is the conclusion of [illegible] that the Jagem meteorite [illegible] chondrite, following the [illegible] classification of the Tschermak-Brezina system (Prior, 1920). [illegible] of the high percentage of [illegible] this meteorite [illegible] mantle of the meteorite-[illegible] with the meteorite-planet hypothesis [illegible] by Brezina in 1880 and [illegible] in 1901, and recently [illegible] of thermodynamic studies. [illegible] supposed to have been [illegible] having had a nickel-iron [illegible] silicate minerals. [illegible] quantities decreasing [illegible] meteorites with small [illegible] throughout a silicate [illegible] near the surface of the [illegible].

TAABLE III

Chemical Analysis of tthe Yonōzu, Japan Chondrite

	Percent
Silica, SiO_2	22.00
Iron Oxide, Fe_2O_3	42.06
Aluminum Oxide, Al_2O_3	3.51
Calcium Oxide, CaO	2.33
Magnesium Oxide, MgO	19.81
Potassium Oxide, K_2O	0.18
Sodium Oxide, Na_2O	1.60
Nickel, Ni	1.72
Cobalt, Co	0.29
Manganese, Mn	0.75
Sulfur, S	1.35
Chlorine, Cl	0.47
Titanium, Ti	0.00
Phosphorus, P	0.46
Carbon, C	None detected
	96.53%

TABLE IV

IOM-8, Yonōzu

Metallic phase

Fe	87.78
Ni	8.53
Co	.57
P	.78
S	1.46
Cl	.52
C	0.00
	99.64

Molecular Proportion $\frac{Fe}{Ni} = 10.81$

Molecular Proportion $\frac{Fe}{Ni + Co} - 10.14$

Non-metallic phase

SiO_2	32.65
Fe_2O_3	24.87
Al_2O_3	5.21
CaO	3.46
MgO	29.40
K_2O	.27
Na_2O	2.37
MnO	1.11
TiO_2	0.00
C	0.00
	99.34

Normative calculation

Hypersthene	32.71
Olivine	41.57
Anorthite	12.57
Diopside	5.15
Hematite	8.00

Metallic phase. . . . . 14.76% by weight
Non-metallic phase. . . 85.24% by weight

In the normative calculation only silica, iron, alumina, lime and magnesia were considered. There is, of course, no anorthite nor diopside in the sections, unless it is in the glass or the very fine portion. Of course, the alumina, etc. may be present in the other minerals as impurities.

TABLE V

Chemical Analysis of the Yonōzu, Japan Chondrite

by M. Kodera, of the Imperial Geological Survey of Japan

Metallic part		Part soluble in acids		Part insoluble in acids	
Fe	7.620	FeS_2	3.299	SiO_2	19.990
Ni	0.270	FeO	17.726	FeO	3.031
Co	0.130	Fe_2O_3	1.314	Al_2O_3	2.658
		NiO	1.464	Cr_2O_3	0.315
		CoO	0.064	MnO	0.651
		CaO	1.180	MgO	9.346
		Al_2O_3	2.972	K_2O	0.231
		MgO	13.149	Na_2O	0.863
		P_2O_5	0.494		
		SiO_2	13.270		

THE GLORIETA, NEW MEXICO SIDERITE (E.C.N. - 1058,356)

Introduction

The first recoveries from the Glorieta fall were made by Mr. Charles Sponsler on August 9, 1884 on the ranch of Mrs. Roival, near Canoncito, Santa Fe County, New Mexico. Mr. Sponsler, who had been prospecting on the Roival Ranch, imagined that he had stumbled upon a valuable ore deposit, although the mass was found lying on top of a rock. The impact with the rock had shattered the meteorite into three fragments. Subsequent to Sponsler's initial discovery, Mr. J. H. Bullock, beginning in August, 1885 spent more than six weeks in a careful examination of the area in which the masses of meteoritic iron had been found and, as a result of his search and excavations, discovered three more masses of the fall. Since the discoveries made by Sponsler and Bullock in 1884 and 1885, the finding of an occasional additional fragment of the Glorieta meteorite has been reported from time to time. At least two of these more recent finds (Albuquerque and Pojoaque) were initially assigned incorrectly to localities remote from Glorieta, but are now accredited to the shower which fell on and near the Roival Ranch.

In order of decreasing size, the six masses found by Sponsler and Bullock may be described as follows: No. 1 weighs

148.5 pounds and clearly exhibits a surface of disruption; No. 2 weighs 115 pounds and shows not only a surface of rupture like that on No. 1, but also a flattened portion 10 by 6 inches which has been interpreted as the surface area which actually struck against the rock; No. 3 weighs 53.5 pounds and shows also a surface of rupture; No. 4 weighs 2.65 pounds and shows the effects of disruption over one-third of its surface, the area of fracture showing coarsely fibrous iron drawn out in the direction of the missing part; No. 5 weighs 2.48 pounds and over five-sixths of the entire surface bears marks of violent disruption; No. 6 weighs 2.31 pounds and is very flat, the fracturing of the mass having left a nearly plane surface suggestive of a cleavage.

Dr. G. F. Kunz, after careful examination of Nos. 1 to 6, concluded that all of these pieces are fragments of a single large meteorite which "flew asunder" when it struck the rock on the Ricoival Ranch. He notes that the 148.5-pound piece was found only 8 feet from the 115 pound and the 53.5-pound pieces, a fact which, in his opinion, demonstrates conclusively that the meteorite burst at impact with the rock and not while traversing the air. Even the small fragments, Nos. 4, 5, and 6, were found at not more than 45 or 50 feet from the large masses, having been hurled to such distances because of their light weight. All of the

fragments were buried at depths of from 3 to 10 inches in the vegetable mold which covers the solid rock in many places. Kunz has attempted to reconstruct the original single mass from these 6 fragments, arriving at an individual with a length of 25 inches, a height of 10 inches, and a thickness of 15 inches (Kunz, 1885, p. 329).

In contrast to the opinion Kunz formed concerning the fragmentation of the meteorite, A. Brezina (1895, p. 20) regarded Glorieta as a siderite which, like Butsura, had burst before reaching the earth and had suffered partial fusion after separation of the pieces in the air. In support of this view, Brezina called attention to the striking differences between the smooth surfaces, coated with fusion crust, which he interpreted as parts of the primary face, and the areas characterized by hackly fracture, occasionally slightly fused, which he regarded as the secondary surfaces.

An analysis of fragment No. 3 by James B. MacKintosh of the School of Mines, New York City gave the following results: Fe - 87.93; Ni - 11.15; Co - 0.33; P - 0.36. In MacKintosh's analysis, carbon, sulphur and other constituents were not determined.

An analysis of the seventh mass recovered from the Glorieta fall was made by L. G. Eakins with the results given below:

fragments were [illegible]

vegetable [illegible]

Kuhn has attempted [illegible]

from these fragments [illegible]

length of 25 inches, a height [illegible]

of 15 inches (Kuhn 1938) [illegible]

In contrast to [illegible]

fragmentation of the [illegible]

[illegible]

[illegible]

[illegible]

of this site, [illegible]

[illegible]

which he [illegible]

[illegible]

[illegible]

An analysis of [illegible]

of the [illegible]

[illegible]

[illegible]

[illegible] were [illegible]

An analysis of the [illegible]

[illegible]

below

Iron	88.760
Nickel	9.860
Cobalt	0.510
Copper	0.034
Zinc	0.030
Manganese	Trace
Phosphorus	0.182
Sulfur	0.012
Silicon	0.044
Carbon	Undetermined
	99.432

Eakins regards this analysis as corresponding to the following constitution:

Nickeliferous iron	98.224
Troilite (FeS)	0.033
Schreibersite (Ni_2Fe_4P)	1.175
	99.432

Although Cohen, Weinschenk, and Brezina have studied certain features of the Glorieta meteorite, this siderite has not received the attention which its many unusual characteristics would seem to merit. The present paper is based on a detailed chemical, mineralogic, and metallographic investigation of a remarkable specimen of the Glorieta Mountain fall (IOM-7) weighing three pounds and twelve ounces.

Megascopic Examination

Megascopic examination of this specimen reveals that it is a club-shaped siderite 23 cm long with a cross-

section about 4 cm in each direction at the widest part (Fig. 30b). It has been sliced, polished, and macroetched along one side (Fig. 30a). Small sections have been removed from one end, one a cross-section and one a section parallel to the long axis, in order to make polished sections for metallographic study.

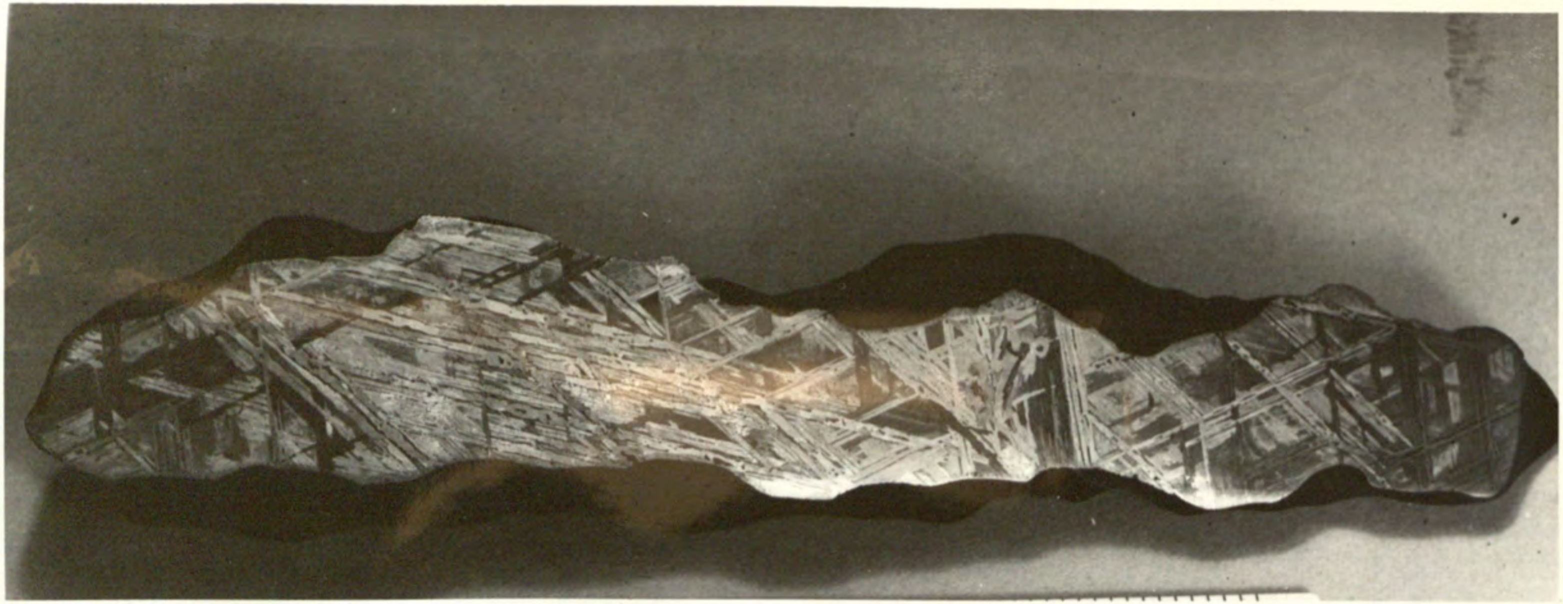
The weathered surface is characterized by angular pittings. The angularity of these pits is a rather unusual feature of meteoric irons. The long, rod-shaped, or club-shaped, habit of the meteorites assigned to this fall is also unusual. The color on the waathered surface is the reddish-brown so common to siderites.

The macroetched surface shows the iron to be an octahedrite, probably a medium octahedrite. A few small areas have been deeply etched and appear granular. It is thought that this indicates areas which had a loosely granular structure prior to etching and were more deeply etched because of the greater surface area exposed to the dissolving action of the etching solution. It is possible that these areas are due to the presence of a mineral much more soluble than the average metallic constituents of the meteorite.

This fall consists of a number of irons, some of which are said to possess pallasitic areas, or areas containing large grains of olivine enmeshed in a network

Figure 30A Figure 30B

Glorieta Mountain Meteorite




52.13
10
1
2
3
4
5
6

of nickel-iron. The specimen studied for this paper exhibits no such areas.

Microscopic Examination

Two polished sections of this iron were prepared for study, one cut parallel to the long axis of the specimen and the other cut at right angles to it. Both were cut from one end of the meteorite. Examination prior to etching revealed small amounts of lawrencite, a ferrous chloride (Fig. 31), and scattered grains of a constituent other than nickel-iron (Fig. 32). Scratching with a needle indicated that this latter is either schreibersite, an iron-nickel phosphide $(Fe,Ni)_3P$, or cohenite, an iron-nickel carbide $(FeNi)_3C$ (Fig. 33). Etching with boiling alkaline sodium picrate proved it to be schreibersite.

Schreibersite is tin-white, like taenite, but can be distinguished from taenite by its greater hardness, 6.5. It is magnetic and readily fusible. It is insoluble in cold dilute acids and therefore is unchanged with ordinary etching.

The polished sections were then etched with Nital, 5 percent HNO_3 in 95 percent alcohol. Because of the unequal solubility constants of the primary constituents, etching brings out the internal structure of the meteorite. The structure and the relationships of the constituents are further emphasized because of the increased dissolving

of nickel-iron. [illegible]
be much to [illegible]

Experimental Procedure

Two polished sections [illegible]
study, one cut parallel to the [illegible]
the other cut at right angles [illegible]
end of the [illegible]
small amounts of [illegible]
and scattered grains of [illegible]
(Fig. [illegible]). [illegible]
labeled [illegible]
(Fe,Ni)[illegible]
(Fig. 73). [illegible]
[illegible] is to [illegible]

[illegible]
distinguished [illegible]
in magnetic [illegible]
dilute acids and [illegible]

The polish [illegible]
a percent [illegible]
equal [illegible]
etching [illegible]
The atmosphere and the [illegible]
further and [illegible]

Figure 31

Lawrencite. Glorieta Mountain Meteorite. x250:

Figure 32

Schreibersite Before Scratching with Needle.

Glorieta Mountain Meteorite. x250:

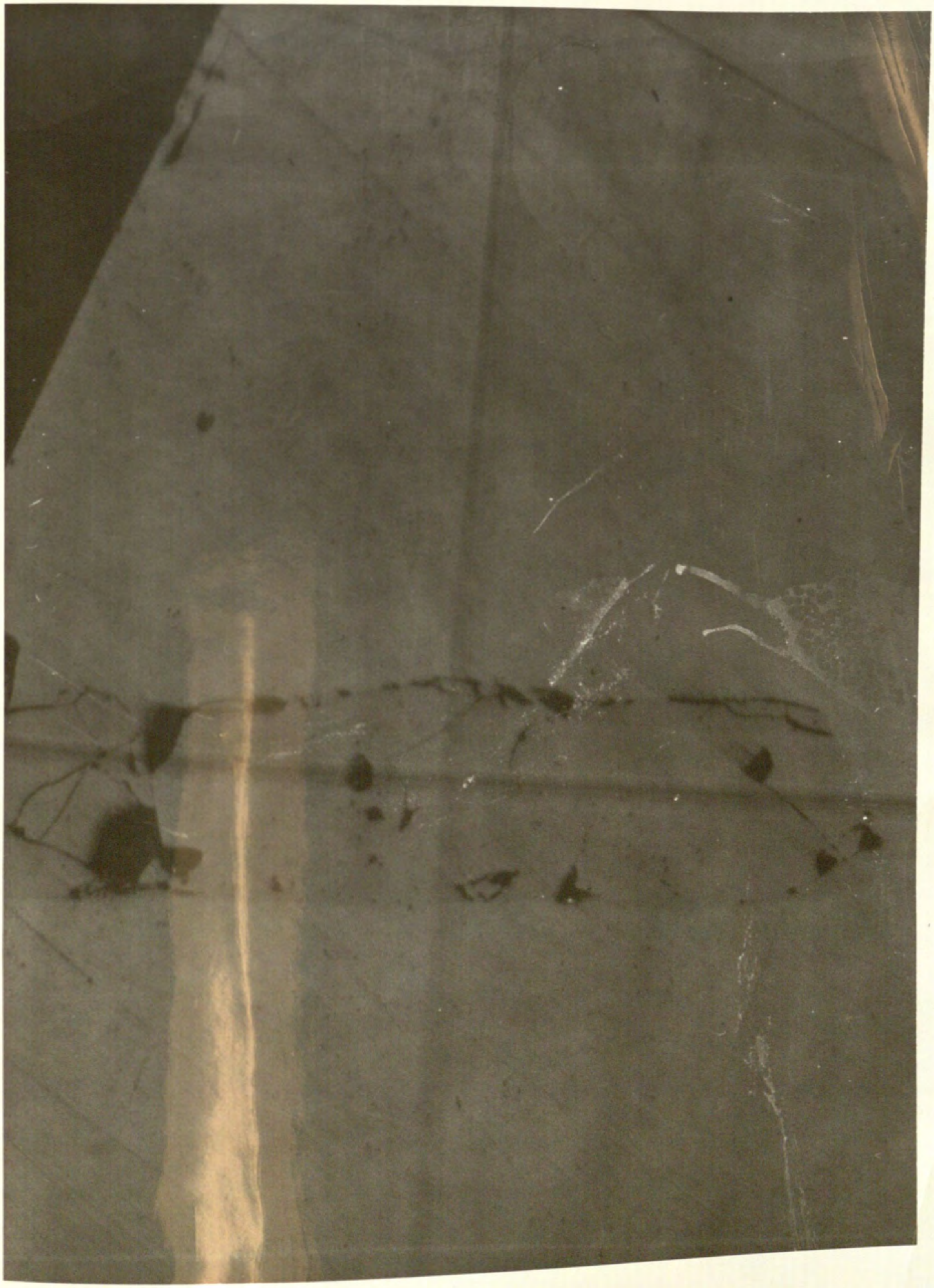
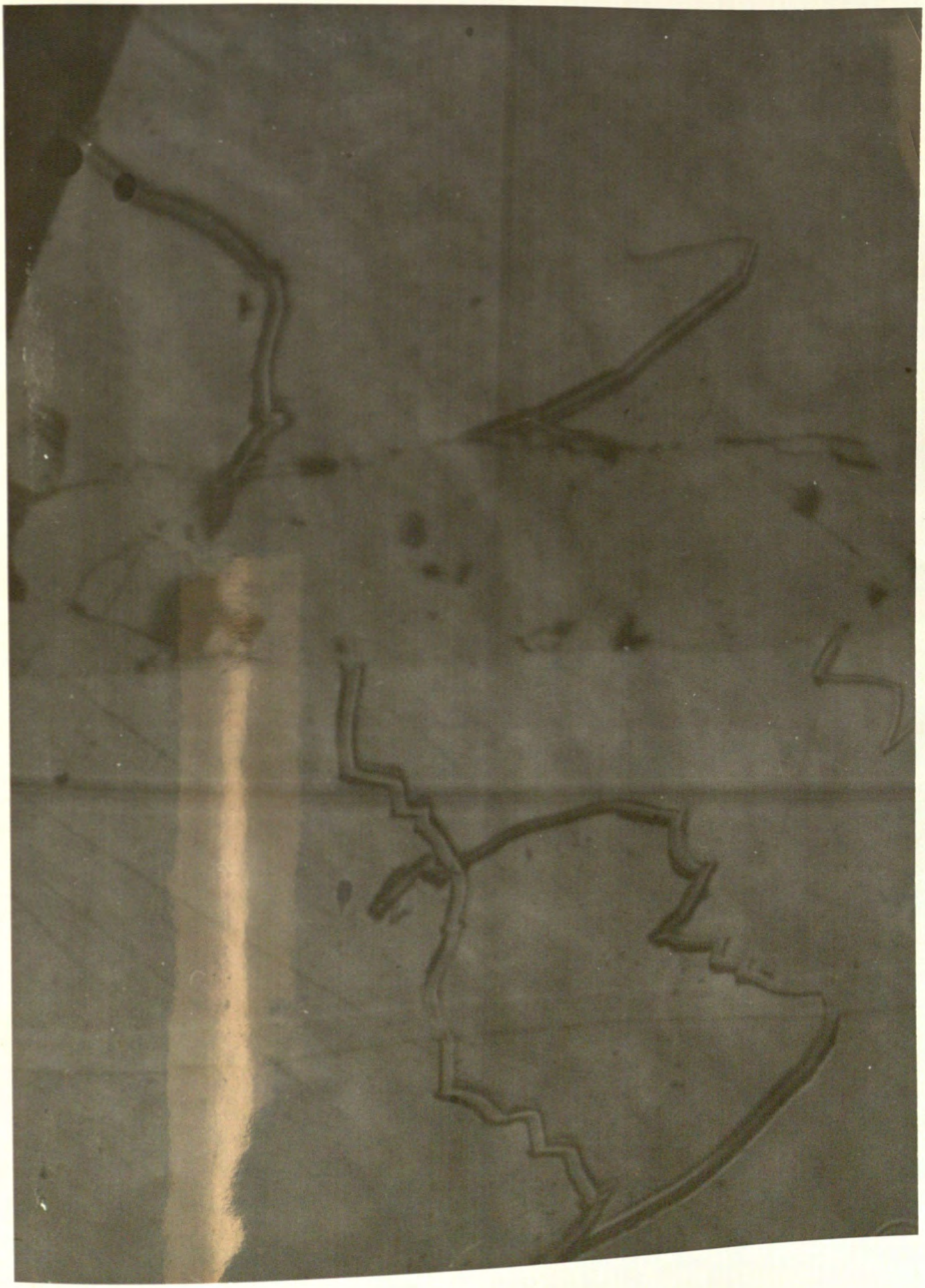


Figure 33

Same View As Figure 32 After Scratching with Needle.

Glorieta Mountain Meteorite. x250:



action along grain boundaries. This is, of course, due to the greater surface area exposed to the action of the etching solution.

Metallographic examination after etching shows the meteorite to be composed of kamacite, taenite, coarse plessite, and dense plessite, with a small percentage of schreibersite. The structure is that of a typical octahedrite, a network of bands crossing one another in two, three, or four directions (Fig. 34). The bands are composed of kamacite, usually bordered by thin lamellae of taenite, an iron-nickel alloy rich in nickel. Filling the angular interstices of the network are areas called fields, which are composed of plessite--a more or less fine mixture of kamacite and taenite--and which assume a great diversity of form and structure (Perry, 1944, p. 4).

Kamacite is the principal component of meteoric irons. It is an alloy composed of approximately 94 percent iron and 6 percent nickel. It is the alpha phase of the iron-nickel equilibrium system. In structure it is body-centered cubic. It is iron-gray, magnetic, and has a hardness between 3 and 4 on the Mohs scale. It etches quickly, being soluble in dilute acids (Perry, 1944, p. 10).

Taenite is the gamma phase of the iron-nickel equilibrium system. In structure it is face-centered cubic. Taenite is composed of iron and nickel in varying proportions, action along grain boundaries, [illegible] to the greater surface [illegible] to the action of etching solutions.

Metallographic examination of [illegible] meteorite to be [illegible] classified [illegible] plessite, and dense [illegible] schreibersite. The [illegible] hedrite, a network of bands [illegible] three, or four directions [illegible] of kamacite, usually bordered by [illegible] an iron-nickel alloy with [illegible] interstices of the network [illegible] are composed of plessite [illegible] kamacite and taenite [illegible] of York and [illegible]

Kamacite is the principal [illegible] iron. It is an alloy [illegible] iron and 6 percent [illegible] iron-nickel equilibrium [illegible] centered cubic. [illegible] hardness between 4 and [illegible] quickly, being soluble in [illegible]

Taenite is the [illegible] lithium [illegible] Taenite is composed [illegible]

Figure 34

Octahedral Structure. Glorieta Mountain Meteorite. x250:

the nickel content ranging from 18 to 48 percent. Formulas corresponding to these percentages of nickel range from Fe_7Ni to FeNi. Taenite is tin-white, elastic, and usually magnetic. It is easily distinguished from kamacite by its white color and its resistance to etchants, it being practically insoluble in cold dilute acids. Because of the varying proportions of nickel and iron the hardness of taenite is not constant. Generally the hardness is approximately equal to that of kamacite (Fig. 35). This illustration indicates that the taenite in this specimen is very slightly harder than the kamacite (Perry, 1944, p. 14).

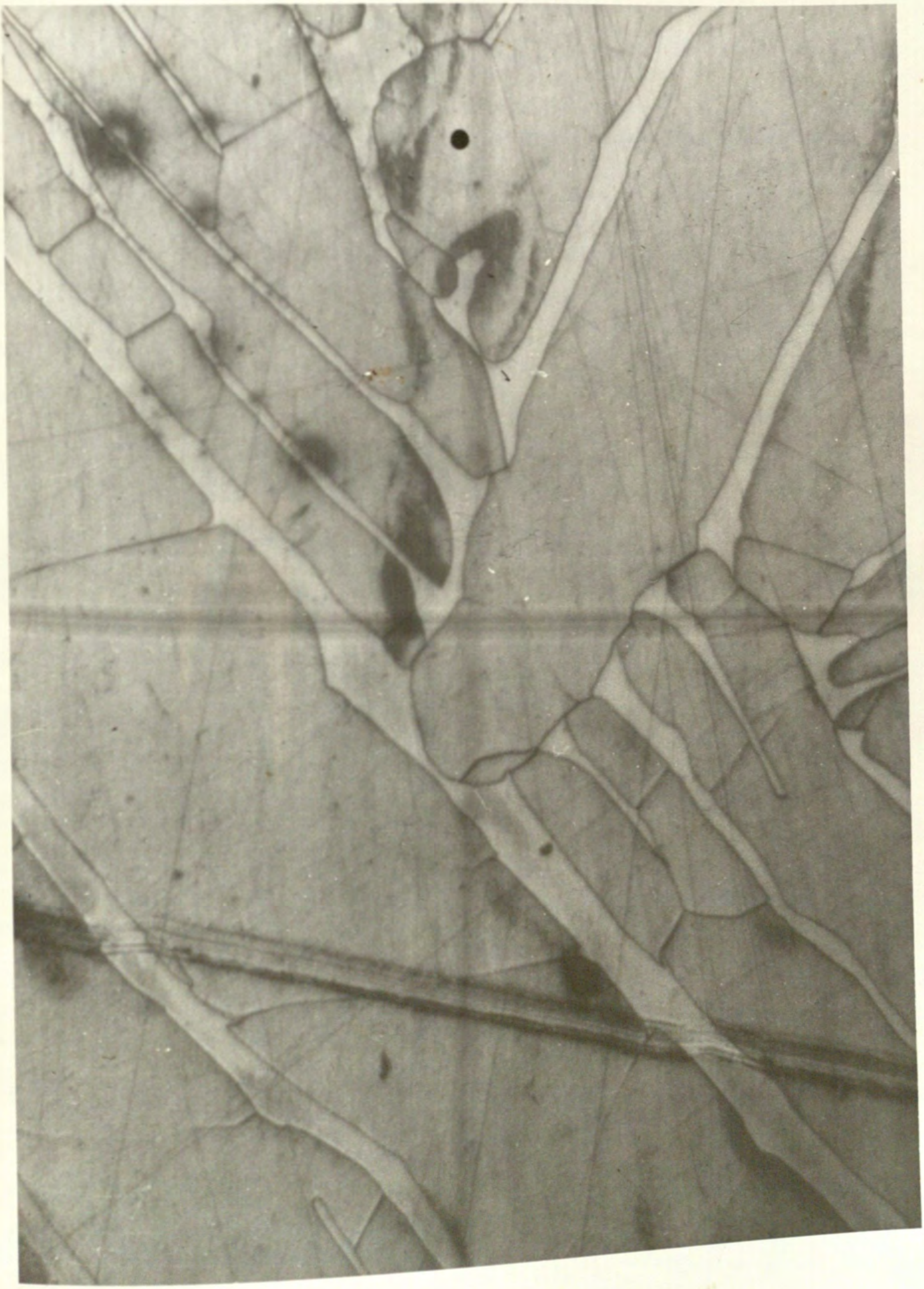
Plessite may be regarded as a supersaturated solid solution of taenite with respect to kamacite, its form depending upon conditions of temperature and the rate of cooling. Plessite in octahedrites is thought to be an alpha-gamma mixture formed during transformation. Its structure is dependent on the thermal range prevailing during transformation, a coarse structure being formed in a high thermal range and an extremely fine structure at low temperatures. Plessite fields are remnants of the gamma phase left in the interstices of the octahedral network, and their structure was developed in the solid state (Perry, 1944, p. 64).

The coarsest types of light plessite often show skeletal growths of taenite, referred to by German writers

Figure 35

Needle Scratch Crossing Kamacite And Taenite Lamellae.

Glorieta Mountain Meteorite. x250:



as combs, parallel with one or more of the surrounding octahedral planes. This structure may be found in this meteorite (Fig. 36). Light, or coarse, plessite is seen to occupy the "field" in the typical octahedral structure (Fig. 37). It can also be found in elongate fields interspersed among kamacite lamellae (Fig. 38). Some dense plessite was also found occupying a similar position (Fig. 39).

Schreibersite particles with sharp, straight edges were noted (Fig. 40). It is possible that these represent traces of crystal faces. The included black areas are typical of schreibersite grains and represent portions torn out during the polishing operation. This phenomenon is an expression of the brittle nature of the mineral.

The kamacite lamellae range from 0.05 mm to 1.75 mm, with the mahority falling within the range between 0.25 mm and 0.75 mm. This places the octahedrite in the class medium octahedrite (Om).

Chemical Analysis

A chemical analysis of this meteorite was made by Dr. E. L. Martin of the Department of Chemistry at The University of New Mexico. This analysis is appended as Table VI. From this analysis the molecular proportions of the metallic constituents were calculated. It is to be

Figure 36

"Comb" Structure. Glorieta Mountain Meteorite. x250

Figure 37

Plessite in "Fields" in Octahedral Structure.

Glorieta Mountain Meteorite. x250:

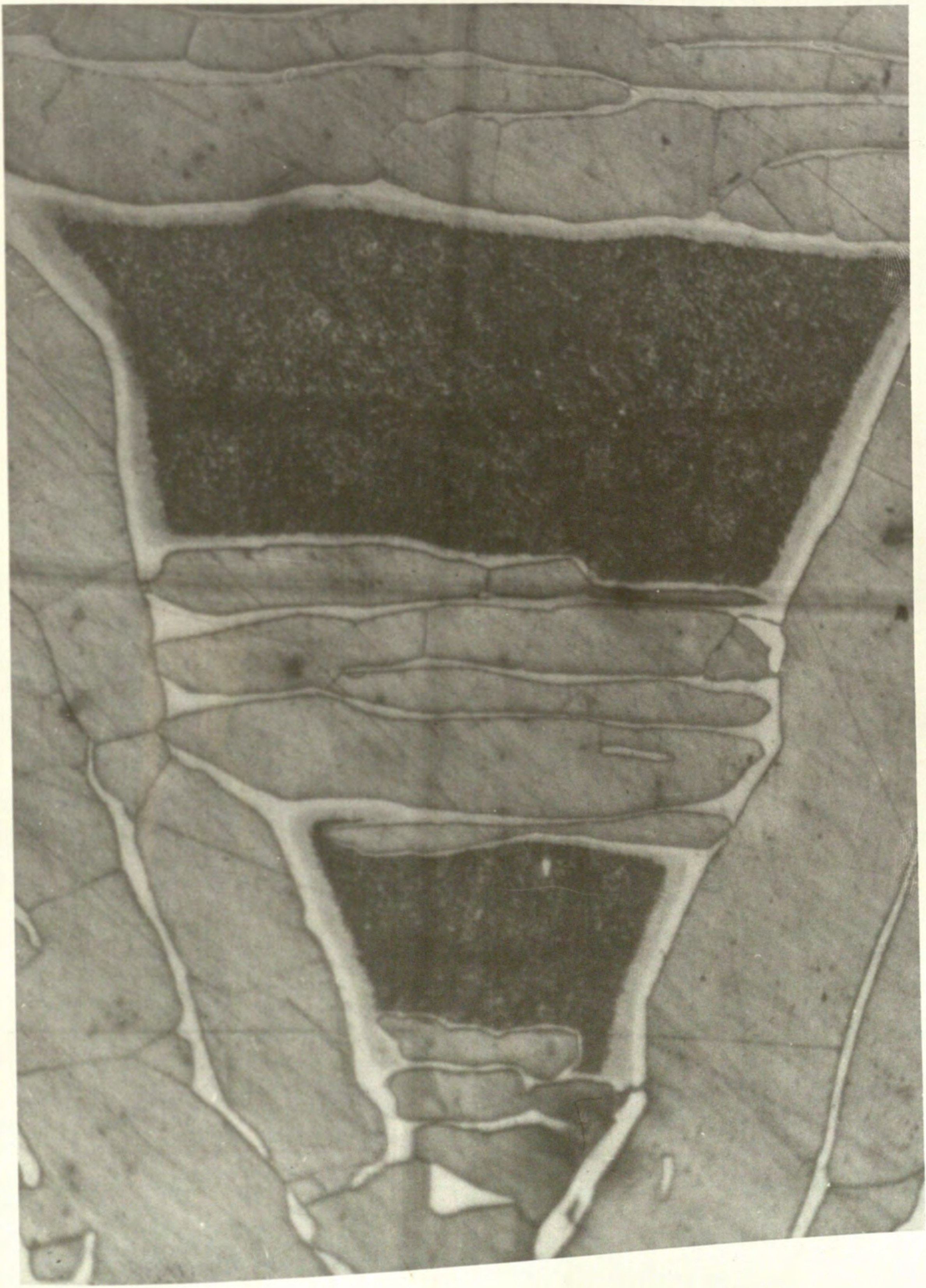


Figure 38

Coarse Plessite Between Kamacite and Taenite Lamellae.

Glorieta Mountain Meteorite. x250:

Figure 39

Dense Plessite Between Kamacite and Taenite Lamellae.

Glorieta Mountain Meteorite, x250:

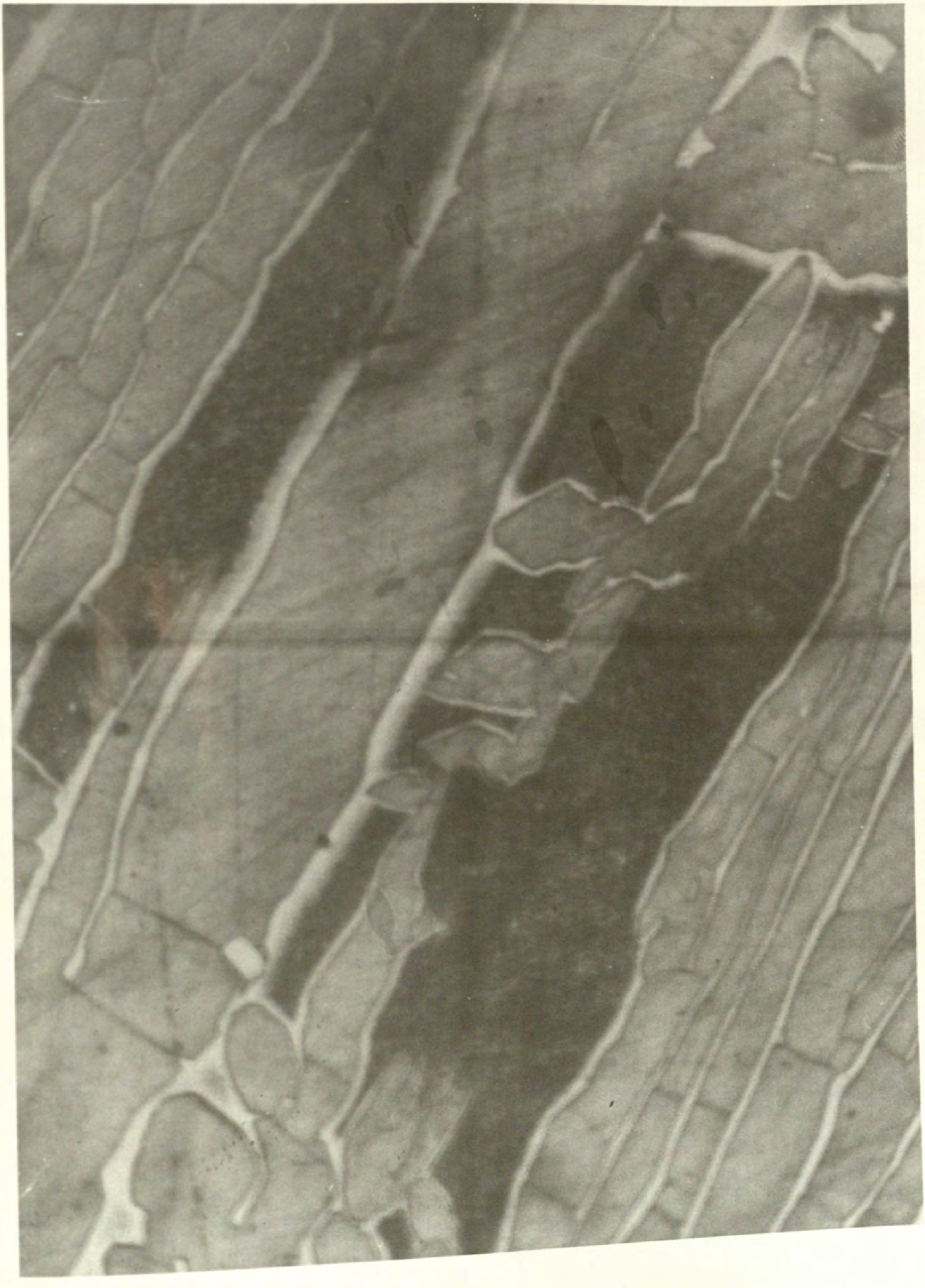


Figure 40

Sclhreibersite Grains with Sharp Boundaries in Kamacite.

Glorieta Mountain Meteorite. x250:

TABLE VI

Chemical Analysis of the Glorieta Mountain, New Mexico Meteorite

	Percent
Iron, Fe	88.37
Nickel, Ni	10.39
Cobalt, Co	0.84
Chlorine, Cl	0.48
Copper, Cu	0.00
Sulfur, S	0.00
Phosphorus, P	0.001
	100.081

noted that an extremely small percentage of phosphorus is indicated, whereas schreibersite was found in considerable quantities in the polished sections. This demonstrates the chief difficulty in attaining an accurate analysis of a meteorite, brought about by the necessity of obtaining a representative sample without destroying a large proportion of the specimen. Evidently the sample taken for analysis failed to include many of the numerous isolated grains of schreibersite.

Conclusion

This meteorite is classified a medium octahedrite (Om). No pallasitic areas were observed in this specimen although such areas have been described in investigations on other members of this fall. Because this specimen consists entirely of the metallic phase it is thought that it must have had its origin in the nickel-iron core of the meteorite-planet.

SUMMARY AND CONCLUSIONS

This thesis presents the mineralogy and chemical analyses of three meteorites. The mineralogical study consists of thin-section, oil-immersion, and polished section studies.

The Lalande, New Mexico chondrite (Chy) and the Yonōzu, Japan chondrite are similar. Both are composed of olivine and enstatite (var. hypersthene), with minor amounts of enstatite-clinoenstatite intergrowths, secondary hematite, and metallic grains. Both are strongly iron-stained by alteration of the olivine and hypersthene. The metallic phase of the Yonōzu, Japan specimen shows some Neumann lines, thought to have been produced by impact with the earth's atmosphere. Troilite is present in the metallic phase of both meteorites.

The Lalande, New Mexico chondrite is presently thought to be a member of the Melrose, New Mexico shower rather than an independent fall.

The Glorieta Mountain, New Mexico octahedrite (Om) is composed of kamacite and taenite, the alpha and gamma phases of the nickel-iron equilibrium system, and plessite, a solid solution of the nickel-iron equilibrium system, with a minor amount of schreibersite, a nickel-iron phosphide. The plessite is of two varieties, light or coarse plessite,

and dense plessite. The light plessite is of a coarse texture, and the dense plessite is of a very fine texture. Both varieties are found in the fields of the octahedral pattern. The width of the kamacite lamellae ranges from 0.04 mm to 1.75 mm but the majority are between 0.25 mm and 0.75 mm.

and dense plessite. The light plessite is of fine texture, and the dense plessite is of a very fine texture, both varieties are found in the fields of the octahedral pattern. The width of the kamacite lamellae ranges from 0.04 mm to 1.75 mm but the majority are between 0.25 mm and 0.75 mm.

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