THE NORTONITE FALL AND ITS MINERALOGY

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Abstract

A brief summary is given of the circumstances attending the observation of, the search for, and the recovery of the achondrites that fell on February 18, 1948 in Kansas and Nebraska. The main mass of this achondritic fall is not only the largest known aerolite in the world but also the largest meteorite of any type of witnessed fall. The weight of the principal mass is inferred to be at least 2360 pounds and the integrated weight of the recoveries so far made is estimated as in excess of 2500 pounds. The recovered achondrites serve as the type stone of a new achondritic subclass, the nortonites, intermediate between the aubrites and the Cumberland Falls whitleyite.

Brief details are given on the distribution of nortonite recoveries, on the apparent and corrected radiant of the shower, and on the real path of the fireball.

The mineralogy of the nortonites is discussed. Megascopically, this achondrite resembles a rhyolite porphyry in which the "phenocrysts" are grayish cleavage enstatite and glassy enstatite, and the fine-grained "groundmass" seems to be solely enstatite. Closer inspection reveals inclusions of nickel-iron pellets; abundant, small flakes of graphite; diallage; and iron-rust stains. Microscopic examination in thin sections and oil immersions confirms the megascopic examination, and reveals that olivine is fairly abundant. Clinoenstatite is intergrown with enstatite in some crystals. Optical constants are given for enstatite and olivine. The meteorite has a fusion rind ranging from 0.2 mm. to at least 17.7 mm. The rind is holocrystalline and is very fine grained.

A polished section of one nickel-iron inclusion was studied. The metallic phase is made up of kamacite and schreibersite. Small amounts of troilite were noted in other metallic inclusions but none in the polished specimen.

Chemical and spectrographic analyses of the stony and metallic phases are given. Tests have been run at the Institute for Nuclear Studies of the University of Chicago on nortonite samples in an effort to detect radioactivities induced by exposure to cosmic radiation. To date, no evidence of such radioactivities has been obtained.

The recovery of this achondrite gives strong support to the "meteorite-planet" hypothesis favored by Boisse, Farrington, and Harrison Brown.

Eight figures and two tables are given.

Introduction

Shortly before 4:56 p.m. C.S.T. on February 18, 1948, a large and brilliant detonating fireball fell near the common boundary of Norton County, Kansas, and Furnas County, Nebraska. Initial reports describing this incident as the fall of an airplane in flames southeast of the airbase at McCook, Nebraska, were transmitted to the Institute of Meteoritics of the University of New Mexico shortly before 6:00 p.m. M.S.T.

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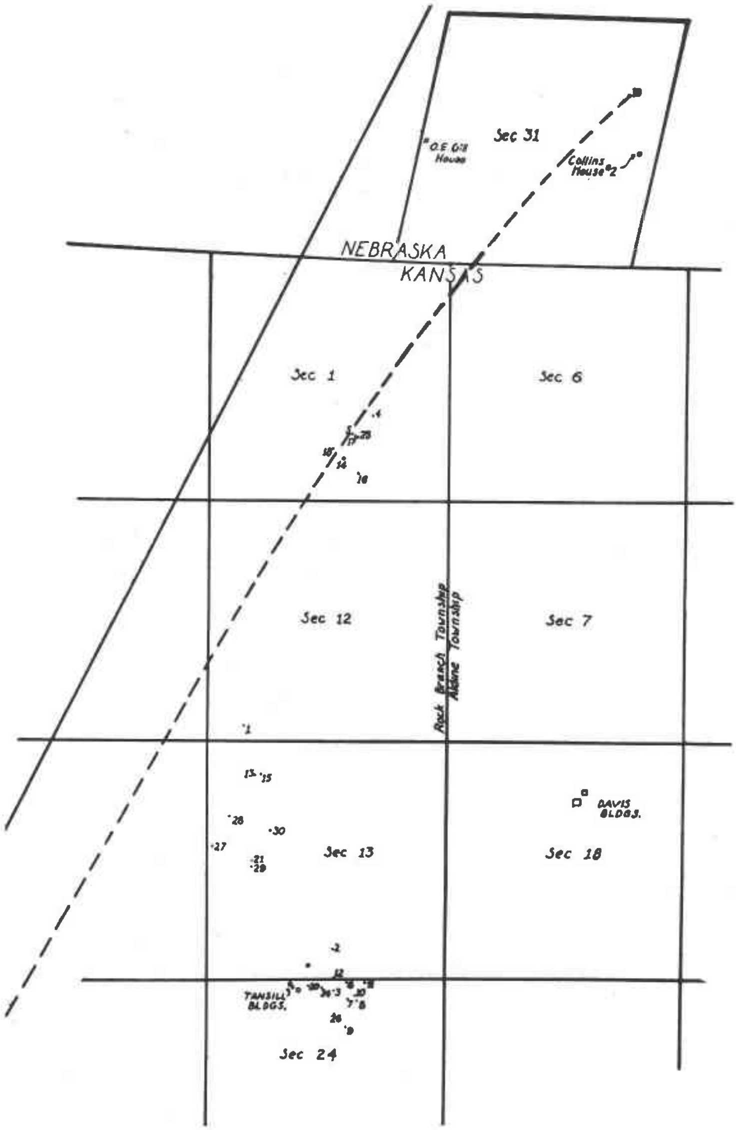

FIG. 1. Distribution of recovered fragments of the Norton County, Kansas-Furnas County, Nebraska meteorite fall of February 18, 1948. No. 18, the $131\frac{1}{2}$-pound meteorite; no. 19, the 2360-pound meteorite. Solid line is the projection of the original path of the meteorite; dashed line is the projection of the real path of the meteorite veering to the east.

Within the next few hours much additional information was secured by means of interrogations conducted through Civil Air Patrol and other channels.

The best observations of the fall were so concordant that by March 3 calculations at the Institute had led to the determination of a provisional "strewn-field" location. This field was elliptical in shape, with major and minor axes of eight and four miles, respectively. The major axis, the direction of which was about N. 25° E., extended from a point about four miles south of the Kansas-Nebraska line, and almost exactly on the 100° meridian, to a point about four miles north of the state line.

A search party from the Institute entered the strewn-field on March 24, 1948. Heavy snowfall rendered effective search impossible, but this first party obtained valuable testimony from eye witnesses and secured many transit measurements of the azimuth and elevation of points on the apparent path of the fire ball. These instrumental measurements confirmed the provisional strewn-field, and gave every indication that the main mass had fallen in the northern end of the fall area in Furnas County, Nebraska. A second Institute party entered this area on April 27, 1948, and searched that portion of the elliptical strewn-field situated in Nebraska. Although the concordant testimony of eyewitnesses in this area completely substantiated the conclusion that the main mass had fallen in Furnas County, no trace of its point of impact could be found.

On revisiting the area canvassed by the first Institute party, the news was received that on April 6 a "strange stone" had been found. This stone turned out to be a fine achondritic mass. An all-out search of the southern half of the strewn-field resulted in more and more finds, culminating in the discovery on May 1 of a deeply buried achondrite weighing 131½ pounds (LaPaz, 1948). However, in spite of all efforts, the main mass of the shower remained undiscovered until, on July 3, a caterpillar tractor started to capsize into the six-foot crater produced by impact of the chief fragment of the fall. Excavations conducted by the Institute of Meteoritics and the University of Nebraska, which had jointly acquired possession of the main mass, showed that this impact crater was over ten feet deep. The locations of the various recoveries are shown in Fig. 1.

Under the direction of Dr. C. B. Schultz, University of Nebraska State Museum, and Professor E. F. Schramm, University of Nebraska, the ponderous and fragile main mass of the achondritic fall was encased in burlap, plaster of paris, and boards and trucked to the Institute of Meteoritics. In spite of the fragile nature of the achondritic material, the sheathing prevented damage to even the sharpest knife edges separating contiguous piezoglyphs (Fig. 2).

Characteristics of the Achondrite and Its Real Path

The stone has an irregular shape; however, a close approximation to its true volume was obtained by treating the achondrite as made up of several regular geometric solids. By this method Mr. Frank Lane, Department of Mathematics and Astronomy, University of New Mexico, found that the volume of the Furnas County stone was approximately 11.8 cubic feet. Adopting the smallest admissible value of the density of the achondrite (3.18), this volume corresponds to a weight of 2360 pounds. The integrated weight of all the fragments so far recovered from the shower has been estimated conservatively as in excess of 2500 pounds.

In view of the relative rarity of achondrites—this class of meteorite constitutes only 9 per cent of the aerolitic falls of the world and makes up

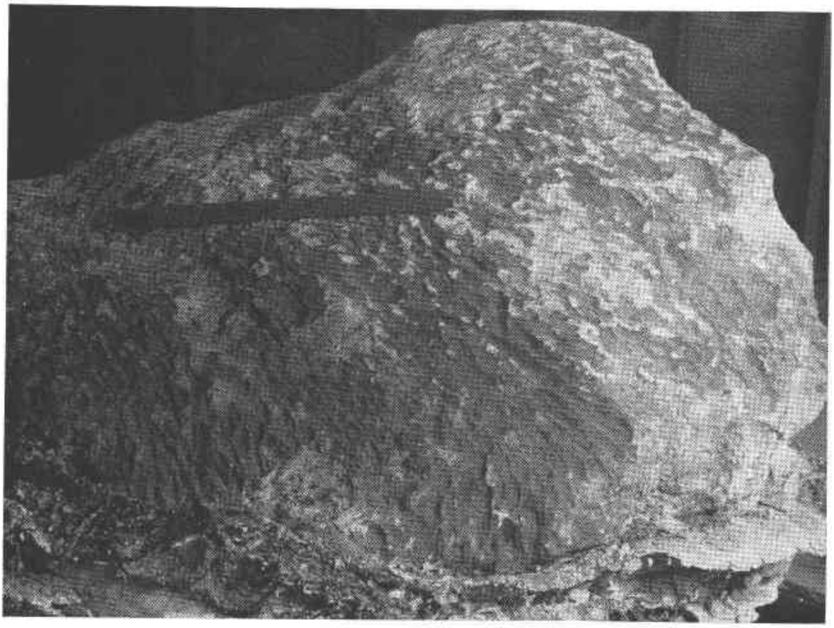

FIG. 2. The main mass of the achondrite, showing piezoglyphs.

an even smaller proportion of the recoveries on a weight basis (Leonard, 1943 and 1946)—the extraordinary nature of the shower of February 18, 1948, as regards magnitude, can be appreciated. However, it is not alone in size that this fall is exceptional. The material recovered in Kansas and Nebraska differs sufficiently from all known achondrites to justify adopting it as the type stone of a new achondritic subclass (Beck and LaPaz, 1949). The role played by the Norton-Furnas achondrite is that of a second link in the chain connecting the aubrites (Au) and the enstatite-achondrites (Cen). The first link is the whitleyite (Merrill, 1921) as shown in the classificational sequence of Leonard (1948). Following Leonard (1948 and 1949), this fall would be assigned the nomenclature A_2no, would occupy a position between the aubrites and the whitleyite, and would be called *nortonite.*

The projection of the path of the achondrite before it was affected by air resistance is shown by the solid line in Fig. 1. The projection of the real path of the meteorite in the atmosphere is shown by the dashed line in Fig. 1. A veering of the real path toward the east, similar to but more pronounced than that shown in Fig. 1, has been found for other well-observed meteorite falls; for example, the recently reported meteorite-crater producing fall of February 12, 1947, in the Maritime Province of the USSR (LaPaz, 1949). The nortonite meteorite exploded at least twice during its visible flight and these explosions produced huge clouds of meteoritic dust.

Calculations from the known time of occurrence of the nortonite shower, the coordinates of the apparent radiant point, and velocity estimates give the following: (1) the geocentric velocity of the fireball was only 5.75 miles/second; and (2) the corrected radiant point had a right ascension of 11°50′ and a declination of $-29°01'$.

Mineralogy

Megascopic Examination. The main mass of the achondrite, the outside of which exhibits fusion crusts ranging in thickness from less than 0.2 mm. to at least 17.7 mm., is beautifully pitted with flight markings, or piezoglyphs (Fig. 2). The color of the fusion rind ranges from white to black, with most of it being a brownish-gray or grayish-brown, putty color. That the fusion was incomplete during its flight through the atmosphere is shown by the trapped angular fragments imbedded in the fusion crust. The appearance of the unfused, main mass of the meteorite suggests a rhyolite porphyry. The "groundmass" is of a grayish-white color, fine grained in texture. The "phenocrysts" are enstatite of two different types. One type is a light-gray enstatite exhibiting the usual pyroxenic cleavage at angles of 88° and 92°, and resembling a weathered feldspar in a porphyry. The other type is a clear, glassy enstatite with no apparent cleavage; this is not unlike the appearance of quartz in a porphyry. The cleavage enstatite reaches a length of 25 mm., and the glassy enstatite occurs in broken fragments of equal length. A closer examination reveals abundant, small flakes of graphite; iron rust stains; a brown, platy mineral identified in thin section as diallage; and, haphazardly scattered through the mass, rounded, superficially oxidized included pellets of nickel-iron ranging in size from very small to at least dimensions of 50 by 35 by 20 mm. (Fig. 3). Local, small slickensided surfaces are present. On the slickensided surfaces observed there seems to be a particular concentration of graphite and iron stain. The largest of such surfaces covered an area of 9 square centimeters.

An interesting, and unprecedented, phenomenon developed on the large mass of the meteorite after its arrival at the Institute of Meteoritics.

When part of the plaster of paris coating was removed, the meteorite grew a "beard;" *i.e.*, a white, fibrous growth appeared on the surface of the meteorite, covering an area of more than 2000 square centimeters. The fibers reached a length of about 5 cm. A qualitative chemical test of the "beard" showed abundant magnesium, water, and carbon dioxide with traces of iron and aluminum. The material effervesced readily in

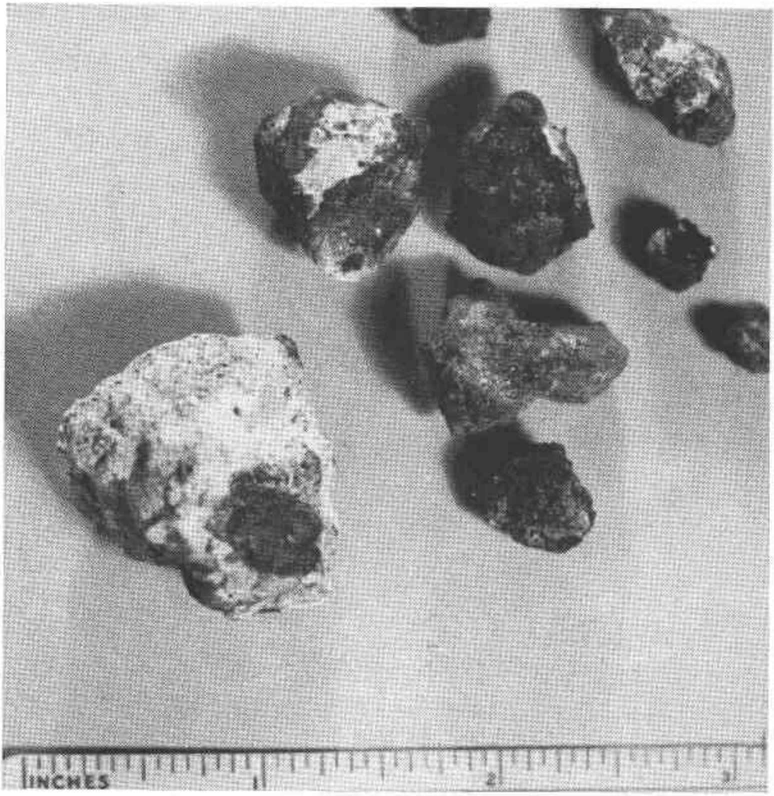

FIG. 3. Collection of nickel-iron inclusions.

dilute cold HCl; it is apparently a hydrated magnesium carbonate. The meteorite had lain in the moist Nebraska soil from February to August, during which time water containing carbon dioxide had penetrated into the interstices of the stone. In Albuquerque, with a higher altitude and drier climate, the water was drawn back out of the tiny openings in the stone, evaporated, and deposited material dissolved from the interior of the meteorite.

The specific gravities of the various components of the achondrite varied from 3.06 to 6.11. The specific gravity of the cleavage enstatite is 3.18 (Jolly balance).

Microscopic Examination. In thin section the cleavage enstatite is seen to make up the main mass of the meteorite, both the "groundmass" and the "phenocrysts." The enstatite ranges from large, well-formed crystals to fine-grained interstitial material (Fig. 4), giving a seriate porphyry texture. Some of the enstatite (the glassy enstatite referred to above) gives an undulatory extinction and a distorted abnormal interference figure, evidence that it is under strain. Other grains of the glassy enstatite

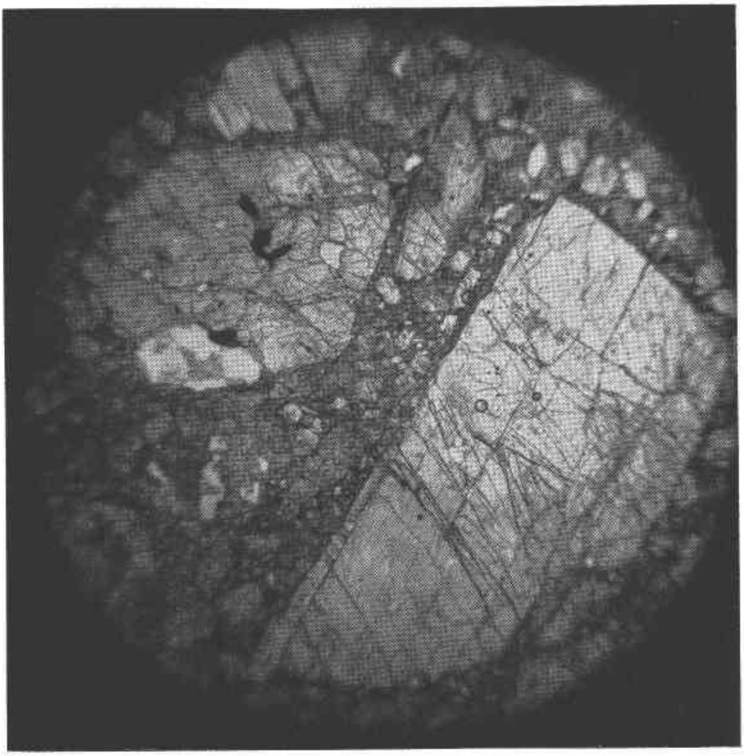

FIG. 4. Photomicrograph of well-developed enstatite crystals. ×200.

give an undulatory extinction but a distinct interference figure. In such cases the optic angle is 80–85°, compared with an optic angle of 40° for the cleavage enstatite. As shown below, this is the only difference in the optical constants of the two types of enstatite. Therefore, the authors have been forced to the conclusion that the difference in the axial angle is a function of the strain. In a few crystals of the cleavage enstatite the appearance in crossed nicols is noteworthy. An enstatite crystal appears homogeneous in plane polarized light, but the same crystal in crossed nicols shows narrow, pinched out bands reminiscent of polysynthetic twinning in feldspars (Fig. 5). The main mass gives the parallel extinction of enstatite; the bands give an inclined extinction up to 20°. There is no noticeable difference in the indices of refraction nor in the interference color, so that the authors have concluded such crystals represent an intergrowth of enstatite and clinoenstatite. Merrill (1921) recognized the same phenomenon in the Cumberland Falls achondrite. Figure 6 shows the same intergrowth of the two pyroxenes, but in this one case the clinoenstatite is in vermicular intergrowth with the host enstatite.

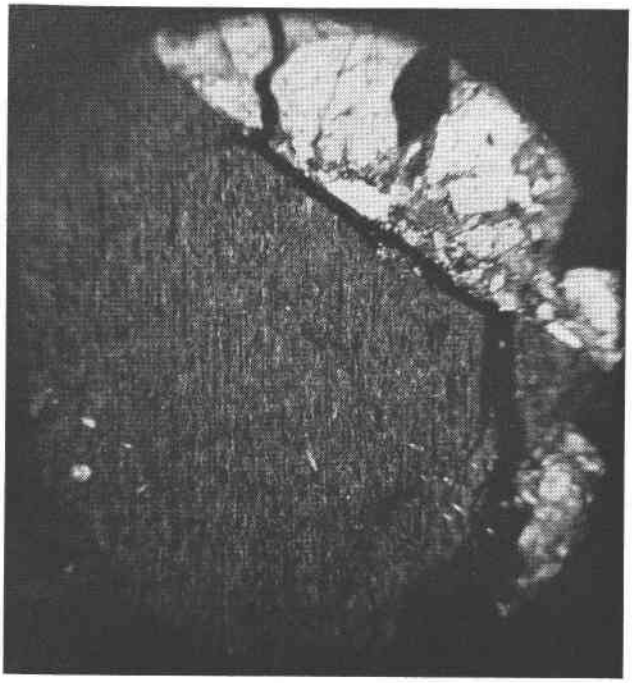

FIG. 5. Intergrowth of enstatite and clinoenstatite, crossed nicols. ×200.

Olivine is fairly abundant intermixed with enstatite in the finer grained portions of the meteorite, and, occasionally, there is a fairly large grain. Most of the olivine is remarkably fresh; only occasionally does one see a slight alteration to serpentine. Some of the olivine is poikilitic in the enstatite. Graphite flakes are abundant. Diallage is scattered throughout the mass in small amounts. In thin section the fusion rind is seen to be holocrystalline and very fine grained. In a few places there are some colorless, clear blebs of glass.

By the oil immersion method the following optical constants were obtained for the cleavage type of enstatite: $\alpha=1.652$, $\beta=1.654$, $\gamma=1.660$; optical character, positive; axial angle$=40°$; dispersion, $r<v$, weak;

optical orientation, X = a, Y = b, Z = c; the axial plane is {010}; cleavage is {110} at 88° and 92°; parting is {010} and is unusually well developed judging from the number of centered biaxial flash figures and the ease

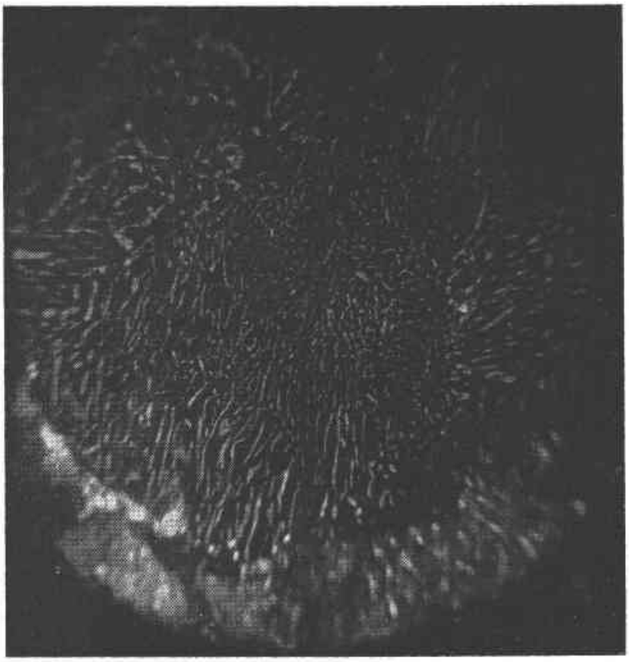

FIG. 6. Intergrowth of enstatite and vermicular clinoenstatite, crossed nicols. ×200.

with which they can be obtained; the cleavage traces are length slow; and the extinction is parallel. The above constants check very well with those of pure artificial enstatite (Larsen and Berman, 1934, p. 118). The small amount of iron in the chemical analysis (below) corroborates the purity of the enstatite.

The glassy enstatite gives the same constants as for the cleavage enstatite, with two exceptions. The glassy enstatite does not cleave or part; rather, it explodes with a conchoidal fracture. Both in thin section and in oil immersion this glassy enstatite is seen to be under considerable internal strain. The other, and more surprising, difference is that the axial angle for the glassy enstatite is 80–85°. Ordinarily, this axial angle would indicate an enstatite with about 9 per cent $FeSiO_3$; but this mineralogical composition would result in higher indices of refraction (approximately, $\alpha = 1.665$, $\beta = 1.669$, $\gamma = 1.674$) than those actually observed. Inasmuch as the glassy enstatite differs optically from the cleavage enstatite only in being under strain, the authors have concluded that the difference in axial angles is a function of the strain.

Isolated grains of olivine gave the following optical constants: $\alpha = 1.645$, $\beta = 1.663$, $\gamma = 1.683$; optical character, positive; axial angle $= 85°$; $r < v$, weak; optical orientation, $X = b$, $Y = c$, $Z = a$; axial plane is $\{001\}$.

The microscopic examination of the fusion rind in an oil immersion shows it to be holocrystalline, very fine grained, and to have an average index of refraction of 1.656.

Polished Section. Photomicrographs of a polished metallic inclusion

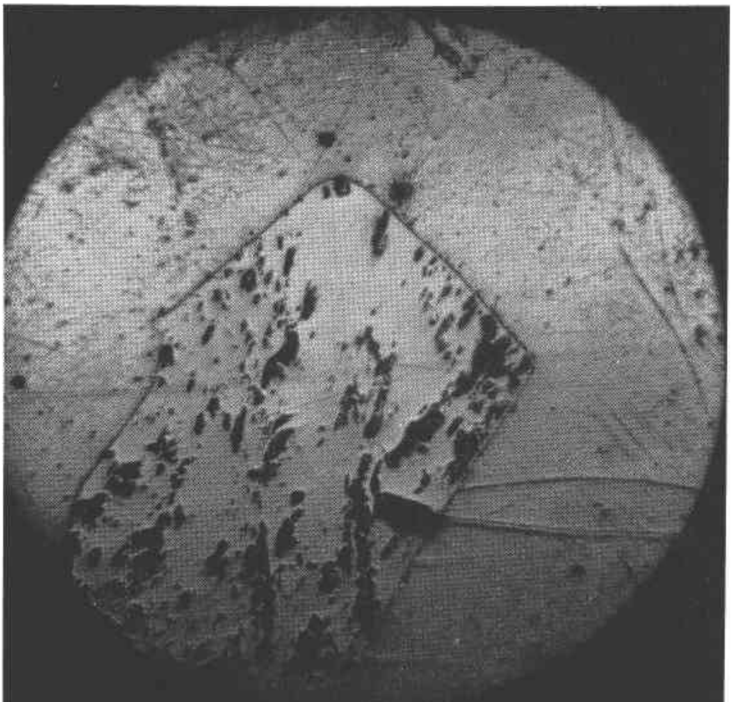

FIG. 7. Photomicrograph of etched surface of nickel-iron polished section. Schreibersite crystal surrounded by kamacite. Nital, 30 seconds. ×200.

from the achondrite are shown in Figs. 7 and 8. The composition of the metallic nodule chosen for polishing is mostly kamacite with conspicuous schreibersite. The schreibersite appears as elongate crystals with sharp grain boundaries; as rounded, elongate bodies; and as tiny, irregular inclusions scattered throughout the kamacite. In the latter case the schreibersite always has an area of lighter colored kamacite concentric about each particle. The cause of these halos is unknown. They may be due to radioactivity or strain. After etching with 5 per cent Nital, the halos disappear. The same etching brings out a fine Neumann structure (Fig. 8).

Small amounts of troilite were noted in two of the metallic nodules, but none in the polished section. Neither the spectrographic nor chemical

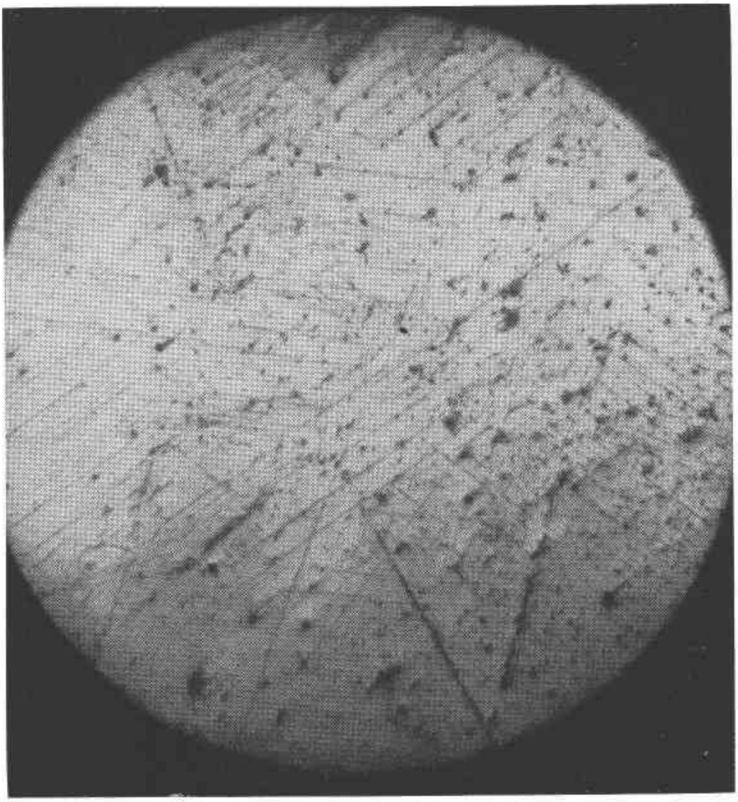

FIG. 8. Photomicrograph of etched kamacite showing Neumann lines. Nital, 30 seconds. ×200.

analyses revealed any sulfur. The small amount of sulfur present presumably concentrated selectively as troilite in some of the metallic nodules.

ANALYSES

Combined chemical and spectrographic analyses of the metallic and stony phases of the meteorite are shown in Tables 1 and 2. For comparison with the stony phase of the nortonite, chemical analyses of Cumberland Falls (Merrill, 1921), Bustee (Maskelyne, 1870), Bishopville (Smith, 1864), and Shalka (Maskelyne, 1870) are also listed in Table 2.

The metallic phase of nortonite, on the basis of mineralogical and chemical composition, is classified as a normal hexahedrite (*H*). This is consistent with the mineralogical composition of homogeneous kamacite (showing Neumann lines), schreibersite, and troilite, and with the chemical composition, particularly the percentage of nickel.

TABLE 1. COMBINED CHEMICAL AND SPECTROGRAPHIC ANALYSIS OF THE METALLIC PHASE OF THE NORTON COUNTY, KANSAS-FURNAS COUNTY, NEBRASKA, ACHONDRITE

Constituent	Per cent
Fe	91.16
Ni	5.82
SiO_2	0.07
P	0.015
Al	1.00
Co	0.37
Cr	0.061
Cu	1.20
Mo	N.D. <0.02
Pb	N.D. <0.02
Sn	N.D. <0.02
Ag	N.D. <0.02
Bi	N.D. <0.02
V	N.D. <0.02
Total	99.696

N.D.: not detected.

$$\text{Molecular ratio } \frac{\text{Fe}}{\text{Ni}} = 16.46$$

$$\text{Molecular ratio } \frac{\text{Fe}}{\text{Ni} + \text{Co}} = 15.48$$

The stony phase of the nortonite is richer in magnesia and poorer in iron than any of the other achondrites. In addition, the nortonite contains more silica than any of the others save Bishopville. The analyses of the nortonite are in accord with the purity and abundance of enstatite as noted under the optical considerations. Assuming, on the basis of the indices of refraction of the enstatite, that the FeO is in the olivine, and considering only SiO_2, MgO, and FeO, the authors calculated a norm for the nortonite as follows:

Enstatite.............	91.00%
Olivine..............	9.00%

On this basis the olivine is 90.56 per cent forsterite, 9.44 per cent fayalite.

From the microscopic examinations and the chemical analyses, the nortonite resembles most closely the whitleyite save the nortonite contains no inclosures of chondritic material. It differs from the bustite in

TABLE 2. COMBINED CHEMICAL AND SPECTROGRAPHIC ANALYSIS OF THE STONY PHASE OF NORTONITE COMPARED WITH CHEMICAL ANALYSES OF THE SAME PHASE OF CUMBERLAND FALLS, BUSTEE, BISHOPVILLE, AND SHALKA METEORITES

Constituent	Nortonite	Cumberland Falls	Bustee	Bishopville	Shalka
SiO_2	56.61	55.172	52.73	57.034	52.51
MgO	39.34	38.734	37.22	33.506	28.35
CaO	1.66	1.586	1.18	2.016	0.89
Al_2O_3	0.71	0.382	—	1.706	0.66
FeO	0.60	2.916	4.28	1.265	16.81
Na_2O	0.10	0.157	—	1.027	0.22
K_2O	0.26	0.150	—	0.089	—
TiO_2	0.06	—	—	—	—
Cl	0.08	0.028	2.35	—	—
P_2O_5	0.07	0.034	—	—	trace
MnO	0.38	0.112	0.01	0.189	—
S	0.00	0.784	—	0.297	0.14
C	0.00	0.164	0.92	—	—
Cr_2O_3	0.117	0.062	—	—	1.25
NiO	0.043	0.123	0.78	0.538	—
CoO	0.005	trace	—	trace	—
CuO	0.033	0.003	—	—	—
MoO_3	0.003	—	—	—	—
PbO	0.008	—	—	—	—
SnO_2	0.001	—	—	—	—
Ignition loss	0.10	0.167	—	1.995	—
Totals	100.180	100.574	99.47	99.662	100.83
$m=$	118.02	23.91	15.65	47.68	3.04

$$m = \frac{\dfrac{\%\text{MgO}}{\text{mol. wt. MgO}}}{\dfrac{\%\ \text{FeO}}{\text{mol. wt. FeO}}}$$

having no oldhamite, osbornite, nor plagioclase. It differs from the chladnites in the high magnesia content. This evidence confirms the conjecture that the nortonite has no counterpart among known achondrites (LaPaz, 1948; Beck and LaPaz, 1949), and justifies its adoption as the type stone of a new subclass of achondrites.

Radioactivities Induced by Cosmic Rays. The Institute for Nuclear

Studies of the University of Chicago subjected samples of the nortonite to radioactivity tests. Counts on the nortonite samples as a whole, as well as on several elements isolated from the sample, using a thin end window counter which should have permitted most of the beta rays to pass through had they been present, revealed no trace of activity other than that attributable to uranium, thorium, and potassium.

Theoretical Considerations

The recovery of the Norton County, Kansas-Furnas County, Nebraska, achondrite gives strong support to the "meteorite-planet" hypothesis originated in 1850 by Boisse and advanced independently by Farrington in 1901. More recently, Brown (1948) has applied thermodynamics to the problem of the composition of meteorites and has given further approval to the hypothesis that meteorites had their origin in a planet roughly the size of Mars. This meteorite-planet was disrupted in some unknown manner—by collision with another planet, by internal explosion, or by tidal disintegration—in the space enclosed by the orbits of Mars and Jupiter. Brown (1948) holds that " . . . the greater the metal-phase content of a meteorite, the further from within the depths of the disrupted planet did it arise. The planet possessed a core of nickel-iron and a mantle of silicate phase containing dispersed metal." The small amount of nickel-iron inclusions in nortonite would argue that this achondrite came from near the surface of the meteorite-planet. The Norton County-Furnas County achondrite shows such dynamic metamorphism as Merrill (1921) had in mind when he described the Cumberland Falls meteorite as supplying "direct evidence of the destruction of some pre-existing planet."

In this sense, the importance from the cosmogonic viewpoint of the recently recovered nortonite is at least as great as that which Merrill assigned to the long famous whitleyite.

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