GEOLOGICAL SERIES
OF
FIELD MUSEUM OF NATURAL HISTORY

Volume VII CHICAGO, DECEMBER 31, 1938 No. 4

ADDITIONAL NOTES ON THE GRINNELL ICE-CAP

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INTRODUCTION

The Grinnell Ice-Cap, which occupies the summit of the highland between Hudson Strait and Frobisher Bay, Baffin Land, was described in a recently published paper (Roy, 1937). At that time it was stated that the ice-cap was not fully explored and that its nature, behavior, and extent were only partially known. Since the publication of the paper, however, the ice-cap has been re-visited by an expedition led by Lieutenant Commander Donald B. MacMillan. Two members of the expedition, Captain John T. Crowell, master of the expedition schooner, *Gertrude L. Thebaud*, and Dr. Martin J. Buerger, of the Massachusetts Institute of Technology and the geologist of the expedition, have kindly supplied me with much additional data regarding the ice-cap. The purpose of this paper is to add these data to the original publication and bring it up to date. Minor changes in the coast line of Frobisher Bay, as observed by Captain Crowell, have also been incorporated in the accompanying map.

Despite the fact that the ice-cap has been visited by six different parties since its discovery by Captain Charles Francis Hall in 1860, some of the essential facts about it still remain to be known. This is chiefly because no party has as yet visited Frobisher Bay with the specific intention of studying the ice-cap. In every instance, the studies made were in the nature of reconnaissance—incidental to other fields of investigation. Expeditions to the American Arctic regions are so costly that it is doubtful if a special expedition to study the ice-cap will ever be sent. The probable results of such an expedition might or might not be commensurate with the expenditure involved.

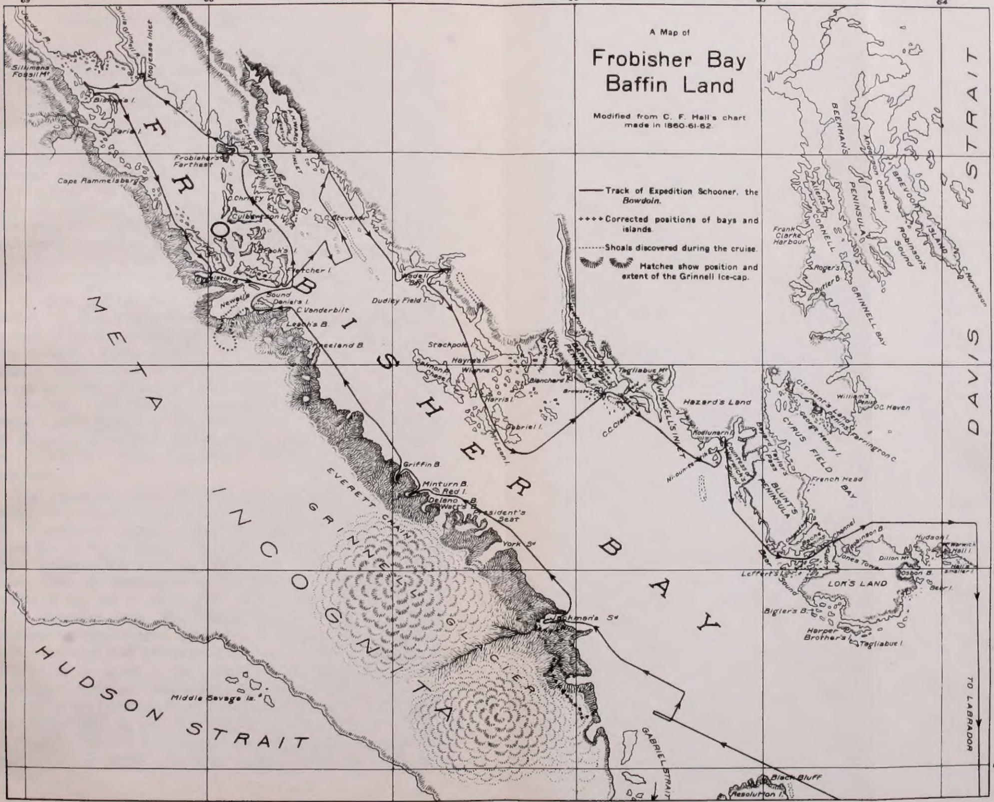
GENERAL DESCRIPTION

The most important observation made by the 1937 MacMillan party was that the ice-cap is not continuous but is separated by a transverse valley or pass into two parts—the southeast and northwest ice-caps. This confirms my previous statement (Roy, 1937, p. 16) that "probably the ice-cap is not continuous but is separated by a non-glaciated area some distance south of lat. 62° 30′ N." The valley which divides the ice-cap transversely (NE-SW) into two separate units is at least 15 miles long[1] and is filled with fluvio-glacial deposits in an uneven manner. In this valley flows a fairly well-developed stream which, about two miles inland, is joined on its northwestern side by another small stream. The combined waters of these streams, derived chiefly from melting snow, flow into Jackman's Sound (lat. 62° 22′ N., long. 66° 10′ W.). In the summer of 1927 we were fogbound in this sound for two days, during which period I was ashore four different times and once climbed 1,830 feet (aneroid), but the fog was so thick that I was unable to get even a good glimpse of the topography. It is, however, of considerable interest to note that several slabs of drift limestone containing fossils of Ordovician age were found at this altitude. Similar fossiliferous slabs were also found in the mountains (alt. 2,500 feet±) in the vicinity of York Sound and across the bay in Barrows Peninsula, a little northwest of Brewster Point. These fossils are unlike the ones collected from the Silliman's Fossil Mount, at the head of Frobisher Bay, indicating that they were brought down there from the interior by the last continental ice-sheet.

Of the two ice-caps, the southeast one is much less known. It is situated at a lower altitude, is smaller in size, dome-shaped, and sends no ice-tongues down to the sea either on the Hudson Strait or Frobisher Bay side. The smaller size and absence of ice-tongues may be traced to the wasting of *névé* and ice by the direct rays of the sun to which the ice-cap is largely exposed. The coast topography bordering this ice-cap has retained more or less of the rounded form left by the earlier continental ice-sheet. This is apparently due to absence of ice-tongues and resulting lack of glacial erosion, and absence of mountain glaciers to carry on destructive processes of quarrying and frost weathering. The depth of the ice-cap and its exact extension either along the coast or inland are not known.

[1] Captain J. T. Crowell writes: "I'm not positive about the extent of the pass, but Professor V. C. Wynne-Edwards told me that he judged he could see about fifteen miles into the pass with no traces of the two ice-caps being connected with each other." (Letter to S. K. Roy, December 13, 1937.)

69°
64°
Jordan R.
Silliman's Fossil Mt.
Silvia Grinnell
Bishop's I.
Faris
63°30'
Cape Rammelsberg
Frobisher Bay
Robinson's Sound
BREVOORT ISLAND
C. Hutchison
DAVIS STRAIT
63°
Oc. Haven
Hudson I.
Mt. Warwick
Hall I.
Dillon Mt.
Hall's smaller I.
62°30'
Osbon B.
Bear I.
TO LABRADOR
62°


A Map of
Frobisher Bay
Baffin Land
Modified from C. F. Hall's chart made in 1860-61-62.
Track of Expedition Schooner, the Bowdoin.
++++ Corrected positions of bays and islands.
........Shoals discovered during the cruise.
Hatches show position and extent of the Grinnell Ice-cap.
FROBISHER BAY
META INCOGNITA
HUDSON STRAIT
DAVIS STRAIT
GRINNELL GLACIER
EVERETT CHAIN
GABRIEL STRAIT
TO LABRADOR
Frobisher's Farthest
Cape Rammelsberg
Sillimans Fossil Mt
Koojesse Inlet
Dudley Field I.
Stackpole I.
Griffin B.
Minturn B.
Red I.
President's Seat
York Sd
Jackman's Sd
Middle Savage Is.
Black Bluff
Resolution I.
Hazard's Land
Kodlunarn I.
BLUNT'S PENINSULA
CYRUS FIELD BAY
French Head
LOK'S LAND
Bigler's B.
Tagliabue I.
Hudson I.
Dillon Mt
Osbon B.
Robinson B.
Lefferts Sound
GRINNELL BAY
BEEKMAN'S PENINSULA
CORNELL PENINSULA
BREVOORT ISLAND
Robinson's Sound
Frank Clarke Harbour
Roger's I.
Butler B.
C. Murchison
Farrington C.
C. C. Clarke
Tagliabue Mt
WISWELL'S INLET
Gabriel I.
Harris I.
Newell's Sound
C. Vanderbilt
Leach's B.
Fletcher I.
Waddell Bay
Brook's I.
Culbertson I.
C. Christy
BECHER PENINSULA
Griffin B.
Delano B.
Watt's B.
Salmon Chase
Haynes I.
Blanchard I.
Brewster
Daniel's I.
Bishop's I.
Faria I.
Jones Tower
Harper Brother's I.
Bear I.
George Henry I.
Clement's Land
William's Penin.
O C Haven
Countess of Warwick's Sound
Anderson Channel
Allen's I.
Iceland B.
Silvia Grinnell R.
Jordan R.
69°
68°
67°
66°
65°
64°
63°30'
63°
62°30'
62°

We do know, however, that it does not extend, along the coast, farther than the shores of Gabriel Strait. According to the Eskimos, the ice-cap does not extend far inland, the interior being practically free of snow during the summer months. It is believed that this southeastern ice-cap is diminishing in size chiefly because, as stated above, of its lower altitude and its southerly exposure. In 1903, thirty-five years ago, Dr. A. P. Low (1906, p. 14), while cruising westward on Hudson Strait along the southern shores of Baffin Land on board the D. G. S. *Neptune* reports: "Far inland is seen the glistening white surface of the great Grinnell Glacier which flows northward into Frobisher Bay." Recent travelers, however, who have passed along the same route do not recall having ever noticed the ice-cap. This would seem to indicate that the ice-cap has so diminished in size that it cannot now be seen from sea.

In sharp contrast with the southeastern ice-cap, the northwestern ice-cap is larger, situated at a higher altitude and fringed by some of the most rugged and picturesque coast topography to be seen in eastern North America. The ruggedness is the combined result of destructive work by the numerous ice-tongues which this ice-cap sends down to the sea, and of quarrying and frost weathering by the many snowdrifts and small mountain glaciers which this fretted upland, known as the Everett Range (see map), harbors. All the major sculptures—cirques, arêtes, horns, U-shaped valleys, etc.—typical of a region supporting mountain glaciers, are to be seen here.

The ice-tongues descending from the northwestern ice-cap are neither very high nor very thick. Occasional calving takes place but the resulting icebergs are small and usually melt before drifting out to the sea (Davis Strait). The huge icebergs that are seen in and about Frobisher Bay have had their origin in the Greenland ice-sheet. Their size removes all possibility of their being the result of calving of any one of the tongues coming down from the ice-cap under discussion here. Dr. Buerger (1938, p. 280) adequately describes a typical tongue. He states: "I was especially interested in the ice-tongue itself and spent some time studying various aspects of it during the ascent to the ice-cap. This particular tongue was a relatively small one, perhaps 800 feet across and some 10 to 15 feet high where it broke off into the sea at high water. Of course, this visible height does not represent the true height of the ice front, for much of the nose of the glacier was buried in its own terminal moraine or under water. The glacier, which is about five miles long

from sea to ice-cap, has sawed a slot for itself out of solid rock, leaving almost vertical walls hundreds of feet high. The talus from these steep sides is continually being removed to the sea in the form of lateral moraine.

"The approach to the glacier was characterized by a milky sea, an indication of the load of rock flour which is produced by the grinding action of the ice. Out of the ice front poured a stream of water into a puddle in the terminal moraine, a picture reminiscent of the horse drinking-troughs of former days. The ice front itself was very interesting. It was composed of a compact mosaic of grains averaging about walnut size but ranging up to, perhaps, two inches across. Each grain was a true, single ice crystal, proof of which was supplied by the swarms of flat air inclusions, all with flat sides parallel.

"The glacier ice is strikingly colored. In addition to the neutral ice color, streaks and areas of the most intense but somewhat pale blue occur. Such areas probably represent healed crevasses and new ice generally. This beautiful blue tint is also found in the small icebergs formed from the local glaciers.

"Much of the glacier surface is dotted with tiny rock particles, blown there from the talus piles by the strong wind. The particles absorb the sun's heat and melt the ice beneath themselves to form holes, into which they sink. The black particle at the bottom makes the hole appear to open into nothingness, and the area gives the impression of a thin crust of honey-combed, rotten ice which might crush through to an interior cavern under one's step. The footing is, of course, quite sound.

"No important central crevasses occur in the tongue except where it originates as an ice stream spilling over from the ice-cap. The central crevasses here are cracks due to the sharp, downward bend in the ice at this initial drop. Below this position the ice takes on a rather uniform, steep slope, and the central crevasses close up and heal. New crevasses occur only along the sides, where diagonal tension cracks develop. They point backwards toward the center of the glacier, giving evidence that the central ice moves faster than the ice near the walls.

"The MacMillan parties climbed the glacier [tongue] on July 29. At this season the surface was running with water, which gathered itself together into streams. These ordinarily disappeared by dropping into the side crevasses, but near the foot of the glacier, where no crevasses occurred because of lack of walls to slow down

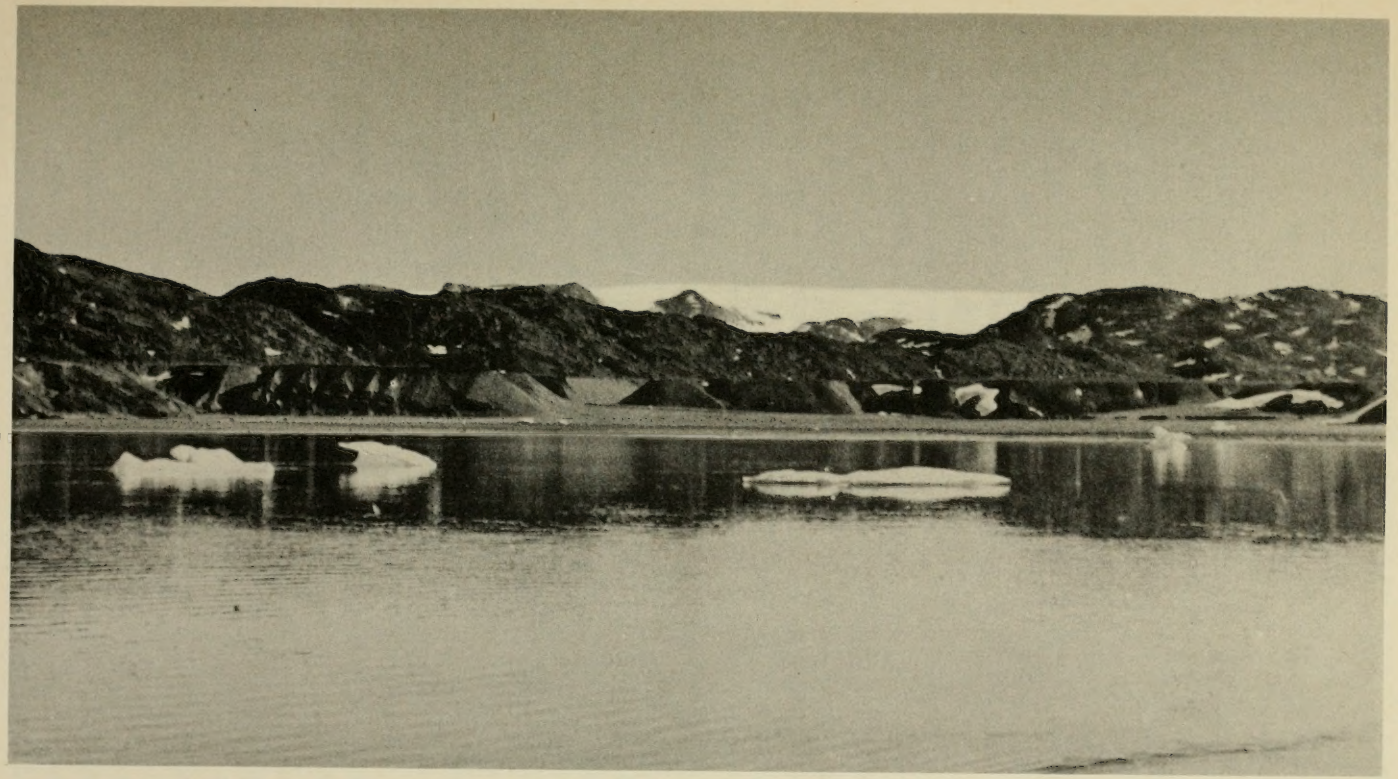


FIG. 26. Southeastern part of the Grinnell Ice-cap, as seen from a distance. Note the rounded coastal topography and the wave cut apron plain. Baffin Land has risen some 180 feet above the present sea level. Neg. No. 79595.

the side ice, swift streams of considerable erosive power developed and entrenched themselves in small ice valleys which were impossible to cross."

The northwest ice-cap is also gently dome-shaped, the gradient of its steepest slopes being less than 200 feet per mile. Its surface is deeply covered with granular snow which makes traveling difficult and dangerous, for one sinks knee-deep into it and is unable to see the snow-covered crevasses. In 1931, two men had a narrow escape from falling into these crevasses while climbing the ice-cap. I quote from Captain Crowell's log book, which may serve as a reasonable warning for future investigators: "I was walking along with Ralph [Ralph E. Brooks, the radio operator] about twenty-five feet in the rear (we were made fast to each other with about thirty feet of twelve-thread manila), when my right foot broke through the crust and I fell forward. Sparks [Brooks] held taut on the line and braced himself, but the snow held the weight of my body, and I crawled out on to firmer footing. I had time, however, to look down that hole where my foot had broken through. As far down as I could see there was nothing but blue space. A few minutes later Ralph broke through with one foot, but he quickly stepped backward."

Similar near disaster befell one of the members of the last MacMillan expedition. He fell through one of these snow-bridged crevasses up to his armpits, but hung on by spreading his arms until help arrived. The crevasses vary in width from a few inches to several hundred yards. To give an idea of their nature I again quote Captain Crowell: "We were forced to zigzag to find ice bridges on which to cross the crevasses. Looking down over the edge we could see no bottom, and chunks of ice thrown in would rattle on down, the sound growing fainter and fainter. We could not hear them striking bottom." The existence of many crevasses indicates that the rock pedestal supporting the ice-cap has many inequalities.

The longitudinal extension of the northwestern ice-cap, that is, its extension more or less parallel to the coast line, is from a little northwest of Jackman's Sound to a little southeast of Griffin Bay, a distance of approximately 25 miles. Its extension inland is not known, but Captain Crowell writes to me stating that Mr. Wynne-Edwards told him that when he was at the top of the ice-cap at an altitude of 2,900 feet (aneroid) he could see its inland edge. In a level country, in middle latitudes, one's range of vision hardly exceeds five miles, but in higher latitudes, such as in this part of Frobisher

FIG. 27. Northwestern part of the Grinnell Ice-cap with tongue-like outlets descending to the sea. Neg. No. 79594.

FIG. 28. Closer view of a tongue of the Grinnell Ice-cap. Neg. No. 79592.

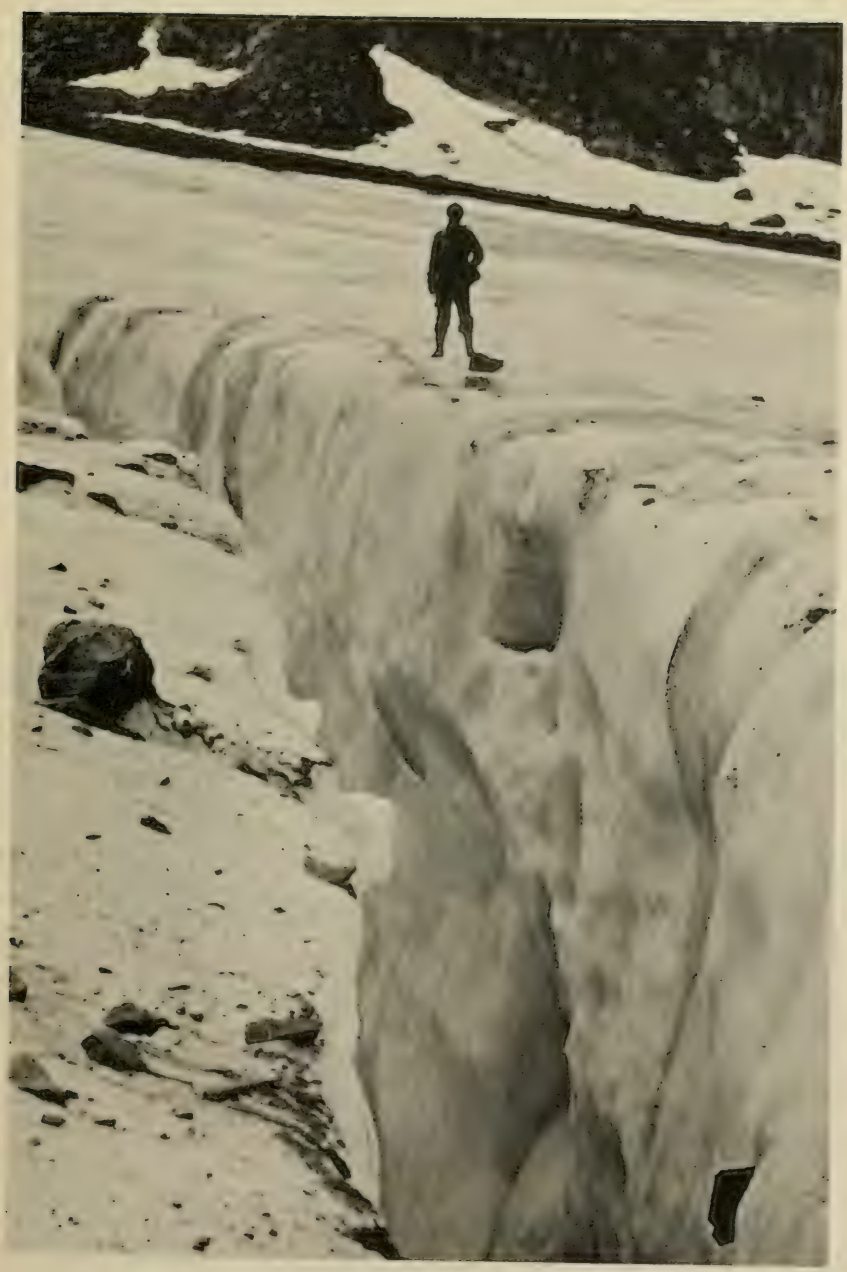


FIG. 29. A crevasse in the Grinnell Ice-cap. Neg. No. 79593.

Bay, which is close to lat. 63° N., the range is vastly increased, perhaps four or five times, if not more, due to abnormally high refraction. Photographs of the ice-cap taken with ordinary F 4.5 camera lens having 5¼″ focal length (aperture f11), from Brewster Point, across the bay, a distance of nearly thirty miles, have been highly successful. Based on these data, it is, perhaps, safe to infer that the inland extension of the ice-cap is about twenty miles.

SUMMARY[1]

The Grinnell Ice-cap occupies the summit of the highland between Hudson Strait and Frobisher Bay, Baffin Land. It may be reached by sailing along the coast of Labrador to Cape Chidley, then across Hudson Strait to Resolution Island,[2] which lies just south of the mouth of the bay.

The ice-cap has characteristics intermediate between those of mountain and continental glaciers. It may well have evolved from earlier mountain glaciers. It is not continuous but is separated by a transverse valley (NE-SW) into two distinct ice-caps—the southeastern and the northwestern. This separating valley is about fifteen miles long and carries two small streams whose combined waters flow into Jackman's Sound (lat. 62° 22′ N., long. 66° 30′ W.).

Of the two ice-caps, the southeastern one is situated at a lower altitude, is smaller in size and sends no ice-tongues down to the sea. The absence of ice-tongues may be traced to the wasting of *névé* and ice by the direct rays of the sun to which the ice-cap is largely exposed. The coast topography bordering this ice-cap has retained the rounded forms left by the earlier continental ice-sheet. The thickness of the ice-cap is not known nor is its exact extension either along the coast or inland known. It probably does not extend more than twenty miles in either direction.

The northeastern ice-cap is larger and situated at a higher altitude. It sends down several ice-tongues to the sea and is fringed by an extremely rugged coast topography, the result of the combined destructive work of the ice-tongues themselves and of the numerous snowdrifts and mountain glaciers which this fretted upland harbors. Cirques, arêtes, horns and practically all major sculptures typical of such a region are to be seen. Calving of ice-tongues takes place but the resulting icebergs are small. Crevas-

[1] Of this paper and previous one (Roy, 1937).

[2] It is now definitely known that Resolution "Island" is really composed of a group of islands.

ses are plentiful, indicating that the rock pedestal supporting the ice-cap has numerous inequalities. So far as known, only a single nunatak, west of Watt's Bay, projects above the ice-cap. The longitudinal extension of the ice-cap, along the coast, is about 25 miles. Its inland extension is perhaps less.

The ice-cap receives its moisture through ascending air currents in the manner of mountain glaciers. The source of moisture is in the surrounding large bodies of water, namely, Frobisher Bay, Davis Strait and Hudson Strait. It is, however, of sufficient size to develop a local descending and centrifugally directed surface air current for a part of the year.

The best time of the year to travel over the ice-cap is in spring, when the winter snows are well impacted and all the dangerous crevasses and water holes are filled. Due to ice conditions, however, it is unfortunately impossible to enter Frobisher Bay at this season. Spring exploration would necessitate spending the previous winter in the area.

ACKNOWLEDGMENTS

I wish to express my appreciation to Dr. M. J. Buerger and Captain J. T. Crowell for supplying me with the data incorporated in this paper. The photographs are by Dr. Buerger and the map is by the Staff Illustrator of Field Museum, Mr. Carl F. Gronemann.

REFERENCES

BUERGER, M. J.
1938. Spectacular Frobisher Bay. The Technology Review, **40**, No. 6, pp. 268–270, 279–284. Also Can. Geog. Journ., **17**, No. 1, pp. 3–17.

HALL, C. F.
1865. Arctic Researches and Life among the Esquimaux, pp. 118, 262–263, 516–521.

HOBBS, W. H.
1935. The Glaciers of Mountain and Continent. Zeits. für Gletscherkunde, Bd. 22, Heft 1/5.

LOW, A. P.
1906. Report on the Dominion Government Expedition to Hudson Bay and the Arctic Islands. 1903–1904, pp. 14, 122.

PORTER, R. W.
1898. Frobisher Bay Revisited. Bull. Amer. Geog. Soc., **30**, No. 2, pp. 108–110.

ROY, S. K.
1937. The Grinnell Ice-cap. Field Mus. Nat. Hist., Geol. Ser., **7**, No. 1.

GEOLOGICAL SERIES
OF
FIELD MUSEUM OF NATURAL HISTORY

Volume VII | Chicago, October 31, 1939 | No. 5

RADIOACTIVE DETERMINATION OF PROTACTINIUM IN SILICEOUS TERRESTRIAL AND METEORITIC MATERIAL[1]

By Robley D. Evans,[2] Jane L. Hastings,[3] and Walter C. Schumb[4]

In order to test more completely the validity of the general rule that the abundance-ratio of the isotopes of any element is a constant, independent of the source or of the mode of combination of the element, it is of interest and importance to determine such abundance-ratios in meteorites, which represent the only available specimens of extra-terrestrial matter. Atomic weight or isotopic abundance-ratios have been determined for carbon, oxygen, silicon, chlorine, iron, cobalt, and nickel by various workers;[5] and in the case of all the elements studied the isotopic abundance-ratios are not measurably different in meteoritic and in terrestrial matter.

In the case of radioactive elements, such as uranium, these abundance-ratios assume additional interest, in that by means of them a knowledge may be obtained of the difference in age between these atoms in the meteorite specimen and in terrestrial substances containing the same element. This subject was discussed in some detail by Evans (Pop. Astronomy, **46**, pp. 159–170, March, 1938), who derived the following expression for the differential age in years of uranium atoms in a meteorite and in the earth:[6]

[1] Contribution from Research Laboratory of Inorganic Chemistry, No. 75, and George Eastman Laboratory of Physics, Massachusetts Institute of Technology.

[2] Associate Professor of Physics, Massachusetts Institute of Technology.

[3] Graduate student, Department of Chemistry, Massachusetts Institute of Technology.

[4] Professor of Chemistry, Massachusetts Institute of Technology.

[5] Baxter and Thorvaldson, Jour. Amer. Chem. Soc., **33**, p. 337, 1911; Baxter and Hoover, *ibid.*, **34**, p. 1657, 1912; Baxter and Parsons, *ibid.*, **43**, p. 507, 1921; Baxter and Hilton, *ibid.*, **45**, p. 694, 1923; Baxter and Dorcas, *ibid.*, **46**, p. 357, 1924; Jaeger and Dykstra, Kon. Akad. van Wetenschappen, Amsterdam, **27**, p. 393, 1924; Harkins and Stone, Jour. Amer. Chem. Soc., **48**, pp. 938, 3233, 1926; Manian, Urey and Bleakney, *ibid.*, **56**, p. 2601, 1934; Jenkins and King, Publ. Astr. Soc. Pac., **48**, p. 323, 1936.

[6] The numerical factor 2.8 has been changed from 1.46 given in the reference cited to 2.8 as the result of more recent work on the actinium series branching ratio by A. O. Nier (Phys. Rev., **55**, p. 150, 1939).

$$t_m - t_e = 2.8 \times 10^9 \log \left(\frac{R_e}{R_m} \right) \quad (1)$$

where t_m and t_e are the respective ages in the meteorite and in the earth, R_e = the ${}_{92}U^{235}$: ${}_{92}U^{238}$ activity-ratio observed in the earth today, and R_m is the same ratio measured in the meteorite.

The present paper reports the results obtained in a portion of a program for the determination of isotopic abundance-ratios in meteorites being carried on jointly in these laboratories; in particular, the determination of the isotopic ratio of ${}_{92}U^{235}$ (or AcU) to ${}_{92}U^{238}$ (or UI) in a specimen of the Pultusk[1] meteorite, which, because of its reported (Evans, loc. cit.) high heliocentric velocity (56 km. per sec.) has been considered as representing not only extra-terrestrial but possibly extra-solar material.[2] The sample used in this work was very kindly furnished to Professor Evans by Mr. Clifford C. Gregg, Director, and Mr. Henry W. Nichols, Chief Curator of the Department of Geology in Field Museum of Natural History, Chicago.

Nier (Phys. Rev., 55, pp. 150, 153, 1939) has recently checked the constancy of the isotopic abundance-ratio of U^{235}/U^{238} in terrestrial material by means of mass spectroscopic determinations on Pb^{207} and Pb^{206}.

In all but very young rocks radioactive equilibrium has been established in the three radioactive series; that is, the rate of disintegration is equal to the rate of formation of all members of each series derived from the three parent elements, ${}_{92}U^{238}$, ${}_{92}U^{235}$ and ${}_{90}Th^{232}$. Therefore, by determining the amount of any one member of a series present, the quantity of any other may be calculated. Thus the determination of the protactinium content of a specimen permits the calculation of the amount of the parent element AcU, and the determination of the radon content of the sample makes possible the calculation of the amount of the parent element UI present, and from these two values the abundance-ratio U^{235}/U^{238} may be obtained.

A method has been worked out by A. v. Grosse (Phys. Rev., **42,** p. 565, 1932) and others (Francis and Da-Tchang, Phil. Mag., **20,** p. 623, 1935) for the isolation of protactinium from other radioactive

[1] A shower of fragments of a stony meteorite fell in Pultusk, Poland, on January 30, 1868.

[2] Professor C. C. Wylie of the State University of Iowa has kindly communicated to us the results of his recent recalculation of the Pultusk trajectory observations, originally reported by Galle in 1868, following interviews with those who observed the meteorite fall. Professor Wylie's extensive experience in such interviews leads him to reduce the reported height of appearance of the meteorite. This has the effect of reducing the computed velocity so that the Pultusk meteorite would be of solar-system origin rather than extra-solar. Professor Wylie has just summarized his work in Science, **9,** p. 264, September 22, 1939.

elements. The present method is a modification of that of A. v. Grosse in that provision had to be made for the elimination of large amounts of silica and some 5 per cent of free metal, along with metal sulphides. The chemical analyses of two specimens of the Pultusk meteorite, as given in Farrington's compilation (Field Mus. Nat. Hist., Geol. Ser., 3, pp. 195–229, 1911), are as follows:

Analyst and date	Spec. no.	SiO_2	Al_2O_3	FeO	CaO	Na_2O	K_2O	Fe	Ni	MgO
G. von Rath..... (1869)	82	41.54	1.17	14.04	0.28	1.34	....	11.51	0.65	26.73
R. Rammelsberg. (1870)	101	35.85	1.96	12.12	1.56	0.95	0.39	15.55	2.21	24.95

EXPERIMENTS

Preliminary work.—The preliminary work for testing the method was carried out on granite of known radium content. All solid reagents to be used were tested separately and a record made of their alpha activity. The efficiency of the method for the removal of radioelements other than protactinium and their isotopes was checked by adding known amounts of solutions of the salts of uranium, thorium, and polonium, respectively, and repeating all operations. These experiments proved that three separations (as described in Table 1 and the section on analytical procedure) removed 94 per cent of the added uranium, 100 per cent of the thorium, and 95 per cent of the polonium. Finally, a small sample of pure protactinium, deposited in zirconium pyrophosphate, and kindly furnished us for the purpose by Dr. A. v. Grosse, was converted into a highly dilute solution. The alpha activity of a portion of this solution was measured, and a known amount of it was carried through the chemical procedure. The activity of the recovered protactinium was determined, whereby it was demonstrated that 90 per cent $\pm$ 6 per cent of the protactinium could be recovered. In view of the many steps required in the analytical procedure employed, this recovery is considered to be satisfactory.

Sampling.—Due to the probability of surface leaching and contamination, only the inner portions of specimens of granite were used. These were ground, first in a steel mortar and finally in agate, both mortars being "rinsed" by grinding inactive sodium carbonate in them before use. After thorough mixing, a third of the finely ground material was reserved in a stoppered bottle for the radon determinations and the remainder used for the separation of protactinium. In the case of the Pultusk meteorite sample, all of the outer black layer, or "skin," was carefully removed and samples of the inner portions were prepared as in the case of the granite.

Analytical procedure.—A 50-gram sample of the siliceous material was treated with 100 cc. of aqua regia and heated on the steam bath for a half hour. After cooling, the diluted acid solution was filtered and the residue dried and ignited in platinum. The filtrate was evaporated and the residue dehydrated. The residue was taken up with concentrated *HCl*, followed by water, and the silica filtered and combined with the original residue. The dehydration process was then repeated. The combined residues were treated several times with 47 per cent hydrofluoric acid to which a few drops of concentrated sulphuric acid had been added, and evaporated to fumes after each treatment. Three times the calculated amount of *HF* was used to insure complete removal of silica, assuming the latter to be 50 per cent of the original sample. The residue then was heated to dull red heat and after cooling was treated with hot, concentrated *HCl* followed by hot water. There remained very little residue and this was filtered off and washed with hot water, dried, ignited, and reserved for future work, if necessary.

The filtrate was combined with that from the final dehydration and the solution was evaporated to 200 cc. To the cooled solution zirconyl chloride solution was added equivalent to 100 mg. of ZrO_2. An excess of 6 N H_3PO_4 was added and the solution stirred for several minutes. The precipitate of zirconium phosphate was allowed to stand at least two hours, then filtered. The precipitate was washed with 5 per cent *HCl*, dried, ignited, and weighed. The filtrate was reserved.

To the zirconium pyrophosphate, which contained the protactinium, 20 cc. of 2 per cent *HF* was added and the vessel heated until the solution was complete. After cooling, solutions of the nitrates of barium, lead, lanthanum, and bismuth, equivalent to 4 mg. of each element, were added. The insoluble sulphates and fluorides of these elements co-precipitate those of radioactive elements other than protactinium, as indicated in Table 1.

TABLE 1.—RADIOACTIVE SEPARATIONS FROM SOLUTION OF ZrP_2O_7+*Pa* IN 2 PER CENT *HF*

Reagent	Radioactive elements and isotopes removed
$Ba(NO_3)_2$	*Ra, MsTh*$_1$, *AcX, ThX*
$Pb(NO_3)_2$	*RaB, ThB, AcB, RaD, ThD, AcD, RaG*
$Bi(NO_3)_3$	*Po, RaC, ThC, AcC, RaE*
$La(NO_3)_3$	*Ac, MsTh*$_2$

After standing for one hour, the precipitates were filtered, using hard rubber funnels. The residues were discarded. This operation was carried out three times to assure satisfactory elimination of

radioactive contaminants because blanks on which only two separations had been made occasionally showed residual counts. The third filtrate was evaporated to dryness, the residue ignited at red heat for ten minutes, and after being cooled each residue so obtained was placed in a separate desiccator to avoid possible contamination.

A portion of the residue was transferred to an agate mortar and finely ground under alcohol. A suspension of the ground material was made in ethyl alcohol and poured upon a weighed silver disc, which had been sealed to a brass evaporating cylinder by means of rubber cement. The alcohol was evaporated in a heated cabinet in an atmosphere of well-aged and hence radioactively inert nitrogen. When the sample was dry, the cylinder and rubber cement were quantitatively removed from the disc and the disc plus the sample was weighed.

Measurement of activity.—The weighed disc, containing the protactinium with zirconium pyrophosphate deposit, was placed in the recording alpha counter. An ionization chamber of the parallel plate condenser type was used, the design and operation of which has been fully discussed by Finney and Evans (Phys. Rev., **48**, p. 503, 1935). The ions formed by the alpha rays are collected, the current amplified, and the resulting galvanometer deflections recorded photographically upon sensitized bromide paper contained in a Telechron-driven drum camera which makes one revolution every two hours. Twenty consecutive hours of observation were generally employed in order to minimize the probable error. These could be recorded on a single sheet of 5 in. $\times$ 37.5 in. paper, by using a laterally moving light source.

The inner parts of the ionization chamber are made of spun copper and are easily removable for cleaning. Some contamination is, of course, inevitable, due to radioactive material in the walls of the ionization chamber, so that even without a radioactive sample in the chamber the record obtained will show some countable alpha rays. Careful cleaning and the use of inactive silver for the metal discs minimizes this "background."

A blank on all reagents was carried along in parallel with the samples and this served as a check on the completeness of removal of radioactive contaminants and on the overall manipulative procedures.

Calculated results and conclusions.—A sample of granite from Ontario, designated as "K.D. Fine," known to be low in radioactive material was selected for a representative terrestrial material. The

protactinium content was calculated from the observed alpha count per cm.^{2} of source by means of the following two equations, discussed in the paper of Finney and Evans (loc. cit.):

$$n_{a'}=\frac{N\mu\tau}{4}\left[\frac{2(R-\rho)-\tau}{(R-\rho)}\right] \tag{2}$$

in which

$n_{a'}$=alpha counts observed per cm.^{2} of source

N=alpha rays per cm.^{3} emitted in the source

R=3.61 air-cm.=mean range in air at 15°C. and 760 mm. for alpha particles from Pa

ρ=0.5 air-cm. (assumed maximum range of short range alpha rays not detected)

$\mu=15.6\times10^{-4}/d$=ratio of range of alpha rays in the solid to the range in air

$\mu\tau$=thickness of source in cm.

$\tau=\dfrac{\text{mass}}{\text{area}\times\text{density}\times\mu}$=source thickness in air-cm.

$$N=\frac{6.02\times10^{23}Q.\lambda.d}{W} \tag{3}$$

where

W=231=at. wt. of Pa

$\lambda=2.5\times10^{-9}\text{hr}^{-1}$=decay constant of Pa

Q=concentration of Pa in gm. per gm. of source

d=density of ZrP_2O_7

The probable error for each background run and determination of alpha rays due to protactinium was calculated in the usual way:

$$P.E.=0.67\left[\frac{\Sigma(x-\bar{x})^2}{n(n-1)}\right]^{1/2} \tag{4}$$

where

$\bar{x}$=the average of n individual observations of x.

The following tables summarize the results obtained with the granite and Pultusk meteorite.

PROTACTINIUM CONTENT OF GRANITE

Sample	Wt. original rock (gm.)	Wt. ZrP_2O_7 + Pa in mg. total	Wt. ZrP_2O_7 + Pa tested in mg.	Observed α count over background	Observed α count over blank	Observed α count for total sample	Pa in 10^{-12} gms. per gm. rock
Blank.....	.....	210	41.5	1.7±1.1	.....	.....	.....
No. 1.....	15.04	199	28.5	0.8±1.3	0±1.7	0±12	0.00±0.23
			42.1	10.0±1.2	8.3±1.6	39±8	0.76±0.16
No. 2.....	15.18	231	52.4	5.6±1.0	3.9±1.5	17±7	0.32±0.13
			47.7	7.4±0.9	5.7±1.4	28±7	0.52±0.13
					Mean.....	24.1±4.6	0.46±0.09

PROTACTINIUM CONTENT OF PULTUSK METEORITE

Wt. original sample in grams	Wt. ZrP_2O_7 +*Pa* in mg. total	Wt. ZrP_2O_7 +*Pa* in mg. tested	Observed α count over background	Observed α count for sample	*Pa* in 10^{-12} gms./gm. meteorite
Blank.....	111	42.7	0.0±0.8	0.	
51.....	110	27.3	0.8±0.6	3.2±2.4	0.018±0.013
		34.2	2.7±0.8	8.7±2.6	0.049±0.013
			Mean.....6.0±1.7		0.035±0.011

In equation (1) above, the quotient of the activity-ratios R_e/R_m is equal to the quotient of the mass-ratios, since the radioactive decay constants and the atomic weights involved cancel out in the quotient.

The mean values of the radium content of these two specimens, as determined by Mr. Clark Goodman of the Physics Department of Massachusetts Institute of Technology, are $0.28\pm0.02\times10^{-12}$ g. *Ra* per gram for the granite and $0.023\pm0.005\times10^{-12}$ for the Pultusk meteorite. The corresponding observed weight-ratios, *Pa*/*Ra* for the granite, and similarly for the meteorite, become 1.64 ± 0.5 and 1.52 ± 0.5, respectively. From these results the conclusion may be drawn that, if the probable errors are considered, there is no appreciable difference in the age of terrestrial uranium atoms and those in this specimen of the Pultusk meteorite. From the chemical standpoint a more definite conclusion may be reached: The method employed for the separation and estimation of protactinium has proved satisfactory for as little as 10^{-13} gm. protactinium per gm. of siliceous material, and with larger samples this limit probably could be set much lower.

This investigation was materially assisted by a grant from the Cyrus M. Warren Fund of the American Academy of Arts and Sciences, which is hereby gratefully acknowledged.

SUMMARY

The protactinium contents of a granite and of a specimen of a meteorite (Pultusk), both high in silica, have been determined by the co-precipitation of the protactinium with zirconium phosphate, followed by purification of the ignited pyrophosphate, employing a modification of the method of A. v. Grosse. The alpha activity of the protactinium thus isolated was measured on a recording alpha-counter and the concentration of protactinium in the two specimens of terrestrial and of meteoritic material calculated.

From these data and the corresponding radium concentrations of the same specimens determined independently, the weight-ratios

Pa:Ra have been derived for the two materials. From these results the conclusion has been reached that within the limits of error the age of the uranium atoms in this specimen of the Pultusk meteorite is the same as for terrestrial uranium.

The method is capable of estimating as little as 10^{-13} g. of *Pa* per gram of siliceous material, and the limit may probably be lower than this if larger samples are taken.

GEOLOGICAL SERIES
OF
FIELD MUSEUM OF NATURAL HISTORY

Volume VII | CHICAGO, DECEMBER 28, 1943 | No. 6

MEASUREMENTS OF THE AGE OF THE SOLAR SYSTEM[1]

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For over a century astronomers have sought a satisfactory explanation for the origin of the earth and the solar system. Successive hypotheses have had some transient successes, but in the end additional astrophysical data or more penetrating mathematical analyses have shown all the hypotheses to be unsound. Recently the hypothesis that the solar system was formed by the condensation of matter produced by a near encounter between two stars has also been shown to be untenable. Spitzer[2] has noted that a filament of stellar material produced by an encounter between two stars would have a temperature in excess of a million degrees centigrade, and he has shown that the gases within such a filament would accelerate outwards and within a few hours would reach the velocity of escape. Thus it seems very doubtful that the stellar encounter theory can survive as an explanation of the origin of the solar system.

As an aid to the construction at some later date of a satisfactory theory concerning the origin of the solar system, it is important to make as many accurate measurements as possible on the physical constants of the solar system. Such measurements include the age of the earth and the age of as many non-terrestrial samples of the solar system as it is possible to obtain.

The only non-terrestrial samples that can be brought to the laboratory are recovered meteorites. A meteorite having a heliocentric velocity, at the earth's distance from the sun, greater than

[1] From a paper presented at the Interamerican Astrophysical Congress at Puebla, Mexico, February 25, 1942.

[2] Lyman Spitzer, Jr., The Astrophysical Journal, **90**, pp. 675–788, 1939.

42.4 km. per second can escape from the sun's gravitational field. Presumably such a meteorite would represent a sample of extra-solar astronomical material. Meteorites having a heliocentric velocity less than 42.4 km. per second are therefore to be taken as extra-terrestrial samples of the solar system.

It is known that distinctly more meteorites strike the surface of the earth between the hours of noon and midnight than in the morning hours between midnight and noon. The direction of the earth's revolution around the sun is such that the forward surface of the earth, which sweeps the space through which the earth travels, is always the half whose time is between midnight and noon. Extra-solar meteorites could be expected to show no preferred direction in space, and should appear randomly in the zone swept out by the earth's motion around the sun. Consequently a predominance of morning falls should be observed if all meteorites were of extra-solar origin. The fact that the majority of the falls are in the afternoon shows that the majority of meteorites move in "direct" orbits, whose direction around the sun is the same as that of the earth's. Paneth[1] ably extends this argument and concludes that all meteorites have since their formation been members of the solar system. Several very bright meteors have been photographed by Whipple,[2] who used two cameras, equipped with "light-chopper" shutters, at the ends of a 24-mile base line near Cambridge, Massachusetts. The heliocentric velocities determined from these observations show that the bright meteors observed so far are of solar origin. However, none of these meteors was sufficiently large to allow it to penetrate the earth's atmosphere completely and land on the earth's surface as a meteorite.

In performing age measurements on meteorite specimens it is important to deal, if possible, with material known to be either of solar or extra-solar origin. Unfortunately one of the rarest astronomical events is the accurate observation of the velocity of a meteor, followed by the actual recovery of the meteorite, if any, resulting from the fall. Circumstances are seldom so favorable. In the painstaking catalogue of *611 Orbits of Big Meteors*, edited by Hoffmeister in 1926 from the life work of von Niessl, only seven recovered meteorites could be named for which any kind of velocity observations had been made while the parent meteor fell through

[1] F. A. Paneth, "The Origin of Meteorites." The Haley Lecture, published by the Clarendon Press, Oxford, 1940.

[2] F. L. Whipple, Proc. Amer. Phil. Soc., 79, p. 449, 1939.

the earth's atmosphere. Of the seven the velocity data on the Rochester and St. Michel meteorites were too doubtful to deserve serious consideration. The available data on the remaining five meteors led to computed heliocentric velocities which follow: Pultusk, 56 km. per second; Homestead, 40; Krähenberg, 57; Orgueil, 52; Treysa, 38.

The largest amount of velocity data available for any meteorite relates to the great fall of stones in Pultusk, Poland, in January, 1868. T. G. Galle[1] interviewed many people who observed this meteorite fall and concluded from these data that the heliocentric velocity of the Pultusk meteorite was definitely greater than the velocity of escape from the solar system. These original observations have recently been reviewed by Professor C. C. Wylie,[2] whose extensive experience in such interviews leads him to reduce the reported height of appearance of the meteorite, from Galle's estimate of over 100 miles to 52 miles, which corresponds to the measured height of appearance of modern spectacular meteors. This has the effect of reducing the computed velocity so that the Pultusk meteorite may have originated in the solar system and would have had an elliptic orbit resembling those of the minor asteroids. We thus assume that the Pultusk meteorite, on which extensive age measurements have been made by methods based on radioactivity, originated in the solar system.

HELIUM AGE MEASUREMENTS

It is well known that the decay of long-lived radioactive substances such as uranium offers a general method of age determination. It has been proved that the rate of radioactive decay does not depend on the age of the atoms involved, and consequently that the decay of uranium and thorium into their daughter products has always proceeded at a uniform rate. Helium is one of the products of these radioactive disintegrations. Assuming that all of the helium formed has remained trapped in the specimen, the age of any sample of terrestrial or meteoritic material is proportional to the ratio of the total amount of helium produced in the sample to the amount of uranium and thorium present. This method of age analysis has been used extensively in the study of terrestrial materials.[3]

[1] T. G. Galle's original papers have been translated and republished serially by W. H. Hass, Popular Astronomy, October, 1942, et seq.

[2] C. C. Wylie, Science, 9, p. 264, 1939.

[3] For example: C. Goodman and R. D. Evans, Bull. Geol. Soc. Amer., 52, pp. 491–544, 1941; C. Goodman, Jour. App. Phys., 13, p. 276, 1942.

The helium method was first developed and applied to meteorites by F. A. Paneth and his students. In their original studies[1] of twenty-three iron meteorites these investigators showed that helium does not leak out of iron meteorites at ordinary temperature. Helium and radium measurements were made on all of these specimens, but it was not possible at that time to perform thorium analyses. By assuming that all of the helium was formed by the decay of uranium it was then possible to calculate maximum values for the age of these iron meteorites. This "age" corresponds to the time which has elapsed since the helium was last quantitatively expelled, or roughly the time which has elapsed since the material last cooled below 1000° C.

The results obtained by Paneth and his co-workers are presented graphically in figure 30. It will be noted that there is an essentially uniform distribution of ages from a maximum of 2,800 million years down to essentially zero (i.e. 100 million years), with no tendency toward grouping about any favored time. A similar plot of the available age measurements on terrestrial surface rocks and minerals has the same general appearance.[2] This fact might at first suggest that meteorites were fragments from large astronomical bodies which broke up at various times in the past, and were hot enough to expel all their helium at the time of fragmentation. However, the well-known Widmanstätten figures, which can be simulated in the laboratory only by the very slow cooling of iron-nickel alloy, are preserved in these samples. The "age" data refer to the elapsed time since the last intense heating, that is, to the time when the existing Widmanstätten figures were formed, since they are probably destroyed by temperatures much in excess of 1000° C. The ages therefore probably refer to the date of formation of a sufficiently large astronomical body to provide for very slow internal cooling. The observed distribution of ages therefore suggests that the formation of new astronomical bodies is a continuous process, possibly still proceeding at a relatively uniform rate.

In 1932 Paneth measured the helium and radium content of a specimen of the Pultusk stone.[3] This measurement led to an age of about 500 million years, but is unquestionably low by an entirely

[1] Paneth, Urry, and Koeck, Nature, March 29, 1930; Paneth, Naturwiss., 19, p. 164, 1931; Paneth and Koeck, Zeit. Phys. Chem., Bodenstein-Festband, p. 145, 1931.

[2] C. Goodman, Jour. App. Phys., 13, p. 276, 1942.

[3] Personal communication from Professor Paneth to Dr. H. Shapley.

unknown amount, because of the ease with which helium was demonstrated to escape from the porous stony mass, in contrast to its proved retention by compact iron meteorites.

More recently Professor Paneth has succeeded in carrying out thorium measurements, as well as helium and radium analyses, on

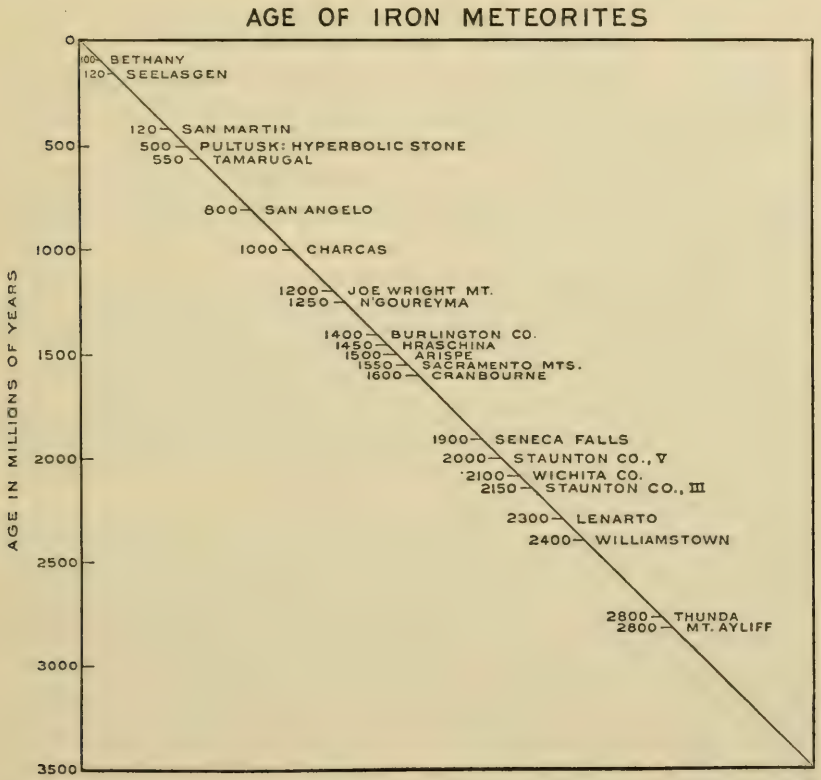

FIG. 30. Age distribution of iron meteorites, based on the helium-radium ratio. Originally these were thought to be maximum values, because of the absence of thorium measurements.[1] Basing his conclusions on new measurements of the thorium, radium and helium content of six iron meteorites,[2] Paneth now believes the radium measurements of the early series to have been too high, so that the true ages-since-solidification may have been three times as great as the values shown. This revision does not alter the conclusions given later in the present paper except by suggesting that some iron meteorites may have solidified long before the earth's crust solidified, and would therefore have helium ages greater than the age of the earth.

[1] Paneth, Urry, and Koeck, Nature, March 29, 1930; Paneth, Naturwiss., 19, p. 164, 1931; Paneth and Koeck, Zeit. Phys. Chem., Bodenstein-Festband, p. 145, 1931.

[2] Arrol, Jacobi, and Paneth, Nature, 149, pp. 235–238, 1942.

samples of four iron meteorites.[1] While the absolute accuracy of the figures is still doubtful the relative values can be taken as a significant guide. These results, in millions of years since solidification, are: Bethany, Goamus 30; San Martin 500; Bethany, Amalia 1000; Thunda >3000. Again a broad and continuous distribution in ages is exhibited.

DIFFERENTIAL AGES BY RADIOACTIVITY

The helium method is not applicable to stony meteorites, because of the inability of the stony mass to retain quantitatively the helium generated in it. Neither is it possible to make age measurements by the lead method, because of the very small amount of uranium and thorium contained in meteorites, and consequently the negligible quantity of lead generated.

Useful information can be gained, however, from a study of the relative abundance of the isotopes of radioactive elements in the meteorites. Such studies possess the unique advantage of eliminating all questions relating to the leakage or leaching of radioactive decay products such as helium or lead. Any physical or chemical processes, such as leakage or leaching, should affect all of the isotopes of the element involved in substantially the same way, leaving their ratios unaltered.

It is well known that all terrestrial specimens of any particular element always exhibit the same isotopic abundance, independent of the place of origin of the parent mineral or rock containing the element. It is also found from isotopic abundance or chemical atomic weight studies in meteorites that the isotopic abundance is the same as in terrestrial materials for all the elements studied so far,[2] namely: carbon, oxygen, silicon, chlorine, iron, cobalt, and nickel.

We shall see below that there is good justification for making the following basic assumption: that the initial isotopic ratio for any element is a constant of nature and is independent of the time or place of origin of these atoms in the galactic system.

Uranium is a mixture of independent isotopes, uranium I and actinouranium, having widely different half-periods. Thus, one-

[1] F. A. Paneth, "The Origin of Meteorites." The Haley Lecture, published by the Clarendon Press, Oxford, 1940.

[2] R. D. Evans, Popular Astronomy, **46**, pp. 159–170, 1938; A. O. Nier and A. Gulbransen, Jour. Amer. Chem. Soc., **61**, p. 697, 1939; G. E. Valley and H. H. Anderson, Phys. Rev., **59**, 113A, 1941.

half of any given initial quantity of the isotope known as uranium I will have decayed in 4,530 million years, while the half-period of the isotope actinouranium is only 710 million years. Thus, in any sample of uranium, the passage of time causes the shorter-lived isotope, actinouranium, to become progressively less abundant as compared with the long-lived isotope, uranium I.

The element potassium is a mixture of three isotopes, two of which are stable, while the third is radioactive with a half-period of 1,600 million years. Thus the radioactivity per gram of potassium, that is, the "specific radioactivity" of any sample of potassium, decreases with time, due to the decay of the one radioactive isotope.

Mass spectroscopic studies[1] of the relative abundance of the uranium isotopes in three uranium minerals from widely different localities have shown a constant abundance ratio of 139 atoms of uranium I per atom of actinouranium. Because these two isotopes decay with different radioactive periods the relative abundance changes with time. In order to explain the constant isotopic abundance found in all samples of uranium either of two assumptions can be made. It is simpler to assume that all uranium atoms were created with the same original isotopic abundance ratio, and at the same time in the past.

The only other assumption that can satisfy contemporary observations on the isotopic abundance is the very *ad hoc* and awkward assumption that after the first sample of uranium was created all successive samples were created with a relative abundance ratio so delicately altered that they would exactly match the alteration which time had imposed upon the relative abundance of the isotopes in the first sample of uranium ever created. This cumbersome assumption seems even more untenable when we consider other long-lived radioactive substances such as potassium. There is no appreciable difference between the specific radioactivity of terrestrial potassium from a wide variety of mineral sources.[2] Here a similar alteration in the isotopic abundance ratio of newly created potassium isotopes would have to be invoked, and the time factor would have to be a different one from that applied by nature to the uranium case, because the half period of the radioactive isotope of potassium is markedly different from the half periods of uranium I and actinouranium. Thus it seems much more satisfactory to assume

[1] A. O. Nier, Phys. Rev., 55, pp. 150–153, 1939.

[2] Biltz and Marcus, Z. anorg. Chem., 81, p. 369, 1913.

that the initial isotopic abundance ratio for any element is a constant of nature.

If a meteorite sample were found to have the radioactive isotopes of uranium or potassium in a relative abundance which differed from the normal terrestrial abundance, it could be inferred that the atoms of the meteorite were created at a different time than the atoms of the same element in the earth. Thus the study of the relative abundance of the isotopes of radioactive substances offers a method of determining differential ages.[1]

THE DIFFERENTIAL AGE EQUATIONS

We derive the equations relating isotopic abundances to the age of the atoms in the following manner: In any particular sample of uranium, let:

A_0 = number of atoms of actinouranium, t years ago

A = number of atoms of actinouranium at present

λ_A = radioactive decay constant of actinouranium

U_0 = number of atoms of uranium I, t years ago

U = number of atoms of uranium I at present

λ_U = radioactive decay constant of uranium I

Then the fundamental equations of radioactive decay become:

$$A = A_0 \epsilon^{-\lambda_A t} \tag{1}$$

$$U = U_0 \epsilon^{-\lambda_U t} \tag{2}$$

Dividing, and denoting a sample of meteoritic uranium by subscripts m, and a sample of terrestrial uranium by subscripts e, we have:

$$(A/U)_m = (A_0/U_0)_m \epsilon^{-(\lambda_A - \lambda_U) t_m} \tag{3}$$

$$(A/U)_e = (A_0/U_0)_e \epsilon^{-(\lambda_A - \lambda_U) t_e} \tag{4}$$

Now, dividing equation 3 by equation 4, we obtain:

$$\frac{(A/U)_m}{(A/U)_e} \frac{(A_0/U_0)_e}{(A_0/U_0)_m} = \epsilon^{-(\lambda_A - \lambda_U)(t_m - t_e)} \tag{5}$$

[1] R. D. Evans, Popular Astronomy, **46**, pp. 159–170, 1938.

We now introduce our single assumption: that the initial isotopic abundance ratio was the same for all samples of uranium, regardless of when and where created; that is:

$$\frac{(A_o/U_o)_e}{(A_o/U_o)_m}=1 \tag{6}$$

Substituting equation 6 into equation 5, and taking natural logarithms of both sides, we have:

$$ln\ [(A/U)_e/(A/U)_m] = (\lambda_A-\lambda_U)\ (t_m-t_e) \tag{7}$$

where (t_m-t_e) is the difference in the time elapsed since the creation of the uranium atoms in the meteorite specimen and in a terrestrial specimen.

Meteorites and terrestrial rocks contain only the order of 10^{-6} grams of uranium per gram of sample. Consequently it is impossible to obtain enough uranium to measure the isotopic abundance ratios $(A/U)_m$ and $(A/U)_e$ by means of the mass spectrograph. We must turn to radioactive methods for the determination of these isotopic ratios.

We can reduce the argument of the logarithm in equation 7 to quantities which can be measured by radioactivity by multiplying its numerator and denominator by λ_A/λ_U, the ratio of the decay constants of actinouranium and uranium I. Thus:

$$\frac{(A/U)_e}{(A/U)_m}=\frac{(\lambda_A A/\lambda_U U)_e}{(\lambda_A A/\lambda_U U)_m}=\frac{R_e}{R_m} \tag{8}$$

where R_e is the ratio of the number of alpha-particles emitted by actinouranium, $(\lambda_A A)_e$, to the number of alpha-particles emitted by the uranium I, $(\lambda_U U)_e$, in the terrestrial sample while R_m is the same "activity ratio" measured in the meteorite sample. Then equation 7 becomes:

$$(t_m-t_e)=\frac{ln(R_e/R_m)}{\lambda_A-\lambda_U} \tag{9}$$

Substituting the known values of the decay constants,[1]

$$\lambda_A = 0.98 \times 10^{-9}\ \text{years}^{-1}$$

$$\lambda_U = 0.153 \times 10^{-9}\ \text{years}^{-1}$$

[1] A. F. Kovarik and N. I. Adams, Jour. App. Phys., **12**, p. 296, 1941; A. O. Nier, Phys. Rev., **55**, pp. 150–153, 1939.

and converting to common logarithms through the relationship $\log x = 2.303\ ln\ x$, equation 9 becomes:

$$t_m - t_e = 2.8 \times 10^9 \log (R_e/R_m) \text{ years} \tag{10}$$

It will be noted that the coefficient of equation 10 is approximately equal to the age of the earth; thus the "activity ratio" R of actinouranium to uranium I has decreased by nearly a factor of 10 during the lifetime of the earth. Equation 10 also displays the fortunate fact that these differential age measurements depend on the ratio of two quantities which are to be determined experimentally, using the same apparatus and techniques on the two samples. Thus minor errors in measurement tend to cancel out, and the apparatus does not necessarily need to be calibrated on an absolute basis, since only ratios are wanted. Moreover, the final quantity sought, $(t_m - t_e)$, depends only logarithmetically on this measured ratio of the activity ratios R_e and R_m.

To derive the equations governing differential age measurements using the specific radioactivity of potassium, we return to equation 7 and write its analog for the case of the potassium isotopes. In any given sample of potassium, let:

N = number of atoms of the radioactive potassium isotope K^{40}
K = number of atoms of stable potassium
λ = total radioactive decay constant of K^{40}

Then remembering that the decay constant of a stable isotope is zero, we have by analogy with equation 7:

$$ln\ (N/K)_e/(N/K)_m = \lambda(t_m - t_e) \tag{11}$$

Again, as in equation 8, we can write:

$$\frac{(N/K)_e}{(N/K)_m} = \frac{(\lambda N/K)_e}{(\lambda N/K)_m} = \frac{S_e}{S_m} \tag{12}$$

where S_e and S_m are the specific radioactivities of potassium samples from terrestrial and meteoritic samples. Terrestrial potassium is[1] only 0.011 per cent K^{40}, while its specific radioactivity[2] S_e is about 23 beta rays per second per gram of potassium element. Probably K^{40} decays by orbital electron capture[3] as well as by negatron beta ray

[1] A. O. Nier, Phys. Rev., **48**, p. 283, 1935.

[2] Mühlhoff, Ann. der Physik, **399**, p. 205, 1930.

[3] R. E. Marshak, Phys. Rev., **61**, p. 431, 1942.

emission. The fraction of the atoms decaying by orbital electron capture appears to be only 3 per cent, and would have the effect of increasing λ in equation 11 by 3 per cent. The decay constant of K^{40} is about 0.43×10^{-9} per year, corresponding to a half-period of 1,600 million years.

Substituting equation 12 and the numerical constants in equation 11 we have, for differential age measurements based on the specific radioactivity of potassium:

$$t_m - t_e = 5.3 \times 10^9 \log (S_e/S_m) \text{ years} \tag{13}$$

MEASUREMENTS RELATING TO THE URANIUM METHOD

To determine the differential age of the uranium atoms in two specimens, as indicated by equation 10, it is necessary to measure the ratio of the number of actinouranium atoms decaying to the number of uranium I atoms decaying per unit time in the sample of uranium. The relatively small difference between the range of the alpha rays from actinouranium and uranium I makes it impracticable to attempt to distinguish experimentally between the alpha rays from these two isotopes in any sample of uranium.[1] Therefore the measurement of the activity of actinouranium is made by separating from the sample one of its long-lived decay products, protactinium, with which it is in radioactive equilibrium. Similarly the activity of the uranium I isotope is determined by measuring the activity of one of its radioactive decay products, radon, with which it will be in radioactive equilibrium.

Experimental techniques of adequate sensitivity and accuracy are available for determining the radon content of rocks and meteorites.[2] The sample of rock or meteorite to be tested is boiled in a direct fusion vacuum furnace, operating at about 2000° C., thus releasing the inert radioactive gas, radon, from the sample. This radon is then conducted to an ionization chamber where its alpha-ray activity is compared with that due to a known amount of radon from a radium standard. Due to radioactive equilibrium in the original sample the number of radon alpha-rays observed per minute is the same as the number of alpha rays per minute produced by the uranium I in the rock sample.

The separation and measurement of protactinium is much more laborious. The chemical methods developed for separating pro-

[1] T. R. Wilkins and D. P. Crawford, Phys. Rev., 54, p. 316A, 1938.

[2] R. D. Evans, Rev. Sci. Inst., 6, p. 99, 1935.

tactinium from rocks and stony meteorites, both of which are rich in silica, have been described.[1] About fifty grams of the siliceous material is heated in aqua regia and then hydrofluoric acid to remove the silica. After the addition of zirconyl chloride to the solution, the protactinium is co-precipitated with zirconium phosphate by the addition of phosphoric acid, leaving uranium, thorium, iron, and magnesium in solution but precipitating lead, barium, bismuth, and their isotopes or homologs among the radioactive decay products present. To assure complete separation of the uranium from the protactinium and zirconium phosphate, this precipitate should be dissolved in *HF* and reprecipitated as phosphate. After being washed with *HCl* the precipitate is ignited to zirconium pyrophosphate, ZrP_2O_7, and weighed. The zirconium pyrophosphate is then taken up in hydrofluoric acid and solutions of the nitrates of barium, lead, lanthanum, and bismuth (each carefully purified of radioactivity), equivalent to 4 mg. of each element, are added. At this stage the many radioactive elements other than protactinium are co-precipitated with their isotopes or chemical homologs of barium, lead, bismuth, and lanthanum, as insoluble sulphates and fluorides, leaving the protactinium and zirconium in solution. The co-precipitation process, using barium, lead, lanthanum, and bismuth, is repeated three times.

Overall control measurements, in which all reagents but no rock was used, show that the procedure, omitting a second precipitation of zirconium phosphate, removes substantially all (97 ± 3 per cent) of a small added amount of uranium, or thorium, or polonium. The recovery of protactinium is 90 ± 6 per cent.

Each 50-gram sample of stony meteorite or terrestrial rock used was made to yield slightly over 100 mg. of zirconium pyrophosphate. This was divided into carefully weighed individual samples of about 40 mg. each. Each sample was finely ground and deposited from an ethyl alcohol suspension, onto a silver disk 11 cm. in diameter and 0.5 mm. thick. The area of the final thin solid sample is 56.7 sq. cm. Thus the source has a thickness which is equivalent for the absorption of alpha rays to only about 4.5 mm. of air, and 46 per cent of all the protactinium alpha rays produced within the sample will emerge with a residual range greater than 5 mm. of air. This is equivalent to saying that the general equations[2] governing the internal absorp-

[1] R. D. Evans, J. L. Hastings, and W. C. Schumb, Field Mus. Nat. Hist., Geol. Ser., 7, p. 71, 1939; Jour. Amer. Chem. Soc., 61, p. 3451, 1939.

[2] G. D. Finney and R. D. Evans, Phys. Rev., 48, p. 503, 1935. Equation 3.

tion of alpha rays in thin sources show that the loss of countable alpha rays will be less than 8 per cent in samples of the area, weight, and composition given above. The source is placed in a parallel plate ionization chamber and the alpha-ray emission recorded by means of a vacuum tube electrometer amplifier and a photographic recording galvanometer (see fig. 31).

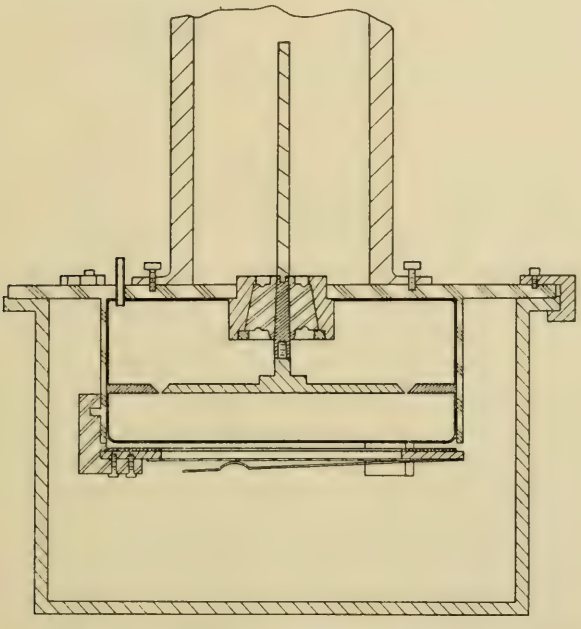

FIG. 31. Cross section showing construction of the parallel plate ionization chamber used for alpha-ray counting, which is similar to that developed by Finney and Evans.[1] The vacuum tube electrometer is located in an evacuated housing above the chamber. The collecting electrode is a circular brass disk, 10 cm. in diameter, and all inner parts are either made of spun electrolytic copper, or are silver plated, to minimize the background. The entire counting chamber is continuously flushed out with nitrogen which has been stored for at least one month, to cause the decay of any initial gaseous radioactive contaminants.

Parallel chemical manipulations and physical measurements were made throughout on a sample of the inside of a Pultusk stone, the outer skin being reserved, and on a terrestrial sample of granite from the Barryfield quarries, two miles east of Kingston, Ontario. Samples of the Pultusk meteorite were kindly furnished by Colonel Clifford C. Gregg, Director, and Mr. H. W. Nichols, Chief Curator, Department of Geology, Field Museum of Natural History, Chicago.

[1] Phys. Rev., 48, p. 503, 1935.

Table 1 summarizes the results obtained on these two materials.

TABLE 1.—SUMMARY OF MEASUREMENTS OF RADIOACTIVITY ON THE PULTUSK METEORITE, AND A TYPICAL TERRESTRIAL GRANITE FROM ONTARIO

	Pultusk Meteorite	Ontario Granite
Total α-ray activity of protactinium, in α per hour per g. of original material	0.10 ±0.03	1.4 ±0.3
Radium content in 10^{-12} g. Ra per g.	0.023±0.005	0.28 ±0.02
Radon α-ray activity in α per hour per g.	3.1 ±0.6	37. ±3.
Activity ratio, R, of protactinium/radon or actinouranium/uranium I	0.032±0.014	0.038±0.009

The total alpha-ray activity of protactinium is obtained by correcting the observed alpha-ray count for the internal absorption of alpha rays within the thin source, for the contamination of the zirconium pyrophosphate with an assumed 3 per cent of the uranium originally present in the sample, for the 90 per cent overall recovery of protactinium in the zirconium pyrophosphate, and for the small activity of the reagents as determined from control runs. The average counting rates were calculated from least squares averages of all observations taken, including alpha-ray counts of about forty hours on the Pultusk specimen, forty hours on the granite specimen, and several hundred hours of background, blank, and control runs. The average background of the alpha-ray counter under the conditions of measurement was 13.3 ± 0.3 alpha rays per hour.

The radium content of both specimens was measured by the radon method described briefly above, and the radon alpha-ray activity given in Table 1 is computed from these radium values by taking the Curie unit as 3.7×10^{10} disintegrations per second per gram of radium. Finally the activity ratio of actinouranium to uranium I, which is the same as that of protactinium to radon, is given in the last line of the table.

Within the probable error of measurement these activity ratios are the same in the Pultusk meteorite and in the terrestrial granite specimen. If we take the actual numerical values as given, then the quotient of the activity ratios R_e/R_m equals 1.2 ± 0.5. Substitution of this value in equation 10 gives

$$t_m - t_e = (0.2 \pm 0.5) \times 10^9 \text{ years} \qquad (14)$$

Thus these measurements indicate that there is definitely no large difference in age between the uranium atoms in the Pultusk meteor-

ite and in a terrestrial granite, and they strongly suggest that the difference between the ages of the atoms in these two samples of the solar system is zero.

It may be remarked that the ratio of the activity of actino-uranium to uranium I as measured in terrestrial uranium minerals lies somewhere between 0.40 and 0.46, with a strong preference being given to the higher value.[1]

It was found impossible to apply the uranium method to the Homestead meteorite, owing to the extremely small radioactive content of this meteorite.

POTASSIUM DIFFERENTIAL AGE MEASUREMENTS[2]

The meteoritic samples of potassium chloride were separated from the center portion of the specimens of the Pultusk meteorite. Samples weighing about 10 grams were disintegrated by treatment with 47 per cent hydrofluoric acid and the excess hydrogen fluoride removed. The large iron and magnesium content was precipitated by ammonium hydroxide and ammonium bicarbonate. The filtrate from this separation was evaporated to dryness in platinum and the excess ammonium salt carefully decomposed. The residue was then treated repeatedly with perchloric acid and alcohol until a constant weight of the final potassium perchlorate was obtained. The potassium perchlorate obtained from several of these separations was combined and treated once more with a perchloric acid and alcohol separation in order to insure a uniform final product, which was then decomposed in a quartz dish at 550° C., leaving potassium chloride. Great care was exercised in the choice and testing of reagents in order that none would be used that had come in contact with any terrestrial potassium during its preparation.

Merck C.P. reagent potassium chloride was used as a terrestrial comparison sample of potassium.

Spectroscopic analyses were made on both samples of potassium chloride used. The terrestrial sample had a purity greater than 99.8 per cent and contained less than 0.01 per cent rubidium. The meteoritic potassium chloride was over 99.2 per cent pure, the major impurity being calcium. The meteoritic potassium chloride contained 0.15 per cent rubidium. Rubidium is also naturally

[1] A. O. Nier, Phys. Rev., 55, p. 153, 1939.

[2] W. C. Schumb, R. D. Evans, and W. M. Leaders, Jour. Amer. Chem. Soc., 63, p. 1203, 1941.

radioactive, but with the purities indicated and under the conditions of measurement used the correction for rubidium activity is only about 2 per cent.

During the course of the work 93.04 grams of meteorite were used and from this material 0.415 gram of potassium chloride was recovered. This amounts to 0.28 per cent potassium oxide in the original

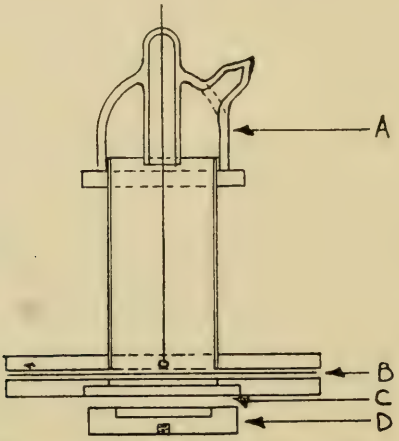

FIG. 32. "Bell" type Geiger-Müller counter and sample holder in half section. The counter is filled with dry air at a pressure of 60 mm. of mercury. All parts are of brass except A which is a glass top cemented to the tube. B is the mica window held in place with machine screws and picein cement. C is machined to receive the sample holder D and ensures uniform geometry to the sample and counter system. The window aperture in C is one inch in diameter.

meteorite, a value somewhat lower than that obtained by Rammelsberg in 1870 on another sample of Pultusk.

The measurements of radioactivity were made by placing the finely ground potassium chloride in a shallow cylindrical well (1.8 cm. in diameter) in a small brass disk (see fig. 32), the powdered sample being leveled by shaking and rocking. This sample was then brought close to a thin (21 microns) mica window of a bell-type Geiger-Müller counter. The amplifier for the counter was of the counting rate meter type, with photographic recording of the average counting rate by means of a drum camera and galvanometer.[1]

Nearly all the potassium chloride used in individual measurements can be recovered effectively and reused. In this manner 0.5 gram of potassium chloride could be used for many repeated

[1] R. D. Evans and R. L. Alder, Rev. Sci. Inst., **10**, p. 332, 1939.

measurements of the beta-ray activity. Owing to the very low specific radioactivity of potassium, reliable radioactivity measurements cannot be obtained on less than about 50 mg. of KCl. The area of the source disk is 2.54 sq. cm.; thus most of the samples had a thickness greater than 20 mg./sq. cm. Under these conditions the internal absorption of the soft beta rays of potassium is appreciable. In order to eliminate the effects of internal absorption, samples of varying total weight from 10 mg. to between 400 and 500 mg. were used. The net observed beta-ray counting rate per gram of potassium chloride is then plotted as a function of the amount of potassium chloride in the sample. Figure 33 shows the results on the terrestrial potassium, while figure 34 presents the observations on the potassium separated from the Pultusk meteorite. Extrapolation of these curves to a sample having zero weight, and hence zero internal absorption, gives the beta-ray activity per gram of potassium for the two specimens.

Comparison of figures 33 and 34 shows that the two curves have the same shape and the same intercept of 240 counts per minute per gram of potassium chloride. The probable error in each extrapolated intercept is about $\pm$ 10 counts per minute. Thus the ratio of the specific activities $S_e/S_m = 1.00 \pm 0.03$. Substitution of this ratio of the specific activities in equation 13 gives for the difference in the age of the atoms in Pultusk and in terrestrial material:

$$t_m - t_e = 0.00 \pm 0.06 \times 10^9 \text{ years} \qquad (15)$$

In agreement with the results obtained on uranium, but with a much smaller probable error, these measurements on potassium indicate that the age of the potassium atoms in the Pultusk meteorite is the same as the age of potassium atoms in the earth.

CONCLUSIONS

Comparative measurements have been carried out on the relative activity of the isotopes of uranium, and of the specific radioactivity of potassium, in terrestrial samples and in the Pultusk meteorite. These measurements show the same relative abundance of the isotopes of uranium and of potassium in both the terrestrial and meteoritic material. Hence they both confirm the basic assumption of the method in so far as the Pultusk meteorite is concerned, and show that the atoms of the Pultusk meteorite were created at the same time as the atoms in the earth.

To fix an absolute age for the time of formation of the Pultusk meteorite we would need to know the age of the atoms in the earth.

Measurements of radioactivity have been made by many methods on hundreds of terrestrial rocks and minerals in order to determine their "age," that is, the elapsed time since the rock or mineral was laid down in its present form and composition. These measurements show age values ranging continuously from zero for recent lavas up to about 2,000 million years. Age measurements by the helium method on rocks[1] and on magnetite minerals,[2] by the lead

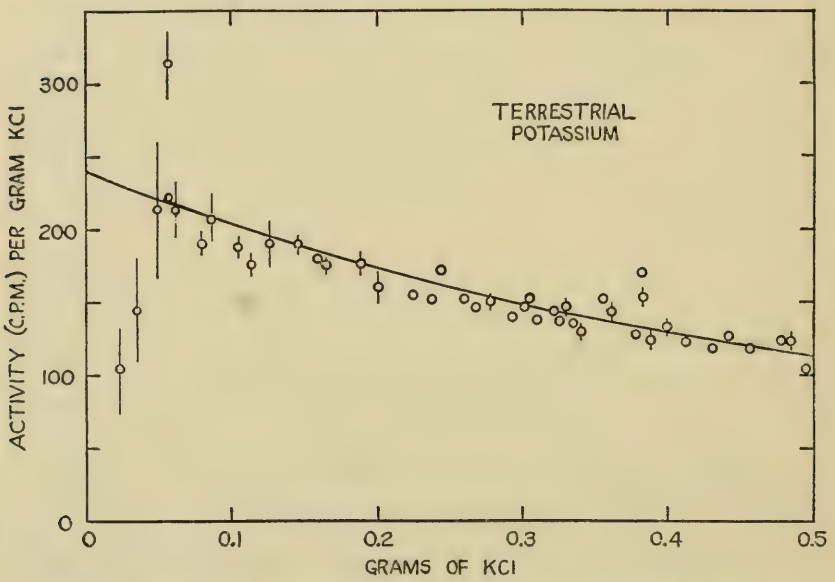

FIG. 33. Terrestrial potassium beta-ray activity per gram of KCl *vs* weight of sample used in the counter shown in figure 32. The probable error of each measurement is indicated by a vertical line through the experimental point. Extrapolation of this curve to a sample of zero weight eliminates the correction due to internal absorption within the various sources used.

method and by the lead isotope ratio method on thorium and uranium minerals[3] agree on the value of about 2,000 million years for the maximum age so far observed in any terrestrial occurrence. Considering the small fraction of the earth's crust which has actually been sampled it is entirely possible that one may eventually find

[1] For example: C. Goodman and R. D. Evans, Bull. Geol. Soc. Amer., **52**, pp. 491–544, 1941; C. Goodman, Jour. App. Phys., **13**, p. 276, 1942.

[2] P. M. Hurley and Clark Goodman, Bull. Geol. Soc. Amer., **52**, pp. 545–559, 1941.

[3] A. O. Nier, Phys. Rev., **55**, p. 153, 1939; A. O. Nier, R. W. Thompson, and B. F. Murphey, Phys. Rev., **60**, p. 112, 1941.

rocks or ores which are somewhat older than 2,000 million years, although present indications are that the distribution in the number of samples of high age decreases rapidly around 2,000 million years and may terminate near that figure.

It is generally agreed that an initially gaseous or molten earth would have solidified in less than 0.1 million years. But the span of time between the formation of an initially molten earth and the

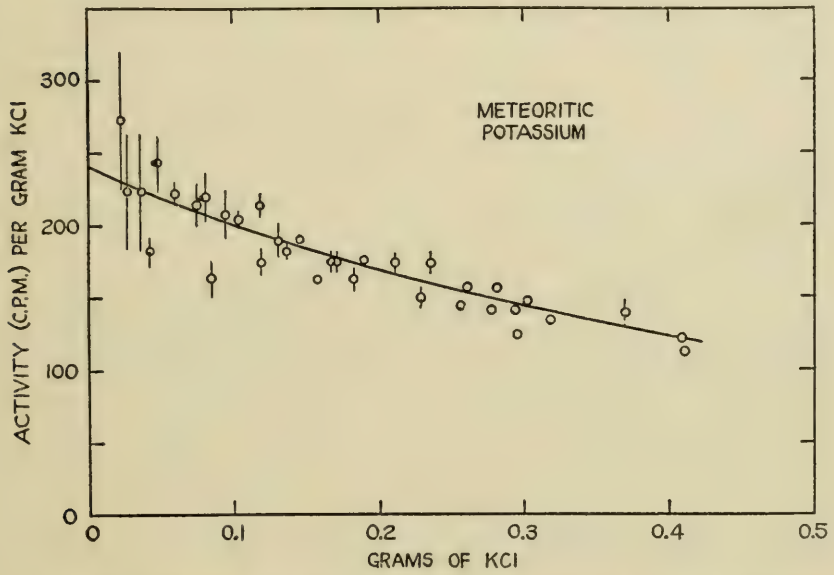

FIG. 34. Beta-ray radioactivity per gram of potassium chloride separated from the Pultusk meteorite, plotted in the same manner as figure 33.

creation of the atoms which it contains is entirely unknown. Present astronomical evidence favors the so-called short time scale of 10^9 to 10^{10} years. Thus, the stability of galactic clusters, the stability of wide binaires, the red-shift in extra-galactic objects, and other phenomena are compatible with a universe having essentially the same age as the earth.[1]

The isotopic abundance ratios have been determined with the mass spectrograph for all known elements. A general rule, apparently related to the fundamental laws of nuclear forces, is that isotopes of even atomic weight are always more abundant than isotopes

[1] Louderback, Evans, Gutenberg, Kuiper, Tolman, and Epstein, "Symposium on the Geologic and the Cosmic Age Scale." Science, 82, p. 51, 1935.

of odd atomic weight for elements whose atomic number is even. If this universal rule is extended to apply to the initial isotopic abundance of the uranium isotopes (even atomic number), then uranium I (atomic weight 238) should always have been more abundant than actinouranium (atomic weight 235). Equation 4 gives the isotopic abundance (A_o/U_o) at any time t_c years ago if A/U is the present[1] isotopic abundance. Substituting $(A/U)=1/139$ and $(A_o/U_o)=1$ in equation 4 we find that actinouranium and uranium I, if already created at that time, would have been equally abundant 6,000 million years ago, and at any earlier time the odd atomic weight isotope actinouranium would have been more abundant than uranium I, in contradiction to the general empirical laws governing the stable isotopes of all elements. This reasoning, if taken seriously, would require that the age of the atoms which compose the earth is something definitely less than 6,000 million years.

Within the relatively limited range of the sampled earth and the sampled meteorite population, all data agree on a period of 2,000 to at most 2,500 million years since the formation of the earth, and suggest the same order of magnitude for the age of the atoms of all elements so far studied in samples of the solar system.

[1] A. O. Nier, Phys. Rev., 55, pp. 150–153, 1939.

GEOLOGICAL SERIES
OF
FIELD MUSEUM OF NATURAL HISTORY

Volume VII | July 29, 1949 | No. 7

THE MAPLETON METEORITE

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INTRODUCTION

Soon after Chicago Museum obtained the Mapleton meteorite, it was briefly described (Roy, 1939). In the following month *Rocks and Minerals* (1939) also published an account that was essentially a copy of the Museum article. Later, Mr. Ben Hur Wilson (1944) wrote a popular description of the meteorite. Since Mr. Wilson's report was based largely upon information supplied by the Department of Geology of Chicago Museum, a general account of the meteorite will not be given here. Instead, a digest of the report has been made, containing certain modifications, and pertinent data relating to the physical features and the internal structure of the meteorite have been added.

MAPLETON

Monona County, Iowa, United States of America.
Latitude 42° 10′ 47″ N., Longitude 95° 43′ 18″ W.
Iron, medium octahedrite (OM).
Found June 17, 1939.
Weight 49 kilograms (108 pounds).
Catalogue number Me 2286.

NATURE OF FIND

The meteorite was purchased by the Museum on July 31, 1939, from Mr. Harvey Meevers, of Mapleton, Iowa. It was accidentally found by him on his farm on June 17, 1939, while he was cultivating corn. According to Mr. Meevers, his cultivator caught behind a heavy "stone" that seemed heavier than any other stone he had

hitherto encountered. He dug it out of the ground and, believing it to be a mass of iron, carried it to his barn for safe-keeping. The find, like many other finds, would in all probability have been forgotten had it not been for a timely article on meteorites published by F. Barrows Coulton (1939). The article reminded Mr. Meevers of the "mass of iron" he had found a few days earlier. He examined

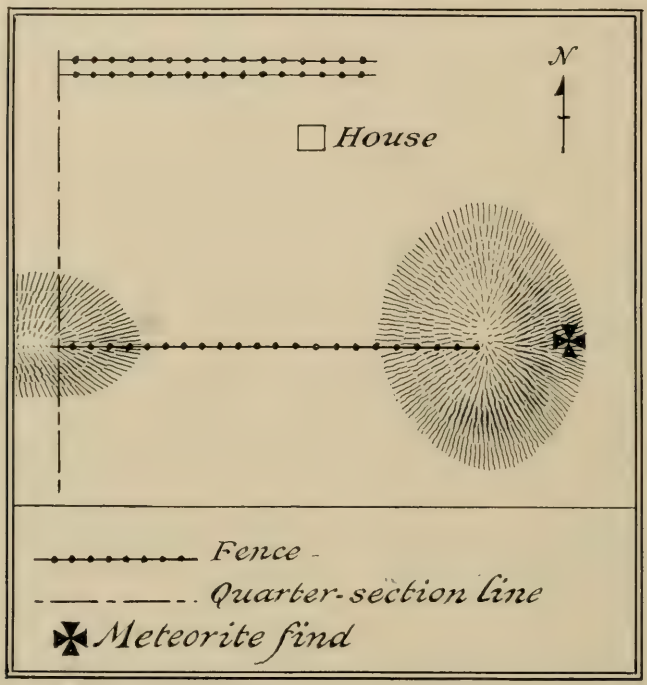


Fig. 35. Diagram showing location where Mapleton meteorite was found.

his find and decided that it might be of meteoric origin; so he sent a small sample, approximately 34 grams, to the Museum for examination. It was found to be an iron meteorite and was purchased by the Museum and named "Mapleton," the name of the town close to which it was found.

LOCATION, DATE, AND TIME OF FALL

Previous to the discovery of this iron, four other meteorites were known from the State of Iowa. Three of these were stone and one was iron-stone. The Mapleton is the only iron meteorite thus far reported from Iowa. It was found on the east slope of a rather

steep hill (fig. 35) in the northwest quarter of Section 15, Township 85 N., Range 42 W., about three miles east and one mile north of Mapleton, Monona County, Iowa (42° 10′ 47″ N. Lat., 95° 43′ 18″ W. Long.).

The date and time of the fall of the Mapleton are not known. When a meteorite is found, a number of "eye-witnesses" usually

FIG. 36. The Mapleton meteorite. About $\times 1/5$.

crop up with divergent reports, and attempts are made to connect the find with one of these reports. The finding of the Mapleton was no exception. Stories of a "fire-ball" streaking across the sky at such and such an hour, day, and year, poured forth in rapid succession, but none of these stories could be verified, much less associated with the Mapleton. However, it is well to point out here that only the surface of the meteorite had suffered oxidation, as evidenced by the partial alteration and decay of the fusion crust. The iron is otherwise remarkably well preserved, and, because of this excellent state of preservation, it may be assumed that the fall took place in recent decades.

Apparently, the meteorite is only a portion of the original mass, as it appears to have been broken. The disruption must have taken place at a considerable altitude while the meteorite still had high velocity. This can be surmised by the presence on the broken side of elongated furrow-like depressions or pittings that could hardly have been formed under reduced velocity.

SHAPE, SIZE, AND SPECIFIC GRAVITY

The general shape (fig. 36), as preserved, does not conform strictly to any of the characteristic forms of meteorites. Roughly, it has a sub-semicircular outline and resembles a flattened cone that has been cut vertically near the center. One side of it is plano-convex; the other is a very low truncated cone with the apex slightly away from the center. The point of the cone was presumably broken off during disruption of the mass, for instead of having the usual smooth surface it is pitted. The slopes of the cone are unequal and considerably damaged and deformed. The pittings of the plano-convex side, some of which are merged into one another, are larger and more circular, but shallower than those of the opposite side. This is to be expected. The plano-convex side is the rear of the meteorite, and was thus less exposed to the heat and friction of the atmosphere. The conical side (the front of the mass) has many elongated pittings, more or less radially arranged on the slopes and edges of the cone, evidence of the passing of air currents from the apex of the cone during its passage through the atmosphere.

In its present state, the meteorite, which probably does not represent much more than one-half of the original mass, weighs 49 kilograms (108 pounds). Its greatest length, breadth, and height are 17½ inches, 9⅞ inches, and 6¼ inches, respectively. The specific gravity is 7.70, which is average for this class of meteorites.

Since its acquisition, the meteorite has been sawed into five sections, consisting of two end pieces, weighing 35.5 and 47 pounds respectively, and three slabs weighing 4,540, 4,280, and 3,381 grams.

The meteorite has not, as yet, been distributed, with the exception of 20 grams sent in exchange to Dr. H. H. Nininger.

CHEMICAL COMPOSITION

Two chemical analyses were made of the Mapleton:

HENRY HERPERS,[1] *Analyst*

Element	*Percentage*
Fe	92.16
Ni	7.61
Co	0.036
Cu	0.003
C	0.14
S	0.01
P	0.10
Cl	0.00
Total	100.059

[1] Formerly Assistant Curator of Geology.

ROBERT K. WYANT, *Analyst*

Element	*Percentage*
Fe	92.22
Ni	7.50
Co	0.08
Cu	0.02
C	0.11
S	0.01
P	0.13
Total	100.07

ANALYTICAL METHODS[1]

Only volumetric methods were used for the determination of iron in the Mapleton meteorite, as gravimetric methods often give high results.

As noted by Henderson (1941), much of the poor agreement in meteorite analysis is caused by the incomplete separation of iron and nickel. The nickel content of the Mapleton meteorite was determined by the use of two different methods. Both methods were found to be satisfactory and the results were consistent.

In one procedure, that of Hillebrand and Lundell (1929), tartaric acid is used to prevent precipitation of iron by ammonium hydroxide. Nickel is subsequently precipitated by the use of dimethylglyoxime. In the other method, originally outlined by Henderson (1941), strong ammonium hydroxide is used to separate the nickel from the iron. Four reprecipitations of iron are made. The combined filtrates are evaporated and salts destroyed. Nickel is then precipitated in an ammoniacal solution by the use of dimethylglyoxime.

The remaining elements determined in the analysis of the Mapleton meteorite comprised less than 0.4 per cent of the total and were determined by the usual procedures used in the analysis of iron meteorites.

STRUCTURE

The internal structure of the meteorite was studied both in macro- and micro-etched sections, and in both sections nital (8 per cent nitric acid) was used for etching. The attack of etchant was much faster than is usually the case. Figures appeared almost instantly on application of the etchant and a satisfactory micro-etching was obtained in less than three seconds. The structure, as shown by the figures, is that of a medium octahedrite with a regular

[1] As used by Robert K. Wyant.

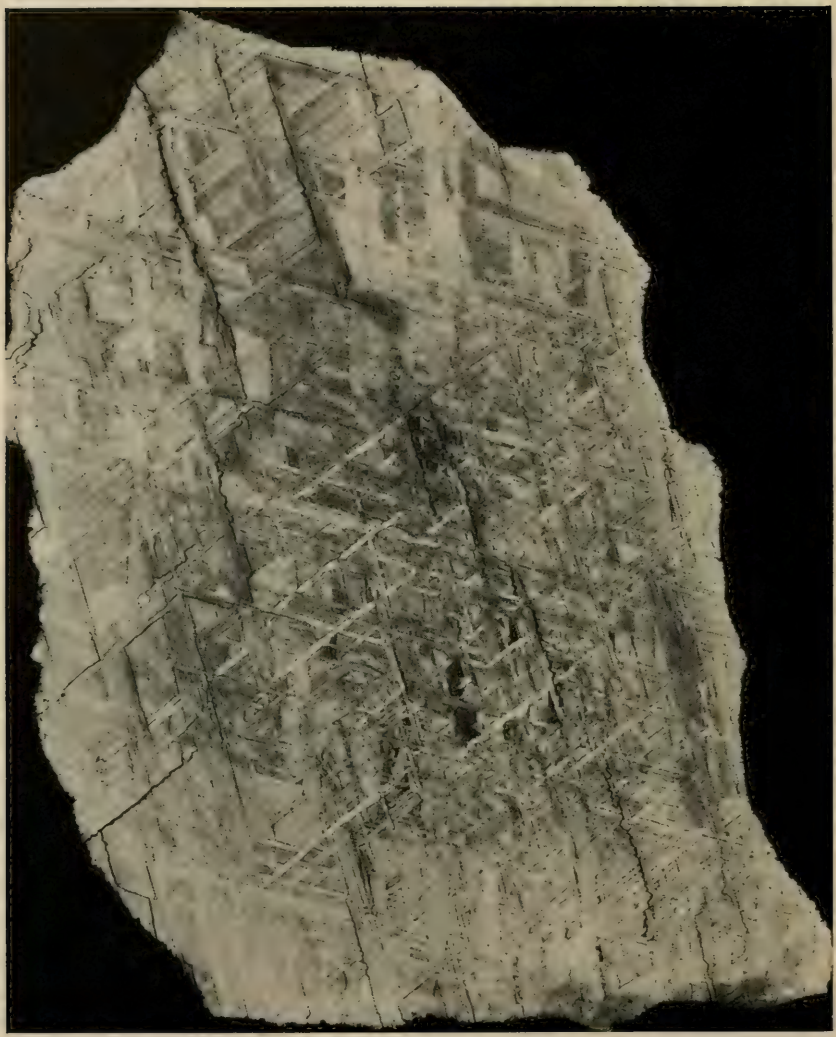


FIG. 37. Slice of Mapleton meteorite, showing well-developed octahedral pattern. About $\times \frac{1}{2}$.

pattern (fig. 37). There are many cracks in the section, most of which follow the general octahedral planes. The cracks are narrow and are stained with limonite.

The zone of alteration is clearly visible. Its inner boundary is slightly lighter, and thus serves as a line of demarcation. The depth

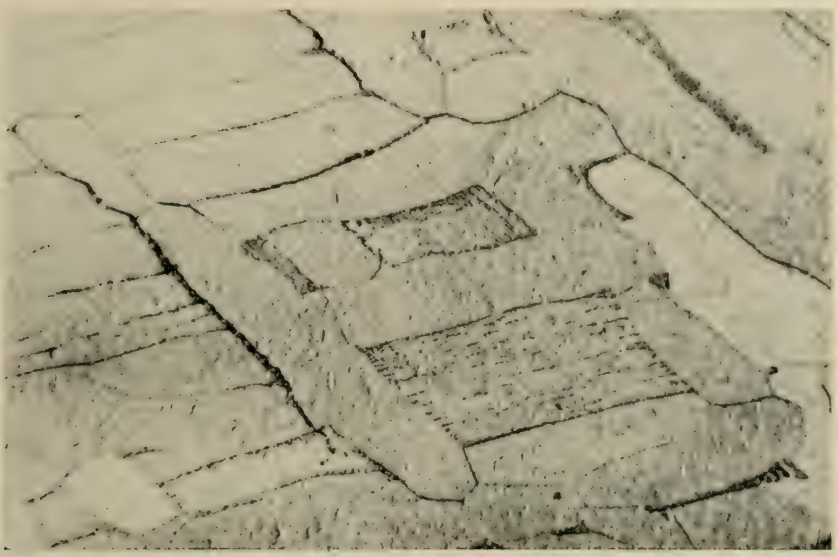


FIG. 38. Typical kamacite bands, showing varying widths. Plessite fields seen here are chiefly rhomboidal. ×10.

to which alteration has taken place is shallow and is variable (from a fraction of a millimeter to 3.3 mm.). This indicates, as has been stated above (p. 101), that the mass had disrupted during its flight to the earth and that different surfaces were exposed to heat for varying lengths of time. The meteorite did not suffer prolonged heating, as might be inferred from the shallow depth of the zone of alteration and from the absence of any marked change in its principal components (kamacite, taenite, and plessite fields) in the altered zone.

The kamacite bands (fig. 38) are fine-grained to granular and vary in width from 0.5 mm. to 1.5 mm. Some are wider and have a swollen appearance, with an average width of 3 mm. These larger bands are not conformable with the octahedral structure (fig. 39), though they are roughly oriented. A few of the larger bands appear to have coalesced into a fascicle. Some of the kamacite bands, in

FIG. 39. At the center are two large kamacite bands. They have a swollen appearance and are not conformable with the octahedral pattern. ×6.

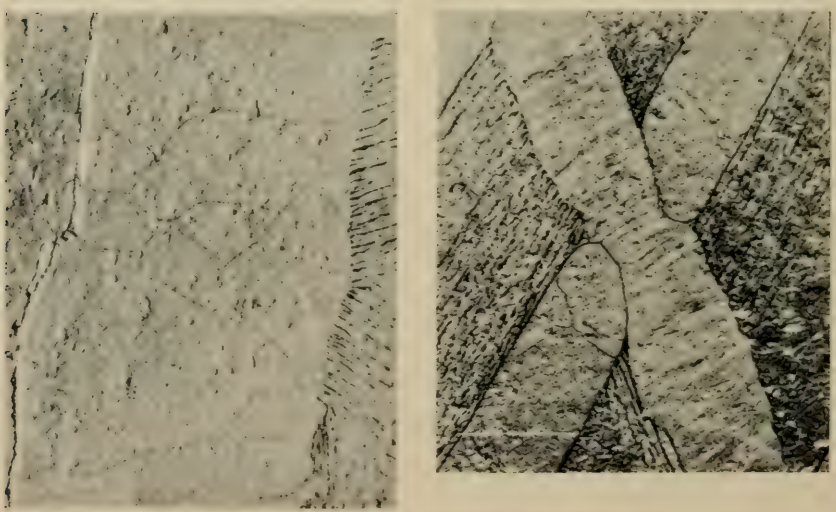
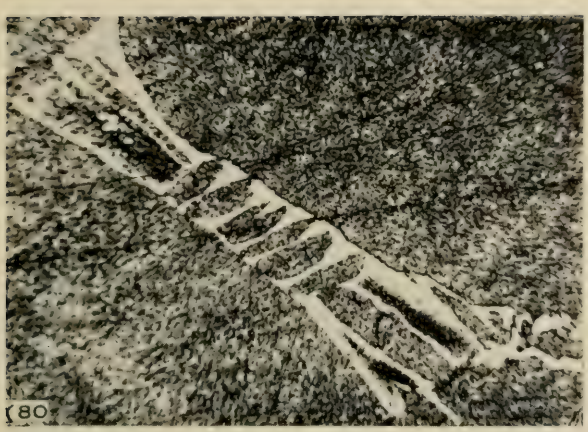


FIG. 40. Left: A kamacite band, showing grain boundaries. Right: Two kamacite bands crossing each other. The angles are occupied by plessite fields. ×13.



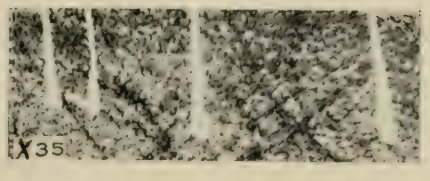


FIG. 41. Taenite lamellae thickened at the ends. Some are looped at the thickened ends and some have darkened cores. Magnifications shown on individual figures.

addition to being fine-grained to granular, have retained traces of taenite particles or lamellae, indicating incomplete separation. Grain boundaries in kamacite bands (fig. 40) are common, more common in one part of the section than in another.

Taenite lamellae bounding the kamacite bands and plessite fields can be distinguished easily by the naked eye. They are not

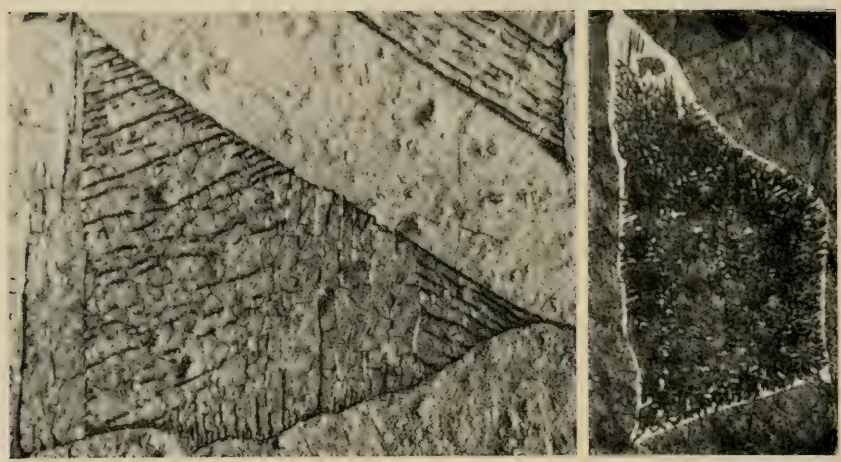


Fig. 42. Enlarged plessite fields. Right: A dense field. ×25. Left: The triangular field with taenite lamellae and kamacite bands running in three directions shows the general octahedral structure. ×14.

uniform in width and are generally wavy. They occur in various forms, as long or short threads, as needles, and as particles. Some, particularly in plessite fields, appear thickened at the ends, near or at the junction of kamacite bands (fig. 41). Under high magnification, many of these are found to be looped at the thickened ends, some having dark cores, very similar to those observed in Seneca Township, Bethany, and others.

Plessite fields consisting of taenite and kamacite are abundant and show an unusual variety of shapes (fig. 42). These fields are both light and dark, the former type predominating. The dark fields, however, are not typical, being not as dark, nor the texture as visibly dense. In some of the fields the kamacite bands bounded by taenite lamellae have three systems, reproducing on a small scale the general octahedral structure. The taenite lamellae in these fields are not always continuous but are often hachured (fig. 43).

Taenite also occurs as particles dispersed in a matrix of granular kamacite in some of the fields. Judging from the relative preponderance of light fields and segregation of clear taenite, it may be

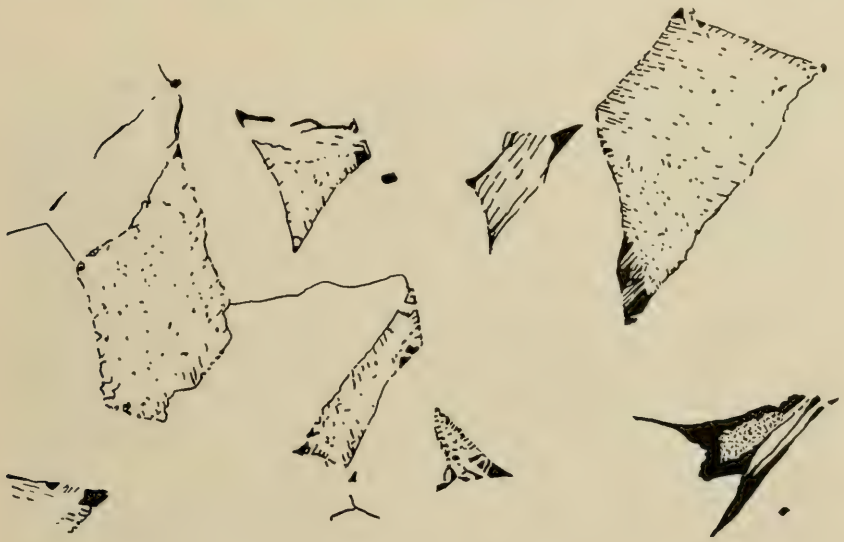


FIG. 43. Plessite fields showing a variety of shapes. ×19. Ink sketches on photographs, using Farmers reducer.

assumed that the gamma-alpha phase of separation was fairly complete.

A certain structural feature (fig. 44) resembling Neumann lines has been observed in a limited small area of the section. The lines are straight and parallel, but not equally spaced. Under high magnification they appear grained and show a sheen. They run across kamacite bands but are interrupted by the taenite lamellae bounding the adjoining plessite fields. The lines below the plessite fields are spaced differently from those above. The fact that the lines occur only in one small and limited area makes the interpretation of them as Neumann lines uncertain. They could be transformation figures described and illustrated by Vogel (1927), and more recently discussed and figured by Perry (1944). The figures are thought to have been produced in the gamma-alpha range, the result of coalescence of microscopic alpha needles developing in gamma iron. The lines observed in this meteorite are, however,

clear cut and lack the characteristic hatched pattern of transformation figures.

Schreibersite in large forms has not been recognized. The matrix of the section, however, is pitted with numerous, small, grayish-black specks that are depressed and angular. These specks

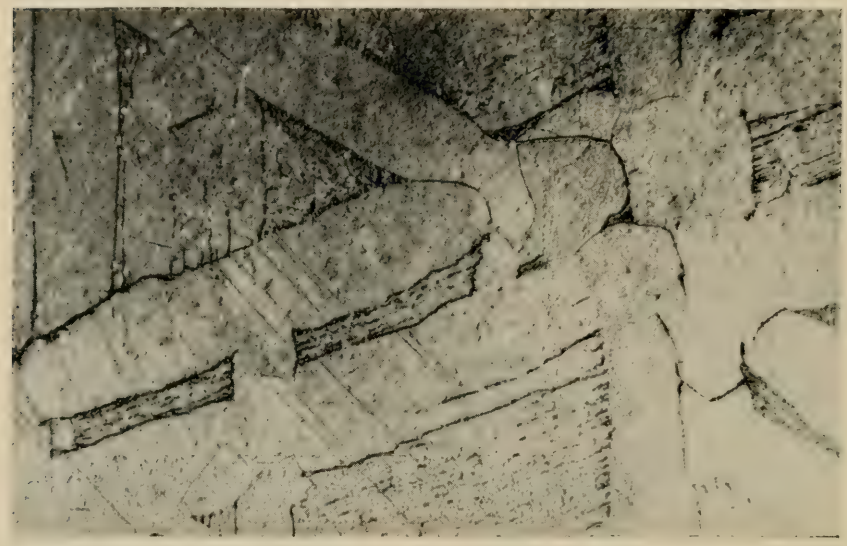


FIG. 44. The lines at the left resemble Neumann lines. They may be transformation figures. ×10.

might have been filled originally with schreibersite particles that were pulled out in the process of grinding and polishing the section. A careful examination of the specks over a large area, however, failed to show any trace of phosphide inclusions.

No other accessory constituents have been observed.

REFERENCES

COULTON, F. BARROWS
1939. News of the Universe. Nat. Geog. Mag., **76**, No. 1, pp. 1–32.

HENDERSON, E. P.
1941. Methods of Determining Nickel and Cobalt in Meteoritic Iron. Amer. Jour. Sci., **239**, pp. 372, 376.

HILLEBRAND, W. F. and LUNDELL, G. E. F.
1929. Applied Inorganic Analysis, p. 316.

PERRY, STUART H.

1944. The Metallography of Meteoric Iron. Bull. U. S. Nat. Mus., **184**, pl. 35, pp. 60–61, 92.

ROCKS AND MINERALS

1939. Field Museum Acquires Mapleton Meteorite. October, **14**, No. 10, p. 320.

ROY, SHARAT K.

1939. Field Museum Obtains First Iron Meteorite Ever Reported from State of Iowa. Field Mus. News, **10**, No. 9, p. 4.

VOGEL, RUDOLPH

1927. Ueber die Strukturformen des Meteoreisens und ihre spezielle Beeinflussung durch Umwandlung und beigemengten Phosphor. Abh. Ges. Wiss. Göttingen, math.-phys. Kl., new ser., **12**, (2), pp. 1–51.

1932. Eine umfassendere Deutung der Gefügeerscheinungen des Meteoreisens durch das Zustandsdiagram des ternären Systems Eisen-Nickel-Phosphor. Abh. Ges. Wiss. Göttingen, math.-phys. Kl., ser. 3, No. 6, pp. 1–31.

WILSON, BEN HUR

1944. The Mapleton Meteorite. Palimpsest. Iowa State Hist. Soc., **25**, No. 5, pp. 129–140.

GEOLOGICAL SERIES
OF
FIELD MUSEUM OF NATURAL HISTORY

Volume VII | August 30, 1949 | No. 8

THE NAVAJO METEORITE

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INTRODUCTION

Preliminary studies on the Navajo meteorite described in this paper were made by the late Dr. Oliver Cummings Farrington and Mr. Henry W. Nichols, both former Chief Curators of the Department of Geology, but, for various reasons, the studies were never completed. Fortunately, notes on their results were kept in the files, and these we have been able to use to advantage. We wish to acknowledge our indebtedness to our predecessors in the study of this meteorite.

NAVAJO

Near Navajo, in Apache County, Arizona, United States of America.
Latitude 35° 20′ N., Longitude 109° 30′ W.
Iron, nickel-poor ataxite (D_2).
Found 1921 and 1926 (two masses).
Total weight 2,180 kilograms (4,814 pounds).
Catalogue numbers, Navajo I, Me 2038; Navajo II, Me 2099.

This is an iron meteorite of more than ordinary significance. An account of its features of special interest will be found on page 118, under the heading "Structure and Constituents."

The meteorite consists of two masses, both of which are remarkable for their size. The larger mass, designated as Navajo I (figs. 45, 46), weighs 1,499.6 kilograms (3,306 pounds); the smaller, designated as Navajo II (fig. 47), weighs 680.4 kilograms (1,508 pounds), making the total known weight of the fall 2,180 kilograms (4,814 pounds).

Navajo I was found July 10, 1921, about thirteen miles from Navajo, in Apache County, Arizona. It was buried in talus at the foot of a ridge of Shinarump sandstone. The finders were Messrs. Robert K. Thomas and Carl Hill, both residents of Navajo. At the time negotiations for the acquisition of the meteorite were in progress, Mr. Thomas stated in a letter to the Museum (dated

FIG. 45. Navajo I, showing a deep fissure that extends half way around it. The chisel marks referred to (see below) are also shown. About $\times 1/6$.

January 1, 1922), "The Navajo meteorite . . . was known to the Navajo Indians since they came to this country about 1600(?) . . . and was covered up with rocks to keep the white man or other tribes from finding it as they thought it sacred. They called it 'Pish le gin e gin' (black iron). They tell me that the marks were there when they first found it and they think the prehistoric pottery-makers cut them in."

The marks referred to in the letter do not appear to be anything more unusual than marks made by someone in an effort to determine the nature of the mass. It should, however, be pointed out here

that the chisels used to make the marks had wider blades than those generally used now, and that picture writings were found on rocks in nearby outcrops.

Navajo II was discovered five years later. It lay about 160 feet northwest of Navajo I, buried in soil formed by outwash from the neighboring ridge. An upright rock was found standing beside it.

FIG. 46. Navajo I. View of side opposite that shown in figure 45, showing another smaller fissure. About $\times 1/6$.

This supports the view expressed by Mr. Thomas that the meteorite had been known to the Navajos for decades prior to its find. Both masses, with the exception of a few small slices cut for study, are now on exhibition in this Museum.

SHAPE, SIZE, AND SURFACE CHARACTERISTICS

NAVAJO I.—Navajo I is roughly spheroidal in form, with an average diameter of 28 inches (figs. 45, 46). Its surface has suffered considerable oxidation and is of rust brown color, but, owing to the arid climate of the region, the oxidation has not penetrated deeply.

Pits of irregular form, which characterize the exterior, were formed at the time of the fall, and no marked differentiation of the pits, which might indicate orientation of the mass, can be observed. In general, the pits are from one to three inches broad and not more than a quarter of an inch deep. Some, however, are only about one-fourth of an inch in diameter and correspondingly shallow. Still less numerous, but more unusual in form, are pits as deep as, if not deeper than, their diameters. One such depression is one-half of an inch in diameter and three-fourths of an inch deep; others are not so deep, but are of about the same diameter. They suggest that a fusible constituent has melted out at these points. The surface of the meteorite, when found, was extensively coated with carbonate of lime, derived from the soil in which the mass was buried. Since its arrival at the Museum, much of this coating has been removed by dissolving it in acid, and, where it has been removed, the surface is black and smooth.

A peculiar feature of Navajo I is a deep fissure that extends half way around it, in some places reaching a depth of six inches. About three inches from this fissure and generally parallel to it, another extends for a distance of a little more than a foot. The edges and walls of the fissure are smooth and rounded, indicating that they were subjected to heat and erosion during the meteor's flight to the earth. They also indicate that the fissures were formed, not from the impact of the meteorite upon the earth, but from shock and air pressure after it reached the earth's atmosphere and prior to its fall. The finders of the meteorite stated that at the time of the find there were many loose fragments of the meteorite in the fissures. These fragments, with the exception of one, were dug out and carried away by souvenir hunters while negotiations for the purchase of the meteorite were in progress. The one fragment that was left had an irregular, finger-like shape and measured about two inches in length. Fragments such as these suggest that, unlike the fissures, the fractures were formed from the impact of the meteorite upon the rocky surface, and that considerable disintegration had taken place within them since the fall. Both the fissures and the fractures could have served as receptacles for the retention of water, which is an effective disintegrating and dissolving agent. Polished and etched slices of the meteorite reveal a number of veins of schreibersite of irregular width and varying course. In places these have decomposed to limonite, and, where the decomposition has advanced far enough, the slices are broken up into small pieces easily. It is not improbable that veins of schreibersite may have existed along the fissures, and

such a process of decomposition may have been in action, resulting in the formation of the fragments referred to above.

NAVAJO II.—Navajo II (fig. 47) is more elongated in form than Navajo I, its dimensions being 34 by 22 by 16 inches. Its surface is not fissured as is that of Navajo I, but the pittings on the two, even those that are of greater depth than width, are similar. Oxidation

FIG. 47. Navajo II. More elongated in form than Navajo I. It is evident that the two masses are individuals belonging to the same fall. About $\times 1/6$.

of the surface seems to have gone somewhat deeper than in Navajo I, and it had no coating of carbonate of lime.

CHEMICAL ANALYSIS

Samples for chemical analysis for both Navajo I and II were secured from an average of the borings obtained by a one-quarter-inch drill penetrating to a depth of two inches. During the drilling it was noticed that the first quarter-inch of the operation encountered much more resistance than the remainder. Moreover, the borings from this outer section were in the form of a powder, while beyond this point they were in the form of shavings. This would indicate that there had been a hardening or tempering of the surface of the meteorite due to the heat of the fall.

A total of five chemical analyses of the meteorite has been made, the earliest by Merrill (1922). Merrill, however, gave only the nickel content (5.81). The other four analyses were made in the Museum by H. W. Nichols and R. K. Wyant, using portions of the same samples. It will be seen from the following results of their analyses that the iron and nickel content are comparable, while there is some variation in the percentage of minor constituents.

	Analysis of Navajo I	Analysis of Navajo II
	H. W. NICHOLS, *Analyst*	
Element	*Percentage*	*Percentage*
Fe	93.60	93.24
Ni	5.43	5.56
Co	0.14	0.13
Cu	0.02	0.005
P	0.41	0.372
S	0.10	0.056
Si	0.14	0.042
Ins	0.14	.....
Total	99.98	99.405
	R. K. WYANT, *Analyst*	
Element	*Percentage*	*Percentage*
Fe	93.62	93.34
Ni	5.37	5.60
Co	0.41	0.47
Cu	0.02	0.01
P	0.28	0.30
S	0.15	0.08
Si	0.10	0.07
Cr	0.02	0.03
Total	99.97	99.90
Specific gravity	7.82	7.80

As seen by the above results the two masses have essentially the same composition, and this fact, taken in connection with the similarity of their etching figures, surface characters, and close association as to locality, makes it evident that they are individuals belonging to the same fall.

STRUCTURE AND CONSTITUENTS

Megascopic examination of etched surfaces of Navajo I was made by Farrington, the results of which, as found in his notes, are as follows: "These, to the naked eye, present only a dull gray, homogeneous appearance, at once classing the meteorite in the group of ataxites. Under a lens, a section, when examined in reflected

light, shows abundant shining needles of rhabdite, quite uniformly distributed. These are rarely more than 0.5 of a millimeter in length and grade from this down to microscopic dimensions. Nearly all lie in one direction, parallel to one another. Scattered here and there are rectangular inclusions of schreibersite which are distinguished

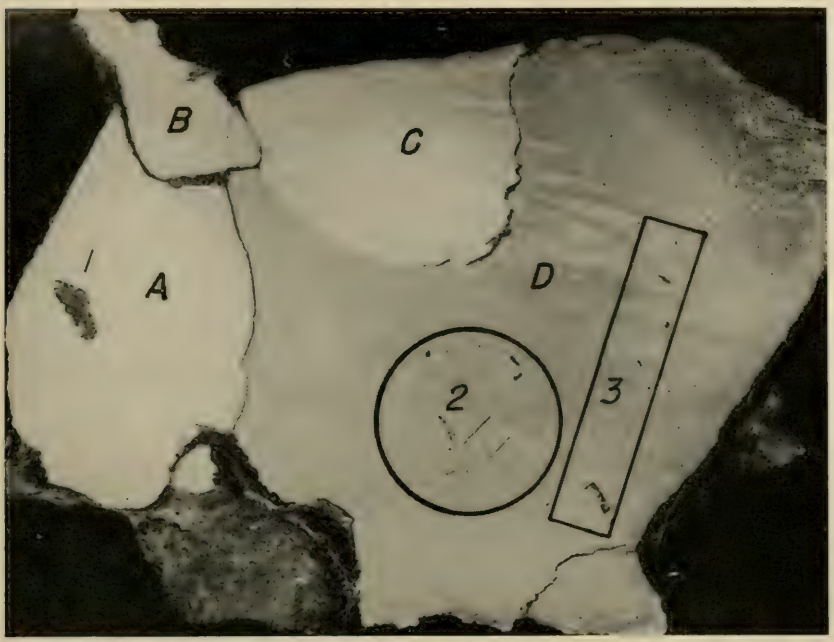

FIG. 48. An etched slice of Navajo II. Nital, 30 seconds. A, B, and C, brighter areas bounded by schreibersite veins. D, darker areas. 1, troilite inclusion bordered and traversed by schreibersite. 2 and 3, rhabdites with schreibersite inclusion. ×2.5.

by their form and larger size, some being 4 sq. mm. in area. These are for the most part near the periphery of the section. With a lens, too, some variations in color of the ground mass from light to dull-gray can be seen. Among the nickel-poor ataxites, to which, as can be seen later by reference to the analysis, this group belongs, the etched surfaces of the meteorite most resemble those of the Locust Grove."

Whether Farrington intended microscopic examination of the meteorite cannot be ascertained, but had he done so he doubtless would have observed additional features and perhaps would have modified some of the results he obtained. For reasons given later,

we have not studied the internal structures of Navajo I, but, based upon our studies of Navajo II, which is but a portion of Navajo I, we hardly can regard the Navajo meteorite as being of the same type as the Locust Grove. The chemical composition of the two does not differ appreciably, but structurally, according to Cohen (1897; 1905), the Locust Grove is granular, whereas the Navajo, as far as our studies show, is homogeneous. The size, form, and dispersion of the rhabdites and phosphide particles in the Locust Grove, as illustrated by Perry (1944), also differ conspicuously from those observed in the present meteorite. In addition, certain important structural features that characterize the Navajo meteorite are absent in the Locust Grove. These features are discussed later and illustrated by figures 50 and 51. The Museum has lent a slice of the Navajo I to Mr. Stuart H. Perry for metallographic studies. This is the same slice studied by Farrington and to which reference has already been made. Mr. Perry expects to publish the results of his work at an early date.

Of Navajo II, a broken-up, polished section consisting of several small pieces was available for study. Originally, the section measured 5 by 9 centimeters and weighed 150 grams. It is apparent that veins of schreibersite of irregular width and varying course traversed the section, and that the breaking up of the section into small pieces was the result of decomposition of these veins to limonite. One of the pieces, sufficiently large for study, was repolished and etched, using nital (5 per cent nitric acid) for periods ranging from a few seconds to five minutes (fig. 48).

It is well to point out here that for microscopic work the time of etching is highly important. Certain features that are visible in light etching may disappear or may not be visible in strong etching, and vice versa. No general rule, however, can be formulated regarding the time of etching required to observe a specific structure in a given meteorite. This is mainly because meteorites, even those that belong to the same group, may vary sufficiently in composition, structure, and relative hardness of their constituents to require different times of etching. An effective procedure to follow is to give a light etch to the specimen at first (for a second or less), gradually increasing the time and examining the specimen periodically between etchings. It will be found that light etching is almost imperative for work at high magnification, and that it is necessary to lower the magnification as the etching is made stronger.

The structure of the Navajo meteorite is that of a nickel-poor ataxite, consisting of a homogeneous mass of kamacite with an

abundance of schreibersite or nickel-iron phosphide, in the form of rhabdites and inclusions. Here the term rhabdite is used for only those forms of schreibersite that have needle-like structure; all others have been called inclusions, and, where necessary, their shape and size have been described. In addition, as referred to above, the section contains narrow, branching veins of schreibersite (fig. 48). The general appearance of the veins is that of a miniature stroke of lightning. The branches are not veins but cracks, barely visible to the

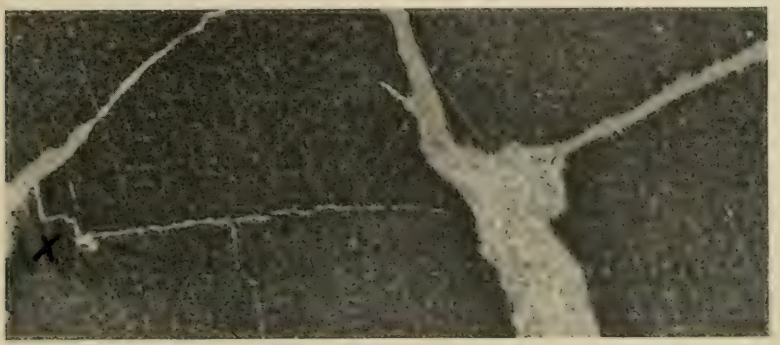

FIG. 49. Cracks at X leading from a schreibersite vein. The pattern is that of a cubic cleavage, characteristic of hexahedrites. ×15.

naked eye. They have a step-like pattern, resembling cleavage of galena (fig. 49). It may be that they are strain cracks that were formed later and that followed the original hexahedrite structure.

There are no traces of grain boundaries in the kamacite, except in one zone around a relatively large inclusion of troilite (fig. 54), but the surface of the kamacite that appears homogeneous under low magnification (×40) presents a feathery and mottled pattern when seen under high magnification (×320). The isolated nature of the grain boundaries indicates that they are remnants of previously established grains. The bulk of the schreibersite bodies is in the form of rhabdites and particles. The particles vary in shape from angular to irregularly rounded dots, and show little or no definite arrangement (figs. 50, 51). The form of the particles indicates diffusion, believed to be caused by reheating. The rhabdites or needles also vary in shape; some have wedge-like structure, but most of them are spindle-shaped (figs. 50, 52). They are arranged at right angles to one another, and appear, as it were, disposed along cubic planes. In the section examined, the needles occur mixed with the particles in three different areas, each of which is bounded by a schreibersite vein (fig. 48, A, B, C). These areas are silver-gray in

color and are visibly brighter than the remaining areas of the section, which are dull-gray (fig. 48, D) and, save for a few scattered diamond-shaped and rhombic schreibersite inclusions, occupied only by the irregularly rounded particles. The variation in color is due to the differences in the degree of surface reflection, the spindle-shaped

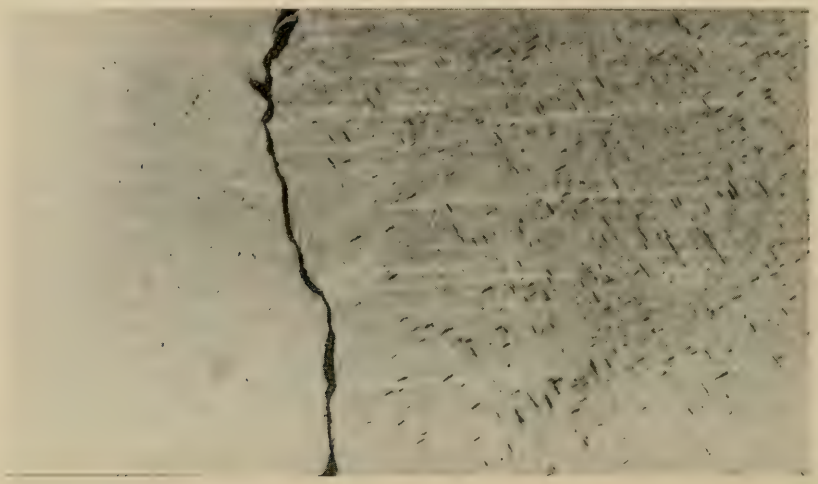

FIG. 50. Enlarged view of a portion of the areas C and D in figure 48. Left of the vein, irregularly rounded schreibersite particles with no definite arrangement. This area contains two sets of Neumann lines, but because of light etching they are barely visible. Right, spindle and wedge-shaped rhabdites oriented nearly at right angles to one another. One set of Neumann lines in this area. Neutral sodium picrate, 5 minutes. ×20.

rhabdites, because of their form and manner of dispersion, reflecting a greater amount of light. No satisfactory explanation, however, can be given here to account for the total absence of the spindle-shaped needles from the dull-gray area, which is separated from the other areas only by veins that are so narrow in places as to be hardly a millimeter wide. That the veins were a factor in causing the difference is suspected, but the processes leading to it are neither clear, nor understood. There are many examples in described meteorites of the occurrence of different-sized rhabdites, as well as gradations of rhabdites to flakes and particles of schreibersite, but so abrupt and conspicuous a change in form and orientation in such close proximity as is the case here, has not been reported. Nor are examples known of similar behavior of any mineral in terrestrial metamorphic rocks. There are good evidences of extra-terrestrial reheating of the meteorite and consequent metamorphism of some

of its constituents. The filling of the cracks with schreibersite to form veins, the presence of remnant grain boundaries, the alteration of kamacite bordering some of these veins, and the partial diffusion of the phosphide particles are all good indices of cosmic reheating.

Besides the two types of phosphide bodies discussed here, there are others, in the shape of slender, long needles, small squares,

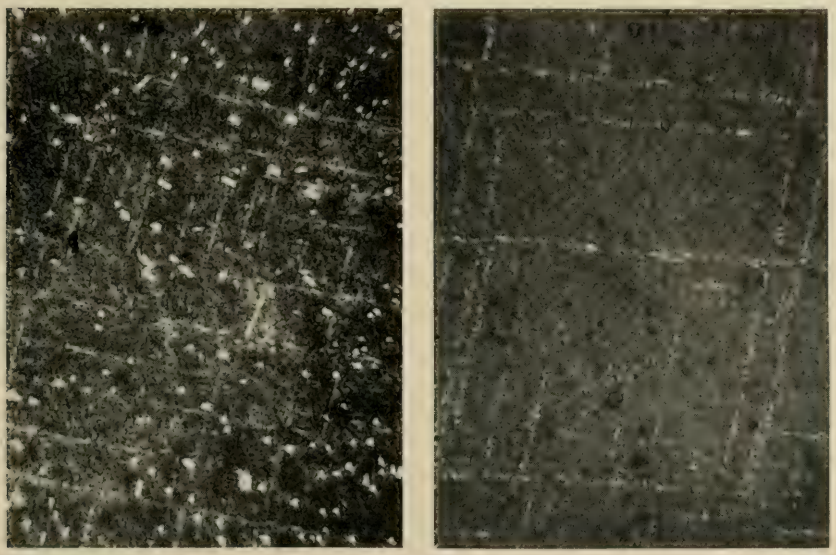

FIG. 51. Irregularly rounded schreibersite particles and lath-shaped bodies (area from figure 48, D) and two sets of Neumann lines. Left, diffusion of schreibersite particles at extreme upper left is apparent. Nital, 30 seconds. ×60. Right, area adjoining that shown to left but treated for 5 minutes with neutral sodium picrate. ×80.

rectangles and laths. These are scattered sparingly here and there without any definite arrangement except in one place, where a number of needles and squares are grouped together more or less radially (figs. 48–2; 54). It is useful to note here that the majority of these bodies are notched at one edge, giving the appearance of being corroded. Whether this is a primary or a secondary feature has not been determined. Of the other constituents, two troilite inclusions have been observed, one a mere dot, the other about 3.5 mm. long and 1.5 mm. wide (figs. 48–1; 54). The larger inclusion is bordered and in one place traversed by schreibersite. A third mineral in this inclusion, probably daubreelite, has been suspected but not confirmed. It is lighter in color than the other two but the grains are so minute and so intimately mixed that its isolation was

impractical. The color of the mineral, the presence of chromium in one of the analyses, and the fact that the meteorite is an ataxite, lend support to the possibility of its being daubreelite.

A most interesting feature of the meteorite is the presence of Neumann lines (figs. 50, 51). With the exception of Forsyth County,

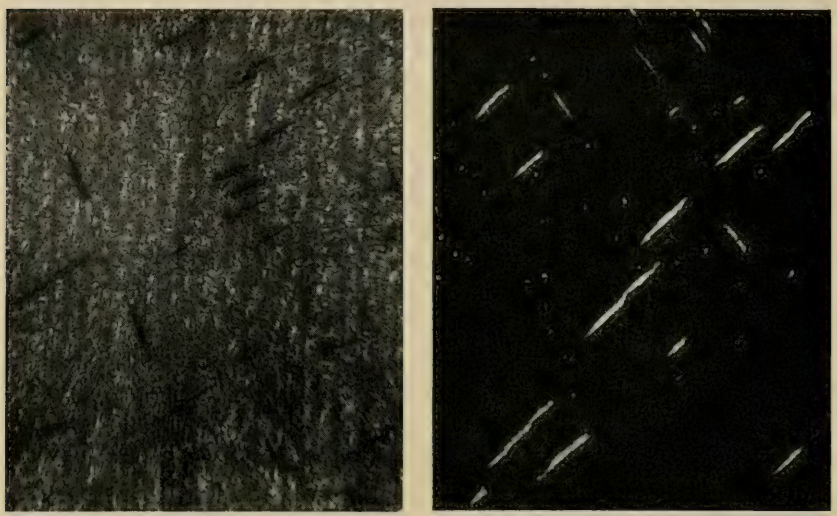

FIG. 52. Spindle- and wedge-shaped rhabdites (different areas from fig. 48, C). Both areas contain one set of Neumann lines (see fig. 50) that are not visible here. Left, treated with neutral sodium picrate, 5 minutes. Right, nital, 30 seconds. Print over-exposed to bring out schreibersite particles. ×180.

no other nickel-poor ataxite showing Neumann lines has, hitherto, been reported. Here again, as in the case of the two phosphide bodies, an abrupt change in the structure of the Neumann lines is manifest. In the areas (fig. 48, A, B, C) bounded by the schreibersite veins the Neumann lines consist of a single set. The lines are parallel and straight, but not always continuous, nor of uniform width, nor evenly spaced. In the remaining portion of the section (fig. 48, D), occupied only by the shapeless or irregularly rounded phosphide bodies, at least in the greater part of it, the Neumann lines consist of two sets of parallel lines—running diagonals of a cubic face. The lines in this area are also not of uniform width, nor are they evenly spaced.

It has been stated before that the meteorite has suffered cosmic reheating. On the basis of past laboratory experiments on the reaction of Neumann lines to heat, it can be assumed with reasonable

certainty that all pre-existing Neumann lines, if there had been any, were obliterated during reheating. The present Neumann lines, therefore, in all probability, were formed subsequent to reheating. The question now arises if they were formed before or after the meteor entered the earth's atmosphere. There is, of course, no proof that

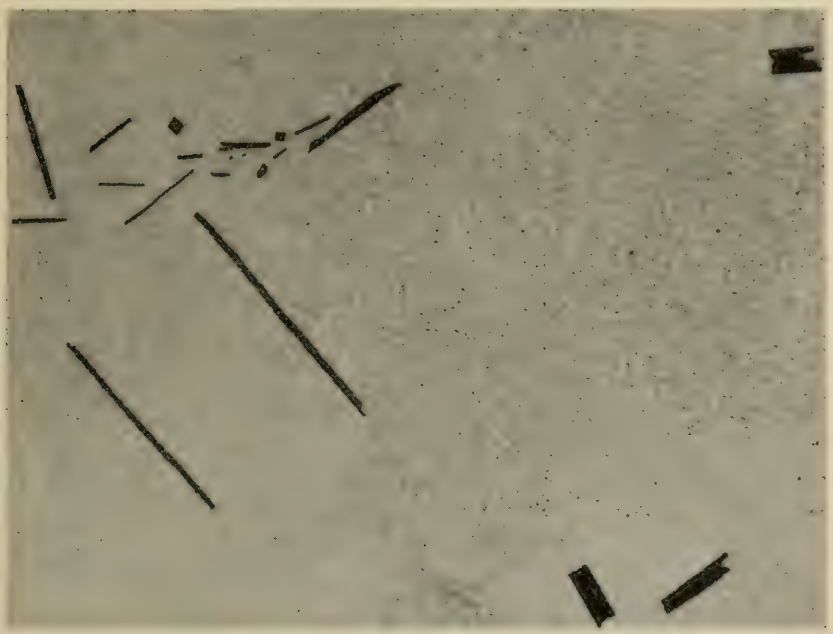

FIG. 53. Rhabdites and schreibersite inclusions of varying shape and size (area from fig. 48, D). Ends of many of these bodies are notched. Neutral sodium picrate, 5 minutes. ×19.

they were not formed cosmically subsequent to reheating. But there is good circumstantial evidence suggesting that they were formed during the meteor's flight to the earth. The meteorite was found in two masses, indicating that the original body was disrupted. Furthermore, one of the masses was deeply fissured. Both of these occurrences—the disruption and the production of deep fissures—are conclusive proof that the meteor during its flight encountered severe air pressure and resulting disruptive stresses. Since Neumann lines have been produced in the laboratory by subjecting artificial irons to violent shock and extensional stresses (Foley and Howell, 1923; Foley and Crawshaw, 1926), there would seem to be reason for supposing that the Neumann lines in the present meteorite were

formed after it entered the atmosphere and followed its course downward to the earth.

This meteorite, which has retained some of the characteristics of a hexahedrite, will serve as an additional example, and perhaps

FIG. 54. Troilite inclusion bordered and traversed by schreibersite. Remnant grain boundaries distinctly visible. Etched 30 seconds with 5 per cent nitric acid in alcohol. ×32.

a typical one, to substantiate the generally accepted belief that ataxites are metamorphosed hexahedrites.

The only other nickel-poor ataxite from Arizona, recently described by Henderson and Perry (1949), is the Pima County meteorite. It was believed to have been found in the vicinity of Tucson, Pima County, Arizona. Both Navajo and Pima County meteorites agree remarkably well in their iron and nickel content but the two can be distinguished readily by the differences in certain of their structural constituents, particularly in the nature and distribution

of the schreibersite bodies. Comparisons show that Navajo, like Pima County, is a distinct meteorite and can not, at present, be assigned to any known type among the nickel-poor ataxites.

REFERENCES

COHEN, E.
1897. Ueber ein neues Meteoreisen von Locust Grove, Henry Co., Nord-Carolina [Georgia]. Sitzber. Berlin Akad., pp. 76–81.
1905. Meteoriten Kunde. Heft 3, pp. 44–47.

FOLEY, F. B. and CRAWSHAW, J. E.
1926. Effect of Air Gap in Explosion System on Production of Neumann Bands. Trans. Amer. Inst. Min. and Metall. Eng., **73**, pp. 948–963.

FOLEY, F. B. and HOWELL, S. P.
1923. Neumann Bands as Evidence of Action of Explosives upon Metal. Trans. Amer. Inst. Min. and Metall. Eng., **68**, pp. 891–915.

HENDERSON, E. P. and PERRY, S. H.
1949. The Pima County (Arizona) Meteorite. Proc. U. S. Nat. Mus., **99**, (3241), pp. 353–355.

MERRILL, G. P.
1922. New Meteorites. Amer. Jour. Sci., ser. 5, **3**, p. 154.

PERRY, S. H.
1944. The Metallography of Meteoric Iron. Bull. U. S. Nat. Mus., **184**. For illustrations of Locust Grove see pls. 10, fig. 2; 65; and 66, figs. 1 and 2; for Forsyth County see pl. 8, fig. 4.

GEOLOGICAL SERIES
OF
FIELD MUSEUM OF NATURAL HISTORY

Volume VII | DECEMBER 22, 1950 | No. 9

THE SMITHONIA METEORITE

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SMITHONIA

Smithonia, Oglethorpe County, Georgia, United States of America.
Latitude 34° N., Longitude 88° 11′ W.
Iron, nickel-poor ataxite (D_2).
Found April, 1940.
Weight 69.85 kilograms (154 pounds).
Catalogue number, Me 2380.

The Smithonia meteorite was secured by purchase from Mr. Corbett Simmons, of Elberton, Georgia. Negotiations for the purchase began in November, 1941, but no settlement was arrived at until September, 1942. During the interval, Mr. Simmons apparently corresponded with others interested in the meteorite.

Referring to the meteorite (Popular Astronomy, **55**, p. 102, 1947), Dr. Frederick C. Leonard, University of California, states: "The place of find was 23° south of west of Elberton, Elbert County, and 23 miles thence in an airline. Presumably the nearest post office being Smithonia, Oglethorpe Co., the name of that town has been given to the meteorite. From the foregoing specification of the place of find, it follows that the coordinate number of the siderite is 0832,340 (Lat. 34° N., Long. 83° 11′ W.)."

Nothing is known about the circumstances of the fall of the meteorite, and all that is known of its history is contained in the following brief account sent to the Museum by Mr. Simmons: "This meteorite fell in Oglethorpe County about 15 miles from Athens, Georgia, at a little place called Smithonia. It was found on what used to be the Jim Smith plantation. At the time of its

FIG. 55. The Smithonia meteorite. The surface is covered with shale or platy oxides. $\times \frac{1}{3}$.

find the land belonged to Mr. Benton. I secured the meteorite from Mr. Benton. It was found at the foot of a hill on the north side, stuck in the ground a little bit. It was reported that one fell over here about six years ago. This one was found in the spring of 1940, about April. The first piece [sample for examination] I sent

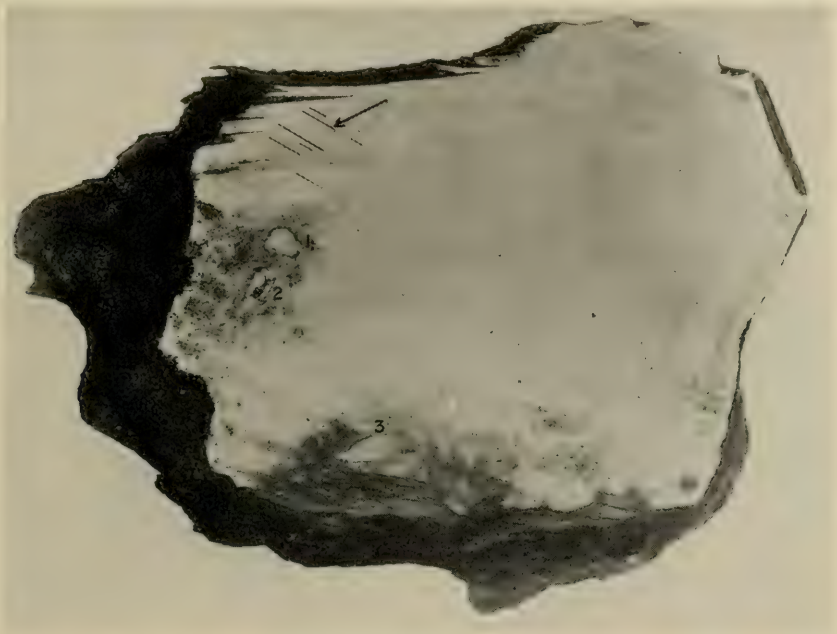

FIG. 56. A polished slice of Smithonia, showing layered structure (upper left). Rhombic pattern (arrow), where two sets of layered plates have intersected, may also be observed. The three (numbered) irregularly rounded bodies are troilite nodules. About $\times 7/10$.

was a piece of the veneering [shale, or platy oxides]. How long would it take to decay that much?" When received at the Museum the meteorite had a thick cover of shale, which would indicate that weathering had progressed for a longer period than six years.

The original crust of the meteorite is nowhere visible, and, as has been mentioned before, the present surface is covered with platy oxides, some of which are rhomboidal in outline. The meteorite is layered and thin plates with perfectly smooth surfaces may be split off. In places where two sets of layered plates have intersected, rhombic pattern is manifest (fig. 56). The layered structure is also responsible for the rapid oxidation of the meteorite.

The shape of the meteorite, as it appears now, is roughly that of a flattened elongated cone (fig. 55). The original shape cannot be reconstructed, chiefly because weathering has progressed unevenly. At one end, however, where it has progressed the least, outlines of

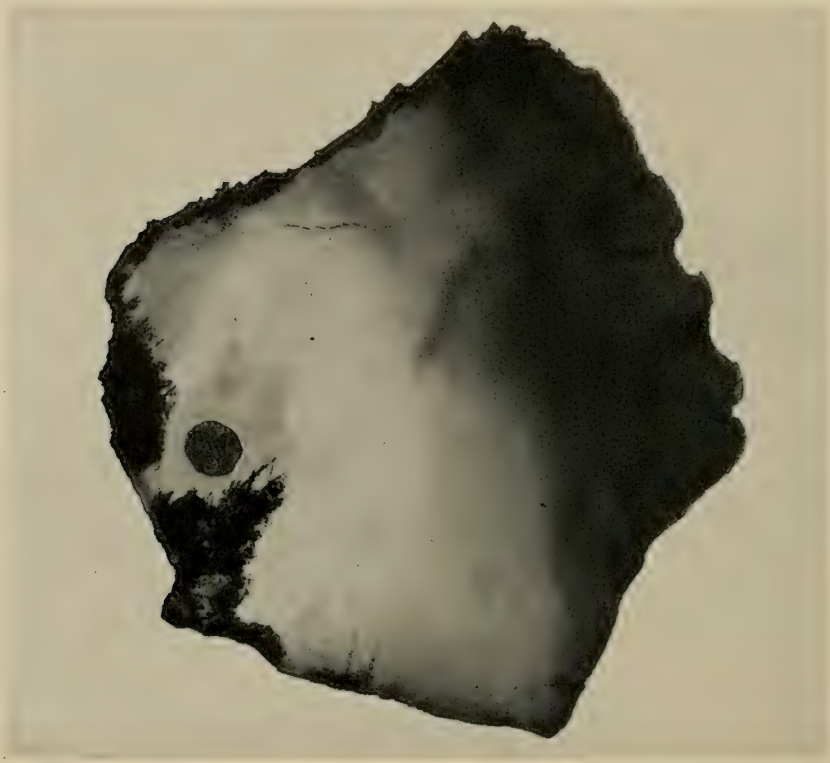

FIG. 57. Etched section with a rounded nodule of troilite, which is partially surrounded by schreibersite. No rhabdites have been observed in this section. About $\times 8/10$.

characteristic pittings are discernible, except that the ridges between the pits have lost their angularities and have become rounded, making the pits appear much shallower than they originally were.

The meteorite weighed 69.85 kilograms (154 pounds) when it was received at the Museum. Since then there has been a substantial reduction in weight, for weathering has caused natural shaling; also, sections have been made for study and exchange purposes. The present weight of the main mass, which has been coated with vinyl-seal as a safeguard against further disintegration, is 65.998 kilograms

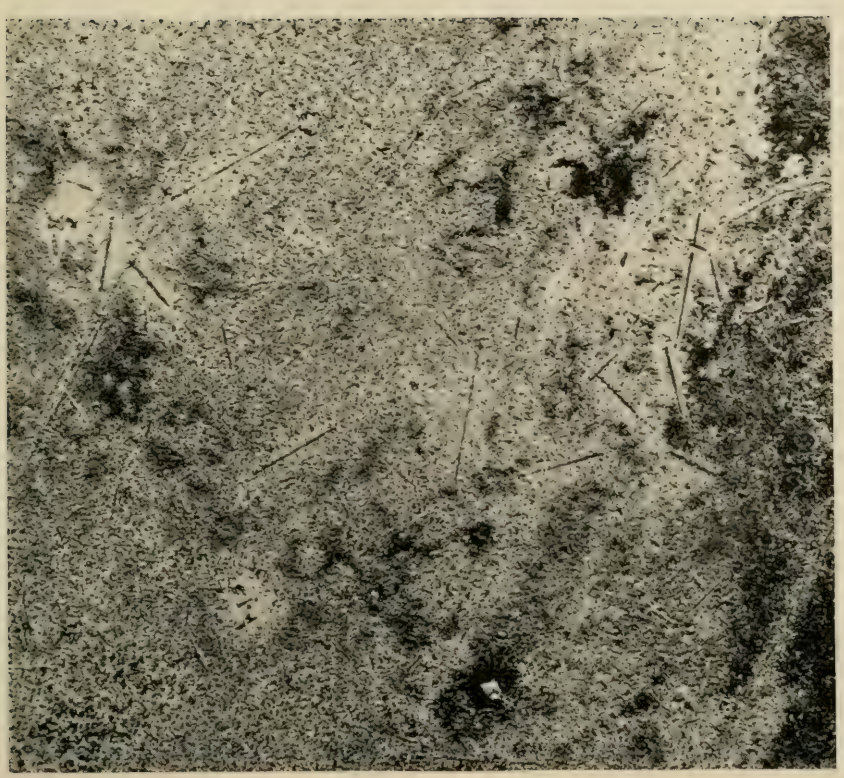

FIG. 58. Undiffused scattered rhabdites seen in an etched section of Smithonia. About × 9.

(145.5 pounds). The original maximum dimensions of the meteorite were 20 x 11 x 7½ inches.

CHEMICAL ANALYSIS

ROBERT K. WYANT, *Analyst*

Element	*Percentage*
Iron	93.42
Nickel	5.58
Cobalt	0.60
Copper	0.03
Phosphorus	0.20
Manganese	none
Chromium	0.04
Carbon	0.01
Sulphur	0.10
Chlorine	trace
Total	99.98
Specific gravity	7.76

Microchemical tests for platinum and tin were negative.

STRUCTURE AND CONSTITUENTS

Except for certain inclusions, little or no structural features can be seen in either the micro- or the macro-etched surface of the sections examined. Under the microscope, the kamacite is homogeneous. There is no trace of grain boundaries but the surface is dotted with numerous minute pits. Some of these are apparently etching pits; others may have contained schreibersite particles that were pulled out during grinding and polishing operations.

Of the accessory minerals, nodules of troilite (figs. 56, 57) and rhabdites (fig. 58) are present. Some of the nodules are partly or wholly surrounded by schreibersite, and some contain inclusions of the same mineral. The rhabdites are scattered sparingly and are clear-cut, showing no signs of diffusion.

In the absence of characteristic structural features of a hexahedrite such as cubic cleavage and Neumann lines, the present meteorite has been classed as a nickel-poor ataxite. It appears that there is no clear line of demarcation between hexahedrites and ataxites, so that exact classification is difficult unless the structural features are clear-cut.

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Volume VII | DECEMBER 22, 1950 | No. 10

THE LA PORTE METEORITE

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LA PORTE

La Porte, La Porte County, Indiana, United States of America.
Latitude 41° 36′ N., Longitude 86° 43′ W.
Iron, medium-course octahedrite (OM).
Found about 1900.
Total weight before cutting, 14,555 grams (32 pounds).
Catalogue numbers, Me 2271 (end piece); Me 2269 (slice); Me 2343 (slice).

The La Porte meteorite (fig. 59) was brought to William N. Rumely's farm supply store at La Porte, Indiana, by a farmer customer who found it on his farm about 1900. The name of the farmer and the location of his farm are unknown, but as the farm was within trading distance of La Porte, it is thought that the meteorite was found somewhere within a radius of twenty-five miles of that town. The meteorite remained in possession of Mr. Rumely until his death. It was then presented to Field Museum by his estate on March 24, 1937. At that time it was thought that the meteorite might have been transported in some way and that it might be a portion of the Kokomo meteorite. The latter was found in Kokomo, Howard County, Indiana, which is about ninety miles southwest of La Porte and near to the place where the present meteorite was found. The Kokomo meteorite, however, is a nickel-rich ataxite; La Porte is a medium-course octahedrite. So there is no possibility of their being individuals belonging to the same fall.

When received, the meteorite weighed 14,555 grams (32 pounds). It had been drilled in two places, apparently to obtain a sample

for chemical analysis. The result of this analysis, if any was made, has not been published, nor is it known. Since then, three analyses have been made at the Museum and one end of the meteorite was sawed to procure two slices, weighing 813 and 973 grams each. The

FIG. 59. The La Porte meteorite. The flat base is due to sawing to procure sections. ×¼.

latter slice, which now weighs 779.5 grams, was recut to provide a sample for analysis and a piece weighing 94.5 grams for exchange. The end piece weighs 10,037 grams (22.13 pounds).

CHEMICAL ANALYSES

Three quantitative analyses of this meteorite have been made since 1937 as follows:

I. H. W. NICHOLS, *Analyst* (1937; *Preliminary Analysis*)

Element	*Percentage*
Fe	91.06
Ni	8.02
Co	0.75
Cu	0.007
Si	0.03
P	0.12
S	0.11
Total	100.10

II. HENRY HERPERS, *Analyst* (1939)

Element	*Percentage*
Fe	92.05
Ni	7.31
Co	0.263
Cu	0.02
P	0.172
S	0.025
C	0.193
Si	0.04
Total	100.07

A. Iron was determined on three samples, and the above percentage is the average of the three.

B. Nickel was determined on two samples, and the above percentage is the average of the two.

C. Microchemical tests indicate the presence of tin and the absence of chromium, chlorine, manganese, and platinum(?).

III. ROBERT K. WYANT, *Analyst* (1949)

Element	*Percentage*
Fe	91.92
Ni	7.29
Co	0.36
Cu	0.01
P	0.13
S	0.10
C	0.15
Si	0.00
Total	99.96
Specific gravity	7.51

A. One sample was used.

B. Microchemical tests indicate the presence of traces of tin and manganese, with chromium, chlorine, and platinum absent.

STRUCTURE AND CONSTITUENTS

The meteorite is a shapeless mass (fig. 59), which indicates that it was broken shortly before reaching the earth and that there was not sufficient time for it to have undergone atmospheric shaping. At one end it is roughly rhomboidal in cross section (fig. 60). The pittings on the sides near this end are large and shallow, the maximum diameter and depth being 55 mm. and 10 mm., respectively. The opposite end is somewhat protruded at one point and the surface adjacent to it is deeply excavated and marked by small pittings

with little or no regularity. Neither the shape nor the pittings provide adequate data to determine the front or the rear of the meteorite.

The crust is thin, averaging barely one-half millimeter in thickness. Its surface is rough, in places shaggy, and scaly from oxida-

FIG. 60. An etched section of the La Porte meteorite. Some of the bands are parallel to a cubic face, others follow the line of an octahedron. ×¾.

tion. It is dark brown in color, with patches of limonite and a few green spots of ferrous chloride.

The zone of alteration is about three-fourths of a millimeter in width and is visible on the unetched polished surface of the end piece. It is indistinct on the etched section, chiefly because the figures have crossed over the altered zone without any marked change.

As has been stated, two slices were cut from the meteorite and both were polished and etched. Roberholdt's method, except for less concentration of acid, was used for etching. Reaction was slow, for nearly twenty minutes were required to bring out the desired effect. The figures observed (figs. 60, 61) show that the meteorite is a medium-course octahedrite, the kamacite bands varying in

FIG. 61. Another etched section. The arrangement of the bands is the same as that seen in figure 60. ×¾.

width between 0.05 and 2 mm. A few exceed 2 mm., which is to be expected in an octahedrite transitory between two classes.

No grain boundaries in the kamacite bands have been observed (fig. 62) but certain markings resembling hatchings are present. These may be scratch marks and some certainly are; others may

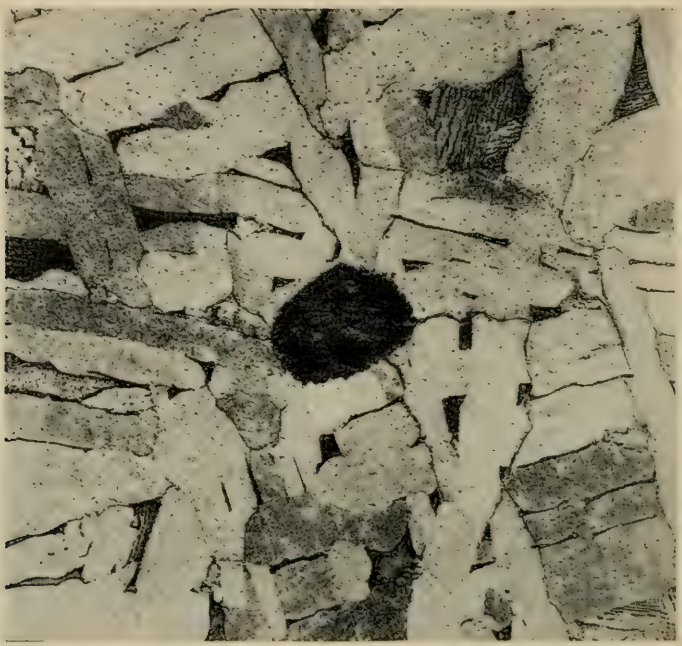

FIG. 62. Enlarged kamacite bands showing no grain boundaries. At the center is a troilite nodule. ×7.

be true hatchings. The bands also contain numerous microscopic pustule-like bodies as well as pits, but the nature of these has not been determined. The former may be the result of differential action of the acid; the latter are probably etching pits.

Taenite lamellae bounding the kamacite bands are typical, either straight, wavy, or irregular, and except for a few dark spots enclosed by taenite lamellae, known as "flecking" (fig. 63), no other special feature of the taenite component has been observed.

Both normal and dense plessite fields (figs. 64, 65) are numerous, and there is little deviation from the usual in the character and disposition of either the kamacite or the taenite lamellae in these fields. Taenite lamellae with thickened ends are relatively rare.

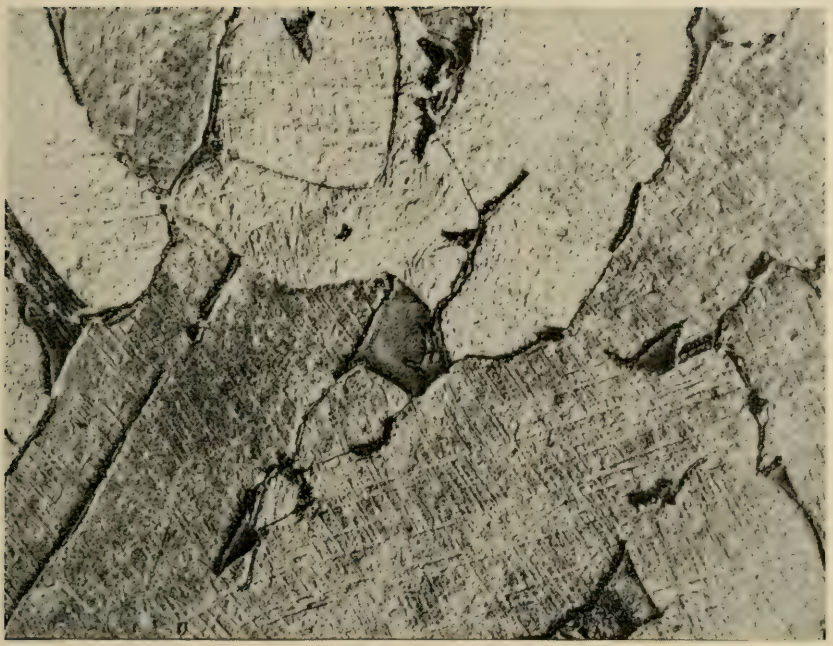

FIG. 63. Enlarged figures showing "flecking" or dark spots enclosed by taenite lamellae. ×10.

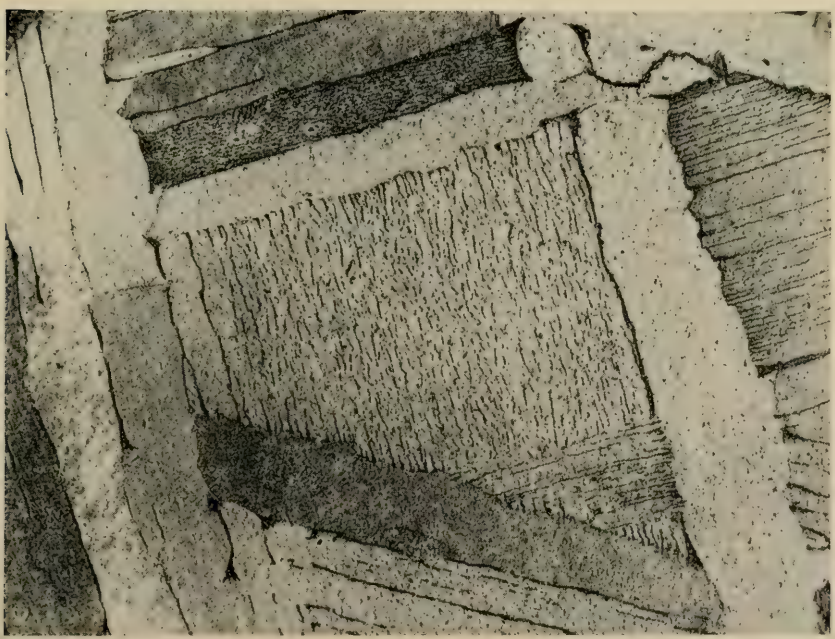

FIG. 64. Enlarged figures. At the center is a typical light plessite field. ×7.

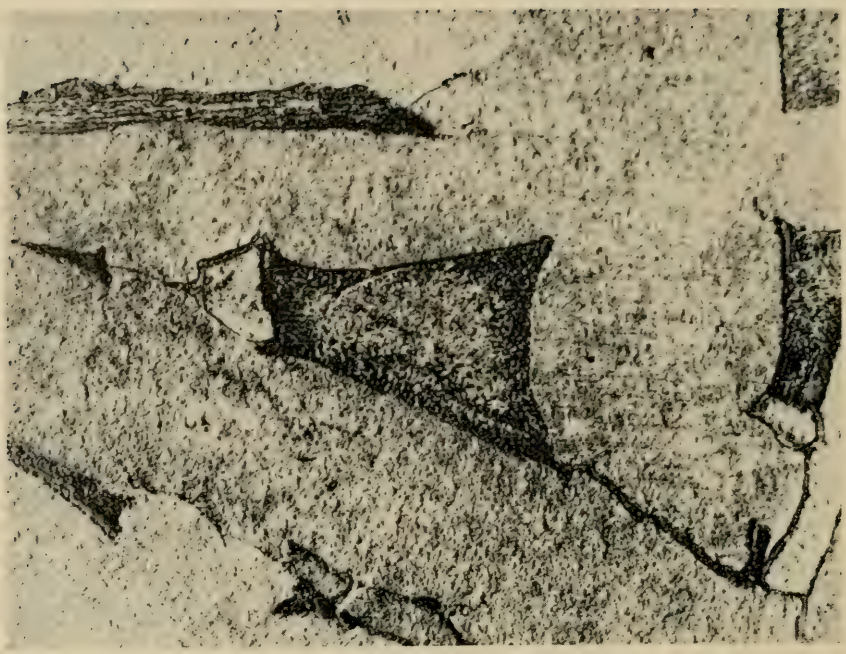

FIG. 65. Typical dark plessite fields. ×15.

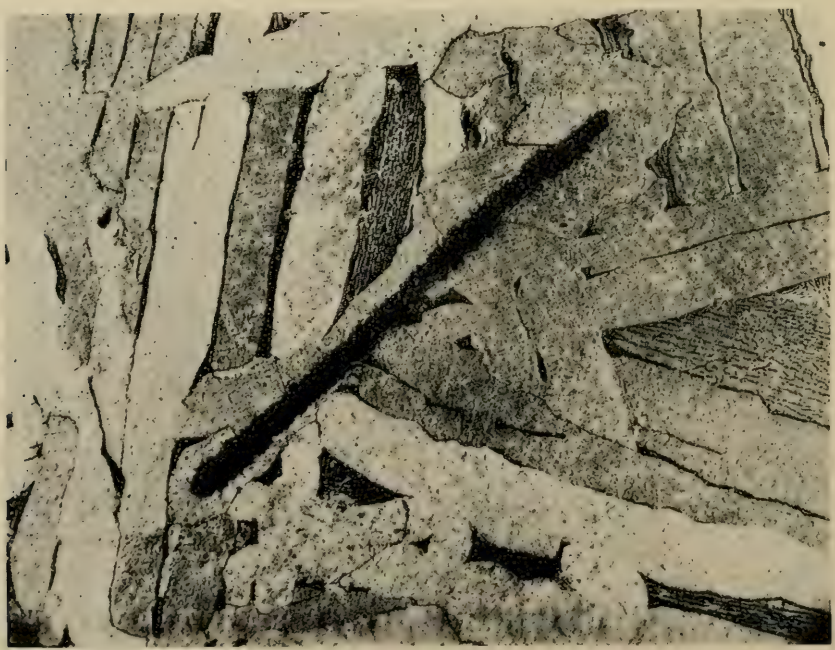

FIG. 66. Enlarged view of an elongated plate-like troilite with serrated edges. ×6.

Most of the fields are four-sided—cubical, rhombic, trapezohedral, or irregularly outlined—and they far outnumber the triangular ones. One reason for this is that the meteorite is cubo-octahedral in structure. Besides possessing octahedral structure, it has bands that run parallel to a cubic face. Modified octahedrites such as

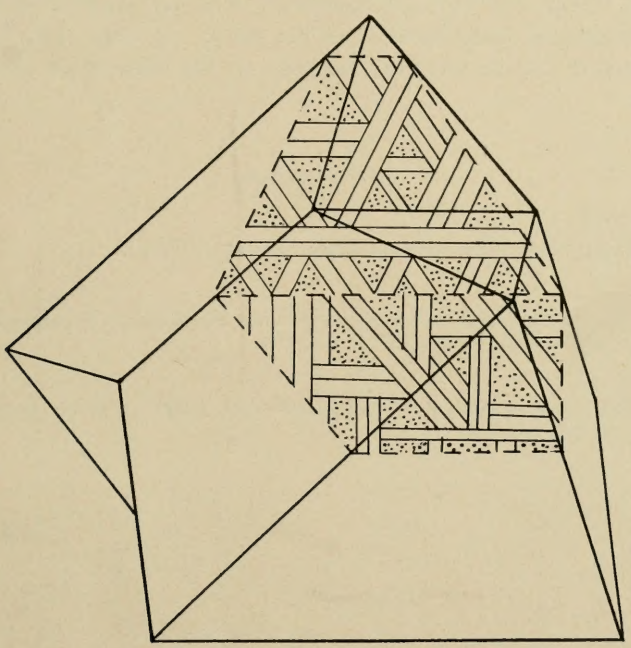

FIG. 67. Diagrammatic perspective illustrating Widmanstätten figures on a section of a spinel twin.

this one have been termed tesseral-octahedrites by Rinne (1910, pp. 115–117). He cites the figures in a section from the Gibeon shower of meteoritic irons (Bethany) as an example. Farrington (1915, p. 95) anglicized the term to tesselated octahedrite. More recently, Spencer (1941, p. 28) proposed the name cubo-octahedrite, which appears to be self-explanatory and more appropriate. This type of structure is thought to result from twinning according to the spinel law. A schematic diagram shown above (fig. 67) may serve to visualize the planes of the structural components. The figure is similar to one shown by Spencer (1941, fig. 7, p. 31) except that the graphic orientation of the spinel twin is changed.

Of the accessory minerals, rhabdites and nodules of troilites are present. Most of the nodules of troilite are visible to the naked eye

and are bounded partly or wholly by swathing kamacite (figs. 60–62). All occur in irregular rounded forms except one, which has an elongated plate-like form with serrated edges (fig. 66), similar to those figured by Rinne (1910, pl. 15, fig. 2). It is about 1.5 mm. in thickness and 13 mm. in length. Since only one such strip has been observed in the two sections examined, it is not possible to say if it has a structural arrangement of its own. It does not, however, follow any of the structural patterns of the figures of the etched section.

REFERENCES

FARRINGTON, O. C.

1915. Meteorites. The Lakeside Press, Chicago, Illinois.

RINNE, F.

1910. Ein Meteoreisen mit Oktaeder- und Würfelbau (Tessera-Oktaedrit). Neues Jahrb. Min., **1**, pp. 115–117, 2 pls.

SPENCER, L. J.

1941. The Gibeon shower of meteoritic irons in South-West Africa. Min. Mag., **26**, No. 173.