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Washington 25, D. C.

METEORITES AND BALLISTICS

By

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Principal Investigator: John S. Rinehart

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ABSTRACT

A meteorite enters the earth's atmosphere at high velocity (11 km/sec to 72 km/sec), is subjected to powerful aerodynamic forces, suffers rapid loss of material through aerodynamic heating and abrasion, but occasionally survives passage and finally may strike the ground, producing an impact crater. The phenomena involved in these encounters of a meteorite with our atmosphere and our lithosphere are ones commonly met with in ballistic studies. For example, the surface features of a number of aerodynamically sculptured meteorites are germane to the complex ballistics problem of ablation of high velocity missiles. Meteorites striking the earth have produced the largest known impact craters and contribute significantly to the physics and chemistry of high speed impact. This paper discusses our recent studies in the inter-related areas, meteoritics, ballistics, and astroballistics, with specific reference to ablation fundamentals, the shapes and surface features of various meteorites, and the nature of impact craters.

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Introduction

This conference is concerned mainly with man's efforts to project missiles at high velocities and to study their flights and impacts. Mother Nature has been in the ballistics business a long time - even longer than Professor Cranz - and this paper is about her missiles and their vagaries. Meteoritics as a recognized science is comparatively young (Brown, 1953). It was not until 1803, when a spectacular fall of stones occurred at l'Aigle, France, that scientists in general and the staid French Academy in particular were forced to admit officially that stones can, in fact, fall from heaven.

Extraterrestrial material of three classes reaches the earth. The most abundant by far is interplanetary dust, the dust from which the zodiacal light (van de Hulst, 1947; Fessenkov, 1951) stems and which very likely is a combination of cometary and asteroidal wastage. The intensely luminous trail of a meteor streaking through our atmosphere is the visible evidence of cometary extraterrestrial material. Occasionally a large chunk of asteroidal material will fall, generating a brilliant fireball. The luminous phenomenon itself is called a meteor and the body that generates the phenomenon is designated a meteoroid. Much uncertainty exists as to the precise physical properties of meteoroids. The consensus is that most meteoroids are fragile, porous bodies of low gross density (Whipple, 1952). Finally, there are the meteorites, ponderable masses of stone and iron, fragments of planets that once resided between Mars and Jupiter in our solar system.

The velocity with which a meteorite can enter our atmosphere is much higher than laboratory-obtained velocities, ranging from 11 km/sec to 72 km/sec (Lovell, 1954; Olivier, 1925). The lower limit is the escape velocity of a body from the earth, i.e., the velocity that a meteorite would acquire in falling toward the earth under gravitational attraction, should the earth and the meteorite suddenly find themselves beside one another with zero relative velocity. The upper limit is imposed by the fact that meteorites are members of the solar system and therefore can not have a velocity greater than 42 km/sec when their distance from the sun is that of the earth. The earth's velocity about the sun is 30 km/sec. Most meteorites (Whipple and Hughes, 1955) enter the earth's atmosphere with velocities in the neighborhood of 17 km/sec. The velocities of cometary meteoroids cover the complete range from 11 km/sec to 72 km/sec. The zodiacal dust will enter the atmosphere with the same velocities, 11 km/sec to 72 km/sec, but will be quickly decelerated and then drift slowly toward the earth.

How many meteoric bodies are there and how are they distributed in time and space? If one goes out on an average clear night to look for meteors he will see about 10 per hour. The fall of a meteorite, on the other hand, is a relatively rare event but frequently a spectacular one (see Fig. 1). It is estimated that only about five per day reach the earth's surface, with an average recovered mass per fall of 20 kilograms. It is extraordinarily difficult to form a realistic idea of the total amount of meteoric material reaching the earth. The estimates given in Table 1 (Watson, 1956) seem to be about as good as we have. Space dust is by far the largest contributor. The earth must intercept large amounts of the zodiacal dust, perhaps as much as one particle per cubic meter, on the average.

Studies of a meteorite's flight through our atmosphere and its subsequent interaction with our lithosphere, as well as the interaction of meteorites with objects in space, lie in the inter-related areas of meteoritics, ballistics, and astroballistics (Thomas and Whipple, 1951a; 1951b). The present paper will discuss recent studies with specific reference to ablation fundamentals, the shapes and surface features of various meteorites, and the nature of impact craters.

General Aspects of Meteorites

Meteorites are designated in either of two ways, as falls or finds, and are given the name of the post office closest to which they are found (Nininger, 1952). As falls, they are actually seen in the act of falling and observers are able to recover them shortly thereafter. If meteorites are stumbled upon *in situ*, recognized for what they are, and saved, they are designated as finds. The total number of falls and finds represented in our museums is listed in Table 2. A particular

Table 1. Daily rate of meteoritic infall

Type	Mass accumulated daily (tons)
Crater-producing and other meteorites	< 1
Fireballs Visual meteors Faint radio meteors Telescopic meteors	1-10
Very faint telescopic meteors Micrometeorites Interplanetary dust	1,000-10,000

fall or find may comprise a number of individual meteorites, sometimes as many as 20,000.

Meteorites range in size from the Hoba West, a 70-ton massive chunk of nickel-iron, which has never been moved from its final resting place in South Africa, to stones the size of peppercorns obtained from showers such as that at Holbrook, Arizona (see Foote, 1912; Merrill, 1912; Rinehart, 1956; Prior and Hey, 1953; Merrill and Foshag, 1943; Krinov, 1955).

The varying shapes of recovered meteorites testify to the rigors of their passage through the atmosphere and the nature of impact. Many freshly fallen irons and stones show evidence of intense sculpturing by the air. There may be gross breakup of the meteorite during flight, or deformation and breakup on impact.

Meteorites are divided into three general groups on the basis of their structure and composition. The irons are dense metallic masses composed principally of nickel and iron, but contain as minor phases, phosphides, sulfides, graphite, etc. (Perry, 1944). The most notable inclusions are diamonds, and the most abundant are large nodules of iron sulfide. The irons have complex structures but they are obviously the descendants, remnants, and in some cases aggregates of large single crystals of nickel-iron (Fig. 2). Those containing 6 to 12 percent nickel are characterized by their Widmanstätten pattern, shown in Fig. 3,

Table 2. Number of falls and finds

Meteorites	Falls	Finds	Total
Iron	42	503	545
Stony-iron	12	55	67
Stones	628	304	932
Total	682	862	1544

a unique and fascinating metallurgical curiosity, exhibiting straight intersecting bands which are parallel to the faces of an octahedron. The bands consist of wide patches of kamacite (nickel-poor iron, body-centered cubic crystal lattice) bounded by thin layers of **taenite** (nickel-rich iron, face-centered cubic lattice). Their genesis lies in the extremely slow cooling rates through the temperature ranges of solidification and transformation. Irons are subject to weathering after they reach the ground; they oxidize and corrode slowly, flaking away with time.

Stony meteorites, the second group, have an extremely complex structure which appears microscopically as a mixture of fragmented crystals that are not easily identifiable but whose main constituent is silica (SiO_2) (see Fig. 4).

Every freshly fallen stone is coated with a thin black layer, about 1/16 inch of vitreous material which has undoubtedly been fused during flight (see Fig. 5).

The meteorites of the third group are made up of approximately equal amounts of stone and iron: in some cases they are sponge-like iron masses with stony material filling the interstices, and in others, iron particles embedded in a matrix of stone. A fourth type, the tektite, which is a glass-like mass, may or may not be of extraterrestrial origin and will not be discussed further here (see, however, Fenner, 1935; Barnes, 1940; and Friedman, Kohman, and Cassidy, 1958).

Phenomena Attending Flight

The flight of a meteorite through our atmosphere is a spectacular ballistic event fraught with intense visual and aural impressions that are reminiscent of a multitude of ballistics problems. Two swarms of large meteorites have fallen in recently recorded history. Both were in Russia. The Tunguska fall of 1907 levelled trees over an area of a 30-mile radius and produced barometric effects that were detected around the world (Krinov, 1955; Watson, 1956). The Sikhote-Alin fall in 1947 sprayed chunks of meteoritic iron in an ellipse covering many square kilometers, and produced some 128 craters (Fessenkov, 1951; Krinov and Fonton, 1952; 1954).

An eyewitness account of the l'Aigle fall of stony meteorites in 1803 is quite typical (Biot, 1803): "On Tuesday, April 26, 1802, [sic] about one in the afternoon, the weather being serene, there was observed from Caen, Pont-Audenen, and the environs of Alençon, Falaise, and Verneuil, a fiery globe of a very brilliant splendour, which moved in the atmosphere with great rapidity. Some moments after there was heard at Laigle, and in the environs of that city to the extent of more than thirty leagues in every direction, a violent explosion, which lasted five or six minutes. At first there were three or four reports like those of a cannon, followed by a kind of discharge which resembled a firing of musketry; after which there was heard a dreadful rumbling like the beating of a drum...a multitude of mineral masses...were seen to fall... The district in which the stones fell forms an elliptical extent of about two leagues and a half in length and nearly one in breadth, the greatest dimension being in a direction from south-east to north-west.. The largest of these stones fell at the southeast extremity of the large axis of the ellipse; the middle-sized ones fell in the center, and the smallest at the other extremity... The largest of all those which fell weighs 17 1/2 pounds. The smallest I saw weigh about 2 gros, which is the thousandth part of the former. The number that fell is certainly about two or three thousand." (See Fig. 6)

From the number of shock-waves or "explosions" felt by the observer in this particular fall, the meteorite must have broken into four large pieces on striking dense atmosphere at low levels. Breakup is the usual fate, particularly of a stony meteorite (Merrill, 1912). Meteorites are fragile bodies in the sense that they are rife with weakly bonded aggregates of large crystals, large fragile inclusions, faults, and cracks. The pressure p on the nose, tending to crush the meteorites, is given by

$$p \propto \rho v^2$$

where ρ is the ambient air density and v the velocity. In Fig. 7 log ρ has been plotted against log v for a large number of meteorites which have been observed to break up (v. Niessl and Hoffmeister, 1925). Note that there appears to be little if any correlation between log ρ and log v. A straight line would indicate a constant breaking strength. Therefore meteorites apparently do not break up when the air pressure reaches some value which might be thought of as the crushing strength of a meteorite.

The dense, persistent trail is also typical of a fall. The trail is partially vapor, but mainly a column of debris removed or ablated from the surface of the meteorite by the intense heating and violent scouring action of the air. And here we come to the most elusive of all ballistics problems: the ablation of a high velocity missile.

Ablation Effects

Ablation of a high velocity missile is an exceedingly complex ballistics problem, involving a wide diversity of disciplines (Thomas and Whipple, 1951b; Thomas, 1956). The occasional ablated meteorite which is recovered can, through post mortem examination of its morphology, suggest salient aspects important to the solution of the problem (Nininger, 1936a; Rinehart, 1957a; 1957b; Farrington, 1915).

First consider the profiles or contours that are characteristic of groups of meteorites. Six typical profiles are shown in Fig. 8. Most ablated meteorites are axially symmetrical. The Grant, New Mexico, meteorite with its evident conical shape is typical of perhaps a dozen large irons. The cone angle usually lies between 80 and 100 degrees. Note particularly the pronounced concavity of the front ablated surface. Several similar meteorites are listed in Table 3.

The Cabin Creek iron is flat or discus shape, a shape characteristic of another group of smaller iron meteorites listed in Table 4. These meteorites were clearly oriented broadside to the air stream during much of their flight.

There are several medium sized chunky irons, weighing 10 to 20 kilograms, on which abrading action is evident but which has not been so severe as to remove completely the angularity of the specimen. Examples are given in Table 5.

Several small irons, listed in Table 6, resemble a pear or foot in shape. It is not entirely clear whether the pear shape resulted from ablation or whether the meteorite existed in this form before its entrance into our atmosphere. Such meteorites, however, exhibit internal evidence of intense surface heating.

Other meteorites of special interest to be discussed later are listed in Table 7.

Table 3. Large conical iron meteorites

Name and Location	Weight kg	Location of Meteorite	Reference
Grant, New Mexico	480	U. S. Nat'l. Museum, Washington, D.C.	Henderson, 1934
Charcas, Mexico	780	Museum d'Hist. Nat'l. Paris	Daubree, 1867
Hraschina, Yugoslavia	301	National History Museum, Vienna	von Haidinger, 1859
Tamentit, Morocco	510	Museum d'Hist. Nat'l. Paris	Lacroix, 1927
La Caille, France	625	Museum d'Hist. Nat'l. Paris	Daubree, 1867
Quinn Canyon, Nevada	1450	Field Museum Nat'l. History, Chicago	Farrington, 1910
Goose Lake, California	1169	U. S. Nat'l. Museum Washington, D.C.	Henderson and Perry, 1958
Murnpeowie, Australia	1145	Sch. Mines and Indust. Mus., Adelaide	Spencer, 1935
Willamette, Oregon	12,247	Amer. Mus. Nat'l. History, N. Y.	Watson, 1956
Youndegin, Australia	927	Museum Geol. Survey, Perth	Fletcher, 1892-3

Table 4. Flat iron meteorites

Name and Location	Weight kg	Location of Meteorite	Reference
Cabin Creek, Arkansas	49	Nat'l. History Museum, Vienna	Kunz, 1887
Algoma, Wisconsin	4	Wisconsin Univ., Madison	Hobbs, 1903
Henbury, Australia	530 (numerous specimens)	Kyancutta Mus., So. Australia U.S. Nat'l. Mus., Wash., D.C., etc.	Alderman, 1932
N'Kandhla, So. Africa	17	Cast in Nat'l. Hist. Musuem, Vienna	Stanley, 1914
Arlington, Minnesota	9	Minnesota Univ.	Hobbs, 1903

Table 5. Medium sized chunky iron meteorites

Name and Location	Weight kg	Location of Meteorite	Reference
Bruno, Canada	13	H. H. Nininger's Collection	Nininger, 1936b
Glorietta, New Mexico	(numerous specimens weighing a few kilograms each)	Nat'l. Hist. Mus., Vienna, etc.	Kunz, 1885
Mapleton, Iowa	49	Field Museum of Nat'l. Hist., Chicago	Wilson, 1944
Quesa, Spain	11	Nat'l. Hist. Museum, Vienna	Berwerth, 1909
Sikhote-Alin, Russia	(numerous specimens weighing a few grams to many kilograms each)	Meteorite Mus., Moscow	Krinov, 1950

Table 6. Pear shaped iron meteorites

Name and Location	Weight kg	Location of Meteorite	Reference
Boogaldi, Australia	2	Technol. Museum, Sydney	Baker, 1900
Charlotte, Tennessee	4	Harvard University, etc.	Troost, 1845
Keen Mountain, Va.	14	U.S. Nat'l. Museum, Washington, D.C.	Henderson and Perry, 1958
Nedagolla, India	4	Cast in British Mus., London	Cohen, 1897
Rowton, England	3	Cast in British Mus., London	Flight, 1882
San Francisco Mountains, Arizona	2	U.S. Museum National Hist., Washington, D.C., etc.	Perry, 1934

Table 7. Several miscellaneous ablated meteorites

Name and Location	Weight kg	Location of Meteorite	Reference
Lafayette, Indiana	0.6	Purdue University	Nininger, 1935
Archie, Missouri	18	U.S. Nat'l. Museum Washington, D.C.	-
Estherville, Iowa	(Numerous small specimens weighing a few grams each)	British Museum, London Peabody Museum, Yale University	Peckham, 1879
Long Island, Kansas	564	Field Museum National History, Chicago	Farrington, 1902
Carbo, Mexico	454	Harvard University	Palache and Gonyer, 1930
Mazapil, Mexico	4	Field Mus., Nat'l. History, Chicago	Hidden, 1887
Goalpara, India	3	Cast in British Museum, London	Tschermak, 1870
Bath Furnace, Kentucky	6	Chicago Nat'l. History Museum	Ward, 1905

One of the smaller stones, Lafayette, is a beautiful and instructive specimen. The plano-convex lenticular shape (large angle, rounded nose, flat base) is representative of most of the smaller stones.

The Archie stony meteorite is an exception. The nose is conical with the same concavity of nose surface observed in the large conical irons. Even tiny individuals of meteorite showers orient themselves stably during flight and become sculptured as evidenced by the very small (15 gram) iron fragment of the Estherville fall. The surface of a meteorite during ablation has a fairly stable geometrical configuration. A question is, does the stable surface shape represent a situation in which maximum ablation, minimum ablation, or some intermediate rate of ablation takes place?

Now for a look at the surfaces of some of these meteorites. The front surface and the rear surface of the flat Cabin Creek iron, an observed fall, are shown in the photograph, Fig. 9. Many large holes have been scoured out of the front face, while the rear surface is quite free from holes. The pits are fairly deep, averaging 5 centimeters, and approximately circular with a diameter of about 8 centimeters. The holes are uniformly distributed over the surface. Closer examination indicates that the pits are slightly elongated with their long axes pointing toward the nose of the meteorite.

Bruno, a small chunky iron, shown in Fig. 10 is roughly 20 centimeters in diameter. The thumbprint-like depressions are characteristic of irons of this size. Little filaments of previously molten metal cover the surfaces of the depressions. The filaments are **indicative** of flow of material along the surface and their strong curvature in certain regions suggests intense air eddies. In fresh falls, such as the Russian Sikhote-Alin meteorite, small solidified droplets as well adhere to the surface.

Nedagolla, an iron whose surface is shown in Fig. 11, is intriguing for its complex pattern of interlaced ridges of material, reminiscent of the appearance of water being driven along a solid surface under the action of a strong wind. The ridges of material and other flow markings seen in Bruno, Lafayette, and Nedagolla suggest that there is a considerable amount of this sweeping type of action.

The ablation of stones proceeds somewhat differently. The large Long Island stony meteorite shown in Fig. 12 is about 70 centimeters in diameter. The smooth nose cap extends back for about twenty centimeters. There is then an abrupt change from the smooth cap to a heavily furrowed and pitted surface; the furrows are 2 to 5 centimeters long, 1 to 2 centimeters wide, and 3 to 5 millimeters deep. Finally, note the great increase in size and depth of the furrows and pits on the rearward surface, which lies very obliquely to the direction of air flow. The furrows are about twice as long, twice as wide, and twice as deep as those on the nose surface. Similar furrows are well developed in the Bath Furnace meteorite (Fig. 13). When pits or depressions are deep and large does this **indicate** a rapid loss of mass? Large meteorites have large pits, and large pits appear when the surface is inclined greatly to the direction of air flow. Once a pit has been formed, will it always remain a pit? The furrowed pattern on stones indicates that the surface may be constantly changing its contour so that depressions become ridges and ridges become depressions.

Is the air flow about a meteorite laminar or turbulent? Air flow over the smooth nose of the Long Island stone may well have been laminar. Back of this region it is evident from the furrowing that the flow has been turbulent.

The side view of the Lafayette meteorite, a small stone about 10 centimeters in diameter, is shown in Fig. 14. The surface is smooth and the flow pattern that the filaments of molten material have assumed is clearly evident. The somewhat different ablated surface of the small stone Goalpara is shown in Fig. 15. Numerous small pits have been scoured out. The rear surface of a small stone like the Lafayette and a large stone like the Long Island is blistered from heat but not ablated.

The physical properties of the material out of which the meteorite is made influence strongly the ablation pattern. A small (2.5 centimeter diameter) ablated Estherville iron was cross sectioned and etched to show details of the ablation process. The section is shown in the photograph of Fig. 16, the front surface being to the left. Note that the black bands, taenite, (nickel-rich iron) have in several places been removed to a greater extent than the surrounding kamacite (nickel-poor iron). It is interesting in this connection to speculate on whether the ablating surface receded in a continuous or intermittent fashion.

Finally, in Fig. 17 we look at the effect of large inclusions, both hard and soft. The upper figure shows the parent meteorite. The lower left hand drawing illustrates the result when the meteorite contains low melting-point brittle inclusions such as troilite (iron sulfide, melting point 1000° F) nodules, as in the Cabin Creek, Grant and Carbo meteorites. The inclusions ablate rapidly, producing holes, but the holes do not seem to influence appreciably the general pattern of ablation (O'Neil and Rinehart, 1957). The lower right hand drawing illustrates the situation when the meteorite contains highly resistant graphite as does Mazapil. Here a thin black crust coats the surface and exhibits well the striae of flow, but in eleven places nodules of graphite, one of which is about an inch in diameter, extrude from the surface.

Heat does not penetrate any appreciable distance into the meteorite beyond the ablating surface. The temperature gradient established within the meteorite will depend upon the surface temperature, the thermal conductivity K of the meteorite material, the rate at which molten material is swept away from the surface, and the length of time the surface is at high temperature. For steady melting the temperature T at some point x beneath the surface is given (Landau, 1950-51) by

$$T = T_o + (T_m - T_o)e^{-\frac{Qx}{K(T_m - T_o)}}$$

where x is measured from the interface between molten and solid metal, Q is the rate of heat transfer across the interface, T_m, is the melting point of the material, and T_o is its interior body temperature. The heat altered layer remaining on the large iron Grant meteorite is, for example, only a fraction of a millimeter thick. The thinness of this altered layer is due to three causes: the rapid removal of melted material, the relative slowness with which heat is conducted inward, and the short time of heating.

Can we tell by looking at the meteorite how much mass has been lost? At present it does not appear that we will be able to do so. A more promising approach is to study the spatial distribution of cosmogenic rare gases within the meteorite remnant as is now being done on Grant and Carbo. How thick a layer of material becomes melted before it is swept along?

Does some material vaporize? Is some plastically deformed which has not yet reached the melting point? Does spallation contribute significantly to loss of mass? These are questions which are difficult to answer because the visible evidence we have relates only to the final stages of flight.

The situation as regards meteors is in a much better state. The basic equations for the study of meteors were derived many years ago (Lindemann and Dobson, 1923; Hoppe, 1937), and an excellent discussion has been presented recently (Whipple, 1952; Hoppe, 1954; Levin, 1956; Öpik, 1933; 1937; 1955).

Three basic assumptions are made: first, loss of mass of the meteoroid is proportional to the energy available from the impinging air molecules. The details of the aerodynamic processes of heat transfer are neglected in this generalized approach.

The second basic assumption is that the radiant energy (light) observed is proportional to the time rate of mass loss multiplied by its kinetic energy of motion with respect to still air. Luminosity arises largely from interaction of ablated material with surrounding air.

Third, in regard to the drag on the meteoroid by the resistance of the atmosphere, the classical Newtonian "putty-ball" model is appropriate.

The two equations most applicable to meteorites are the drag equation, a consequence of the third assumption,

$$\frac{dv}{dt} = -\Gamma \frac{A}{m} \rho v^2 \quad ;$$

and the mass loss equation, a consequence of the first and third assumptions,

$$\frac{dm}{dt} = \frac{\Lambda}{2\zeta} A \rho v^3 \quad ,$$

where A is the presented area; ρ, density of air; v, velocity; Λ, heat transfer coefficient, and ζ is the "heat of ablation". The value of ζ for any particular material depends upon how the material is removed, whether by vaporization, melting or breakage. The quantities Γ, $\frac{A}{m}$, and ρ are clearly variables during the descent of a meteorite and very likely Λ and ζ are also variables. The drag coefficient Γ, about 1/2, will not vary greatly and experiments with ultra high speed pellets suggest that A/m will also be a slowly varying function (Rinehart, 1952; Allen, Rinehart, and White, 1952; White, Rinehart, and Allen, 1952; Rinehart, Allen, and White, 1952). Extensive photographic meteor observations have given quite consistent results (Whipple, 1952; Thomas and Whipple, 1951a). In this case it is the derived quantity

$$\sigma = \frac{\Lambda}{2\Gamma\zeta}$$

which is obtained directly from the reduction of observations.

For meteors, the mass at any point along its trajectory is given by

$$m = m_{\infty} \exp. \left[\frac{\sigma}{2} (v^2 - v_{\infty}^2)\right] .$$

By using the value of σ obtained from meteors, $\log \sigma = -11.75$, and by applying it to the entry of a large meteorite, it was found that for initial velocities of 12, 20, and 70 km/sec the ratio, m/m_{∞}, equals 0.3, 0.03, and 1.2×10^{-19}, respectively (Thomas and Whipple, 1951a). This value is not inconsistent with observations. The greatest uncertainty lies in the values of the heat transfer coefficient Λ and the energy of ablation, ζ. Meteor results and high speed wind tunnel studies indicate values of Λ as low as 0.01 (Thomas and Whipple, 1951b). The energy of ablation, ζ, will depend upon how material is removed. If vaporized, as it may be at very high velocities, then ζ is heat of vaporization. Later it will be heat of fusion. Occasionally a chunk will be mechanically broken off and in this case ζ will have an exceedingly low value. It is likely that even on the same meteorite, ζ and Λ may each simultaneously have several different values, depending upon what is happening at a particular point on the surface.

Impacts

When we consider impact we are concerned, first, with impacts in space of the very tiny bits of meteoritic material;

and secondly, with impacts on the earth of much larger meteorites, so large that they plummet through our atmosphere and strike the earth with velocities essentially unchecked. If it weighs less than 100 tons, a meteorite will be slowed to its terminal velocity, at most a few thousand feet per second, strike the earth at an angle of approximately 90°, and simply bury itself. Above 1000 tons a meteorite will retain most of its cosmic velocity and on impact produce a large scar.

First let us consider the impact of micrometeorites. It is only in space, where the earth's mantle of air cannot slow them down, that they have high velocities. Some of our rockets and satellites indicate through telemetered pulses that such matter is impacting on them. The velocities, 11 km/sec to 72 km/sec, are considerably higher than any attainable in the laboratory so that there has been no direct observation possible. Presumably on striking an object a small meteorite would vaporize, its kinetic energy going into vaporization of the particle, vaporization of part of the target material, melting, plastic flow, and crushing (see Cook, 1956; 1957; Kineke and Gehring, 1957; Rinehart, 1950; Rostoker, 1953; Birkhoff et al., 1948). The net result will be the formation of a damaged region, whose extent will depend upon the momentum and kinetic energy of the impacting meteorite.

The failure processes will in most cases be either momentum-absorbing ones or energy-absorbing ones. Failure in which the material is simply dislodged by the impulse of the impact, and offers the inertia of its own mass as a resistance to motion, will be a momentum-absorbing one; while the formation of a crater in a body which *steadily* continues to resist application of the force, is an energy-absorbing one.

Phenomenologically the volume of damage, V, can be expressed by

$$V = (\tfrac{1}{2} mv^2) \sum K_1 + (mv) \sum N_1$$

where K_1 and N_1 are constants which depend upon the mechanical and thermodynamic properties of the target and the missile. The constant K_1, for example, might refer to that part of the volume resulting from vaporization, K_2 to that part resulting from melting, and K_3 to that part due to plastic flow. Generally a high velocity particle fired in the laboratory will produce a hemispherically shaped crater, (Rinehart, 1950; Helie, 1840; Rinehart and Pearson, 1954), quite reasonably so since the forces are radially acting ones. Presumably similar craters would be formed at the exceedingly high speed velocities of impact of micrometeorites.

The impacts of much larger meteorites give us the great terrestrial meteorite craters (Gilvarry and Hill, 1956). There are twelve thoroughly authenticated craters or groups of craters listed in Table 8 (Watson, 1956). In addition, there is the large crater in northern Canada which many believe to be meteoritic in origin.

The Arizona Crater is a large bowl-like depression lying in a sandy semiarid region of northern Arizona (Nininger, 1956; Barringer, 1905). In outline (Fig. 18), it is a rough square about 4100 feet across and 600 feet deep, with an elevated rim rising 160 feet above the surrounding plain. What was the event that caused this crater? How fast was it moving? From what direction did it come? How large was it? These questions are largely unanswered in spite of numerous surveys and investigations (Öpik, 1936). A survey was conducted in the summer of 1956 by the Smithsonian Astrophysical Observatory (Rinehart, 1957c; 1958). Our objective was to make a systematic investigation of the distribution of the minuscule bits and pieces of meteoritic material that are scattered through the mantle of soil surrounding the crater, with a view to fixing more closely the mass of the meteorite that made the crater and the direction of flight. Samples of soil were taken every one-half mile over an 80-square-mile area, and sifted by screen and magnetic separator. Curves of equal abundance of meteoric material are shown in Fig. 19. The material is distributed over a symmetrical swath running nearly west to east (actually 16 degrees north of east) with the greater amount of material piled up on the eastern side. From these observations we concluded that the direction of approach was from southwest to northeast. The total amount of meteoritic material in the soil is approximately 12,000 tons, a minimum mass for the meteorite that made this crater, and a mass not far different from the mass predicted from small scale terrestrial experiments (Rinehart, 1950). Metallurgical examination indicates that much of the material was hot and some molten when it landed. The meteorite may very likely have exploded on impact, scattering into bits and chunks.

No really large mass of meteorite has ever been found associated with a large meteorite crater. The largest mass yet found at the Arizona crater weighed 1400 pounds and it seems unlikely that any sizable portion of the meteorite still lies under the floor of the crater.

It is a mistake to treat the formation of a meteorite crater as a hydrodynamic problem; rather, it is a problem of the strength properties of materials. Consider again the Arizona crater. The rim rises above the surrounding plain to a uniform height of 160 feet. Gross tilting and faulting are about the same all around the rim. When the meteorite struck, the strata fragmented; they did not bend in a plastic sense. Uplifts are in the form of faulting. No actual plastic flow of rock occurred except perhaps in the immediate vicinity of the impact point. The fragmentation or faulting probably radiated out from the point of impact and ceased only when the stress of impact had decayed to a value less than the fracture strength of the rock. The mechanical properties of the strata *in situ* are perhaps the dominant factors in determining the configuration that the strata assume after impact. Any anisotropy in mechanical properties will be reflected in the contour of the crater and the distribution of debris. The pattern might therefore bear little relation to the direction of impact.

Are the craters on the moon (see Gold, 1955; Urey, 1952; Gilbert, 1896) (Fig. 20) meteoric in origin? Many are convinced that they are and Fig. 21 shows a relationship between crater diameter and crater depth (Baldwin, 1949). Terrestrial impact and explosion craters, meteorite craters, and the moon craters all fall neatly on the curve. It seems more likely that of those on the moon some are impact craters, others are volcanic in origin, and some may be faults. On the moon, small craters which have been partially obliterated by large craters are never found, although they would be expected from a bombardment of meteorites. Likewise there are no elliptical or asymmetrical craters. Many craters form lines reminiscent of volcanic vents lying along faults. The central peaks are puzzling (Alter, 1956a; 1956b; 1957). If we need an excuse for going to the moon it lies in our desire to solve this mystery of the origin of the craters.

Table 8. Characteristics of terrestrial meteorite craters

Name and Location	No. of Craters	Approx. Diameter (ft.)	Depth (ft.)
Arizona, U.S.A.	1	4150	570
Odessa, Texas, U.S.A.	3	550 70	14 17
Brenham, Kansas, U.S.A.	1	36 x 56	10
Boxhole, Australia	1	600	50
Campo del Cielo, Gran Chaco, Argentine		Many depressions and small lakes from 20 to 254 feet in diameter. One 175 ft. diameter crater is 16 feet deep.	
Estonia	6	(1) 300	45*
		(5) 30 to 120 ft. in dia., 3 to 12 feet deep.	
Wabar, Arabia	4	330	40
		180 x 130	-
	2 craters buried in sand		

---

*Filled with water

Table 8. Characteristics of terrestrial meteorite craters (cont'd.)

Name and Location	No. of Craters	Approx. Diameter (ft.)	Depth (ft.)
Henbury, Australia	13	75	-
		90	-
		135	10-18
		135	10-18
		75	-
		240	12-25
		660-360	40-50
		175	3-15
		60	-
		45	-
		60	-
		30	3
Delgaranga, Australia	1	230	16
Tunguska, USSR		10 to 200 craters ranging in dia. from 30 to 150 feet and up to 12 feet in depth.	
Sikhote-Alin, USSR	106 craters, largest 85 feet across.		
Wolf Creek, Australia	1	2800	160
Chubb, Canada	1	10,000	-*

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*Filled with water

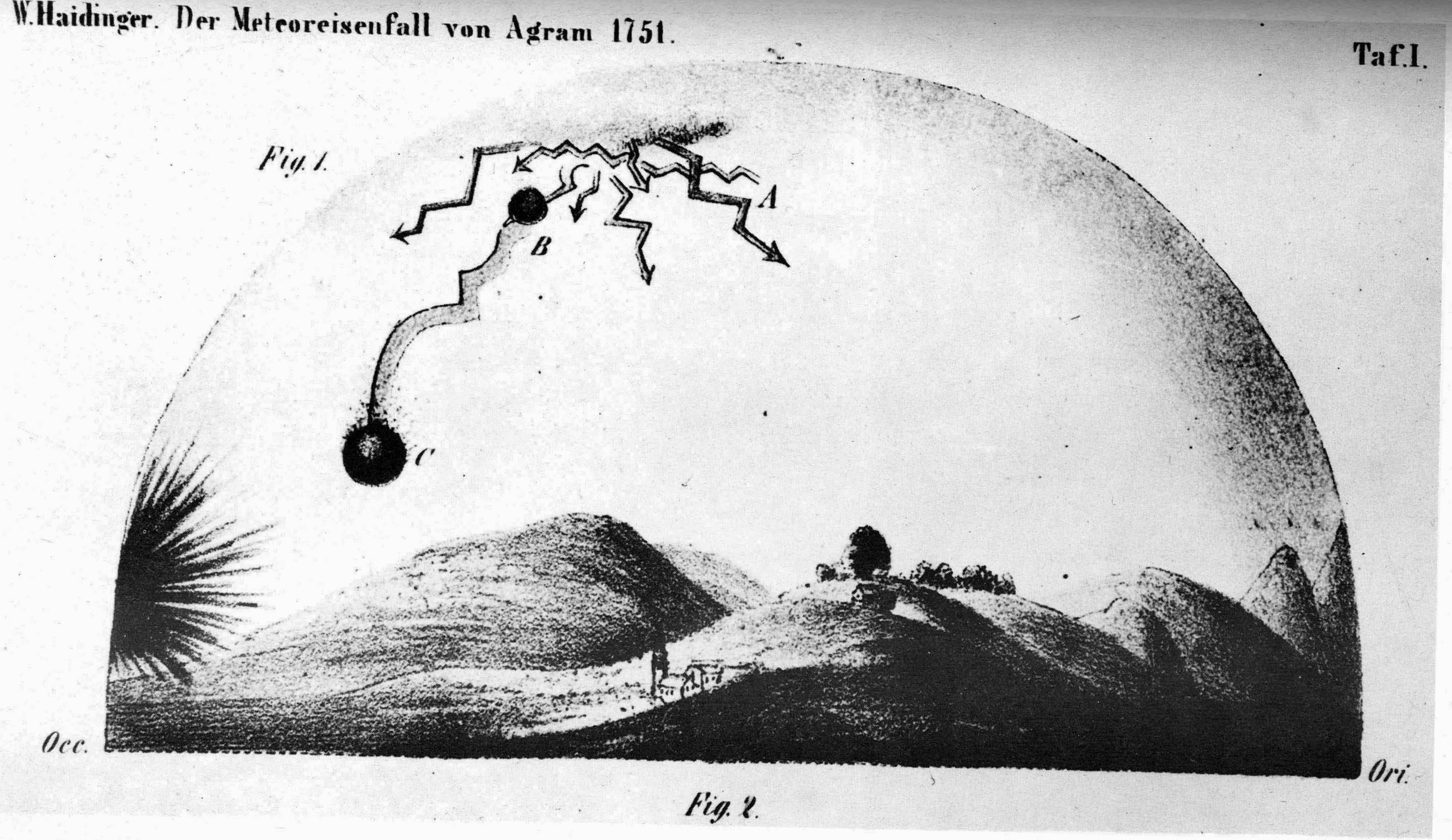


Fig. 1 Agram or Hraschina, Yugoslavia, fall of 1751. Artist's conception from eyewitness accounts. Two irons, 40 kg. and 9 kg., respectively, were recovered (after von Haidinger).

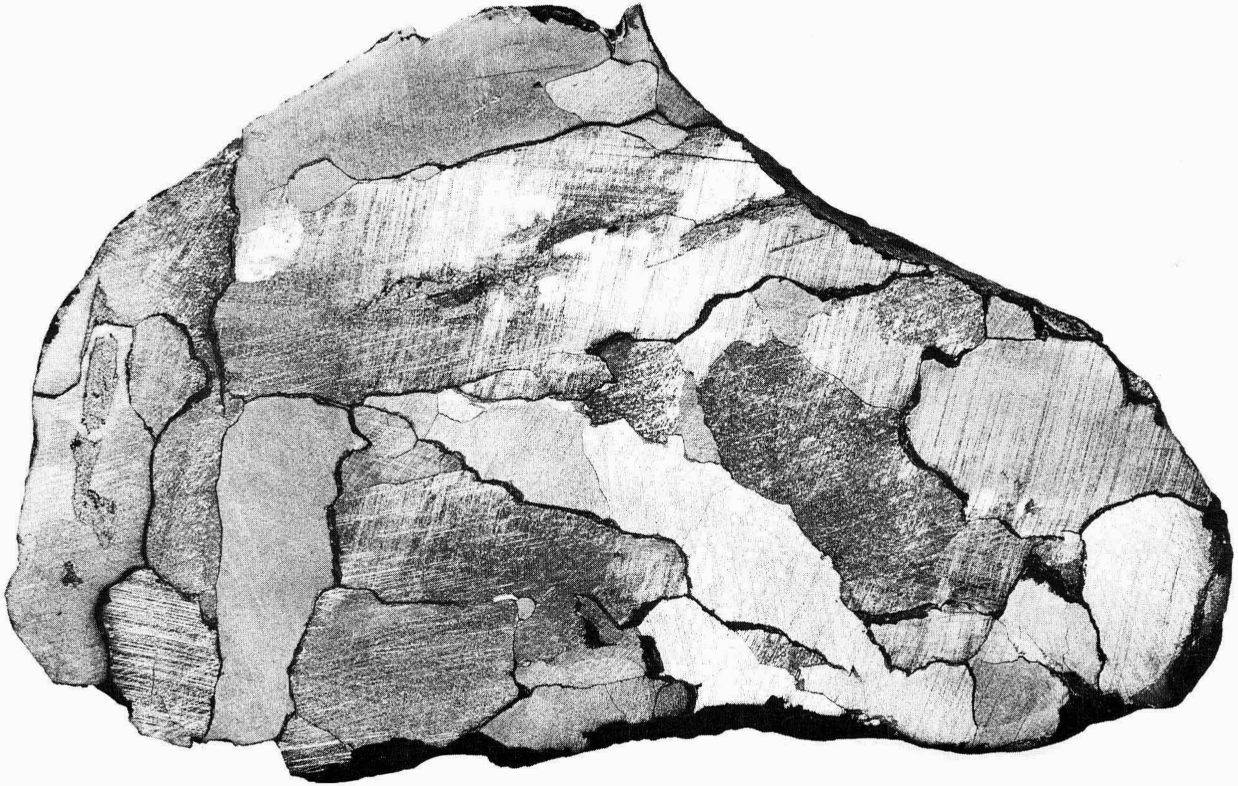


Fig. 2 Etched cross section of Sandia Mountains, New Mexico, hexahedrite. Each area of the conglomerate is a single crystal of body-centered cubic nickel-iron. Bright scratch-like lines are Neumann bands (mechanical twins). Natural size. (Smithsonian Institution photograph.)

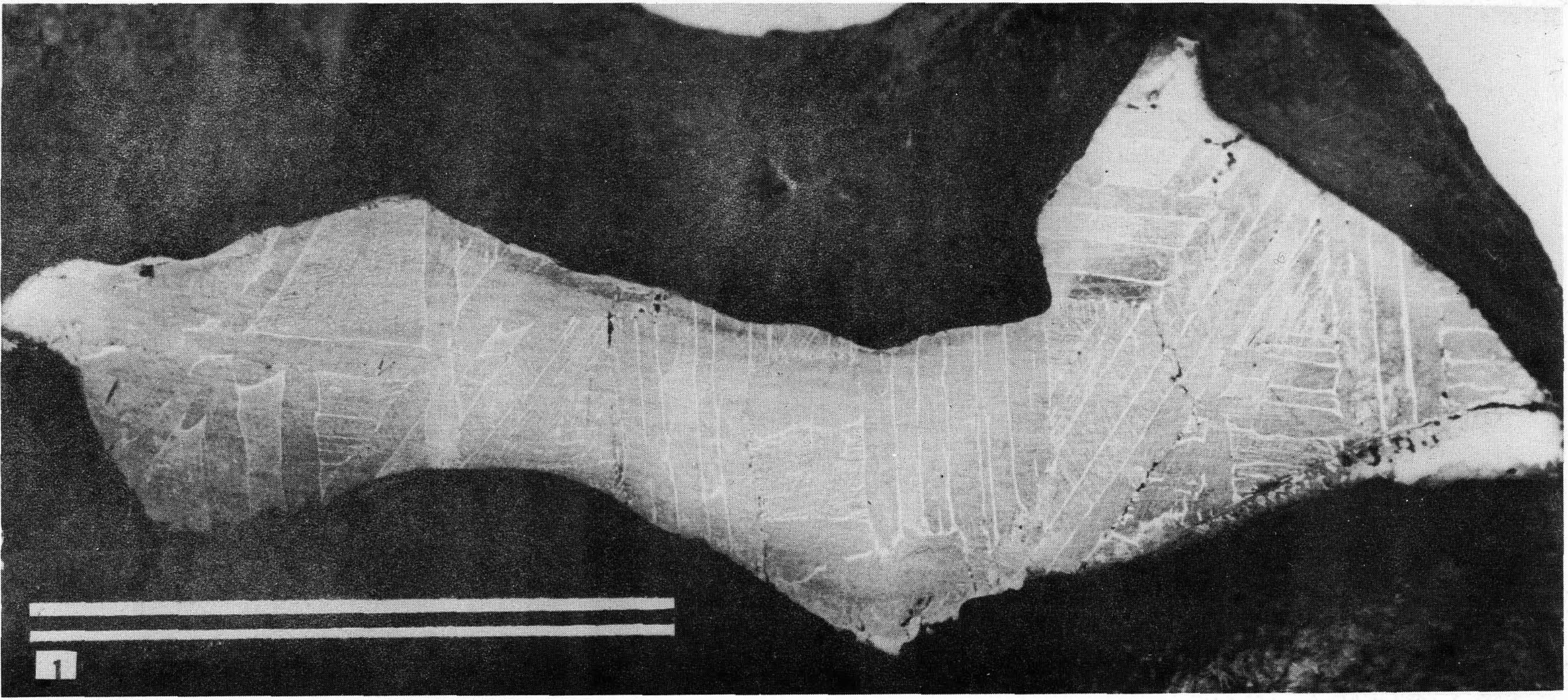


Fig. 3 Etched cross section of Briggsdale, Colorado, octahedrite, showing Widmanstätten pattern. Narrow light bands are taenite (face-centered cubic nickel-iron) and dark areas are kamacite (body-centered cubic nickel-iron). Scale in foreground 2.5 centimeters long. (American Meteorite Museum photograph.)

Fig. 4 A slice of the Brenham, Kansas, stony-iron meteorite, a pallasite. Note Widmanstätten pattern juxtaposed with iron mesh whose interstices are filled with glassy-silica olivine. Natural size. (Smithsonian Institution photograph.)

Fig. 5 Pricetown, Ohio, stony meteorite. Weight 480 grams. Black fusion crust has been chipped off in several places, exposing light colored stony interior. Twice natural size. (American Museum of Natural History photograph.)

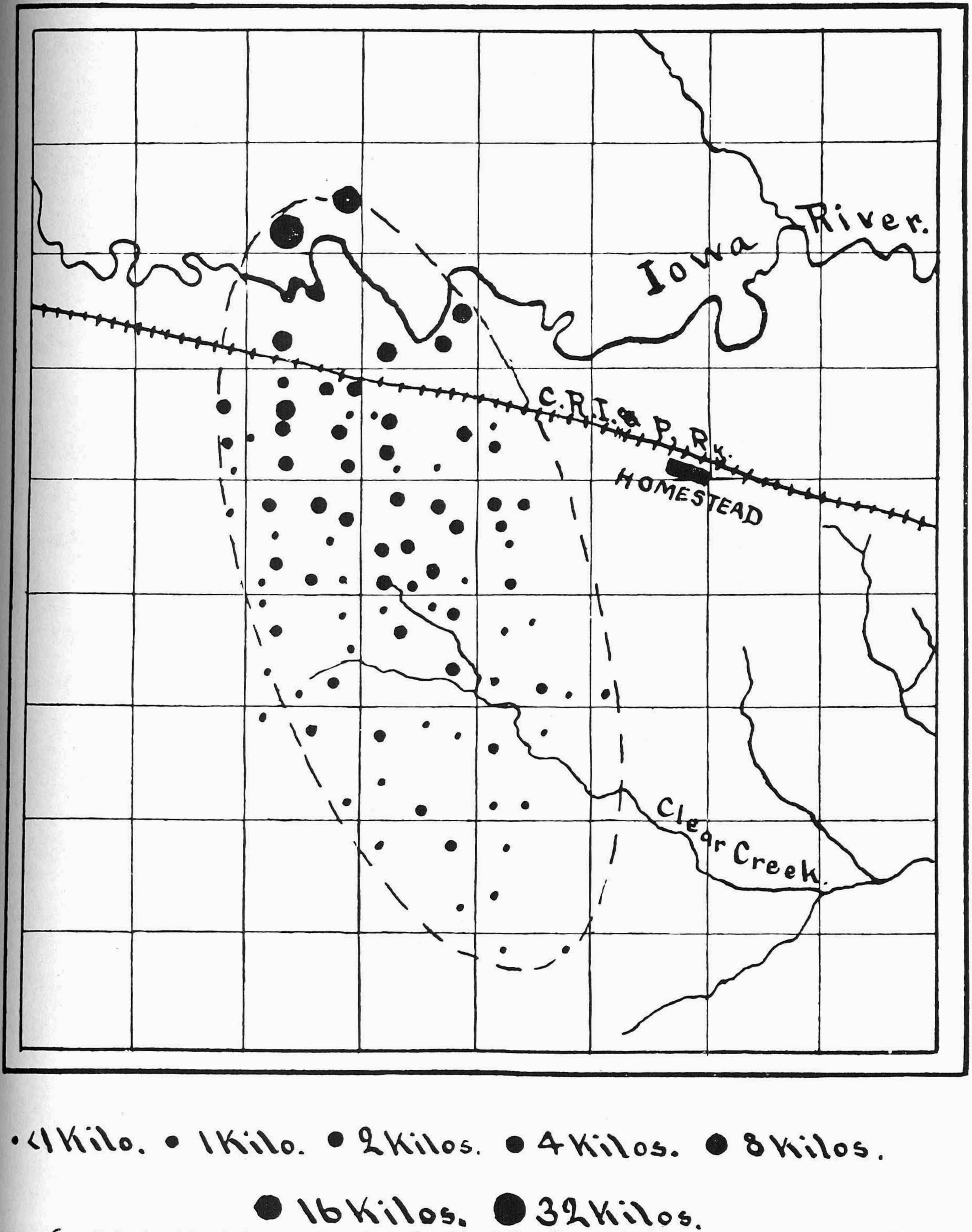


Fig. 6 Distribution of the individuals of the Homestead, Iowa, meteorite shower, a typical fall. The shower moved from south to north, the larger individual pieces being carried farther by their greater momentum. The squares in the diagram represent a square mile each (after Farrington, 1915).

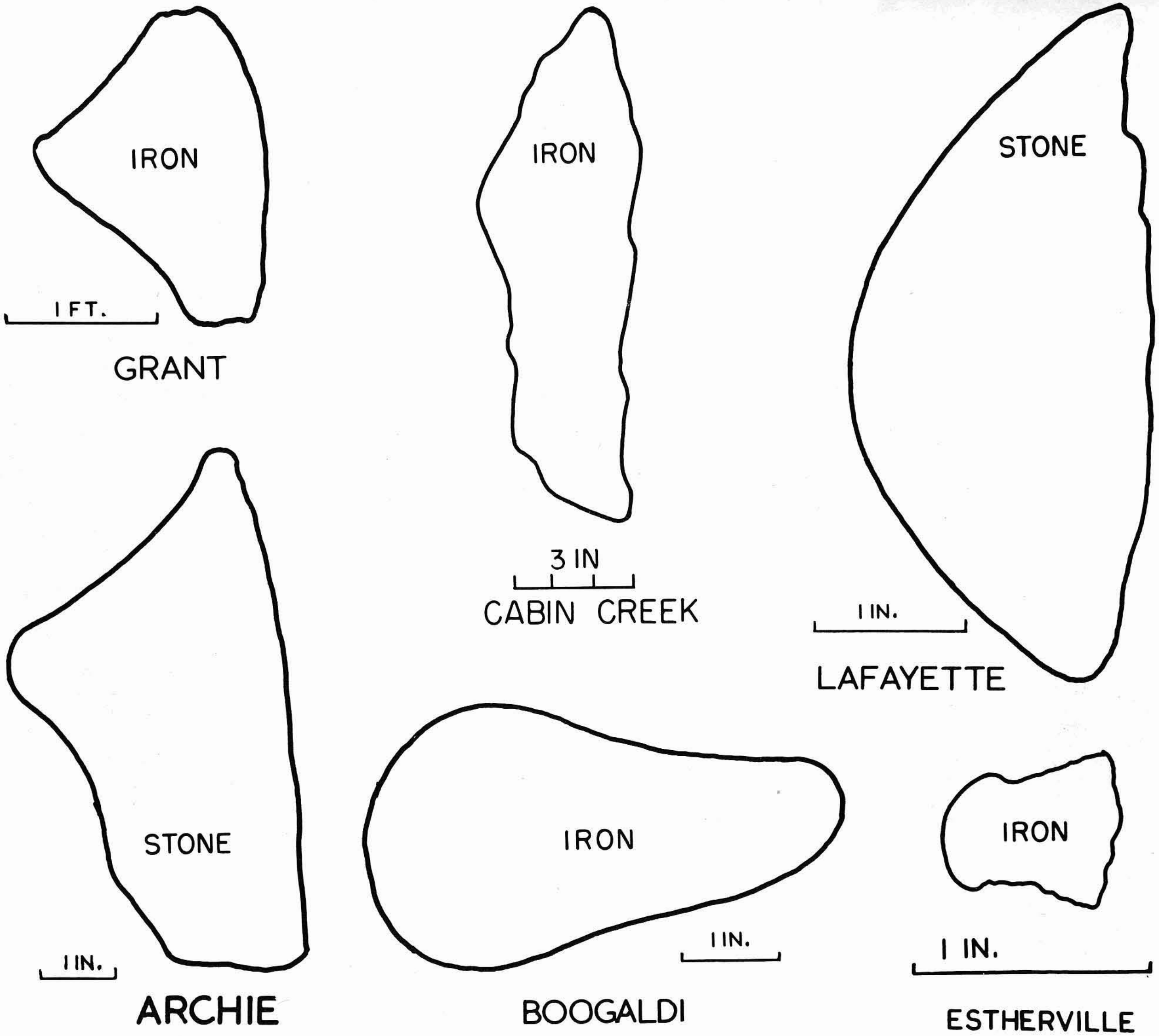


Fig. 8 Profiles of several meteorites. See tables in text for types and weights. Scales are widely different.

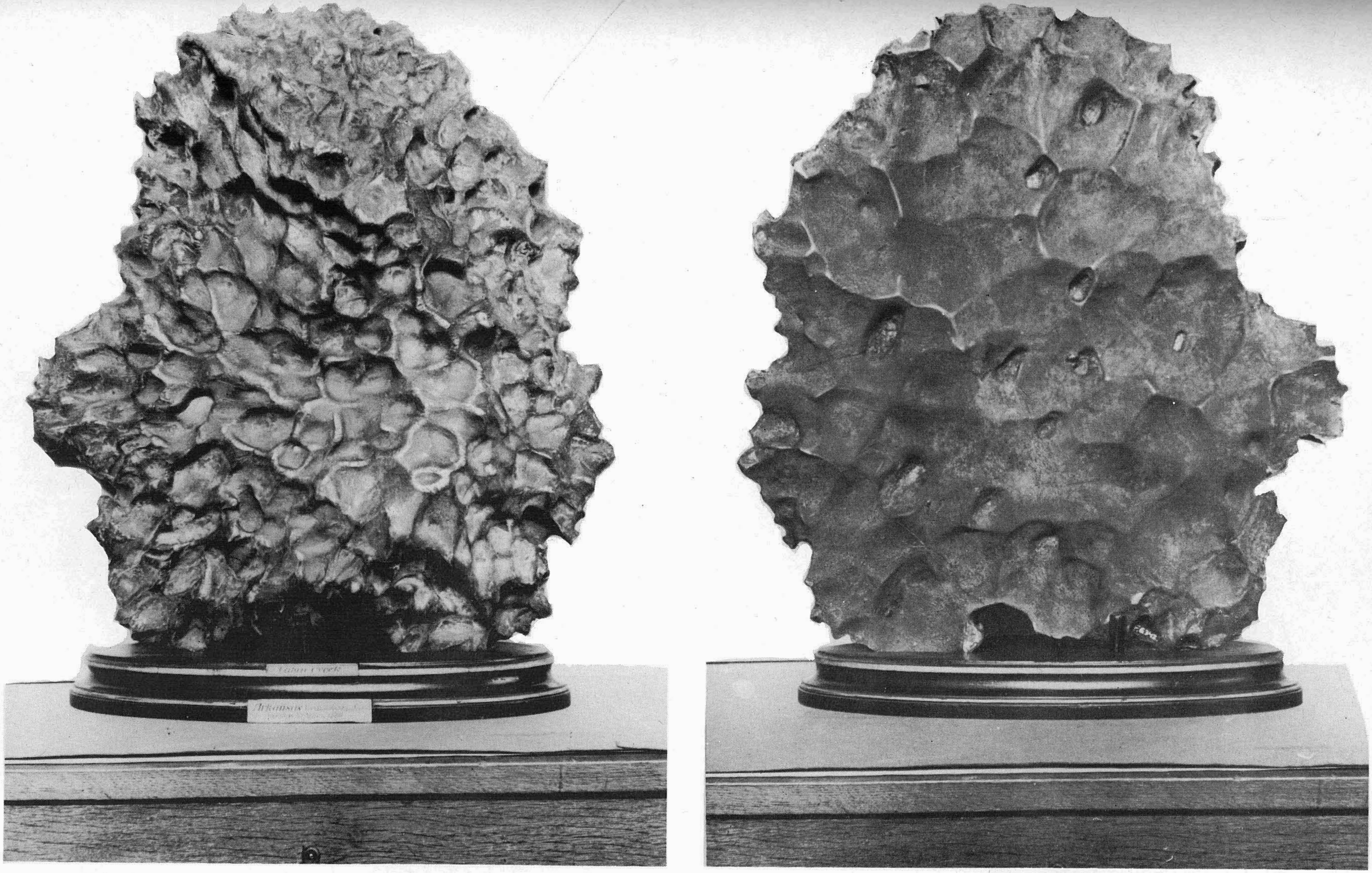


Fig. 9 Front (left) and rear (right) views of Cabin Creek, Arkansas, iron meteorite. Note large scooped out pits in front surface and their absence in rear face. About 1/3 natural size. (Photographs by E. P. Henderson.)

Fig. 10 Photograph of Bruno, Canada, iron, showing thumbprint-like surface markings. About natural size. (American Meteorite Museum photograph.)

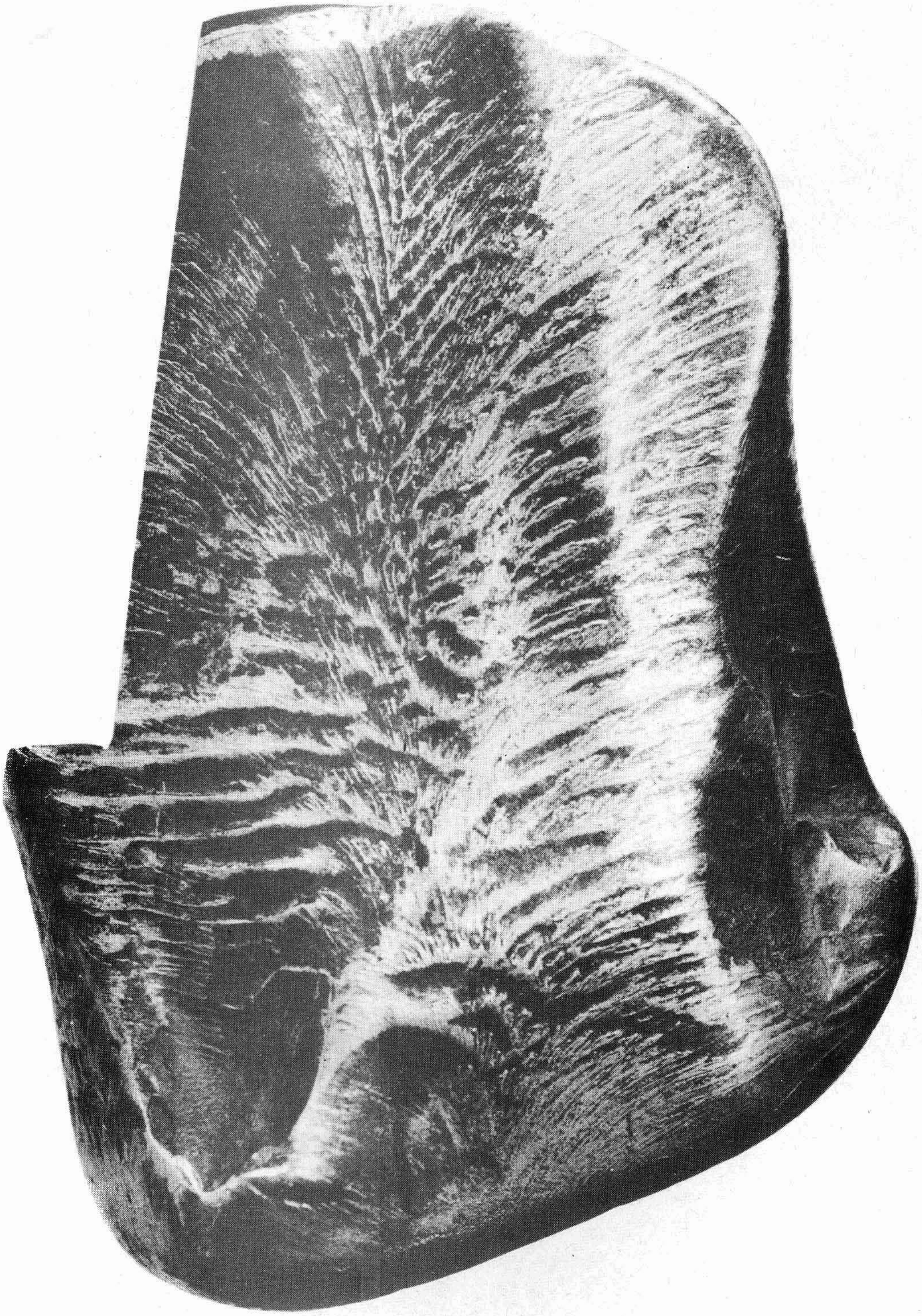


Fig. 11 Surface of the Nedagolla, India, iron. Interlaced wavelets of material are of interest. Piece has been cut from it. About natural size. (British Museum photograph.)

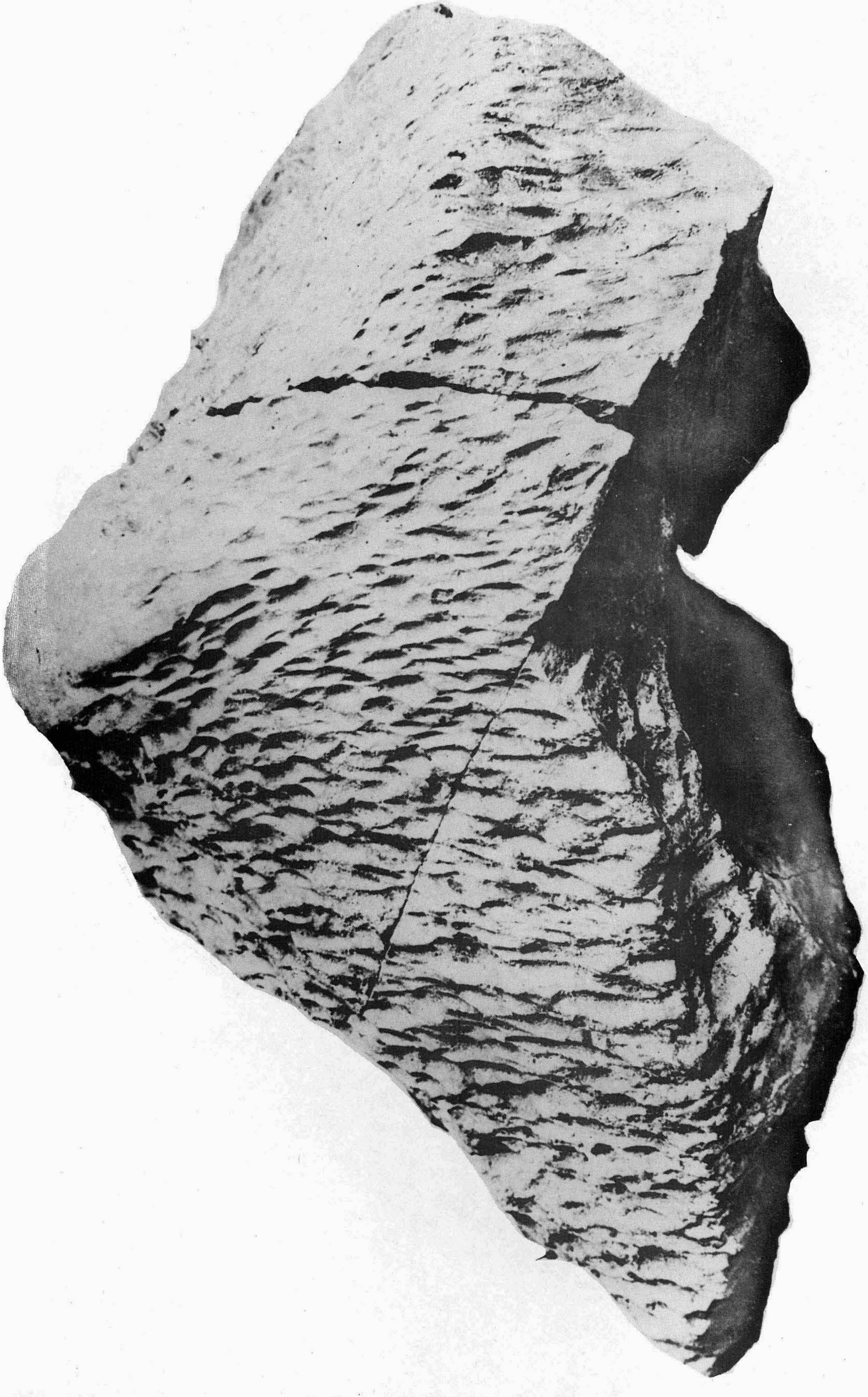


Fig. 12 Large Long Island, Kansas, stony meteorite. Specimen about 70 centimeters in diameter. (Chicago Natural History Museum photograph.)

Fig. 13 Surface detail along ablated side surface of the large Bath Furnace, Kentucky, stony meteorite. About 1/2 natural size. (Chicago Natural History Museum photograph.)

Fig. 14 Side view of small Lafayette, Indiana, stony meteorite. About 1/2 natural size. (Chicago Natural History Museum photograph.)

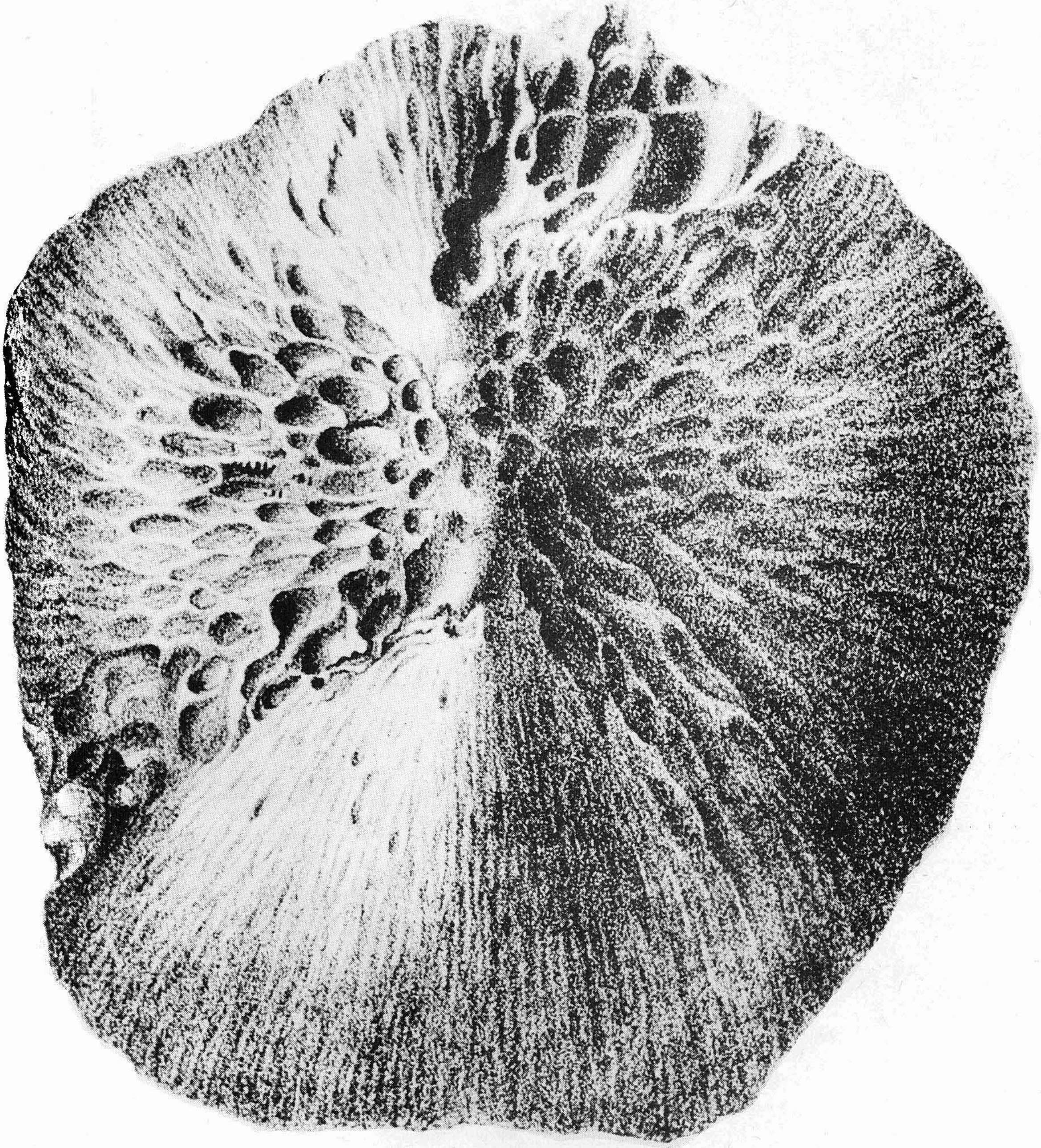


Fig. 15 Front side of Goalpara, India, 3 kg. stone, showing radial arrangement of pittings. Approximately natural size. (After Farrington, 1915.)

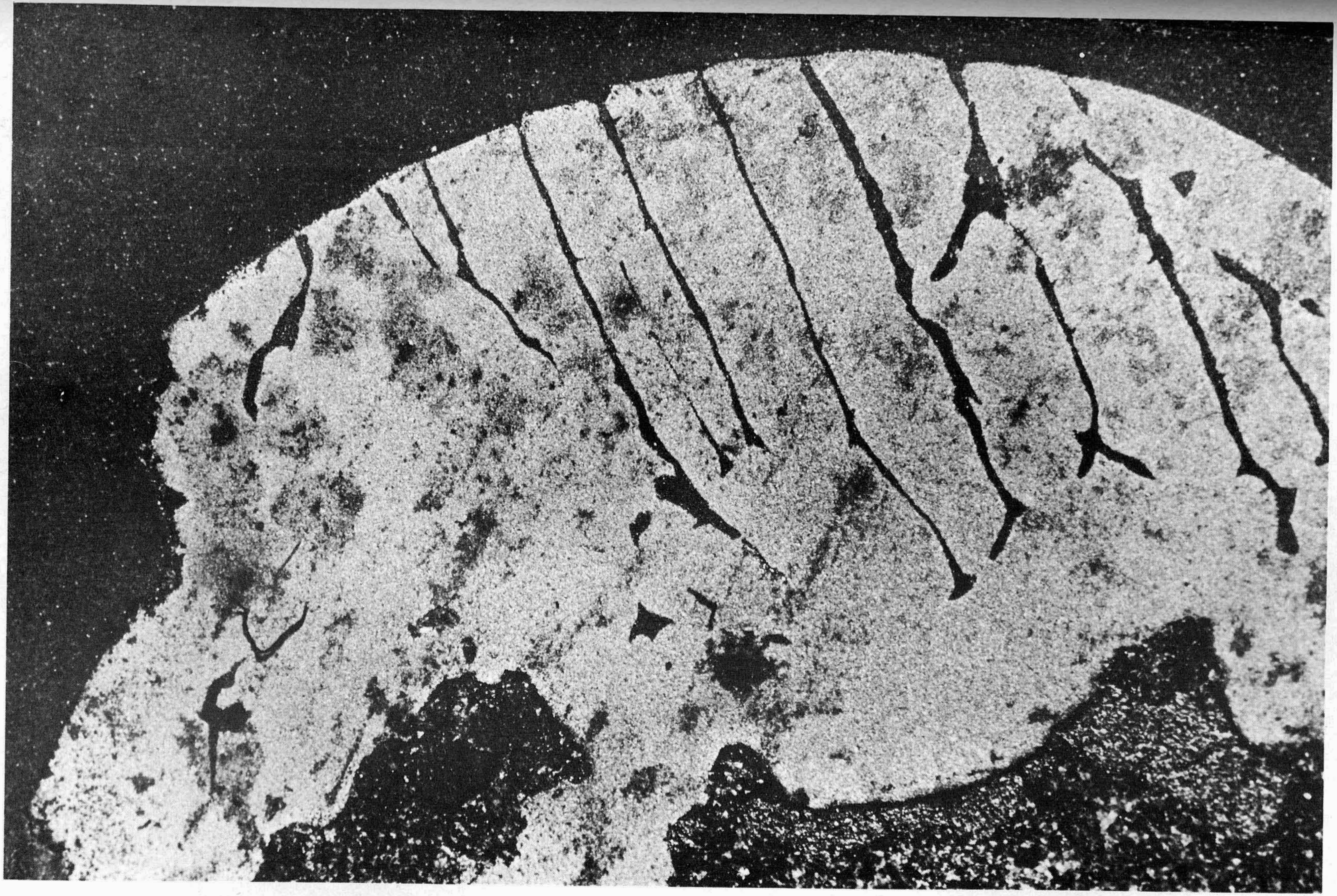


Fig. 16 Etched cross section of tiny (2.5 centimeters in diameter) individual iron of Estherville, Iowa, shower. Ablated surface at top. Dark bands are taenite and light regions, kamacite. Specimen is embedded in dark plastic material. About 16 times natural size.

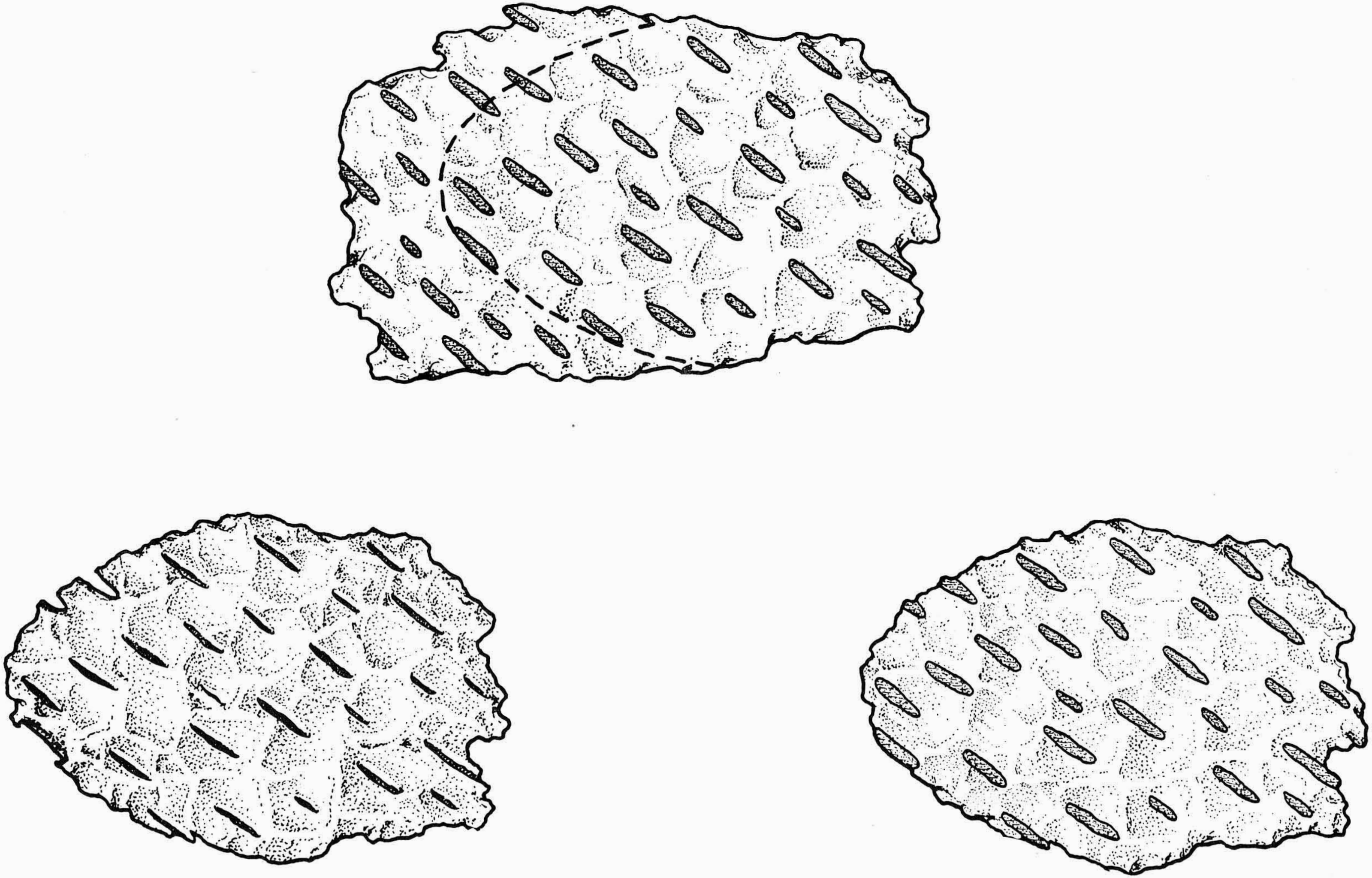


Fig. 17 Drawing demonstrating the effect of inclusions on ablation. Upper center figure, unablated meteorite. Lower left, one containing soft or easily ablated inclusions; lower right, one containing inclusions highly resistant to ablation.

Fig. 18 Aerial photograph of the Arizona Meteorite Crater. (U.S. Air Force photograph.)

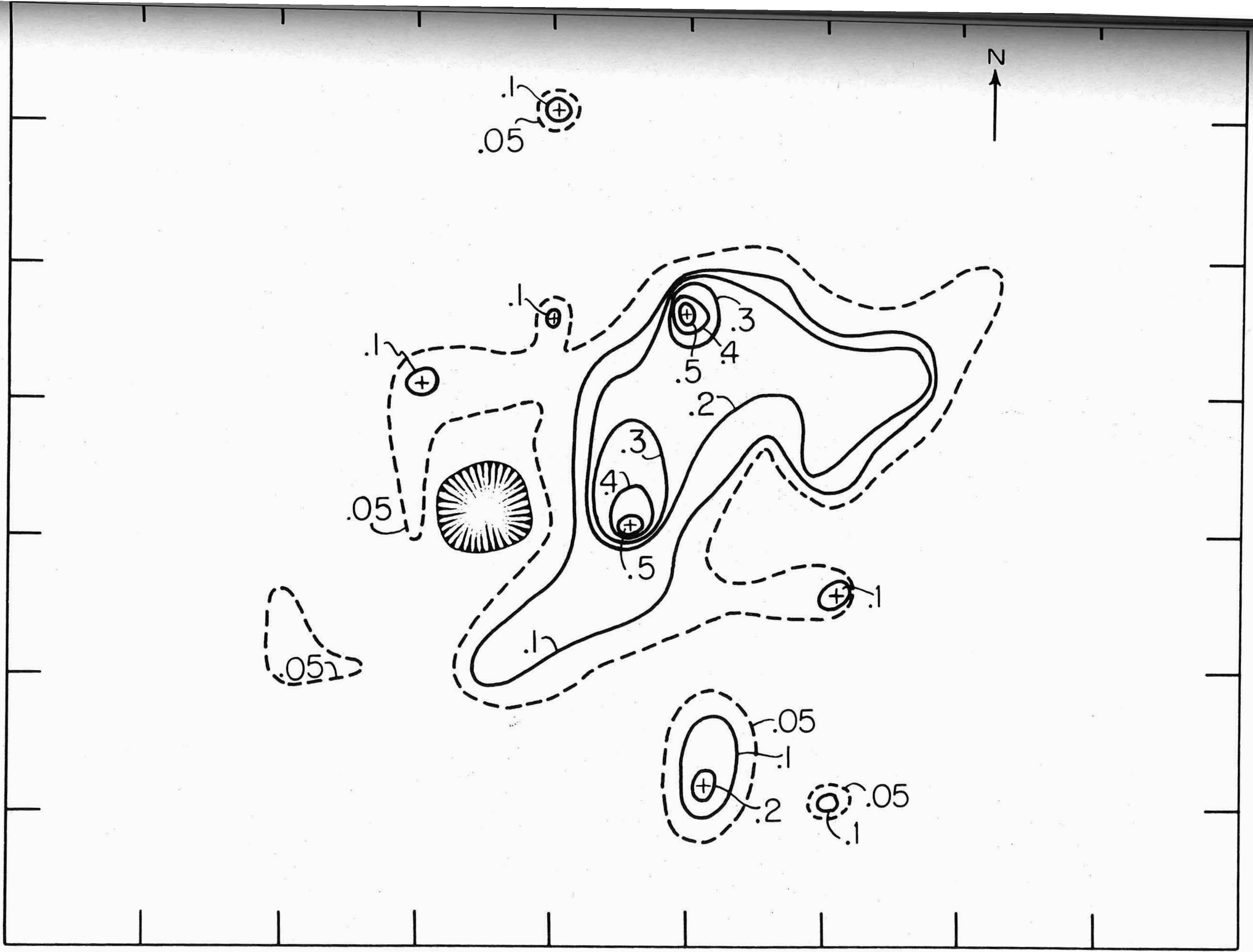


Fig. 19 Contours of equal abundance of meteoritic debris around the Arizona Meteorite Crater (after Rinehart, 1958).

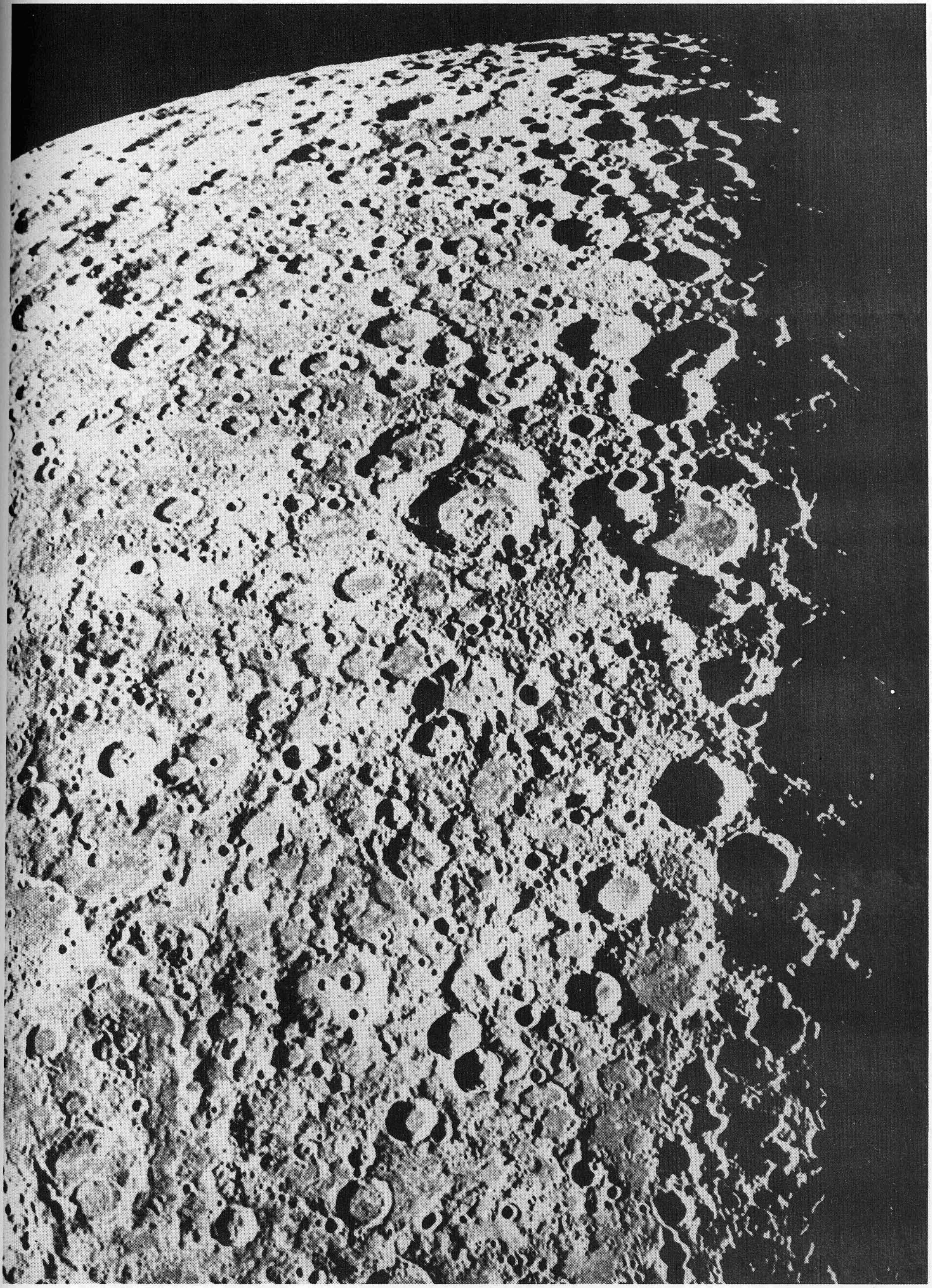
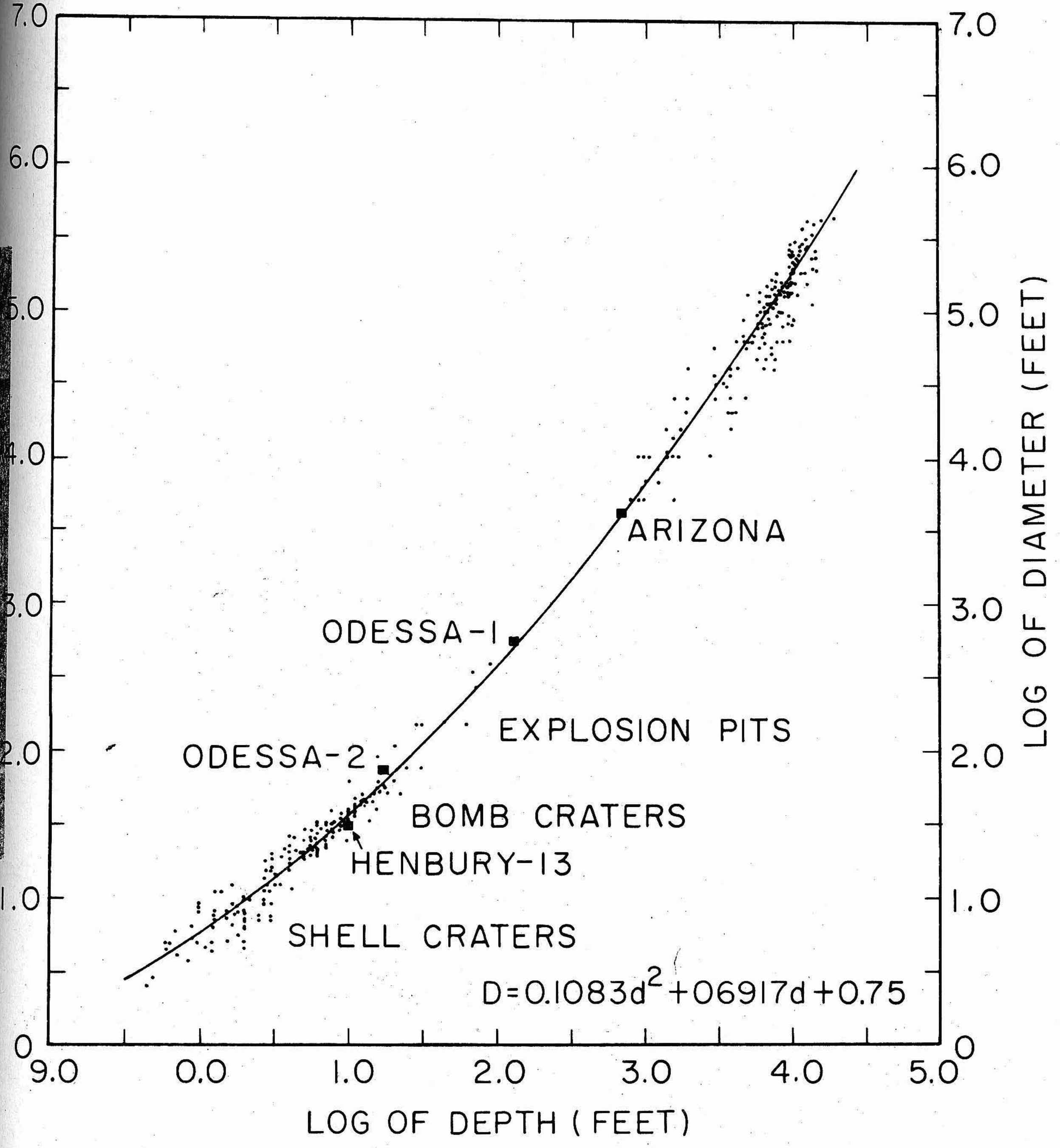


Fig. 20 The moon's cratered surface.(Lick Observatory photograph.)



IG. 21 RELATIONSHIP BETWEEN DIAMETER AND DEPTH OF TERRESTRIAL EXPLOSION CRATERS; TERRESTRIAL METEORITIC CRATERS, AND LUNAR CRATERS OF CLASS I. (AFTER BALDWIN, 1949.)

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