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O. RICHARD NORTON

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# Contents

## Appendices

## CHAPTER THREE

# External morphology of meteorites

Ask anyone you know to describe the most general characteristics they expect to see in a meteorite and they invariably give you three: heavy, black, and full of "holes". Although these characteristics are quite true for some meteorites (actual holes are rare in meteorites but many iron meteorites are deeply pitted), they are also true for Earth basalt. Others might say that meteorites are primarily made of iron and are attracted to a magnet. But then so is terrestrial magnetite (frequently mistaken for a meteorite), and, in fact, most stony meteorites. How then can you recognize a meteorite? The recognition and recovery of meteorites in the field is fundamental to everything else that follows. We must first be able to identify a fallen meteorite before we can probe its interior for the secrets it holds. H.H. Nininger, the great meteorite hunter of the twentieth century, in his public lectures and in his writings often lamented the surprising fact that meteorites were not part of the study of rocks in geology classes, either elementary or advanced. Yet, ironically, meteorites, more than terrestrial rocks, tell us much about Earth's origins. They are as old as the Solar System and considerably older than the crustal rocks of the Earth. Except for specialized graduate courses in large universities with planetary science curricula, the situation has changed very little. This chapter (and those to follow), then, is as much for budding geologists (and their teachers) as it is for the meteorite collector.

# Some general characteristics

Put in the simplest of terms, meteorites are rocks. Like terrestrial rocks the majority of meteorites are made of aggregates of crystalline minerals. For the most part the minerals of meteorites are common to terrestrial rocks but the way in which they are displayed in meteorites is unique to meteorites. The internal texture of meteorites is an important diagnostic characteristic discussed in detail in the chapters to follow. This chapter deals with the exterior characteristics of meteorites as we find them in the field. No one has ever seen a meteorite as a *meteoroid* in its natural space environment so we do not know what a truly pristine meteoroid looks like. We found in Chapter 2 that meteoroids are modified by heating, mechanical stresses and ablation. What we find on Earth has therefore been terrestrialized to some degree. Fortunately, most of the modifying effects occur on the exterior of the meteorite. The interior remains relatively pristine much as it was in its former space environment provided it doesn't remain undiscovered for too long.

In the most general terms, meteorites are classified into one of three broad categories: *stones*; *irons*; and *stony-irons*. The stones are rocks made up of common silicate minerals. These minerals are usually in a crystalline form small enough to require a magnifier or microscope to see them. Their arrangements within meteorites are quite different than inside most terrestrial rocks which suggests radically different origins for them. The irons are, as the name implies, made primarily of iron alloyed with nickel. Most iron meteorites are at least 90% iron with nickel, cobalt, sulfur and other elements making up the remaining 10%. The stony-irons are a mixture of both silicate minerals and iron–nickel alloy. The ratio of stone to iron can vary considerably from meteorite to meteorite or even within a single meteorite but is roughly two parts stone to one part iron by volume.

## Falls and finds

Meteorites are designated as either *falls* or *finds*. The distinction between them is important, statistically. Meteorites classified as falls are those observed to fall and then picked up shortly thereafter. Finds are meteorites that were not seen to fall, remaining undiscovered for a period of years and then subsequently recognized and recovered. If we divide all known meteorites into these two groups, an important conclusion is reached. Of the observed falls, 94% are stones, 5% are irons and 1% are stony-irons. Therefore, we correctly conclude that the vast majority of meteorites falling to Earth are stones. Yet, if we look at the total inventory of meteorites worldwide which includes *both* falls and finds, we find only 69% are stones, 28% are irons, and 3%, stony-irons. Why the contradiction? Simply because stony meteorites, especially terrestrially weathered specimens, are more difficult to distinguish from ordinary terrestrial stones than either irons or stony-irons; the numbers reflect the ease with which iron meteorites are recognized and recovered by the general population. This is strongly substantiated if we look at the totals among the meteorites classified as finds alone. Here, stones drop to 56%, irons increase to 40% and stony-irons increase to 4%. I must add here that scientists seldom search random areas for meteorites (Antarctic and Sahara Desert meteorites excepted) and fewer yet see them actually fall. Most finds are made by ordinary people who work and play out-of-doors: farmers plowing their fields; highway construction crews; and an army of weekend rock and gold hunters scattered across the countryside.

## Density

Most meteorites have densities greater than the average terrestrial rock. This means that for a given size, meteorites are heavier than most terrestrial rocks. Most stony meteorites are tightly compacted with little pore space. The most common stony meteorites, the *ordinary chondrites*, have a density range of between 3.5 and 3.8 g/cm$^3$. By comparison, granite, an igneous rock that makes up much of the Earth's crust, has a density of 2.7 g/cm$^3$. Meteorite high densities are due primarily to the presence of iron. Some of this iron is locked in iron-bearing silicates but some contain as much as 20% in the metal phase. There is sufficient elemental iron in most of the ordinary chondrites that they are attracted to a strong magnet and metal detectors will detect them (as relic or trash indications!). Rare type chondrites, the so-called *EH chondrites*, can have as much as 35% iron metal. Of the chondritic meteorites the *carbonaceous chondrites* show the greatest variation in density. Of the seven known groups, three contain abundant chemically bound water with little or no metal. The other carbonaceous chondrite groups contain variable amounts of unaltered metal. Thus, the group as a whole vary in density between 2.2 and 2.9 g/cm$^3$.

The irons, not surprisingly, are the densest of the meteorites. They contain variable amounts of iron alloyed to nickel with accessory metal sulfides, carbides, and phosphides. They have densities twice that of the stones ranging between 7.5 and 7.9 g/cm$^3$. Their composition resembles no rock type on Earth but they are probably similar to Earth's core material. (Earth's core density is considerably greater than iron meteorites since the core is under a high state of compression. Uncompressed, Earth core material is probably very similar in density to iron meteorites.) There is no mistaking an iron meteorite. Its weight alone attracts attention. The stony-irons, being roughly two-thirds silicate minerals to one-third iron–nickel alloy by volume have densities that lie somewhere between the stones and irons.

## Size

Meteorites show an enormous variation in size from micron-sized dust particles filtering slowly through the atmosphere to giants weighing many tons. The average meteorite found on Earth is about the size of a baseball. The size of a meteorite depends upon its impact history in space as well as its fragmentation history in the atmosphere and its further fragmentation when it impacts Earth. The vast majority of meteoroids fragment as they ablate in the atmosphere. It is no surprise that the largest meteorites in the world are irons since they have greater tensional and compressional strength than stones and are better able to withstand the aerodynamic pressures encountered during atmospheric passage as well as the forces at impact. A large iron meteorite has the best chances of remaining in one piece (assuming no pre-entry fractures exist) if it enters the atmosphere at large zenith angles with a velocity of less than 12.3 km/s. A meteorite with a diameter of 5 m entering at a 60° zenith angle and a speed of 10 km/s may impact without fracturing, but impact speeds of more than 2–4 km/s will produce a crater and vaporize the meteorite in the process.[1]

There is therefore a limit to the maximum size of an iron meteorite reaching Earth that depends upon the heat generated at impact. This is determined by the initial mass of the meteoroid before it enters the atmosphere, its initial velocity and its remnant cosmic velocity when it hits the ground. We saw in Chapter 2 that meteorites over about 10 tons retain some of their cosmic velocity right to the Earth's surface. For example, if a 1000 metric ton iron meteorite hits the top of the atmosphere at 20 km/s at a zenith angle of 45°, it retains about 63% of its cosmic velocity and about 90% of its initial mass when it strikes the Earth. Given that it doesn't break up in the atmosphere it retains a residual cosmic velocity of about 12.6 km/s with 900 metric tons of its mass still intact when it impacts. The meteoroid possesses enormous kinetic energy at impact, most of which is converted almost instantly to heat. An iron meteoroid of this mass and speed will generate about $8 \times 10^{13}$ J of energy or almost 19 000 cal/g of heat on impact. Now, 19 000 cal/g is an enormous amount of heat especially when we compare it to a common value such as 540 cal/g necessary to turn water to a vapor at 100 °C. V.F. Buchwald points out that the element carbon has one of the highest heats of vaporization of any known material, 13 000 cal/g. In the example above, even if the meteorite were pure carbon, it would vaporize on impact. This heat of impact is more than sufficient to vaporize the meteorite on impact even though some of the energy is consumed in producing a shock wave in the ground and a crater a few hundred feet across. Many such craters are known on Earth. Meteor Crater, Arizona, is the classic example and the best preserved impact crater on Earth. It was produced by an iron body estimated to be about 30 m in diameter. Nothing remains of this body today other than fragments off the main mass (Fig. 3.1). Since meteorites heavier than 100 tons retain substantial amounts of their original cosmic velocity and

Fig. 3.1. A 240 g fragment of a Canyon Diablo iron meteorite from Meteor Crater. The hole results from terrestrial weathering within thin-walled ablation cavities. Specimen dimensions are approximately 75 × 67 mm. (Photo by Michael Casper.)

Fig. 3.2. Angularity of a 920 g Gao-Guenie H5 chondrite. Note the flat surfaces nearly at right angles to each other. These are surfaces produced by fragmentation in the atmosphere along preexisting fracture lines acquired while in space. The sharp edges have been rounded by ablation. Specimen dimensions are 113 × 94 mm. (Photo by Michael Casper.)

mass, they tend to self destruct on impact. If the meteorite enters at a zenith angle of 60° to near grazing incidence, its speed might be slowed sufficiently to reach Earth without destroying itself or fragmenting. The fact we see no meteorites larger than the Hoba iron (60 tons) may simply mean that very few large meteorites in the 100+ ton category satisfy these criteria.

## Meteorite shapes

Meteorite shapes are dictated primarily by ablative forces and fragmentation. The original shapes are never retained and remain unknown. Most stony meteorites have random shapes since they almost always explosively disrupt and fragment high in the atmosphere. They break along deep, possibly preexisting fractures; and, like crystalline rocks on Earth, when stony meteorites break, sharp edges result. If fragmentation occurs high in the atmosphere at or near the beginning of the ablation process, the sharp edges are rounded by ablation and the rough broken faces often retain a remarkably flat surface smoothed over by the fusion process so that many stony meteorites have obvious angularity (Fig. 3.2). The overall surfaces of stony meteorites are smooth and slightly undulating, suggesting uneven ablation processes. Sometimes stones develop flattened depressions with raised edges. Superimposed over these depressions may be small pits where turbulent flow of superheated gas has ablated specific areas (Fig. 3.3). They range in shape from nearly circular to highly elliptical. Hand specimens frequently show pits the size and shape of a human thumb print. These "thumb prints" are called *regmaglypts* or sometimes *piezoglypts*. Their shape and size relate to their location on the meteorite and to areas of differing ablation.

Iron meteorites have irregular shapes. If they are associated with impact craters, they tend to be flattened and fragmented like shrapnel from an exploded bomb. Meteorites from the Sikhote-Alin fall that were produced by large individuals exploding on impact are typically jagged and distorted. Meteorites from the same fall that did not shatter on impact or were not involved in explosions are more rounded and show remarkable deep pitting and flow structures. Some specimens show characteristics of both types. Figure 3.4 illustrates the two opposing sides of a Sikhote-Alin iron meteorite. The left side shows shallow smoothed-over

Fig. 3.3. This 800 g Holbrook L6 chondrite shows a slightly concave face (right) containing shallow cavities or regmaglypts produced during the ablative process. The face measures 300 mm in the longest dimension. The largest Holbrook specimen recovered weighs 6.6 kg and resides in the collection of the Center for Meteorite Studies at Arizona State University. (Photo by Michael Casper.)

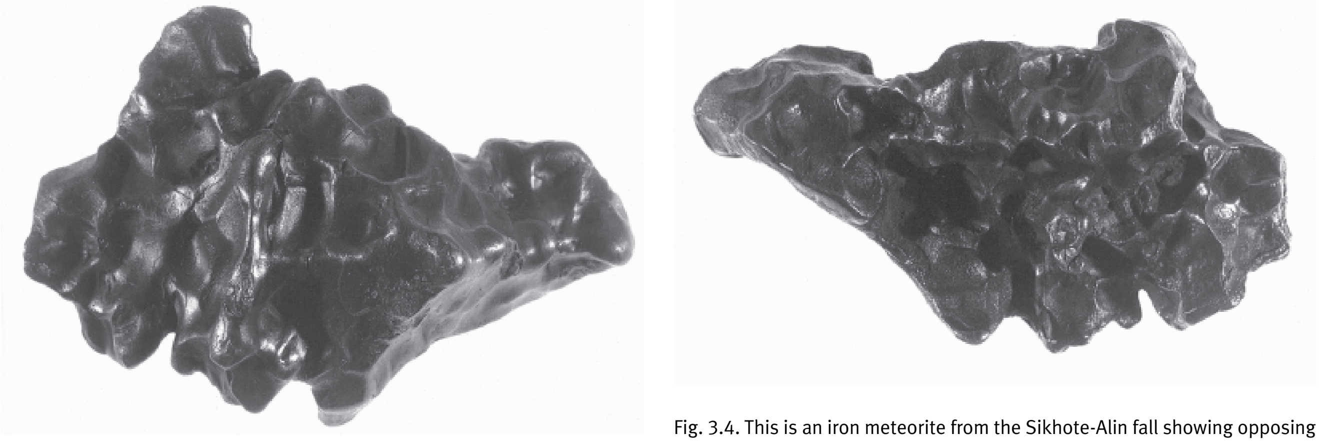

Fig. 3.4. This is an iron meteorite from the Sikhote-Alin fall showing opposing sides. The left side shows a heavily ablated and melted face where the ablation pits have been smoothed over. The right side shows deep pitting on a fragmented side that suffered less ablation and melting. The specimen is 12 cm in length. (Photos by O. Richard Norton.)

pitting, many with elliptical shapes where melting has taken place after the pitting formed. The right side shows deep, subcircular pitting on an obvious fragmented side. This meteorite was in the early stages of ablation when fragmentation took place off the main mass. The raw fragmented side apparently turned, orienting itself toward the forward-proceeding side, producing deep pits and all but erasing the fragmented nature of the meteorite. What was once the side of a large mass became oriented away from the forward end. Material accumulated on this now rear-facing side, flattened and broadened the pits.

Unlike stony meteorites that are composed of minerals each with individual crystal structures, irons are constructed around a single cubic crystal form, either octahedral or hexahedral and they tend to break along natural crystal boundaries. Figure 3.5 shows two sides of a Sikhote-Alin specimen. On the left is a surface with many ablation pits. Near the end of its ablation period, the meteorite suffered fragmentation off the main mass. The right picture shows the fragmented side and a careful examination will reveal triangular-shaped structures that are expressions of the octahedral dipyramids around which the nickel–iron alloy is structured.

Pits on iron meteorites are much deeper than on stones, suggesting differential melting of softer minerals. They tend to be edged by sharp ridges that in some cases terminate in sharp points, a quality much valued by the collector. Commonly, nearly spherical inclusions or nodules of iron sulfide (troilite) are found in the interiors of many iron meteorites that have a substantially lower melting point than the surrounding iron–nickel alloy. If these inclusions are near the surface, they can rapidly ablate away leaving round cavities. A most extraordinary case of pitting is found in the Goose Lake iron. Within this meteorite some of the pits have larger diameters than their openings. Just how ablation could have formed them is something of a mystery. Many believe these pits were produced by terrestrial weathering of less resistant materials (Fig. 3.6).

Fig. 3.5. These two photos show front and back sides of a Sikhote-Alin iron meteorite. The left image shows an ablated smooth surface with extensive pitting. The right image shows the opposing side where fragmentation took place near the end of the ablation period revealing parallel-running linear features typical of octahedrite meteorites. The specimen measures 11.8 × 9.5 cm. (Specimen provided by Dr David Mouat, Desert Research Institute, University of Nevada System. Photos by O. Richard Norton.)

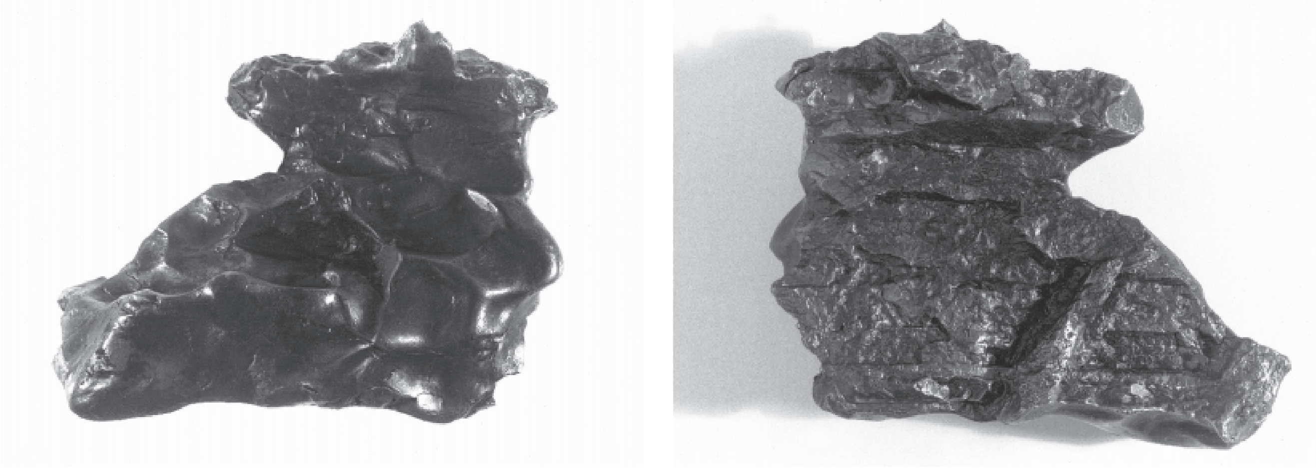

Fig. 3.6. View of a surface section of the 1169.5 kg Goose Lake iron meteorite showing deep, rounded cavities. The largest cavity shown is over 50 mm in diameter. (Photo by O. Richard Norton.)

## Oriented meteorites

During their atmospheric flight, most meteoroids tumble randomly. This tends to smooth out irregular meteorites into roughly elliptical or subspherical shapes. Many mimic the appearance of rounded riverbed stones. About 5% of all stony meteorites exhibit a symmetry that suggests they have somehow oriented themselves as they ablated. Such meteorites are referred to as *oriented*, usually having the appearance of a steep-sided cone or flattened shield. These shapes strongly suggest that the meteoroid has maintained stabilized flight through most of its visible trajectory. Meteoroids tend to orient themselves in a configuration that produces maximum drag forces. This means that a meteoroid with a flattened shape or a large flat area on an otherwise random shape will orient the flat side perpendicular to the direction of maximum drag (Fig. 3.7). This stabilizes the meteoroid and prevents tumbling. To produce the oriented shape requires that the stone remain stationary as it ablates or that it rotate about an axis perpendicular to the flat face and along its direction of motion. Once the meteoroid has attained its orientation, the front end (end facing the direction of travel) begins to experience the greatest ablation, being sculpted by the air currents flowing at hypersonic velocity around the front end. Here the material melts rapidly and flows toward the rear of the meteoroid where it accumulates, building a broad apron. At the same time, the front end or *brustseite*[1] becomes narrow, forming a symmetrical cone or in some cases, a flattened shield shape.

Orientation is more common in iron meteorites if they don't disrupt in flight. About 28% show some signs of orientation and many are nearly perfect cones or shields. The great Willamette meteorite is remarkably bell-shaped (Fig. 2.22). The stony meteorite from Adamana, Arizona, is nearly a

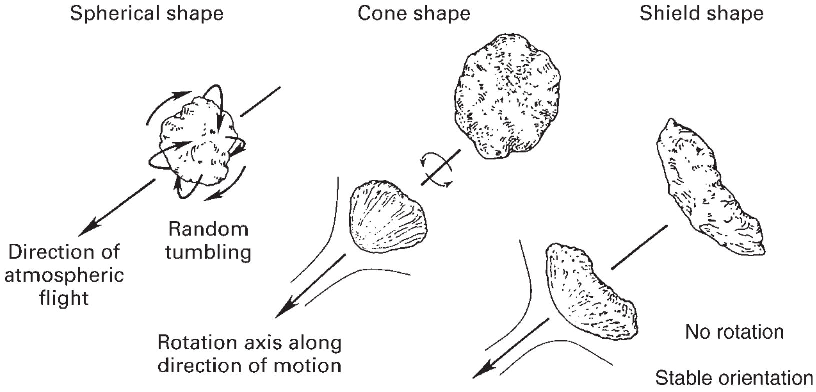

Fig. 3.7. A meteorite that stabilizes during atmospheric flight may become oriented with respect to its direction of motion. Here the flat side experiences maximum drag, causing it to orient so that it spins around its direction of travel with maximum ablation on the forward-facing side. Ablation soon forms a cone or shield shape.

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[II] The word *brustseite* is German literally translated as *breast side*, or more appropriately, *front side*. It is a seldom used term in meteoritics today but still useful when referring to oriented meteorites which in many cases mimic the shape of the human female breast.