1
Introduction

Of the approximately 40 000 tonnes of extraterrestrial material that the Earth captures annually, 1% or less is in pieces big enough for recovery by witnesses of their fall. The dust that makes up the bulk of this material comes from cometary and asteroidal sources, with a small proportion from interstellar space. Most recovered meteorites are pieces broken from asteroids and a few may be from comets. Additionally, there are >20 lunar meteorites, and >20 meteorites almost certainly are from Mars. Meteorites are classified as stony, stony iron and iron on the basis of their proportions of silicate minerals and metallic iron-nickel. A more fundamental distinction is that between the stony meteorites called chondrites and all other meteorites. This acknowledges that the chondrites, the most numerous of meteorites, have quasi-solar compositions and other properties that mark them as little-fractionated primordial materials. In contrast, other meteorites have compositions that testify to more or less extensive differentiation within their parent bodies.

1.1 The flux of extraterrestrial material

The quantity and types of natural material that fall to Earth from space are briefly summarized here. More comprehensive information is available in the series of papers edited by Peuker-Ehrenbrink and Schmitz (2001), on which this account is largely based.

As it orbits the Sun, the Earth constantly encounters solid objects, or *meteoroids*, of varying sizes. When a meteoroid enters the atmosphere, friction causes heating. The degree of heating depends on the size, velocity and angle of incidence of the incoming object. Large and fast objects with steep trajectories are heated more strongly than small, slow objects with grazing angles of entry. Most dust is heated to fusion and incandescence, producing the streaks of light that we call *meteors*. A proportion of interplanetary dust particles <100 μm in size arrives essentially unscathed and survival of some μm-sized interstellar particles that enter the atmosphere at velocities in excess of 100 km/sec is even possible (Taylor *et al.*, 1996), but none has yet been identified in collections of micrometeorites. *Micrometeorites* are smaller than 2 mm, too small to be recovered individually. During atmospheric flight the surface of a larger meteoroid, <100 tonnes, melts or boils and a bright fireball is produced. The melt and vapor are swept into the atmosphere and take the heat with them; the inside stays cold. Most meteoroids undergo fragmentation during deceleration. If material survives hypersonic flight, it falls under gravity to become a meteorite or meteorite shower. The last melt on the surface solidifies to a usually dark gray-to-black fusion crust. Most meteorites are cold when they land. They preserve records of their history in space that may span 4570 Myr (million years). Meteoroids more massive than 100 tonnes and tough enough not to fragment in the atmosphere are only partially decelerated by friction and strike the surface at hypersonic velocity. They explode on impact. The body of the meteoroid is destroyed during the excavation of an impact crater, but fragments tend to be ejected from the posterior surface. Fragments of meteorite may therefore be found on crater rims or in the surrounding terrain, but are seldom found within explosion craters. Most of the impactor is vaporized and in the absence of surviving fragments its identity may be revealed by the relative abundances of the trace elements that were injected into the impact melts beneath the crater.

Definition: a meteorite is a natural object that survives its fall to Earth from space.

The rate at which extraterrestrial material strikes the Earth bears on many geological and astronomical questions. These range from the chemical history of our planet's crust to the origin of the zodiacal light to the frequency of life-threatening impact, such as that which created Mexico's huge, buried Chicxulub structure 65 Myr ago. The flux also concerns space travellers, for whom extraterrestrial debris is a hazard. For these reasons the mean annual flux has been estimated in many ways. Estimates span six orders of magnitude, but have converged to $(10^4–10^5)$ tonnes/yr. Perhaps the most important conclusion from these diverse studies is that meteorites large enough for individual identification comprise a tiny proportion, probably $<1\%$, of the material captured by the Earth.

Some of the means used in the past to estimate meteoroid fluxes – for example extrapolation from the mass of recovered meteorites and collection of particles at, or near, the Earth's surface – are now known to be thoroughly unreliable. In recent years most studies of the total flux have been of two types: (1) measurement in terrestrial sediments of the abundances of elements or isotopes of extraterrestrial origin; and (2) detection and/or collection of particles outside the Earth's atmosphere. The meteorite flux has been independently estimated from photometry of meteorite-producing bright fireballs and from the statistics of meteorite recoveries in hot deserts and Antarctica.

Analysis of sediments deposited slowly over very long periods, for example marine clays, avoids the severe problem of industrial contamination that affected earlier studies of particles recovered from the sea floor, glacier ice and the atmosphere. Analyses of sediments, however, must be corrected for the terrestrial contribution of the element or isotope in question, and such corrections may be uncertain. A further uncertainty lies in estimating the proportion of the extraterrestrial contribution lost to the oceans by solution (Peucker-Ehrenbrink, 2001). Osmium isotopic ratios in loess deposits were used as one end-member in a model of mixing with extraterrestrial osmium in sediments. He concluded that the annual flux over the past 80 Myr was $(3.0 \pm 1.5) \times 10^4$ tonnes, the only deviation being an excess that correlates with the Chicxulub impact at the Cretaceous/Tertiary (K/T) boundary.

Particle fluxes have been measured on spacecraft since the days of the *Apollo* Moon missions. Such measurements are immune to contamination by the industrial and volcanic particles that compromise near-Earth samples, but until recently they sampled only relatively large particles. Hence most of the micrometeoroid mass distribution had to be extrapolated from relatively imprecise radar observations. This limitation has been overcome by studying impact pits on the Long Duration Exposure Facility (LDEF) satellite. The flux calculated by S. G. Love and D. E. Brownlee from the LDEF data – $(4 \pm 2) \times 10^4$ tonnes/yr – is significantly higher than earlier spcaecraft-based and meteor-based estimates and agrees with the estimate based on osmium isotopes. Additional direct measurements of the flux are reviewed by Zook (2001). He suggests that the flux essentially resides in grains with masses of $(10^{-16}$–$10^{-4})$ kg, there being a contribution from interstellar grains "with a mean mass around 3×10^{-16} kg". From estimates of impact velocity Zook argues that $<25\%$ of micrometeorites are asteroidal, the bulk being of cometary origin. In contrast, Kortenkamp *et al*. (2001) conclude that most dust in the inner Solar System is derived from families of asteroids. Some estimates of the mean annual flux on Earth, and its variations, are tabulated (table 1.1).

Discussion of the frequency of colossal, life-destructive meteoroid impacts was stimulated by the discovery of the K/T boundary event. Peaks in extraterrestrial ^{3}He in sediments have been found over (36.5–34.0) Myr and during interglacial periods of the Quaternary. The former range includes two impact craters and has been taken as indicative of an enhanced flux of long-period comets (Farley, 2001). The inferred variation in the flux in the Quaternary is only a factor of 2.5 and alternatively may be the result of terrestrial factors. There is no ^{3}He "spike" at the K/T boundary which indicates that the delivery of this nuclide to sediments differs from that of noble metals. Agreement between the short-term flux on spacecraft and the long-term flux recorded in sediments obviates the need for a random contribution from larger objects. This supports Wetherill and Shoemaker (1982), who suggested from

Table 1.1 *Estimates of the annual global flux of extraterrestrial material*

Material	Estimate	Method	Reference
Micrometeorites	$(4\pm2) \times 10^4$ tonnes	Impacts on spacecraft	Love and Brownlee (1993), see Zook (2001)
Total flux	$(3.0\pm1.5) \times 10^4$ tonnes	Ir and $^{187}Os/^{188}Os$ ratios in sediments	Peuker-Ehrenbrink (2001)
Total flux	qualitative, variable peak at 36.5 –34.0 Myr	^3He in sediments	Farley (2001)
Meteorites	4 500 falls >1 kg 13 700 falls >100 g	Photometry of bright fireballs	Halliday (2001)
Meteorites	1278–4906 falls >1 kg 4855–16863 falls >100 g	Find statistics and weathering rates in deserts	Bland (2001)

a study of near-Earth objects that impacts of meteoroids <1 km in size may be common enough to be insignificant in terms of the global flux.

Some tens of tonnes to perhaps 100 tonnes of meteorites contribute to the flux of extraterrestrial material, but of the estimated 13 700 meteorites of mass >100 g that land each year (Halliday, 2001), we normally recover only five or six. This is partly because almost three-fourths of meteorites land in the oceans and most of the rest fall in unpopulated areas which are still surprisingly widespread on our crowded planet. Another reason lurks in the word "recoverable". Although tiny, newly fallen meteorites have been recovered under unusual circumstances – the one-gram Revelstoke meteorite was found because it landed on snow – most meteorites of <100 g (about the size of a golf-ball) are lost among the rocks and soil that cover the Earth's surface. Larger meteorites, too, often pass unnoticed if they do not fall within a few hundred meters of a witness, or damage property. It is because the recovery of a newly fallen meteorite is so exceptional that big falls like Sikhote-Alin and Norton County (both 1947), Allende and Murchison (both 1969) and Jilin (1976) excite meteorite researchers and trigger years of study.

1.2 Kinds of meteoritic material

There is a rather arbitrary division of meteoritic material into micrometeorites, which are <2 mm in size, and meteorites, which are >10 mm. The former are recovered collectively from deep-sea sediments, from melted Antarctic or Greenland ice, or by trapping in the stratosphere. In contrast, meteorites are usually identified and collected individually, although a number of spatially associated objects may have resulted from a multiple fall. Ten millimeters is about the smallest size of meteorite that can be visually identifed from several meters distance on ice or in favorable conditions in a hot desert. There is, therefore, a hiatus between about 2–10 mm in the size distribution of meteoritic material in collections.

1.2.1 Meteorites

These are assigned to three categories on the basis of their contents of two kinds of material, metallic iron-nickel and silicates. *Iron* meteorites consist almost wholly of metal and *stony* meteorites principally of silicates. *Stony irons* contain roughly equal proportions of metal and silicates. In old literature these may be referred to as *siderites*, *aerolites* and *siderolites*, respectively. A few meteorites lie near boundaries between these categories and some cross them (for example, stony irons, some samples of which are almost pure metal), but the basic classification is serviceable. Each major category has many subdivisions, but we shall consider only the most important of them in this section.

The gross classification of meteorites, summarized in table 1.2 below, has changed little since the nineteenth century, but our understanding of their relationships has changed a great deal. One major advance, even since Dodd (1981), has been the increasing use of oxygen isotopic ratios to identify groups of meteorites, or the components of meteorites, that formed from the same "parcels" of Solar System matter. We have known for some time that the distinction between chondrites and other meteorites is fundamental. The chondrites, which are far more numerous among observed falls than all other meteorites combined (table 1.2), have chemical compositons that closely resemble that of the volatile-free Sun. They are, therefore, regarded as chemically *primitive*, in contrast to other meteorites and, indeed, to all known Earth or Moon rocks which are *differentiated* materials whose distinctly non-solar compositions testify to melting, crystallization and other chemical processes. A further advance since 1981 is the separation, from rare chondrites in the laboratory, of mineral grains whose isotopic compositions are thought to record nuclear processes in stars. Chondrites have yielded stardust that has remained unaltered since it was injected into a protosolar molecular cloud. By contrast, differentiated meteorites, like the rocks that make up the Earth and Moon, have experienced processes which obliterated the record of their earlier history.

Of the two kinds of stony meteorites, *chondrites* are by far the more numerous. They take their name from *chondrules*, generally mm-sized, near spherical masses of silicates, more rarely of metal and/or sulfide, that are present in most chondrites and the most abundant objects in many of them (fig. 1.1). The textures of chondrites indicate that they have not melted since they formed by the accretion of their different constituents. Chondrites are so numerous and so philosophically important that they will hold our attention throughout much of this book. We discuss their

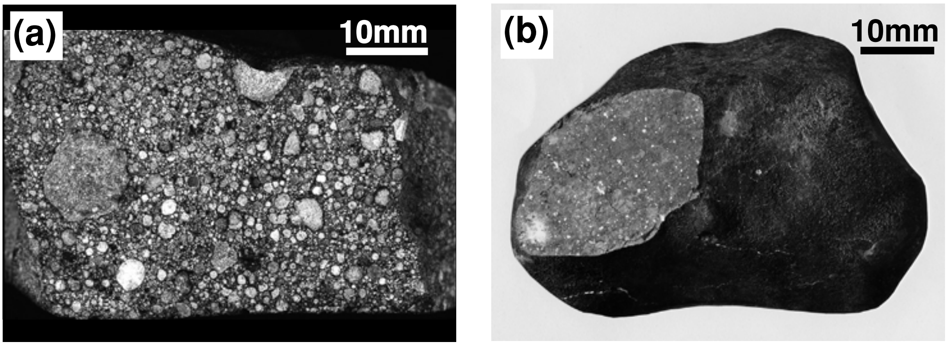

Fig. 1.1 Ordinary chondrites: The most common type of meterorite.
Composed of silicates, with lesser amounts of Fe, Ni metal and troilite, FeS, they have quasi-solar compositions and have not melted since their formation 4560 million years (Myr) ago.
(a) Bishunpur, LL3.1: Polished surface with abundant subspherical silicate chondrules set in dark matrix. © The Natural History Museum, London.
(b) Siena, LL5: A stone of the shower that fell in Italy in 1794. Rare, shiny flecks of metal are visible on the polished face. The stone is coated by a matt black fusion crust that formed by solidification of the last melt that was produced by frictional heating in the atmosphere as the stone slowed to subsonic velocity. Meteorites normally are named after a place near their landing site, Bishumpur in India or Siena in Italy. © The Natural History Museum, London.

classification in chapter 2, their components in chapter 3, the three main classes of chondrites – carbonaceous, ordinary and enstatite – in chapters 4 and 5, their chronology in chapter 6 and their formation processes in chapter 7.

Achondrites are stony meteorites that lack chondrules and most are chemically dissimilar to chondrites. Achondrites range from rare, partially melted, strongly recrystallized chondrites to more numerous igneous rocks (fig. 1.2) and mechanical mixtures (*breccias*) of igneous fragments derived from them. These meteorites are diverse objects comprising almost pristine chondrites to monomineralic rocks similar to terrestrial dunites or pyroxenites and rocks that resemble basalts in texture and mineralogy. The genetic affinities of achondrites are diverse also. Some are related to stony irons, others to certain types of chondrites, yet others are from the Moon and, probably, Mars. A few have no known relatives. The classification of achondrites is introduced in chapter 8, continues through chapter 9 and their genetic relationships are discussed in chapter 11.

Almost all iron meteorites, one of which is shown in fig. 1.3, have a characteristic texture that is revealed by polishing, then etching with acid. This is the Widmanstätten pattern, an intergrowth of two Fe,Ni alloys with different crystal structures and different Ni contents. Bulk Ni content and thermal history controlled the degree of development and coarseness of the Widmanstätten pattern and textural properties have been used to assign the irons into three major classes and

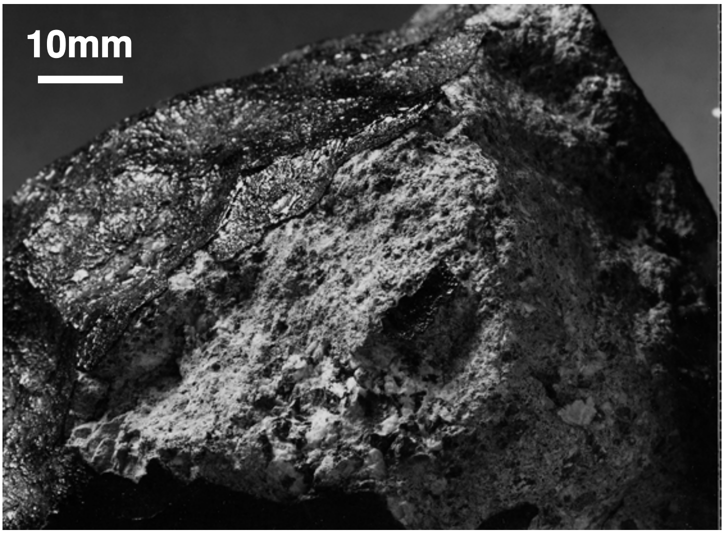

Fig. 1.2 Sioux County eucrite: one of a shower of stones that fell in Nebraska in 1933.
This basaltic meteorite is composed of fragmented rock and mineral grains produced by melting on an asteroid. One fragment, bottom center, is an intergrowth of white feldspar and dark pyroxene. The shiny black fusion crust, upper left, is typical of such meteorites. © The Natural History Museum, London.

some smaller ones. More fundamentally significant, however, is the subdivision of the irons into 12 groups on the basis of trace element contents (chapter 10). Most stony irons belong to one or other of two chemically and texturally distinct kinds of meteorites. *Pallasites* (fig. 1.4) consist of crystals or crystal fragments of magnesian olivine ($[Mg,Fe]_2SiO_4$) in a continuous matrix of metallic Fe,Ni. *Mesosiderites* (fig. 1.5) are more or less recrystallized mechanical mixtures of silicates and metal. The mesosiderites and pallasites are related to a major group of stony meteorites and to a major group of iron meteorites. The origin and early history of these related groups, which comprise a *petrogenetic association*, are discussed in chapter 11.

1.2.2 Micrometeorites

Micrometeorites were discovered by the "Challenger" oceanographic expedition in the 1870s and correctly identified as extraterrestrial. These *cosmic spherules* were extracted from clays from the deep oceans. Sources and collecting methods of micrometeorites are succinctly reviewed by Taylor and Lever (2001). D. E. Brownlee recovered large numbers of micrometeorites from the central Pacific by towing a magnetic rake over the ocean bottom. Concentrations of micrometeorites with algae, *cryoconite*, have been obtained from pools of melt water on the Greenland

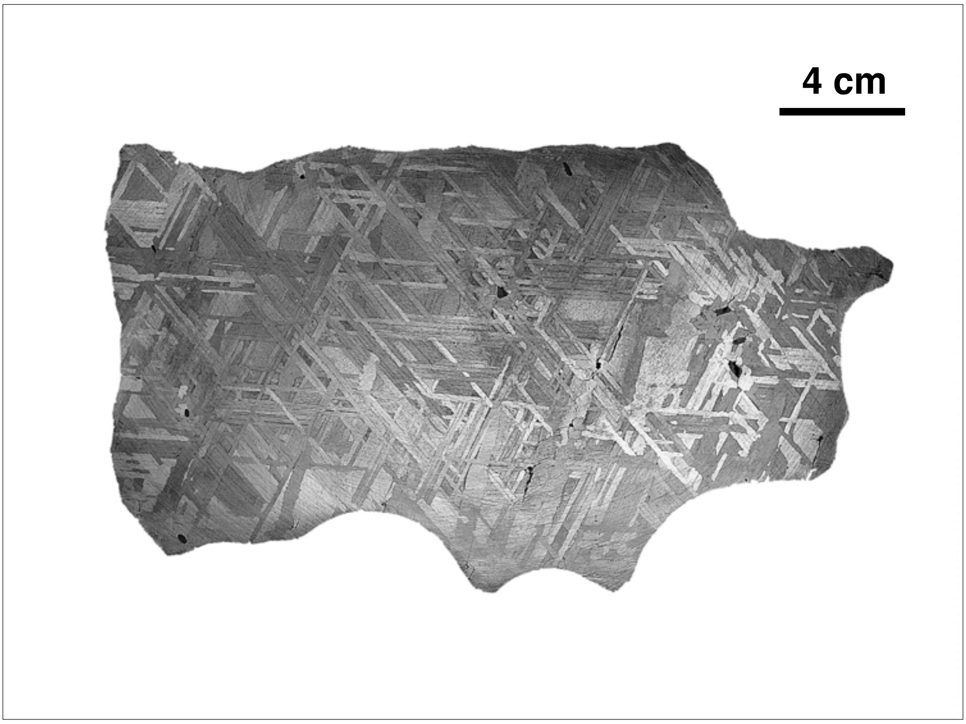

Fig. 1.3 Henbury iron meteorite: Polished and etched face.
The criss-cross structure is an intergrowth of two Fe,Ni alloys, know as the Widmanstätten pattern, that is present in most iron meteorites. The Henbury iron exploded on impact about 5000 years (5 kyr) ago as it formed a group of craters in Northern Territory, Australia. The bulk of the iron vaporized on impact, but some fragments were scattered around the craters. © The Natural History Museum, London.

ice cap. By melting 100 m^3 of Antarctic ice and filtering the water, M. Maurette and colleagues recovered some 20 000 micrometeorites. Another large collection came from the water well at the South Pole scientific station.

From each source, the micrometeorites range upwards in size from 50 μm to 2 mm. There is a broad correlation between size and the degree of heating undergone by a micrometeorite during atmospheric entry. The smaller the size the greater likelihood that the object radiated away frictional heat and hence remained unmelted. Larger micrometeorites are more likely to be scoriaceous in texture as a result of incomplete melting and frothing, while cosmic spherules suffered complete melting. All micrometeorites appear to have been altered or contaminated to some extent during their sojourn in the atmosphere or by their immersion in fresh or salt water or in ice. Those from the polar regions are the least altered.

Since the mid-1970s, micrometeorites have been collected in the stratosphere by specially adapted aircraft operated by NASA. While cruising at 20 km altitude

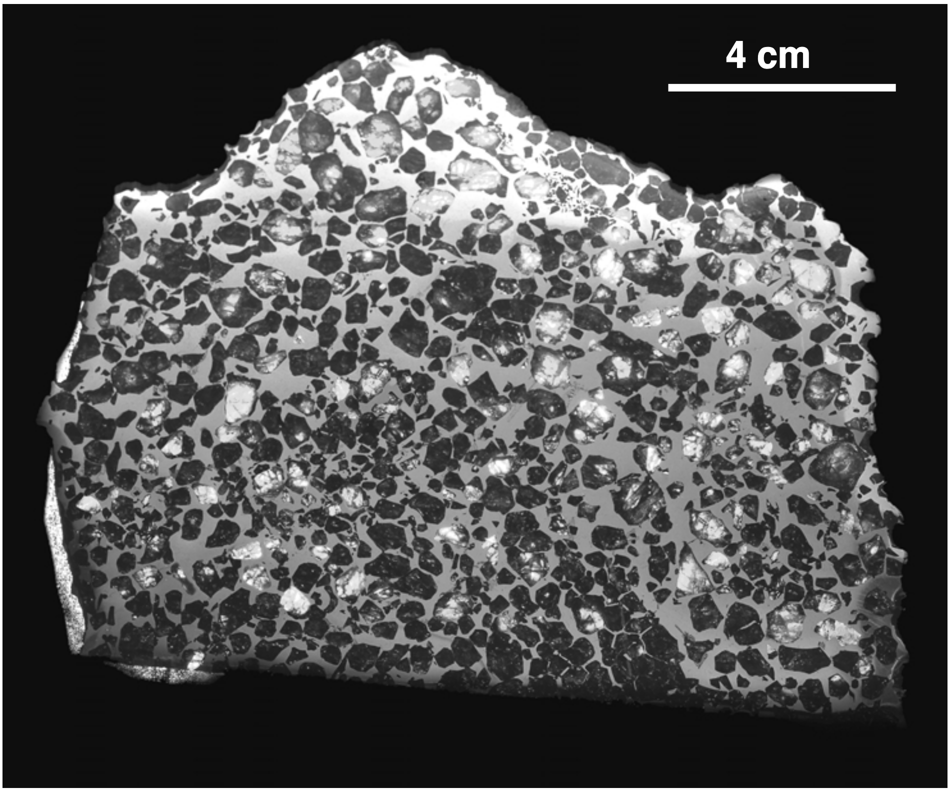

Fig. 1.4 Esquel, Argentina, pallasite: polished face of this stony iron meteorite. Pallasites formed when molten Fe,Ni metal was gently injected into a coarse granular mosaic of olivine grains. This is part of a slice cut from a 1.5 tonne mass found in 1951. © The Natural History Museum, London.

the aircraft deploy panels coated with silicone grease, to which dust particles stick. Before descending, the panels are retracted to avoid contamination with terrestrial dusts. In clean conditions in the laboratory the panels are washed with freon to dissolve the silicone and allow the dust particles to be filtered out. The interplanetary dust particles (IDPs, or *Brownlee particles*) thus obtained range from 1 to 40 μm in size, but most are 5–20 μm and many suffered little atmospheric heating. Most IDPs are of silicate and roughly half are dry and porous, the remainder being hydrated and non-porous. Their mineralogical and isotopic properties indicate that the porous, anhydrous IDPs constitute a population of extraterrestrial material that differs from larger micrometeorites and from meteorites. Porous, anhydrous IDPs may be the only sample of cometary material currently available for study on Earth.

Some micrometeorites and IDPs have affinities with carbonaceous or ordinary chondrites, but micrometeorites are important in their own right and are not considered further in this book. The interested reader may consult Rietmeijer (1998) for

Fig. 1.5 Mincy, Missouri, mesosiderite: polished face.
Mesosiderites are stony iron meteorites that are the result of violent mixing of Fe,Ni metal with basaltic material and nodules of olivine. They are genetically related to eucrites, pallasites and iron meteorites such as Henbury. © The Natural History Museum, London.

a review of IDPs or papers 1–9 and 12 in Peuker-Ehrenbrink and Schmitz (2001) for coverage of the field as a whole.

1.3 Sources of meteorites

Before the first *Apollo* lunar landing, the Moon, the asteroids (or minor planets) and comets were thought to be the most likely sources of meteorites. The Moon seemed particularly attractive as the parent of the basalt-like achondrites because Earth-based observations of our satellite's dark lowlands, or maria, suggested that they are basaltic lava plains. This was confirmed by samples returned by the American *Apollo* and Soviet *Luna* missions, but the lunar samples differ significantly in chemistry, age and oxygen isotopic composition from the basalt-like achondrites, which rules out a common source. We know that we do have lunar meteorites, most of which came from the light-colored highlands rather than the dark maria. Basalt-like achondrites are samples of two other parent bodies. One probably is a large asteroid, the other almost certainly is Mars.

From the direction and velocity of their associated fireballs we know that a handful of chondrites had orbits like those of Earth-crossing asteroids. The reflectance spectra of asteroidal surfaces and estimates of the densities of asteroids support the view that most meteorites came from them. Originally, however, there appeared to be a dynamic difficulty in transferring large amounts of material from