Types of Extraterrestrial Material Available for Study

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There is a vast range of extraterrestrial materials available for study: meteorites (asteroidal, lunar, and martian, possibly cometary), micrometeorites and interplanetary dust particles (asteroidal and cometary), and Apollo and Luna samples. We review source objects for various materials. We relate meteorites, and components separated from them, to stages of solar system evolutionary history, from condensation of primordial solids through aggregation, alteration, differentiation, and brecciation. We also consider the presolar history of grains from interstellar and circumstellar environments. The hierarchy of discrete components is intimately intertwined with the parent object categories, as the parent objects all carry material from a variety of sources and processes. These materials can be studied with an enormous variety of analytical techniques and instrumentation. We also briefly discuss source objects that have the potential to yield material for analysis, but have not yet been recognized as having done so (Venus, Mercury), and the outward signs of planetary impacts (craters, tektites).

1. INTRODUCTION

There is a vast range of extraterrestrial material available for investigation. A brief summary of that which is most readily recognized includes meteorites (asteroidal, lunar and martian, plus possibly cometary), micrometeorites (asteroidal and cometary), and Apollo and Luna samples. The purpose of this introductory chapter is to outline the research potential that the material represents. A traditional view is that meteorites are subdivided into stones, stony-irons, and irons, and that these different groups yield information about early solar system and planetary history. And that is a useful description. But increasing numbers of meteorites available for laboratory analysis, coupled with high-precision instrumentation capable of measuring ever-more specific areas or zones within meteorites, have redefined the ways in which we interpret the data now available to us. We use meteorites, and components separated from them, to follow all stages of solar system evolutionary history, from condensation of primordial solids, through aggregation, alteration, differentiation, and brecciation. We can also trace the presolar history of subsets of grains. Interplanetary dust particles (IDPs) collected from the stratosphere are frequently highly porous, fragile aggregates (<10 μm in diameter) of anhydrous minerals believed to come from comets. We have no other material that, with any such certainty, could be taken as cometary. Hydrated IDPs, and the larger micrometeorites (<500 μm diameter) collected from polar meltwater, are asteroidal, and might sample regions of the asteroid belt not supplied to Earth as meteorites. We can use extraterrestrial material to place our solar system into the wider context of the astrophysical evolution of the local galactic neighborhood. In order to achieve this goal, extraterrestrial materials are investigated using a range of complementary techniques, both space- and groundbased. This chapter will provide a very brief overview of what extraterrestrial materials are available for study, what their source regions are, and the types of investigations applied to them. We also attempt to place the different extraterrestrial materials in the approximate context of their astrophysical evolution, as detailed in other chapters in this volume.

2. TOOLS FOR THE STUDY OF EXTRATERRESTRIAL MATERIALS

2.1. Remote Measurements

Much of the discussion in this volume is based on results from laboratory-based studies of meteorites; however, it is useful to summarize the other types of observations and measurements that can be applied to extraterrestrial materials. At the very least, it helps place meteorites in their correct scientific context within the exploration of the solar system and beyond. It also helps to provide a bridge between the different communities of scientists who study extraterrestrial objects.

2.1.1. Telescope instrumentation. The acquisition of images and spectral data from both space- and groundbased telescopes is an important complement to laboratory data. Images from the Hubble Space Telescope (HST) have by themselves served to revolutionize our understanding and appreciation of the universe that we inhabit. Solar system objects (comets, asteroids, and planets and their satellites) are regularly observed by telescopes. Observations of star formation and of the presence and structure of protoplanetary disks around young stars have informed models of grain growth, disk formation, and evolution (e.g., *Throop et al.,* 2001). Spectral measurements across a range of wavelengths, and perhaps most particularly in the infrared (first by the Infrared Astronomical Satellite, then the Infrared Space Observatory, and currently the Spitzer Space Telescope), have also brought about a fresh understanding of the properties of dust grains in different astrophysical sites. The identification of crystalline, rather than amorphous, silicates, plus recognition of silicate compositional variations in the dust around stars (e.g., *Molster et al.,* 2002), have strengthened links between astronomical and laboratory measurements. Instruments on groundbased telescopes have also contributed to understanding of our solar system evolution, with observations of planet-forming disks (e.g., *Greaves et al.,* 1998; *Wahhaj et al.,* 2003), discoveries of extrasolar planets (e.g., *Mayor and Queloz,* 1995), asteroid observations (e.g., *Bus et al.,* 2002), and measurement of micrometeoroid flux [e.g., the radar observations described by *Meisel et al.* (2002)]. As new generations of groundbased telescopes, with large collecting surfaces and adaptive optics, are developed, such contributions can only become increasingly frequent.

2.1.2. Orbiting (and flyby) spacecraft. In the 15 years since *Meteorites and the Early Solar System* was published (*Kerridge and Matthews,* 1988), we have become much more familiar with the surface landscapes of many of the bodies within the solar system as a result of the high-quality, high-resolution images taken by a variety of spacecraft. Magellan at Venus (e.g., *Saunders et al.,* 1992); Clementine and Lunar Prospector at the Moon (e.g., *McCallum,* 2001); Mars Global Surveyor (e.g., *Albee et al.,* 1998), Mars Express (e.g., *Chicarro,* 2004), and Mars Odyssey at Mars (e.g., *Saunders et al.,* 2004); Near Earth Asteroid Rendezvous (NEAR) at asteroid 433 Eros (e.g., *Veverka,* 2002); Galileo at Jupiter (e.g., *Young,* 1998); and Cassini at Saturn (e.g., *Porco et al.,* 2005) have all been instrumental in giving us new perspectives on our neighbors. Imagery has been complemented by radar, spectral, and magnetic surveys, allowing understanding of planetary structure, surface composition, and atmosphere. Dust fluxes in space have been measured by spacecraft on their way to other destinations, including Galileo (*Grün et al.,* 1992), Ulysses (*Grün et al.,* 1992, 1993), Cassini (*Altobelli et al.,* 2003), and Stardust (*Tuzzolino et al.,* 2003).

2.1.3. Landing spacecraft. Apart from the Moon, only Mars, Venus, Saturn's giant satellite Titan, and a single asteroid have had craft land on their surfaces. In the past 15 years, 11 spacecraft have been launched to Mars, 7 of which carried landers; unfortunately, only 3 (Pathfinder, Spirit, and Opportunity) landed successfully. Even so, we have made great strides in our comprehension of surface processes on the Red Planet. Landing on Venus is an even greater challenge than Mars, and nothing has been attempted since the Soviet lander, Venera 14, spent 60 minutes on the venusian surface in 1982 before failing (e.g., *Moroz,* 1983). The Huygens probe descended through Titan's thick and cloudy atmosphere, revealing tantalizing glimpses of a landscape apparently carved by rivers (possibly of methane) and icy boulders covering an icy surface (*Lebreton et al.,* 2005). The NEAR probe made a successful, controlled descent to the surface of 433 Eros, taking the closest images that we have of an asteroid surface (e.g., *Veverka et al.,* 2001). While not technically a "landing," the Galileo mission sent a probe down through Jupiter's atmosphere in 1995, sending back data on the composition and structure of the gas giant (e.g., *Young et al.,* 1996).

2.1.4. Sample return. The next stage, relating remote observations to laboratory analyses, has to be through direct sample return. Lunar samples (totaling almost 300 kg) from the Apollo and Luna missions have been available for analysis for over 30 years. Missions are in progress to collect material from additional sources, although at a much reduced weight level (picograms to micrograms). Genesis, a mission to collect samples of the solar wind, returned to Earth in September 2004; although the landing was less successful than planned, it is anticipated that almost all the mission science will be recoverable. Stardust, the mission to Comet Wild 2, will return cometary, interplanetary, and interstellar dust in 2006, and Hayabusa, the mission to asteroid Itokawa, will bring back a sample of the asteroid in 2007. Beyond these missions, both the European Space Agency and NASA are planning martian sample return missions within the next decade. The much lower masses of returned material required for analysis from post-Apollo missions are a result of major advances in the sensitivity, precision, and resolution of analytical instrumentation.

2.2. Direct Measurements

Direct analysis of an extraterrestrial sample begins with a preliminary low-resolution optical study. In other words, someone looks at it! While this is painfully obvious, it is a necessary first step, and serves to distinguish between metallic and stony objects. The presence of fusion crust shows the freshness, or otherwise, of a fall, while its texture (glossy or matte) can help distinguish between melted and unmelted stones, and its degree of completeness can indicate whether the meteorite is a complete stone, or part of one that broke on impact. The occurrence and extent of weathering rind, surficial evaporates, oxide veining, and rusting also give some idea of the terrestrial environment in which the meteorite has resided prior to collection.

Following preliminary examination, almost any and every analytical method known to scientists has been used to analyze extraterrestrial materials. Texture and mineralogy is determined by conventional thin-section techniques, after which structure and major, minor, trace-element, and isotopic chemistries are determined using a vast range of instrumentation. Techniques include optical and electron microscopy; electron, ion, proton, and X-ray probes; stable and radioactive isotope and organic mass spectrometry (using thermal, resonance, acceleration, or plasma ionization); and optical, infrared (IR), ultraviolet (UV), Mössbauer, nuclear

TABLE 1. Sources of extraterrestrial material.

Source	Material	Epoch
Sun	Meteorites; lunar material (Apollo, Luna, meteorites)	Planetary
Moon	Lunar material (Apollo, Luna, meteorites)	Planetary
Earth	Craters; tektites	Planetary
Mars	Meteorites	Planetary
Asteroids	Meteorites	
	Unmelted	Nebular
		Accretionary
		Parent-body epoch A (aqueous and thermal alteration)
	Melted	Parent-body epoch B (differentiation and core formation)
	Brecciated	Planetary
Comets	IDPs	Nebular
Extrasolar	Meteorites, IDPs	Presolar

magnetic resonance (NMR), and Raman spectroscopy — the list is almost endless. And these instruments are becoming increasingly precise, using ever smaller amounts of material, allowing subtle effects of zonation, overgrowths, and alteration to be traced.

3. PARENT OBJECTS

If all the observational and analytical techniques outlined above were brought into play, there would be very few extraterrestrial materials *not* available for study. However, we will confine our discussion to physical samples that can be examined in the laboratory. So, what sort of parent objects are we considering (Table 1)?

3.1. Asteroids

Most of the extraterrestrial materials that we study come from the asteroid belt, a region of space between about 2 and 4 AU from the Sun. The belt is not an homogeneous array of asteroids. Rather, the objects within it are from groups of varying composition — metallic and nonmetallic, melted and unmelted. There are many different classes based on asteroid composition (from reflectance data) — a recent compilation recognizes 26 separate groups (*Bus et al.,* 2002). Asteroids are not expelled at random from within the asteroid belt, but through a combination of gravitational, collisional, and thermal radiation effects, drift into specific regions, or resonances, from which they are subsequently ejected. The meteorites that fall on Earth, then, are an incomplete sample of the asteroid belt, probably sampling <2% of the cumulative surface area of the asteroids, albeit distributed over several broad regions (e.g., *Farinella et al.,* 1993; *Bottke et al.,* 2002). The asteroidal origin of meteorites is inferred from their ancient age, and deduced by observation. Two classes of observation link meteorites to asteroids. Spectral reflectance measurements of asteroidal and meteorite surfaces give a close match for asteroids and meteorites of a variety of classes [e.g., basaltic achondrites match closely to Vesta (*Burbine et al.,* 2001); carbonaceous chondrites match C-class asteroids (*Burbine et al.,* 2002)]. There are, however, paradoxes in this comparison, in that the largest group of stony meteorites, the ordinary chondrites, has no good spectral match with any common asteroidal class (*Binzel et al.,* 1998). Additionally, the asteroid for which we have the best surface composition, the S-class 433 Eros, might be an altered ordinary chondrite, or, less plausibly, a primitive achondrite (*Nittler et al.,* 2001). Space weathering has been proposed as an explanation for the dichotomy; further remote observations and an asteroid sample return mission are required for successful resolution of the puzzle (*McCoy et al.,* 2001).

The second method for linking meteorites with asteroids rests on observations of incoming fireballs and the ability to track their trajectory and thus calculate an orbit for the meteoroid (*Halliday et al.,* 1996). This has been undertaken successfully for about half a dozen specific meteorites, all of which have been shown to follow orbits that have their apogee within the asteroid belt. It is not possible to link specific meteorites with specific asteroids. Automatic camera networks have the potential to photograph incoming objects, allowing the subsequent recovery of newly fallen meteorites that would otherwise have become lost (e.g., *Bland et al.,* 1999).

3.2. Comets

There are two possible reservoirs of cometary material available for study, one that is widely accepted as cometary, the other more problematic. The former is the reservoir derived from interplanetary dust particles (IDPs) — numerous measurements using a variety of techniques have indicated that anhydrous, C-rich IDPs are likely to be cometary in nature (e.g., *Bradley and Brownlee,* 1986; *Thomas et al.,* 1993; *Bradley,* 2003). More problematic is whether there are any meteorites that might be derived from comets. Each time a comet makes its periodic visit to the inner solar system, more of the ice that comprises a substantial fraction of the cometary nucleus sublimes, releasing dust and gas to form a spectacular tail. Eventually, as more and more material is lost from the nucleus, the cometary orbit decays, and the comet falls into the Sun. Images from the Solar and Heliospheric Observatory (SOHO) satellite have shown that fragmentation and erosion of Sun-grazing comets are relatively common occurrences (*Sekanina,* 2003). However, it is conceivable that a cometary nucleus might fall to Earth and be collected as a meteorite (e.g., *Anders,* 1975). *Campins and Swindle* (1998) reviewed the likely features of cometary meteorites, and concluded that no single known meteorite group matched all the characteristics. They also discussed the possible presence of cometary material as xenoliths within unequilibrated meteorites, a suggestion that has been pursued by analysis of the Krymka unequilibrated ordinary chondrite (*Semenenko et al.,* 2003).

3.3. The Moon

The Moon has been a source of extraterrestrial materials for laboratory study ever since the return of samples from the Apollo 11 mission in 1969. Material collected by astronauts is available from the six Apollo missions (~382 kg) and the three robotic Luna probes that returned material: Luna 16, 20, and 24 (~0.3 kg). Much of the Apollo and Luna material is regolith soil of varying composition, containing a variety of clast types (e.g., *Korotev,* 1998a,b, 2001; *Papike et al.,* 1998). A new source of lunar material became available to the community in the early 1980s — that recovered on Earth as lunar meteorites. Since recognition of ALHA 81005 as a lunar meteorite in 1982 (*Score and Mason,* 1982; *Bogard,* 1983), many fragments of lunar meteorites have been found by meteorite recovery programs; the Sahara and Oman Deserts seem to be particularly fruitful search areas. Although the arrival of lunar meteorites is a haphazard process, with no specific region of the Moon being sampled in any systematic fashion, lunar meteorites have extended the range of lunar materials available for study (e.g., *Warren et al.,* 1989). They are frequently fragmental breccias, containing clasts of unusual basalts not previously identified in any catalog of lunar samples (e.g., *Korotev,* 1999). The most comprehensive and up-to-date list of lunar meteorites is maintained by R. L. Korotev at Washington University (*http://epsc.wustl.edu/admin/resources/meteorites/moon_meteorites_list.html*).

3.4. Mars

Unlike the Moon, no samples have (as yet) been returned directly from Mars, either by robotic probe or astronaut; since the earliest martian sample return mission is not set to launch until after 2010, we are likely to be closer to the production of *Meteorites and the Early Solar System III* than the current volume before any such samples do come back. We are, however, in receipt of a number of martian meteorites that sample a variety of igneous rock types (e.g., *Meyer,* 2003). A rationale for the martian origin of the rocks has been rehearsed many times (e.g., *McSween,* 1985), but a précis of the explanation is that the meteorites have crystallization ages younger than asteroids (e.g., *Nyquist et al.,* 2001), and that many of them contain pockets of melt glass in which martian atmospheric gases have been trapped (*Bogard and Johnson,* 1983). The assumption that these meteorites are from Mars is now widely accepted. The original three groups, shergottites, nakhlites, and Chassigny, have been supplemented with the orthopyroxenite ALH 84001. Shergottites have also been subdivided into basalts and lherzholites (*McSween,* 1994), with a recent suggestion that there might be a third subdivision, olivine-phyric shergottites (*Goodrich,* 2003). Although the martian meteorites are all igneous rocks, they have varying crystallization histories, and have been used to explore planetary processes on Mars. Petrogenetic analysis of the shergottites has allowed development of theories of basaltic fractionation and crystallization on Mars during magma genesis (e.g., *McCoy et al.,* 1992; *Wadhwa et al.,* 1994; *Borg et al.,* 2002; *Goodrich,* 2003). The recognition of complex assemblages of secondary minerals (halite with carbonates and clays) in nakhlites has led to interpretation of the scale and mode of fluid flow on the surface of Mars (e.g., *Bridges and Grady,* 1999, 2000). Although the "life on Mars" question continues to be debated quite actively, the identification of structures argued to be the fossilized remains of martian micro-organisms in ALH 84001 (*McKay et al.,* 1996) does not attract much support: *Treiman* (1998, 2003) presents a viewpoint that is held by many professional meteoriticists.

3.5. Nucleosynthetic Sites

Materials that originated in several different nucleosynthetic sites are to be found within primitive chondrites; they are present at levels of a few parts per billion to parts per million. The grains have generally been isolated through vigorous and lengthy acid-dissolution procedures (e.g., *Amari et al.,* 1994; *Lewis et al.,* 1994), thus they are very refractory materials. Because of the nature of the preparation procedures, any presolar silicates were destroyed during isolation of the refractory species; more recent developments in analytical techniques have allowed presolar silicates to be identified *in situ* in IDPs and meteorites (*Messenger et al.,* 2003; *Nagashima et al.,* 2004). The most abundant materials that have been identified as presolar include silicon carbide (SiC), graphite, diamond, and oxides. Less-abundant grains include nitrides. Specific types of grains and their characteristics are outlined below; here, we give a very brief summary of the parent objects from which they are likely to be derived. The presolar cloud has been the recipient of material from a multitude of sites; on the basis of their isotopic compositions, the grains may be assigned to specific astrophysical locations.

Nanodiamonds are generally assumed to be the most abundant of the presolar grains found in meteorites, present in concentrations of several hundred parts per million in CI1 and CM2 chondrites (e.g., *Huss and Lewis,* 1995; *Russell* *et al.,* 1996a). Although their precise origin is not fully understood, the nanodiamonds are presumed to have formed by chemical vapor deposition in the expanding shell of a type II supernova (*Clayton et al.,* 1995) with heavier elements produced by the r- and p-processes (e.g., *Ott,* 2003), then trapped by ion implantation (e.g., *Koscheev et al.,* 2001). Diamonds have also been observed in the dusty disks around stars (e.g., *Van Kerckhoven et al.,* 2002), implying possible circumstellar, as well as interstellar, origins. However, in contrast, there is some evidence, based on the relative abundances of nanodiamonds in meteorites and IDPs, that not all the nanodiamonds are presolar (*Dai et al.,* 2002).

Presolar graphite comprises ~2 ppm of CM2 chondrites (*Anders and Zinner,* 1993); transmission electron microscopy (TEM) and Raman spectroscopy of presolar graphite show that it exhibits a range of crystallinities, from poorly graphitized carbon to well-crystalline graphite (*Bernatowicz et al.,* 1991; *Zinner et al.,* 1995). The precise origins of presolar graphite are the least well understood of all the "exotic" grains. Possible sources for different groups of graphite include an ONe nova explosion (*Amari et al.,* 2001), He-burning in Wolf-Rayet stars or type II supernovae (*Anders and Zinner,* 1993; *Hoppe et al.,* 1995), or ion-molecule reactions in molecular clouds (*Zinner et al.,* 1995). Meteoritic SiC grains have also emanated from several different astrophysical environments, including low-mass AGB stars, J- and R-type carbon stars, and ejecta from type II supernovae (e.g., *Alexander,* 1993; *Anders and Zinner,* 1993; *Hoppe et al.,* 1996; *Zinner,* 1997). However, most SiC grains (~90% of the total) belong to a single population, thought to be synthesized in an expanding envelope around thermally pulsing low-mass asymptotic giant branch (AGB) stars (e.g., *Anders and Zinner,* 1993; *Hoppe et al.,* 1996).

As well as inorganic species, organic presolar grains are present, mostly in CM and CI chondrites (e.g., *Sephton and Gilmour,* 2000). They are presumed to be species produced by ion-molecule reactions on grain surfaces in the interstellar medium (*Ehrenfreund and Charnley,* 2000). Remnants of such interstellar material have also been identified in IDPs (*Messenger,* 2000).

One of the most exciting and philosophically rewarding results of separation and analysis of presolar grains from meteorites has been the dialogue that this has enabled between astronomers, astrophysicists, and meteoriticists, and the fresh understanding the results have given to nucleosynthetic processes during stellar cycling. Astrophysicists can now constrain their theoretical calculations using real data obtained on components from stars at different stages of their lifetimes. Likewise, results from presolar organic components can be used to constrain the thermodynamics of ion-molecule reactions in the interstellar medium.

3.6. The Sun

The Sun is a source of material for laboratory investigation, although perhaps only indirectly. Samples from the Sun are preserved, implanted within surfaces that have been exposed to the solar wind (SW) and to solar energetic particles (SEP). The composition of the present-day SW is well known from analysis of foils exposed at the lunar surface during the Apollo missions (*Geiss et al.,* 2004). The Moon has been a major source of SW-bearing materials. The lunar regolith has provided samples of both the current and ancient SW, and attempts have been made to use Apollo samples of varying antiquity and maturity to trace variation in SW through time (e.g., *Becker and Pepin,* 1989; *Wiens et al.,* 2004a,b). Meteorite regolith breccias have also contributed to understanding of the SW; gas-rich breccias record implanted SW and SEP (e.g., *Pedroni and Begemann,* 1994). More recently, the Genesis mission exposed a variety of pure collector materials to the SW for 2.5 years (*Burnett et al.,* 2003) in order to obtain sufficient material for precise elemental and isotopic compositional determination.

3.7. Additional Sources of Extraterrestrial Material?

Thus far, we have discussed source objects that we know have supplied extraterrestrial material to Earth. But there are other potential reservoirs of extraterrestrial specimens, not all of which are necessarily recognized by conventional wisdom as being bona fide sources. In this section we will consider, in an increasingly speculative fashion, what other materials might be, or might become, available for study.

3.7.1. Extraterrestrial "meteorites." The strict definition of a "meteorite" refers to a naturally occurring sample of extraterrestrial material that has fallen to Earth. Analogous specimens have been identified within samples collected from the Moon (e.g., *Anders et al.,* 1973; *McSween,* 1976; *Rubin,* 1997) and given the name of the locality from which they were collected. Pictures of the surface of Mars show landscapes strewn with rocks, and in January 2005, the Opportunity rover took images of an iron meteorite. This first meteorite to be recorded on Mars' surface has been given the rather uninformative name "Heat Shield Rock" (*Jet Propulsion Laboratory,* 2005). We do not know what proportion of martian surface rocks are likely to be samples of asteroids (or indeed the Moon or even Earth). The statistics of this particular problem have been considered by *Bland and Smith* (2000). Ordinary chondrites are the most numerous type of meteorite on Earth; it would be unfortunate if the first-ever sample returned from Mars by a space mission turned out to be an ordinary chondrite.

3.7.2. Space debris. Artificial space debris includes micrometer- to millimeter-sized particles from solid fuel rocket motors, flakes of paint, globules of sodium from coolant systems, fragments of craft destroyed by impacts or explosions, and frozen astronaut urine from early space missions (*Graham et al.,* 1999, 2001). As more satellites are launched into orbit, it is apparent that the flux of artificial space debris will increase, providing not just a greater hazard to orbiting craft and astronauts, but also interfering with the collection of natural micrometeoroids. On a larger scale, space debris also encompasses the hulks of satellites and rocket stages long since forgotten in terms of their primary missions. Because of the inherent dangers of space debris to future missions, communications satellites, and astronauts, the orbits of all pieces greater than a few centimeters in size are monitored (e.g., *Africano and Stansbery,* 2002). It has been argued that such objects should be preserved in space as part of our cultural heritage (e.g., *Gorman,* 2005). This would effectively raise the status of space debris to that of exoarchaeological artifact, the management of which should ensure its survival into the future.

3.7.3. Meteorites from Mercury and Venus. Other parent bodies that may come to be represented in the meteorite collection on Earth include Venus and Mercury. For many reasons, the likelihood that venusian meteorites are possible is somewhat remote (e.g., *Gladman et al.,* 1996). However, it is important to recall that in the late 1970s a number of dynamical arguments were used to counter the notion of martian meteorites. So we should remain open to the possibility of Venus as a source of meteorites (e.g., *Goodrich and Jones,* 1987). The prospects for the recognition of a mercurian meteorite have been outlined by *Love and Keil* (1995). A conclusion of this work, and that of *Gladman et al.* (1996), was that meteorites from Mercury were a distinct possibility. The potential identification of the first mercurian meteorite (*Palme,* 2002) was complete speculation based on the description of an unusual meteorite (*Ebihara et al.,* 2002).

3.7.4. Ice meteorites. Comets have impacted Earth throughout its history. Indeed, there is evidence (somewhat controversial) for accretion of relatively small comets by Earth (e.g., *Frank and Sigwarth,* 1997). It has been suggested that ice meteorites (rich in ammonia) might fall, and could be collected in Antarctica (e.g., *Bérczi and Lukács,* 1994), although this idea is not generally accepted, and it is hard to envisage how the mechanism might work.

3.7.5. Sedimentary meteorites. All the martian meteorites that we have in our collections are igneous. But given that fluid has played such a prominent role in shaping Mars' surface, it is possible that sedimentary rocks might be present — and hence might be ejected to Earth as sedimentary meteorites. The method by which we could identify such specimens is unclear: Experiments to simulate atmospheric entry and survival of sedimentary meteorites were inconclusive (*Brack et al.,* 2002). *Wright et al.* (1995) speculated that such meteorites could be collected from Antarctica. When such samples are eventually collected, group names based on composition have already been suggested ["amathosites" for sandstones and "calcarites" for limestones (*Cross,* 1947)], although these terms are so outdated that a more modern nomenclature would be much more appropriate.

3.7.6. Extraterrestrial artifacts. Throughout the ages, iron meteorites have been turned into artifacts, both for ceremonial and for utilitarian use (see examples quoted in *Buchwald,* 1975). There is, however, another aspect of this process of misidentification that needs to be considered, i.e., one that involves extraterrestrial artifacts. While this is a subject that demands skepticism, there are compilations of accounts of high-technology artifacts and unusual materials allegedly observed to fall from the sky (e.g., *Corliss,* 1977, 1978). It has been proposed that the possibility of extraterrestrial artifacts from pre-human layers of the geological record is "worth objective analysis" (*Arkhipov,* 1994, 1996). The objectives of the Search for Extraterrestrial Intelligence (SETI) are considered by most people to be reasonably worthwhile; the search for extraterrestrial artifacts on Earth is merely an extension of this philosophy.

4. STAGES IN METEORITE HISTORY AND EVOLUTION

4.1. Introduction

As of June 2005, there were around 31,000 recognized meteorites maintained in collections throughout the world (*Grady,* 2000; *Grossman,* 2000; *Grossman and Zipfel,* 2001; *Russell et al.,* 2002, 2003, 2004, 2005), so there is no shortage of material for study. However, of these, only 1200 have been observed to fall, and so are free from the highest levels of terrestrial contaminants that can obscure results from analysis. Meteorite classification is treated fully in the next chapter; here, we confine ourselves to a bare outline of different meteorite types, to give context to the description of meteoritic components. Thus asteroidal meteorites are now divided into two large groups, one that includes melted meteorites (irons and stony-irons and the stony achondrites), the other of which comprises all the unmelted stones (chondrites). It is the chondritic meteorites, with their primitive compositions, that have yielded the most insight to preplanetary processes, but only 63 (around 5%) of the classified meteorite falls are carbonaceous chondrites or unequilibrated ordinary chondrites. In contrast, melted asteroidal meteorites have played a prominent role in the comprehension of planetary differentiation and core formation (83 of the meteorite falls, or almost 7% of the total). Analyses of whole-rock meteorites and components separated from them have provided complementary datasets that enable complex meteorite histories to be deduced. The most cursory inspection of a meteorite shows it to be heterogeneous (Fig. 1). Even the earliest analyses of meteorites separated metallic phases from nonmetallic (*Howard,* 1802). There are, however, excellent reasons for continuing to perform chemical and isotopic analyses of whole-rock specimens. It is the bulk (chemical and isotopic) chemistry of a meteorite that enables recognition of relationships between meteorites, and therefore assignation to an individual parent body (although not to a precise parental source such as a specific asteroid). However, although bulk analytical data enable meteorite groups to be recognized, analysis of discrete components within a meteorite is required to give more detailed and specific accounts of formation histories. An individual meteorite can be separated into discrete components, each set of which may trace different processes. Discrete components can be ordered in a hierarchical fashion that approximates a chronology of processes experienced by the parent

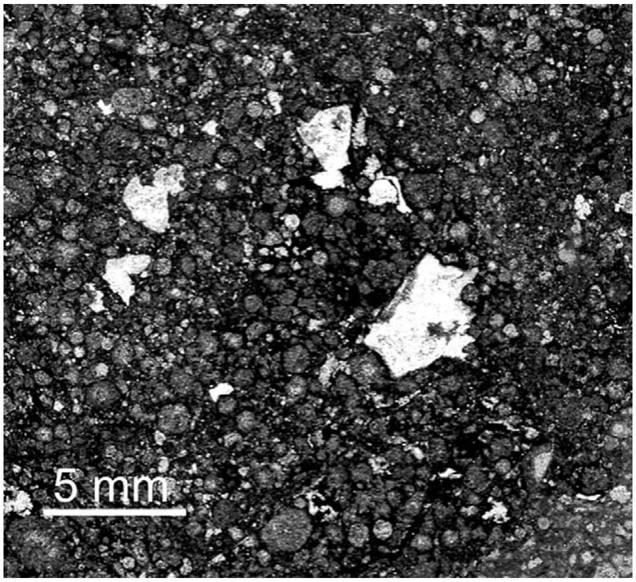

Fig. 1. Thin section of the Vigarano chondrite, showing chondrules and CAIs (nebular) and interchondrule matrix (accretionary). Presolar grains are embedded within the specimen. Subtle differences in color and chondrule/matrix ratio indicate that the meteorite has been brecciated and reaggregated.

object (Table 2). The subdivisions within this section approximate the sections into which the rest of this volume is divided.

4.2. The Presolar Epoch

A volumetrically insignificant but scientifically critical component within chondrites is their complement of interstellar and circumstellar grains. The family of grains most recently analyzed in the laboratory is that of grains formed prior to the accretion of the solar nebula. Lumped together in the broad category of "presolar grains," these materials have a variety of origins. The grains thus pre-date the major chondritic components, and occur as several populations of grains with different grain sizes (e.g., *Anders and Zinner,* 1993; *Nittler,* 2003). The presence of the grains was first inferred in the late 1970s to early 1980s on the basis of the isotopic composition of noble gases (*Alaerts et al.,* 1980). The unusual isotopic signatures of the noble gases implied the existence of several different hosts; analyses of acid-resistant residues suggested that the hosts might be carbon-rich. In 1983, combustion of a set of residues yielded the first C and N isotopic compositions of the grains (*Lewis et*

TABLE 2. Extraterrestrial material available for analysis.

Epoch	Process	Meteorites		IDPs	Component
		Unmelted	Melted		
Presolar	Nucleosynthesis	X		X	Circumstellar and interstellar grains (SiC; graphite; nanodiamonds, etc.); GEMS
	Interstellar chemistry	X		X	Organic molecules
Nebular	Formation of primary solids	X		X	CAIs; chondrules; silicates; metal; sulfides
Accretionary	Formation of planetesimals	X			Chondrule rims; dark inclusions; interchondrule matrix; phyllosilicates(?)
Parent-Body A	Aqueous alteration	X			Secondary minerals (carbonates, magnetite, phyllosilicates, etc.)
	Thermal alteration	X			Silicates
Parent-Body B	Differentiation		X		Achondrites
	Core formation		X		Iron meteorites
Planetary	Early solar irradiation	X	X	X	Regolith breccias
	Long-term solar irradiation				Lunar samples (Apollo, Luna, meteorites)
	Cosmic-ray irradiation	X	X	X	Plus returned space hardware
	Lunar history		X		Lunar samples (Apollo, Luna, meteorites)
	Martian history		X		Martian meteorites
	Collision	X	X		Shock veins; impact melts; implanted species
	Impact				Craters, tektites

al., 1983; *Swart et al.,* 1983). Individual grains of all these types except diamonds are now analyzed routinely by ion microprobe. Individual crystallites of nanodiamonds are only ~3 nm across, thus isotopic measurement of discrete grains is not yet possible (and may never be possible), even with the most sensitive of techniques. The grains are characterized and classified according to the isotopic composition of their major elements (including C, Si, O, Mg) (e.g., *Hoppe et al.,* 1994, 1995). Gases trapped within the grains (including N, Ne, Xe) are measured by mass spectrometry (e.g., *Huss et al.,* 2003). The isotopic compositions of minor and trace elements associated with specific nucleosynthetic processes are also measured by ion microprobe (e.g., Ba, Sm) (*Ott and Begemann,* 1990; *Zinner et al.,* 1991) or resonance ionization mass spectrometry (e.g., Zr, Mo) (*Nicolussi et al.,* 1998), while the identification of subgrains within grains has been recognized through analytical transmission electron microscopy (e.g., *Bernatowicz et al.,* 1991), and can now be analyzed by ion microprobe (*Stadermann et al.,* 2003a). Meteorites are not the only objects that are host to presolar grains: Interplanetary dust particles contain species that were irradiated prior to accretion and might therefore be interstellar in origin (*Bradley,* 1994). These subcomponents, known as GEMS (glass with embedded metal and sulfides), contain silicates, a few of which have unusual O-isotopic compositions (*Messenger et al.,* 2003) indicative of a preserved circumstellar component; the search for other isotopically anomalous species within GEMS has not yet been successful (*Stadermann et al.,* 2003b). Interplanetary dust particles contain other presolar components, including circumstellar forsterite crystals (*Messenger et al.,* 2003) and organic compounds with large enrichments in D and N (e.g., *Keller et al.,* 2000). The organic species are similar to those observed in molecular clouds, and along with the presence of inorganic presolar grains imply that IDPs are the most isotopically primitive materials available for laboratory investigation.

Apart from the GEMS, the measurements outlined above have almost exclusively been undertaken on populations of grains produced after extensive demineralization of whole-rock primitive chondrites (e.g., *Amari et al.,* 1994, *Lewis et al.,* 1994). Less-destructive separation techniques are being developed (*Tizard et al.,* 2005), and analysis of individual presolar grains *in situ* within a meteorite is a goal that is coming into sight (*Nagashima et al.,* 2004). Automated mapping of thin sections by probe techniques show the most promise in this respect (e.g., *Messenger et al.,* 2003; *Mostefaoui et al.,* 2003), and can also be applied to components within other types of extraterrestrial materials.

The foregoing discussion focuses on inorganic (although still mainly carbon-bearing) populations of presolar grains. There is also a vast range of organic presolar components available for measurement. These components are present in the most primitive chondrites (CI, CM, and unequilibrated ordinary chondrites, or UOCs), as well as in IDPs. They are characterized by elevated D/H and $^{13}C/^{12}C$ ratios, and encompass a range of materials from simple aliphatic to complex aromatic (e.g., *Cronin and Chang,* 1993). Laboratory analysis of presolar organic materials tends to be the domain of organic chemists and their range of techniques, including pyrolysis and combustion gas chromatography–isotope ratio mass spectrometry (GC–IRMS).

4.3. First and Second Nebular Epochs

Components separated from extraterrestrial materials that trace primary processes are materials that are presumed to have formed in the solar nebula; in this volume, that period is divided into the first and second nebular epochs, reflecting first the genesis of the materials, then their processing into objects prior to accretion into planetesimals. CI chondrites are the meteorites with compositions closest to that of the solar photosphere, and so are often taken to be the most primitive, i.e., closest in composition to the dust from which the solar system aggregated. They have, however, suffered extensive exposure to fluids. Perhaps more useful for a better understanding of primordial materials are the CV3 and CO3 carbonaceous chondrites and UOCs. These are specimens that have chondritic compositions and are altered very little by secondary parent-body processing (*McSween,* 1979). They are not, as was originally thought, totally unaltered, but exhibit minimum levels of aqueous alteration and thermal metamorphism. They have distinct chondrules and CAIs, and thus provide readily recognizable components that can be identified as representative of material from the earliest nebular epochs. As well as primary silicates and oxides in CAIs and chondrules, components include metal and sulfides.

Mineralogy plus major-, minor-, and trace-element and isotopic chemistry of mineral grains allows inference of condensation sequences, nebular oxygen fugacity, and irradiation history, as well as thermal evolution. Isotopic composition of primary components has been particularly successful in delineating the heterogeneous nature of the presolar nebula. An absolute chronology for primary components has been outlined on the basis of high-precision Pb-Pb dating (e.g., *Amelin et al.,* 2002); the results provide a marker to which all other processes can be related. The presence of decay products from short-lived radionuclides has been used to infer relative chronologies for the different nonmetallic components in primitive chondrites (e.g., *Russell et al.,* 1996b; *Srinivasan et al.,* 1996), assuming production of the nuclides by an external source just prior to collapse of the nebular cloud (e.g., *Wadhwa and Russell,* 2000). However, scenarios involving spallation by neutrons close to an energetic young Sun have upset the chronological argument (*Shu et al.,* 1997). Distinction between the two competing hypotheses is still awaited and, we hope, almost resolved, as increasing instrumental precision allows measurement of ever-smaller quantities of decay products from radionuclide systems with shorter and shorter halflives (*McKeegan et al.,* 2000; *Chaussidon et al.,* 2002).

4.4. Accretion Epoch

The accretion epoch is the period of time during which primordial components aggregated into planetesimals. Nebular gas had started to dissipate, and the accretion disk had begun to accumulate into discrete planetesimals. During aggregation into parent bodies, and the subsequent lithification of those parents, there was a period of "intermediate alteration." Processing of primary components at this stage occurred through gas-solid exchange, during solid-solid collision, and possibly through fluid-solid interactions. Materials most likely to have been produced and processed during this epoch include interchondrule matrix (*Alexander,* 1995), accretionary rims on chondrules (e.g., *Metzler et al.,* 1992; *Bischoff,* 1998; *Vogel et al.,* 2003) and CAIs (e.g., *Krot et al.,* 2001; *Wark and Boynton,* 2001), and dark inclusions (e.g., *Weisberg and Prinz,* 1998; *Zolensky et al.,* 2003). There are arguments as to whether such components were produced during the final stages of the nebula prior to accumulation into parent bodies or were produced on the parents themselves (e.g., *Krot et al.,* 1995). Recent work has suggested that phyllosilicates, commonly assumed to have a parent-body origin, might also have been formed in the nebula (*Ciesla et al.,* 2003).

4.5. Parent-Body Epoch A: Thermal and Aqueous Alteration

Following on from aggregation into planetesimals, the first planetary epoch encompasses the time during which mild to moderate heating of the planetesimals took place, as well as collisions between planetesimals. As with the nebular and accretion epochs, most of the information for this period is obtained from components within chondritic meteorites. In theory, the recognition of secondary components in chondritic meteorites should be fairly straightforward. Melting of ice, and the subsequent reactions between solid and fluid on parent bodies, led to the formation of secondary minerals (e.g., *Grimm and McSween,* 1989) such as carbonates and magnetite, the alteration of primary silicates (olivine, pyroxene) to phyllosilicates, and oxidation of metal and sulfide grains (e.g., *Browning et al.,* 1996). Carbon-rich planetesimals, such as the parent objects of CM2 meteorites, had an additional suite of secondary alteration products resulting from hydrous pyrolysis of organic compounds (*Sephton et al.,* 2000). As heating continued, or reached higher levels in planetesimals with little or no ice, thermal alteration took over from aqueous alteration, and dehydration and thermal metamorphism produced a different crop of secondary minerals (e.g., *Nakamura et al.,* 2000). It has been recognized for many years that textural and mineralogical changes brought about by secondary alteration helps to subclassify chondrites into petrologic types (e.g., *Sears et al.,* 1980). Analysis of secondary minerals yields information on the extent of alteration, fluid composition, and alteration temperature. Radiogenic isotope systematics, such as I-Xe, of secondary minerals reveal the timing of fluid alteration (e.g., *Swindle,* 1998). Variations in O-isotope composition of different components (carbonate, magnetite, phyllosilicates) show the extent of fluid-solid interaction and constrain the fluid composition and alteration temperature (e.g., *Clayton,* 2003).

4.6. Parent-Body Epoch B: Differentiation and Core Formation

Continued thermal evolution of asteroidal parents eventually resulted in melting of the silicates, differentiation between metal and silicate, and segregation of metal into planetesimal cores; collision between asteroids also continued. All these processes can be traced through analysis of components from melted meteorites. These are a very broad category of meteorites that includes magmatic and nonmagmatic iron meteorites, pallasites, mesosiderites, and achondrites.

4.6.1. Differentiation. Trace-element and isotope variations in silicates from achondrites record the magmatic processes that they have experienced and allow associations of complementary igneous rocks to be recognized. So, for instance, it is clear that the howardites, eucrites, and diogenites form a sequence of rocks that sample different depths from a single asteroid class (e.g., *Mittlefehldt et al.,* 1998). An interesting development of recent years has been recognition of primitive achondrites as bridges between melted achondrites and unmelted chondrites; this recognition has been based on the analysis of mineral chemistry, as well as textural variations (e.g., *McCoy et al.,* 1997) and O-isotope relationships (*Clayton and Mayeda,* 1996). Radiogenic isotope systems, such as Mn-Cr, Fe-Ni, and Sm-Nd, record the onset of planetary differentiation and its duration (e.g., *Lugmair and Shukolyukov,* 1998; *Shukolyukov and Lugmair,* 1993; *Blichert-Toft et al.,* 2002).

4.6.2. Core formation. The most extensive planetary melting ultimately leads to metal extraction and core formation. To trace these processes, we have the magmatic iron meteorites and pallasites. The original subdivision of iron meteorites on the basis of texture has been replaced by classification into groups with distinct trace element chemistries. However, the two schemes, textural and chemical, give complementary information on cooling history as well as parent-body relationships (e.g., *Malvin et al.,* 1984; *Naryan and Goldstein,* 1985). Components within iron meteorites available for study include the major iron-nickel alloys (kamacite and taenite) plus minor components such as sulfides, phosphides, and graphite; many iron meteorites also contain silicates, allowing connections to be made with less-differentiated materials. Shock-produced phases, e.g., diamonds, record collisional history for iron meteorite parents. Radionuclide systems, such as Pd-Ag (*Chen and Wasserburg,* 1990), Re-Os (e.g., *Horan et al.,* 1998), and Hf-W (*Kleine et al.,* 2002; *Yin et al.,* 2002), are used to understand the differentiation and cooling histories of melted meteorites (*Halliday et al.,* 2001). The chemistry of silicate and metal fractions in pallasites give information about processes occurring within their source regions, although the location of this source region, at the core-mantle interface (e.g., *Wasson and Choi,* 2003; *Minowa and Ebihara,* 2002) or at a more shallow depth below a thick regolith (*Hsu,* 2003), is still debated.

4.7. Planetary Epoch

Parent-body surfaces (including the Moon and Mars, as well as asteroids) are subject to modification by external agents. Evolution of asteroidal parents continues even after the internal heat sources that drove alteration and metamorphism have cooled and the parent objects have solidified. The main agents of change are collision and irradiation, and both melted and unmelted meteorite groups are equally affected. Ejection from the asteroid belt, transition to Earth, and terrestrial history prior to collection are all events that can be traced through the study of meteorites.

4.7.1. Parent-body modification. Collision between asteroids leads to regolith formation, compaction, and lithification, and the signatures of these processes are found in brecciated meteorites. The type of materials that were produced during these tertiary processes are veins and pockets of shock-produced glass, minerals altered by remobilization of fluids (sulfidization), as well as the introduction of clasts or xenoliths of the impactor (*Keil et al.,* 1997). Investigation of clast variety and the composition of clasts in different hosts allows elucidation of the collisional history of the asteroid belt and the extent to which bodies have been broken up and reaggregated (e.g., *Scott,* 2002). Recognition of melted clasts in primitive meteorites is also a constraint on the chronology of parent-body formation (e.g., *Gilmour et al.,* 2000).

Implantation of species from the SW also modifies regolithic surfaces; this is particularly relevant for samples from the lunar surface, where implantation at different epochs has allowed changes in composition of the SW to be inferred, with all the implications that this has for solar evolution (e.g., *Kerridge et al.,* 1991). "Gas-rich" meteorites represent compacted regoliths from the surfaces of primitive asteroids, and record the effects of SW interaction from early in the history of the solar system. These same samples also experienced the effects of irradiation by cosmic rays (generally protons of 10–100 MeV energies, capable of penetrating rocks to depths of typically 50 cm). The result of cosmic-ray exposure is production of damage tracks (by relatively heavy ions) in the irradiated zone, along with the transmutation of elements by spallation, i.e., nuclear erosion resulting in the production of light elements from heavier target atoms. On the basis of measurements of spallogenic (or cosmogenic) isotopes made on inclusions separated from gas-rich meteorites, *Wieler et al.* (1989) concluded that irradiation times were on the order of millions to tens of millions of years (compared with a few hundred million years for lunar regolith samples).

Measurements of cosmogenic nuclides are also widely used to assess the length of time that meteorites have been exposed in space as small bodies, i.e., following their removal from an asteroidal (or planetary) parent body. Cosmic-ray-exposure age indicates the length of transit time between ejection from a parent object and its arrival on Earth. For example, on the basis of such measurements, *Schultz et al.* (1991) found that over half of all H-group chondrites had cosmic-ray-exposure ages of around 7 Ma, and inferred that the parent body of the H chondrites must have undergone a major disturbance about 7 m.y. ago.

4.7.2. Terrestrial history. The focus of most research on extraterrestrial materials is on preterrestrial components. In practically all cases, a meteoriticist would prefer to analyze only freshly recovered meteorite "falls," to ensure a minimum of terrestrial contamination. Realistically, though, this is almost impossible — the "fall" population is much smaller and more restricted than that of meteorite "finds," and accounts for less than 4% of all known meteorites (*Grady,* 2000; *Grossman,* 2000; *Grossman and Zipfel,* 2001; *Russell et al.,* 2002, 2003, 2004, 2005). In order to gain a full understanding of solar and presolar history, it is necessary to study the terrestrial histories of meteorites, to disentangle any effects that might result from terrestrial rather than preterrestrial alteration. Hence characterization of the type of weathering products (degree of rusting, formation of clay minerals, and secondary salts such as carbonates and sulfates) and their extent are essential steps that must be taken to ensure that the petrology, texture, and chemistry of the samples have not been compromised by their terrestrial sojourn. The terrestrial history of a meteorite, of course, can also be used to generate useful information about solar system history. Terrestrial age dating using several radiogenic systems (^{10}Be, ^{14}C, ^{36}Cl) allows pairing of meteorite "finds" (e.g., *Jull et al.,* 2000; *Nishiizumi et al.,* 2000). Population studies of meteorite "falls" and "finds" have been used to infer flux rates (e.g., *Bland et al.,* 1996), the breakup of asteroidal parents (e.g., *Schultz et al.,* 1991), and a possible change in population of the asteroid belt (e.g., *Dennison et al.,* 1986).

4.7.3. Craters and tektites. The final types of extraterrestrial materials considered here are not materials *per se*, but signatures left behind by extraterrestrial impactors. These signatures fall into two groups that record the terrestrial consequences of extraterrestrial objects. The first group comprises craters, their sizes and morphologies, and the changes manifest in the host rocks through impact. The presence of craters on planetary surfaces yields information about the age and activity of those surfaces (e.g., *Shoemaker,* 1998); crater-counting studies yield relative chronologies (e.g., *Hartmann and Neukum,* 2001), while crater-size distributions help interpretation of impactor fluxes (e.g., *Ivanov et al.,* 2002). Many craters have meteorites associated with them, almost all of which are iron meteorites. For craters where no macrometeorites occur, it is possible to derive the composition of the projectile from analysis of impact melt rocks; the technique also is applicable to lunar melt breccias (e.g. *Norman et al.,* 2002). The more minor group of samples that comes under this section is that of tektites, glasses formed during impact (e.g., *Koeberl,* 1986). They can be useful indicators of impact angle and the areal distribution of impact ejecta, and can also be used to date craters (e.g., *Deutsch and Schaerer,* 1994).

5. SUMMARY

We have attempted to outline the range of extraterrestrial materials available for study, and which form the basis for the observations and conclusions contained in the rest of this volume. We have categorized materials on the basis of their original parent body (asteroid, comet, etc.), and then tried to formulate a hierarchical description of discrete components in terms of the types of processes the material might have experienced (primary condensate, secondary alteration, etc.). The hierarchy of discrete components is intimately intertwined with the parent-object categories, as the parent objects all carry material from a variety of sources and processes. We have tried to relate them to the subjects of the chapters that follow this one. We have briefly discussed source objects that have the potential to yield material for analysis, but have not yet been recognized as having done so (Venus, Mercury), and the outward signs of planetary impacts (craters and tektites).

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