# Meteorite Evidence for the Accretion and Collisional Evolution of Asteroids

**Edward R. D. Scott**
*University of Hawai'i*

Meteorites contain a record of impacts during all stages of asteroid origin and evolution: the formation and accretion of chondritic particles; the alteration, metamorphism and melting of asteroids; and the erosion and disruption of asteroids by hypervelocity impacts. A review of meteorite classification shows that numerous meteorites are not readily classified because they do not fit simple models for asteroid formation and evolution that assume impacts were only important during the final stage of asteroid evolution and because of inadequate understanding of asteroidal impacts. Chronological, textural, and thermal constraints allow us to identify meteorite impact breccias that formed during accretion (e.g., Kaidun), when asteroids were partly molten (e.g., mesosiderites), and during the subsequent disruption of asteroids (e.g., L chondrites). Studies of chondrites including Kaidun suggest that chondrules accreted with similar-sized fragments of preexisting bodies that formed at greater heliocentric distances. In the inner solar system, chondrules appear to have been crucial for initiating accretion. Without chondrules and rock fragments, dry dust failed to accrete to the nebular midplane because of nebular turbulence and spiraled into the protosun. The tiny mass of asteroids may be partly due to inefficient chondrule formation beyond 2 AU or less-efficient delivery of chondrules from near the protosun.

## 1. INTRODUCTION

Meteorites and returned asteroid samples are keys to understanding the chemical, mineralogical, and physical properties of near-Earth and main-belt asteroids. We know a lot about the chemical, mineralogical, and physical properties of meteorites but are still very ignorant about the corresponding properties of their parent asteroids and possible matches between meteorite classes and asteroid types (*Burbine et al.,* 2002). To make progress in understanding the formation and evolution of asteroids, the origin of meteorites, and the formation of chondritic components we urgently need to know more about the composition and structure of asteroids. Our poor understanding of how impacts modified asteroids and meteorites is a major barrier in achieving these goals. Impacts controlled the formation of asteroids and their destruction and were a major factor in their geological evolution (e.g., *Scott et al.,* 1989). Understanding the role of impacts is critical if we wish to learn how diverse types of chondritic materials accreted into asteroids, how and when 99.9% of the solid material in the asteroid belt was lost, and how impacts changed the chemical, mineralogical, and physical properties of chondritic and differentiated asteroids.

A simple model for the geological evolution of chondritic and differentiated asteroids has four stages. Chondrules, metal grains, and other components were formed, probably in the solar nebula. These accreted together to form parent asteroids. Some of these bodies were subsequently melted, forming metallic cores and olivine-rich mantles; others were metamorphosed or aqueously altered. After the asteroids had cooled, they were eroded by impacts for 4.5 G.y. or disrupted. However, this simple model is inadequate as detailed petrologic studies and radiometric ages suggest that the four stages overlapped in time. Chondrules, for example, appear to have accreted with fragments of preexisting asteroids (e.g., *Scott et al.,* 1996). Some chondrites and eucrites are breccias of materials excavated by impacts from different depths that were metamorphosed after assembly (e.g., *Yamaguchi et al.,* 1997). In addition, few chondrites and differentiated meteorites experienced simple cooling histories after peak temperatures were reached, probably because of disruption by impacts (*Scott and Keil,*1999).

Here I review the meteorite evidence for impact processing, both during and after accretion, in the light of studies of terrestrial, lunar, and laboratory impacts and impact modeling. I first review the variety of meteorites, emphasizing those features and rocks that do not fit simple models for the accretion and geological evolution of asteroids.

## 2. METEORITE TYPES AND PARENT BODIES

Meteorites are divided into two classes: chondrites and differentiated or nonchondritic meteorites (*Brearley and Jones,* 1998; *Mittlefehldt et al.,* 1998). Chondrites are aggregates of silicate and metallic particles and are remarkably similar in composition to the condensable material in the Sun. Except for H, He, C, N, O, and the inert gases, elemental ratios are very largely within a factor of 2 of those in the solar photosphere (*Wasson and Kallemeyn,* 1988). Differentiated or nonchondritic meteorites are igneous rocks and differ considerably from the Sun in composition. Three types are distinguished: irons, achondrites, and stony irons, most of which are thought to be derived respectively from the core, mantle and crust, and core-mantle boundary of melted asteroids. Differentiated meteorites have elemental ratios that may be up to 10–1000× different from solar values.

Largely as a result of meteorite discoveries in Antarctica and various deserts around the world, the number of known meteorites has increased in the past 20 years from 3000 to around 20,000, allowing for pairing of fragments (*Bischoff,* 2001). Detailed studies of these meteorites suggest they come from 100–150 different parent asteroids (*Burbine et al.,* 2002). However, a surprising number cannot be readily classified as chondritic or differentiated. This suggests that our ideas about the formation of meteorites and the evolution of their parent asteroids may require modification.

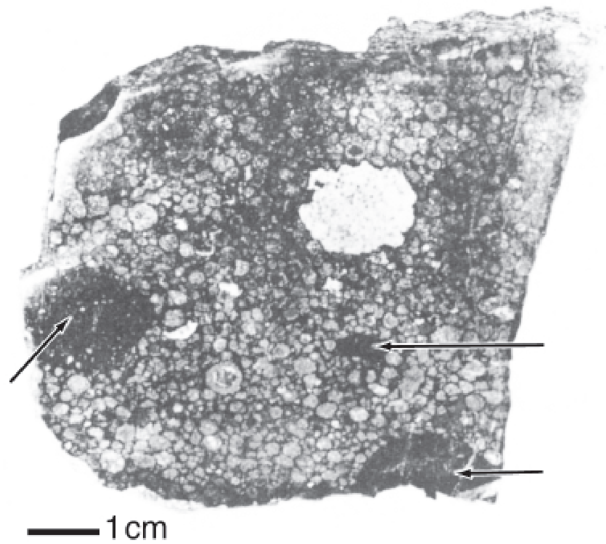


**Fig. 1.** Polished slab of the Leoville CV3 chondrite showing numerous chondrules, one large and several small, white Ca-Al-rich inclusions (CAIs), and three dark inclusions, which are marked by arrows. Chondrules and CAIs formed in the solar nebula but dark inclusions are probably fragments of preexisting bodies that accreted with chondrules and CAIs. (Photo courtesy of Alfred Kracher and Klaus Keil.)

### 2.1. Chondrites

*2.1.1. Components.* Chondrites are mixtures of diverse types of materials that formed in different parts of the solar nebula under very different thermal conditions. Chondrules are rounded particles, typically millimeter-sized, that formed from molten silicate droplets (*Rubin,* 2000). Various kinds of chondrules, associated metal grains, and the rarer Ca-Al-rich inclusions (CAIs) formed at high temperatures (1200°–2000°C) in the solar nebula (*Ireland and Fegley,* 2000). Before these components accreted they were commonly coated or mixed with volatile-rich, fine-grained matrix material, which contains micrometer- and submicrometer-sized grains of circumstellar grains and clearly experienced less thermal processing (*Ott,* 2001).

Chondrites also contain angular rock fragments. Many are clearly pieces of chondrules and CAIs, some are foreign fragments of known meteorite types (*Lipschutz et al.,* 1989), but most are matrix-rich chondritic fragments called dark inclusions (see Fig. 1) (*Kracher et al.,* 1985; *Johnson et al.,* 1990; *Endress et al.,* 1994). Most dark inclusions are heavily altered, have sizes comparable to those of chondrules and CAIs, may contain smaller chondrules than their host chondrites, and some are rimmed by matrix material (e.g., Fig. 1 of *Scott et al.,* 1996). Their I-Xe ages suggest they were altered before their host chondrites (*Hohenberg et al.,* 2001). Thus some dark inclusions appear to be fragments of chondritic bodies that may have spiraled toward the protosun and then accreted with chondrules to form new kinds of chondrites.

*2.1.2. Formation of chondrules and CAIs: How and where?* Most authors infer that chondrules and CAIs formed in the solar nebula by some kind of localized heating mechanism such as nebular lightning, magnetic reconnection flares, or gas dynamic shock wave (*Rubin,* 2000; *Jones et al.,* 2000). Some authors invoke prior formation of chondrule-free planetesimals. *Weidenschilling et al.* (1998), for example, suggest that planetesimals in resonance with Jupiter attained high eccentricities, generating bow shocks in the nebula gas that melted dust, forming chondrules. A few authors have argued that chondrules formed by impacts of molten planetesimals (e.g., *Sanders,* 1996; *Lugmair and Shukolyukov,* 2001) or impacts into asteroidal regoliths (e.g., *Symes et al.,* 1998). However, formation of chondrules by impacts between solid or molten asteroids appears inconsistent with many properties of chondrules and chondrites (*Taylor et al.,* 1983; *Taylor and Scott,* 2001).

It is commonly thought that CAIs and chondrules formed in the asteroid belt and were quickly accreted into asteroids (e.g., *Alexander et al.,* 2001). However, new models suggest that they may have formed close to the protosun and were then distributed across the solar nebula by a bipolar jet flow (*Liffman and Brown,* 1996; *Shu et al.,* 2001; *Ireland and Fegley,* 2000; *Krot et al.,* 2001). If this model is correct, the conclusion derived from inferred $^{26}$Al concentrations that CAIs predate chondrules by a million years or more (*Wadhwa and Russell,* 2000) may not be valid, as $^{26}$Al may have been produced by intense particle irradiation near the young Sun.

*2.1.3. Chondrite classes, groups, and origins.* Three main classes of chondrites, enstatite, ordinary, and carbonaceous, are subdivided into 12 groups. One group, R chondrites, and several ungrouped chondrites do not fit into these three classes (Fig. 2). Within each chondrite group, with the possible exception of CR and CH chondrites, the proportions of chondrules and other chondritic components and the bulk composition of each chondrite are surprisingly uniform. As for all meteorite groups, it is plausible that the members of each group come from a single body, but multi-

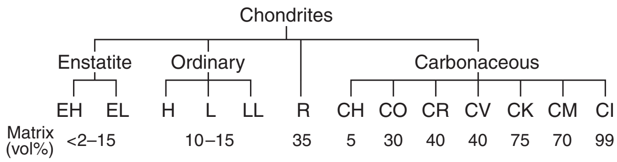


**Fig. 2.** Classification and matrix concentrations in 13 chondrite groups, 12 of which belong to the enstatite, ordinary, and carbonaceous classes. R chondrites and ungrouped chondrites, which are not shown, do not fit into these three classes. Chondrite groups are arranged in approximate order of increasing matrix concentration (data from *Scott et al.,* 1996). Properties of meteorites and asteroids suggest that this sequence corresponds very approximately to increasing formation distance from the Sun (*Rubin and Wasson,* 1995). Almost all the other mineralogical, chemical, and isotopic properties of these groups do not correlate with the matrix concentration, suggesting that chondritic asteroids did not form simply from a disk of solid materials with compositions that varied smoothly with heliocentric distance.

ple bodies cannot be excluded. The ungrouped chondrites probably come from another 13 or more bodies (*Meibom and Clark,* 1999). The rate at which new types of carbonaceous chondrites are being discovered and the strange properties of recently discovered groups suggest that the known chondrites may represent only a minor fraction of the chondritic asteroids and the precursor material of differentiated asteroids.

Oxygen-isotopic analyses show that chondrules in each class are quite distinct and must have been derived from at least three separate reservoirs (*Clayton,* 1993). Chemical and mineralogical studies confirm that chondrules in H, L, and LL chondrites are not fundamentally different and might be derived from a single reservoir by size sorting. A similar relationship holds for EH and EL chondrites, but the properties of carbonaceous chondrites are much more diverse and appear to require at least four separate sources. (Carbonaceous chondrites have little in common except high abundances of refractory elements.) Thus the parent asteroids of the chondrites probably formed from at least six separate reservoirs of chondrules with remarkably little mixing between the reservoirs.

*2.1.4. Chondritic asteroids.* *Sears* (1998) and *Akridge et al.* (1998) argued that chondrites are biased samples derived from the outer few kilometers of asteroids where chondrules formed by impact and that we have not sampled the asteroids' chondrule-free dusty interiors. However, concentrations of chondrules and matrix material are rather uniform in each group (Fig. 2) and we certainly have meteorite samples from the mantles and cores of differentiated asteroids (see below). Since ordinary chondrite parent bodies were baked at high temperatures, any loosely consolidated dirt should have been converted to rock capable of surviving the journey to Earth. In view of other difficulties with impact origins for chondrules (see above) and the likelihood that our samples come from ~24 or more chondritic asteroids, it seems unwise to conclude that the interiors of chondritic asteroids are devoid of chondrules. In the absence of returned samples from asteroids, we will assume that we have sampled the interiors of chondritic asteroids.

Possible links between chondrite groups and asteroid types are discussed by *Burbine et al.* (2002). Enstatite chondrites, which may be derived from two or more M asteroids, probably formed closer to the Sun than other chondrites (*Wasson,* 1988; *Rubin and Wasson,* 1995; *Lugmair and Shukolyukov,* 1998, 1999). The E-type asteroids, which appear to be the source of the closely related aubrites (enstatite achondrites), are also found at the inner edge of the belt (*Bell et al.,* 1989). Ordinary chondrites are probably derived from three or more S(IV)-type asteroids, fragments of which may be classed as Q-type asteroids among near-Earth asteroids. CI, CM, CR, and CK chondrites are probably derived from C-type asteroids, which are concentrated further out in the asteroid belt (2.5–3.5 AU). CV and CO chondrites may come from K-type asteroids, which are largely from the Eos family at 3.0 AU (*Bell et al.,* 1989). The most porous and possibly very primitive chondrite, Tagish Lake, is a CM-like chondrite that is very rich in C (~5 wt%), $H_2O$, and presolar grains (*Brown et al.,* 2000). It contains fewer chondrules and CAIs than CM chondrites, and is thought to be derived from one of the D-type asteroids (*Hiroi et al.,* 2001), which lie beyond 2.9 AU and probably dominate the asteroid population beyond 4 AU (*Jones et al.,* 1990).

Properties of chondrites and asteroids suggest there were some systematic variations in the properties of accreting planetesimals that survive today in the asteroid belt despite some mixing due to subsequent orbital evolution of the asteroids and their impact debris. At the inner edge of the asteroid belt, chondritic asteroids tend to be chondrule-rich and matrix-poor, like E and O chondrites (Fig. 2), and volatile concentrations in the matrix material are relatively low. In the outer parts of the belt, chondritic asteroids tend to have much higher proportions of matrix to chondrules and the matrix material is richer in water and other volatiles.

The degree of alteration and metamorphism experienced by the parent bodies of chondrites also varied across the belt (*Keil,* 2000). At the inner edge, peak temperatures were generally higher. Chondrites in the EH, EL, H, L, and LL groups were all heated in the temperature range ~400°–950°C. The most deeply buried probably experienced the highest temperatures (type 6), whereas the least-metamorphosed (type 3) were closer to the surface. Enstatite chondrites experienced little if any aqueous alteration prior to metamorphism, and ordinary chondrites experienced only mild alteration in the most-fine-grained portions. The exceptional CH chondrites resemble ordinary chondrites in that they contain very little water and matrix material but experienced lower peak temperatures (<300°C). They may have formed closer to the Sun than other chondrites.

Further out in the asteroid belt, the carbonaceous parent bodies experienced aqueous alteration at temperatures of ~0°–300°C (CM, CR, and CI bodies). In bodies that were heated to 300°–500°C, volatiles were lost and aqueous alteration merged into fluid-assisted metamorphism (CO and CV). The most metamorphosed carbonaceous chondrites are found in CK chondrites (types 4–6), which are almost completely dry.

## 2.2. Differentiated Meteorites

Differentiated meteorites formed in asteroids that melted shortly after they accreted (*Wadhwa and Russell,* 2000; *Taylor et al.,* 1993), and are commonly divided into achondrites, irons, and two kinds of stony irons, pallasites and mesosiderites (*Shearer et al.,* 1998). Conventional views suggest that differentiated meteorites should consist of easily characterized rocks from the core, mantle, or crust of asteroids.

The largest class of achondrites are the HED meteorites (~80% of achondrite falls): the howardites, eucrites, and diogenites, which are very probably derived from Vesta (*Keil,* 2002). Another Vesta-like body is required for the basaltic meteorite, Northwest Africa 011 (*Yamaguchi et al.,* 2001), conceivably the parent asteroid of 1459 Magnya (see *Burbine et al.,* 2002). Studies of the HED meteorites and remote sensing indicate that Vesta differentiated to form a core, mantle, and crust. It experienced a high degree of melting, possibly complete melting, probably due to $^{26}$Al decay. Thus Vesta can be considered as the smallest terrestrial planet (*Keil,* 2002). However, it may be incorrect to consider Vesta as the archetypal differentiated asteroid as most may have lost their basaltic magma because of explosive volcanism (*Keil,* 2000).

Excluding meteorites from Mars and the Moon, there are four major groups of achondrites: ureilites, aubrites, brachinites, and angrites (*Mittlefehldt et al.,* 1998). These meteorites appear to be derived from four parent asteroids with very different igneous and impact histories from Vesta. Ureilites are largely unbrecciated, coarse-grained, igneous rocks made of olivine and pyroxene. Aubrites are brecciated rocks largely composed of coarse-grained enstatite that formed from a body distinct from the parent bodies of the EH and EL chondrites (*Keil,* 1989). Brachinites are unbrecciated, igneous rocks containing 80–95 vol% olivine and 0–10 vol% plagioclase, and angrites are unbrecciated, plagioclase-poor, basaltlike igneous rocks. None of these groups of achondrites is a close match for the products predicted by simple models of asteroid differentiation, suggesting that igneous processes in asteroids were much more complex than commonly appreciated (*Mittlefehldt et al.,* 1998).

Brachinites may be derived from A-type asteroids, aubrites from E-type asteroids, and ureilites and angrites from S asteroids (*Burbine et al.,* 2002).

## 2.3. Other Types of Meteorites

Textbooks imply that chondrites and differentiated meteorites are so different that even a simple-minded robot should be able to distinguish these two basic types of asteroidal material! However, our museums contain many strange meteorites that required detailed laboratory studies before they could be assigned to one of these two classes, and others that still have controversial classifications. Most of the difficulties have arisen because of disagreements about the role of impacts in the formation of these meteorites.

*2.3.1. Impact melts.* Meteorites identified as chondritic impact melts are mixtures of unmelted chondritic material and melt veins with chondritic composition and widths of less than a few centimeters; e.g., Rose City and Chico (*Bogard et al.,* 1995). However, two rocks that appear to be melted chondrites are quite different. Patuxent Range 91501 is an 8.5-kg igneous-textured rock containing a few volume percent of metal-troilite nodules (Fig. 3). Without detailed bulk chemical and O-isotopic analyses and mineral compositions, we would not know that it is probably an impact melt from the L-chondrite body (*Mittlefehldt and Lindstrom,* 2001). The second, Abee, was for many years the best-studied EH4 chondrite, but subsequent studies showed that it is actually an impact melt and that its chondrule-shaped features are merely ghosts from the original structure (*Rubin and Scott,* 1997). Its origin is still poorly understood.

*2.3.2. Metal-chondrite breccias.* The best-studied meteorite breccias that consist of metal veins or regions and chondritic fragments are Netschaevo (classed as a IIE iron) and Portales Valley [classified as an H6 chondrite (*Grady,* 2000)]. Both must have been deeply buried when they cooled as their metal portions developed Widmanstätten patterns (Fig. 4). Impacts created the chondritic fragments but it is not known how molten metal was formed and how

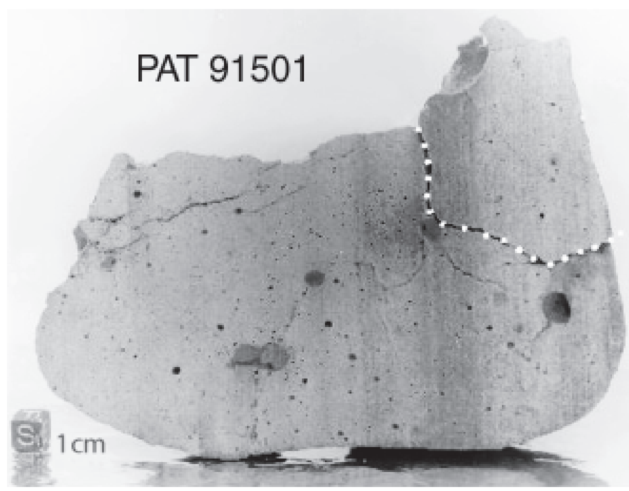


**Fig. 3.** Polished face of the PAT 91501 meteorite showing a uniform fine-grained rock with black vesicles under 3 mm in size and rounded or elongated, gray nodules of metal and troilite, which are up to a centimeter in size. Chemical and O-isotopic analysis of the silicates suggest that it is an impact melt from the L-chondrite parent body (*Mittlefehldt and Lindstrom,* 2001). However, unlike nearly all other impact-melted meteorites, it contains very few unmelted, chondritic grains, and none of these grains are shocked. A cometary projectile may have been responsible for the high degree of melting and vaporization. (Vertical lines are saw marks. Photo courtesy of D. Mittlefehldt and NASA Johnson Space Center.)

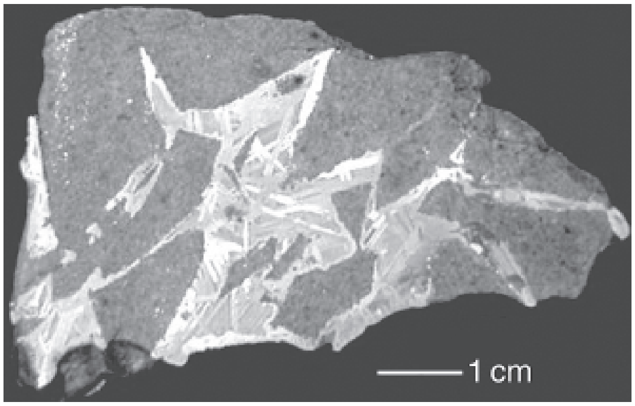


**Fig. 4.** Slice of the Portales Valley meteorite showing dark angular clasts of what appears to be an H6 chondrite separated by light-colored veins of metallic Fe,Ni, which have been etched to reveal a Widmanstätten pattern of oriented kamacite plates. An impact created the angular clasts but it is not known how the molten metal was formed, mixed with chondritic clasts, and then cooled slowly to form the Widmanstätten pattern. (Photo courtesy of Marvin Killgore.)

it was mixed with chondritic material. Both impact heating and internal heating have been proposed (see *Rubin et al.,* 2001a).

*2.3.3. Metal-rich chondrites.* Most chondrites contain <15 vol% metallic Fe,Ni, but two newly discovered types contain much more metal. CH chondrites contain 20 vol% metallic Fe,Ni, while two CB chondrites, QUE 94411 and HaH 237, have ~70 vol% metallic Fe,Ni; one of these was initially classified as an iron meteorite (*Weisberg et al.,* 2001). Metal particles in these two chondrites are chondrule-sized and appear to have similar condensation histories to the chondrules (*Krot et al.,* 2001). The chondrites also contain small amounts of hydrated matrix (*Greshake et al.,* 2002) and might be derived from hydrated M-class asteroids (*Rivken et al.,* 1995). Because they are so different from other chondrites in their composition and texture, some authors have suggested that metal-rich chondrites might be impact products, not true chondrites (*Wasson and Kallemeyn,* 1990). Their bulk Fe/Mg ratios are 1.7–9× above the solar ratio and their volatile elements are depleted by factors of up to 30×, placing them well outside the envelope of chemical compositions of other chondrites.

Three related meteorites, Bencubbin, Weatherford, and Gujba, all contain ~60 vol% metallic Fe,Ni and may also be metal-rich chondrites. However, they lack CAIs and their classification is less certain (*Rubin et al.,* 2001b). (Bencubbin was once classified as a mesosiderite.)

*2.3.4. Partly differentiated meteorites.* Acapulcoites and lodranites appear to represent the transition between chondrites and achondrites. Acapulcoites contain relict chondrules and have chondritic compositions but were heated up to 1000°C so that millimeter- to centimeter-sized metallic veins formed. They were not hot enough to lose much metal or basalt. Lodranites were heated to higher temperatures and are depleted in plagioclase and troilite, which are both concentrated in early silicate and metallic melts. Most authors envisage that internal heating was responsible, but impact heating has also been invoked (*Rubin et al.,* 2001c). *McCoy et al.* (2000) infer that the parent asteroid of these rocks would have internal chemical and mineralogical heterogeneities on scales of >200 m. The asteroid Eros lacks heterogeneities on this scale but minor igneous differentiation cannot be excluded as impact mixing may have homogenized its surface (*McCoy et al.,* 2001).

*2.3.5. Metal-rich achondrites.* Two meteorites, Mt. Egerton and Itqiy, appear to be igneous rocks made of ~20 vol% of metallic Fe,Ni intergrown with coarse-grained enstatite crystals (*Mittlefehldt et al.,* 1998; *Patzer et al.,* 2001). Since molten silicate and metallic Fe,Ni should readily separate in internally heated asteroids, they may have formed by impact. However, neither contains relict chondrules or clasts and their bulk composition is far from chondritic. Five other metal-bearing enstatite meteorites have been identified as impact melts of enstatite chondrite parentage by *McCoy et al.* (1995) and *Burbine et al.* (2000). Other workers favor an origin from indigenous melts from the aubrite parent body.

*2.3.6. Achondritic breccias containing chondritic material.* Most meteorite breccias contain only a tiny fraction of material that could have come from a separate parent body (e.g., *Lipschutz et al.,* 1989). However, the aubrite, Cumberland Falls, contains abundant chondritic clasts that were probably derived from a single projectile.

*2.3.7. Chondritic breccias containing achondritic clasts.* Some chondrites contain achondritic clasts that are obviously impact melted material. But a few clasts in type 3 ordinary chondrites appear to be fragments of differentiated asteroids and may have been acquired during accretion (see *Mittlefehldt et al.,* 1998, pp. 168–171).

*2.3.8. Other oddball meteorites.* A few meteorites, e.g., Enon, Bocaiuva, and Northwest Africa 176, are composed of ~50 vol% chondritic silicate inclusions in metallic Fe,Ni (*Liu et al.,* 2001). In these meteorites, the silicate inclusions do not resemble rock fragments and the meteorites might be strongly metamorphosed metal-rich chondrites or some kind of impact melt product.

The abundance of meteorites that lie outside the envelope of standard chondrites and differentiated meteorites suggests that our schemes for classifying meteorites are too simple-minded and that geological processes on asteroids, especially impacts, were more complex than we commonly appreciate. In addition, these meteorites emphasize the limitations of remote analyses of asteroids and the need for careful characterization of returned samples.

## 3. METEORITE EVIDENCE FOR ASTEROIDAL IMPACTS

Information about asteroidal impacts has been culled from three types of meteoritic evidence: mineral and rock textures, radiometric ages, and other constraints on the thermal histories of minerals. The degree of shock in minerals and clasts and the extent and nature of brecciation in meteorites provide direct clues to the impact history of meteorites and their constituents (e.g., *Scott et al.,* 1989; *Stöffler et al.,* 1991; *Bischoff and Stöffler,* 1992). However, shock and impact deformation effects are commonly heterogeneous and notoriously difficult to interpret. For example, several studies of the martian meteorite ALH 84001 have failed to agree on whether it suffered one major impact that formed a large complex crater (*Scott et al.,* 1998) or numerous impacts and one thermal metamorphic event (*Treiman,* 1998).

Radiometric ages of meteorites combined with other kinds of chronological constraints such as cosmic-ray-exposure ages can provide invaluable constraints on the nature of impact events (*Bogard,* 1995). However, radiometric chronometers are reset in impacts by postshock heating, which depends on shock pressure and the crater setting. Thus any proposed relationship between a radiometric age and a specific impact may be controversial. For example, *Turner et al.* (1997) argued that their 3.9-G.y. $^{40}Ar$-$^{39}Ar$ age for ALH 84001 was a metamorphic age and that the plagioclase glass and other shock metamorphic features formed during an impact 13 m.y. ago that removed the rock from Mars and exposed it to cosmic rays without significant reheating. However, constraints from the magnetization record suggest that the rock was not shocked or reheated significantly when it left Mars, unlike other martian meteorites, and that the 3.9-Ga event was the major impact that damaged the rock (*Weiss et al.,* 2000).

The ~3.9-G.y. $^{40}Ar$-$^{39}Ar$ ages and thermal histories of mesosiderites, which are essentially unshocked metal-silicate breccias, were initially interpreted to result from a near-catastrophic impact that reheated the breccias at the time of heavy lunar bombardment (*Bogard et al.,* 1990). However, additional studies of the thermal histories of metallic and silicate minerals suggested that mesosiderites were probably cooling slowly deep inside a large parent body at that time. The major impact that created the metal-silicate breccias occurred much earlier, probably at ~4.45 Ga (see *Scott et al.,* 2001).

These studies show that understanding the impact histories of meteorites may require several independent thermal constraints in addition to radiometric ages. Below I summarize how meteorite evidence can illuminate our understanding of various impact phenomena during the accretion and evolution of asteroids. The final section describes in more detail how impact studies have been used to infer the impact history of specific meteorite parent bodies.

### 3.1. Accretion of Asteroids

For accretion to occur, impact velocities must be less than about twice the escape velocity, which for a 100-km-radius asteroid is ~140 m/s. At these velocities, silicates are broken but not shocked or heated sufficiently to reset radiometric clocks. Thus accretional impacts can only be dated indirectly.

Models for accretion in the asteroid belt generally envisage micrometer- or submicrometer-sized dust grains sticking together and settling to the midplane of the nebula to form a dense layer of dust, which because of gravitational instabilities or some other mechanism was converted into a disk of kilometer-sized planetesimals. Several arguments suggest that asteroids may not have accreted this way. First, as discussed earlier, many chondritic asteroids accreted largely from chondrules, not dust. In many cases, the fine-grained dust accreted as rims on chondrules or other large particles. In addition, chondrules appear to have accreted with fragments of preexisting bodies that were large enough to undergo alteration and possibly also melting. Second, dry, solid silicate grains would probably not adhere to each other (*Wood,* 1996), and nebular turbulence may have prevented loose grain aggregates from settling to the midplane to form a gravitationally unstable layer (*Cuzzi et al.,* 1996, 2001). Third, as discussed below, the extraordinarily diverse menagerie of chondrite groups appear to require more complex accretion models.

*3.1.1. Chondrite compositions.* Although the matrix concentration in chondrite groups appears to be correlated with formation location (Fig. 2), it is not correlated with the concentration of refractory or moderately volatile elements or the bulk O-isotopic composition. Thus chondritic planetesimals did not simply form from a disk of solids with compositions that varied smoothly with radial distance. The bulk composition of a chondrite group or chondritic asteroid must have depended on two or more nebular parameters, e.g., the time and place of accretion (e.g., *Clayton,* 1993).

Since chondrules accreted from at least six separate reservoirs, the accretion process must have ensured that each asteroid acquired chondrules from a single reservoir. Whether chondrules formed near the protosun or in the asteroid belt, the time for an asteroid to accrete from a single reservoir of chondrules must have been much less than the time required to generate a new reservoir or chondrules at that location. In addition, early-formed asteroids had to be isolated from late-formed reservoirs of accreting chondrules. Thus chondrule formation and accretion may have been sporadic processes, ensuring that the composition of accreting material did not vary smoothly with time or radial distance.

*3.1.2. Role of chondrules.* Chondrites with the lowest concentrations of chondrules, CI, CM, and Tagish Lake, all have heavily hydrated matrix material. Not one of the undifferentiated asteroids that we appear to have sampled delivers chondrites that are composed largely of dry matrix material with few chondrules. Even without chondrules, such materials should be recognizable as chondritic from their near-solar bulk compositions. It is therefore probable that planetesimals in the inner part of the asteroid belt and in the terrestrial planet region did not form without chondrules and similar-sized particles. Either chondrule formation was remarkably efficient at these locations or fine dust failed to accrete without coating chondrules.

*Cuzzi et al.* (1996, 2001) infer that chondrules played a key role in triggering the accretion because chondrules and particles with similar aerodynamic stopping distances were concentrated at transient locations between turbulent eddies. Some of these accumulations settled to the midplane, drifted inward, and accreted into planetesimals. Dust and fluffy grain aggregates were carried along by the gas into the protosun. Episodic addition of chondrules to the nebula and planetesimal accretion may have allowed chondrules from different reservoirs to accrete without significant cross contamination.

The apparent tendency for the matrix concentration to increase with increasing inferred formation distance suggests that in the cooler parts of the solar nebula, fine-grained solids accreted without the assistance of chondrules. Ice crystals and sticky organics may have allowed grain aggregates to grow large enough and dense enough to decouple from the turbulent nebular gas and descend to the midplane to accrete. In the inner solar system, temperatures were probably too high for ice and organics to coat grains so that only chondrules or particles with comparable aerodynamic stopping distances acccreted.

*3.1.3. Kaidun chondritic breccia.* The Kaidun chondrite (Fig. 5) is unique as it consists almost entirely of millimeter- and submillimeter-sized fragments of various types of chondritic material: CI, CM, CR, EH, and EL chondrites, material similar to the Tagish Lake chondrite, and unidentified material (*Zolensky et al.,* 1996; *Zolensky and Ivanov,* 2001). Some Kaidun clasts resemble the dark clasts in CR chondrites (*Zolensky et al.,* 1996), which accreted with CR chondrules. In addition, many clasts are unshocked and probably formed very early as the carbonates in all lithologies appear to have formed <$10^6$ yr after CAIs (*Hutcheon et al.,* 1999). It seems probable that the clasts impacted at relatively low velocities and that the parent body of Kaidun accreted from fragmental debris from preexisting asteroids.

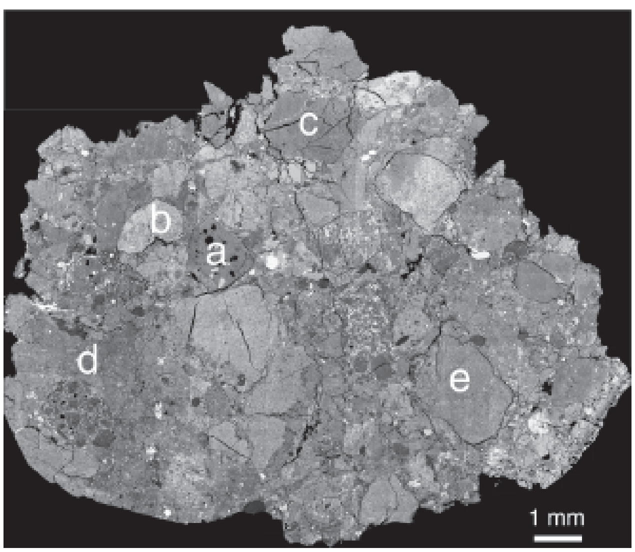


**Fig. 5.** Backscattered electron image of a thin section of the unique Kaidun chondrite, which is mostly composed of millimeter- and submillimeter-sized fragments from many other chondritic bodies. Some identified fragments include impact melt (a), enstatite chondrite (j), CI chondrite (c), CM chondrite (d), and Tagish Lake-type material (e). Kaidun, which has the highest proportion of rock fragments to chondrules of any chondrite, may be an accretionary breccia that formed by turbulent accretion of fragments in the nebula when few chondrules were available. (Image supplied by Michael Zolensky.)

The Kaidun breccia might usefully be considered as a chondrule-poor chondrite that is exceptionally rich in chondritic clasts. If there was a pause in chondrule formation or deposition at some nebular location, the abundance of tiny asteroidal fragments suspended in turbulent gas may have built up until rock chips, rather than chondrules, triggered planetesimal accretion.

Asteroidal fragments may also have played a role in transporting water across the asteroid belt during accretion. Experiments and theory suggest that slow kinetics prevented the formation of hydrous silicates in the nebula and that nebular temperatures in the asteroid belt probably exceeded the condensation temperature of water ice [~180 K (*Fegley,* 2000)]. Water may have accreted into asteroids in the form of particles of ice that drifted inward from beyond the nebular snowline (*Cyr et al.,* 1998), or fragments of outer planetesimals that contained hydrous silicates.

Many details of asteroid accretion remain obscure but the turbulent accretion model of *Cuzzi et al.* (2001) seems to offer a good framework for understanding an early stage in the accretion of components in chondrites. Further studies of chondrule and fragment sizes in Kaidun and other chondrites are needed to test the ideas discussed above.

### 3.2. Mass Loss from the Asteroid Belt

Models for the solar nebula based on the existing bodies suggest that ~99.9% of the solid material in the asteroid belt, 1 $M_\oplus$ or more, failed to accrete into asteroids or was removed soon after. At Mars' location, ~95% of the solids may have been lost. If Jupiter formed rapidly in ~100 yr from gravitational instabilities, it is possible that Jupiter prevented planetary embryos from accreting in the belt while allowing the terrestrial planetary embryos to develop (*Kortenkamp and Wetherill,* 2000). But if Jupiter formed in $10^7$ yr from a solid core that subsequently accreted nebular gas, planetary embryos may have formed in the asteroid belt. In this case, the mass of the asteroid belt may have been removed largely by gravitational perturbations or collisional fragmentation followed by nongravitational removal of asteroid chips by, for example, gas drag, or by some combination of all three processes (*Wetherill,* 1989). The survival of Vesta's crust argues against collisional fragmentation as the major process. Most authors have therefore investigated gravitational perturbations by the embryos themselves and the giant planets to clear the asteroid belt (*Chambers and Wetherill,* 2001; *Petit et al.,* 2002). However, it is not clear whether lunar-sized bodies could have been removed from the asteroid belt without leaving a more traumatic collisional record in the meteorites and surviving asteroids.

If chondrules were as critical for asteroid formation as we infer, the efficiency of chondrule formation and accretion may have been important factors affecting the mass of the asteroids. Chondrule production, or chondrule deposition from bipolar flows, may have decreased with increasing distance from the protosun. If a large mass deficiency existed in the asteroid belt prior to the accretion of planetesimals, few asteroids would have been able to accrete, according to *Wetherill* (1989). However, accreting solids may have been heterogeneously distributed in the belt. For example, turbulent accretion of chondrules and particles with similar aerodynamic stopping distances may have focused solids to specific locations where planetesimals formed.

### 3.3. Impact Heating

The effectiveness of impact heating of asteroids has been a controversial issue in meteorite studies. Various authors have argued that impacts caused extensive metamorphism or melting on the parent bodies of almost every kind of meteorite (e.g., *Takeda,* 1993; *Rubin,* 1995). However, studies of terrestrial craters, shock experiments, and theoretical considerations suggest that impacts were probably not a significant source of heat for metamorphism and melting for asteroids under a few hundred kilometers in diameter (*Keil et al.,* 1997). The current mean impact velocity of asteroids, ~5 km/s (*Bottke et al.,* 1994), is scarcely above the threshold impact velocity required to generate shock pressures high enough to completely melt materials. Much of the impact melt that is generated on asteroids is ejected with velocities that exceed the asteroid's escape velocity. The volume of melt may increase for very porous asteroids, but this does not alter the basic conclusion that mean temperatures of asteroids increase by <100°C even in the largest impacts (*Keil et al.,* 1997).

### 3.4. Regolith Formation

For nearly all groups of chondrites and achondrites, we have samples that contain solar-wind gases and solar-flare tracks due to exposure in the top millimeter of their parent-body regoliths (*Bunch and Rajan,* 1988; *McKay et al.,* 1989). These regolith breccias provide our only tangible samples of grains that have been on the top surfaces of asteroids. However, the proportion of grains exposed to solar flares, which is lower than in typical lunar regolith breccias, is too low to allow definitive inferences to be drawn about the optical properties of asteroidal surfaces. Possibly because of efficient mixing of irradiated and unirradiated grains, there are only very minor chemical and mineralogical differences between regolith breccias and unirradiated fragmental breccias or, in the case of chondritic bodies, unbrecciated samples. Regolith breccias contain only a percent or so of foreign clasts, mostly carbonaceous chondrite material as most projectile material is lost during impacts on asteroids.

Achondritic and many chondritic regolith breccias appear to have been lithified by localized shock melting. We lack iron and stony-iron meteorite breccias with solar-wind gases, possibly because regolith on their parent bodies could not be converted to coherent rocks by localized shock melting of minerals. Carbonaceous chondrite regolith breccias tend to have the lowest concentrations of track-rich grains and solar-wind gases and may have been lithified by alteration. Shocked carbonaceous chondrites containing hydrous minerals are not known, perhaps because of devolatilization on shock release.

### 3.5. Fragmentation and Reaccretion

For seven groups of meteorites, there is textural and cooling rate evidence suggesting that their parent bodies were fragmented and then largely reaccreted so that material from diverse depths of the target asteroid were mixed together. These seven bodies are the parent bodies of the Shallowater enstatite achondrite, mesosiderites, H chondrites, L chondrites, ureilites, IVA irons, and the parent body of IAB irons and winonaites (*Keil et al.,* 1994; *Benedix et al.,* 2000; *Scott et al.,* 2001). For all bodies except the H- and L-chondrite bodies, the targets appear to have been hot enough prior to impact to contain at least minor amounts of melt. This does not necessarily imply that few cold meteorite parent bodies were fragmented and reaccreted as it is easier to recognize mixtures of materials from different depths when the targets contain some melt.

Low-resolution, smoothed-particle hydrodynamics computer simulations for 50–300-km-diameter targets suggest that for undifferentiated and fully differentiated target asteroids, near-catastrophic impacts can mix significant proportions of materials from all depths (*Love and Ahrens,* 1996; *Scott et al.,* 2001). However, these studies have done little more than prove the concept and more detailed modeling of near-catastrophic impacts is needed.

Existing studies suggest that impacts do not gradually strip mantles from the cores of differentiated asteroids. Cores and mantles of differentiated asteroids were probably mixed together before disruption by catastrophic impacts. Thus the rarity of olivine-rich, metal-free asteroids may reflect impact scrambling rather than near-total fragmentation of differentiated asteroids smaller than Vesta (*Burbine et al.,* 1996). Some S asteroids may be differentiated asteroids that were disguised by impact scrambling (*Scott et al.,* 2001).

### 3.6. Case Histories

*3.6.1. Ordinary chondrites.* Despite many constraints from mineral cooling rates, $^{40}$Ar-$^{39}$Ar ages, and studies of regolith and fragmental breccias, there are disagreements about the nature of the parent bodies of ordinary chondrites.

The parent bodies of the H and L chondrites probably suffered one or more major impacts that may have mixed materials from all depths (*Keil et al.,* 1994). Some ordinary chondrites are breccias consisting of the most metamorphosed and presumably most deeply buried type 6 material mixed with the least-metamorphosed type 3 material. A few such breccias experienced temperatures above 500°C after assembly suggesting that at least one major impact occurred >4.4 G.y. ago when the parent asteroid was cooling but still hot. The wide range of cooling rates in metal grains in some regolith breccias combined with impact and thermal modeling suggest that the H and L parent bodies were broken up and reassembled between 4.4 G.y. and exposure to cosmic rays <100 m.y. ago (*Taylor et al.,* 1987). However, the thermal modeling depends critically on assumptions about the porosity and thermal conductivity of the ordinary chondrite bodies (see *McSween et al.,* 2002). Layers of regolith <1 km thick can drastically reduce the rate of cooling of 100-km-radius asteroids and enhance the thermal gradients near the surface of the asteroid (*Haack et al.,* 1990). Thus *Akridge et al.* (1998) argue that H chondrites are derived from depths of <10 km from a 100-km radius asteroid and that most of the interior of the parent body has not been sampled, contrary to *Bennett and McSween* (1996). Further thermal modeling to fit the constraints imposed by $^{40}$Ar-$^{39}$Ar ages would be useful.

One candidate parent body of H chondrites, 6 Hebe, is an atypical S(IV) type as it shows rotational spectral variations. *Gaffey and Gilbert* (1998) suggest that these are due to impact-formed melt sheets on Hebe or residues of metal-rich projectiles, and that these supply meteorites such as Portales Valley (Fig. 4) and the IIE iron, Netschaevo. However, the link between IIE and H chondrites is not well established (*Bogard et al.,* 2000), Portales Valley probably formed at depth as it cooled slowly, and known asteroids are too small to generate impact-formed melt sheets (*Keil et al.,* 1997). Studies of complementary metal-poor samples would help us to understand the formation of metal-chondrite breccias and possible links with H chondrites but such samples have not yet been identified.

The high proportion of heavily shocked L chondrites with $^{40}$Ar-$^{39}$Ar ages around 500 m.y. shows that the L-chondrite parent body suffered a major impact at this time. *Haack et al.* (1996) argue that the L chondrites are derived from a kilometer-sized rubble pile or fragment ejected from near the impact point of a catastrophic dispersion event. This event may have been responsible for the deposition of numerous ordinary chondrites in 450-m.y.-old limestone in Sweden when the meteorite flux on Earth may have been 10–100× higher for ~30 m.y. (*Schmitz et al.,* 1997). *Nesvorný et al.* (2002) suggest that the parent body of L chondrites and the Flora asteroid family may have been the same body.

*3.6.2. Mesosiderites.* These differentiated meteorites are all breccias composed of roughly equal proportions of metallic Fe,Ni and silicate. The silicate portion consists of fragments of rocks and silicate minerals in a fine-grained fragmental or igneous matrix (Fig. 6). The rock and mineral fragments are pieces of basalts, gabbros, and pyroxenites with minor amounts of dunite. Thus their constituents could have been derived from all levels of an igneously stratified asteroid that was similar but not identical to the parent body of the howardites, eucrites, and diogenites, presumably Vesta (*Keil,* 2002). Geochemical evidence suggests that the metal was molten prior to the impact that mixed metal and silicate. The major puzzle for understanding mesosiderites has been the small amount of olivine, which should have been abundant in differentiated asteroids. One model suggests that the olivine is confined to metal-poor regions that are poorly sampled and that the ingredients in mesosiderites are derived from a single body that was scrambled by a large impact (*Scott et al.,* 2001). An alternative idea is that the mesosiderite body formed when molten metal from the core of a projectile was mixed with crust from the mesosiderite parent body in a 1-km/s impact (see *Rubin and Mittlefehldt,* 1993). However, impacts at this velocity would probably have been very rare at the time of metal-silicate mixing, which has been inferred to be 100–150 m.y. after the solar system formed. At the current mean impact speed of 5 km/s, projectile material is almost entirely lost (*Love and Ahrens,* 1996).

The large M-type asteroid, 16 Psyche, has been suggested as a scrambled parent body for mesosiderites as it lacks a dynamical family that might have formed if Psyche

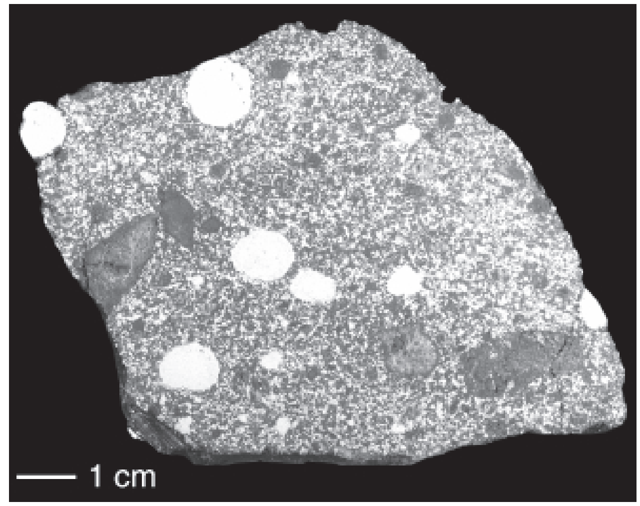


**Fig. 6.** Polished slice of the Barea mesosiderite showing a mixture of centimeter-sized spherules of metallic Fe,Ni (light) and angular fragments of basaltic rock (dark) embedded in an intimate metal-silicate matrix. This breccia formed when molten metal from the core of an asteroid was mixed with mantle and crustal rocks. The impact was probably a near-catastrophic event that scrambled metal and silicate from a single asteroid that broke up and reaccreted (*Scott et al.,* 2001). The alternative explanation, that the molten metal and rock were derived from separate asteroids that collided at low velocity during accretion (*Rubin and Mittlefehldt,* 1993), appears less plausible as radiometric ages suggest that mixing occurred 100–150 m.y. after the solar system formed, long after asteroids accreted.

were an exposed core from a 500-km-diameter asteroid (*Davis et al.,* 1999). However, an estimate of the density of Psyche by *Viateau* (2000) is too low to be consistent with this model. Field work would be useful to test these ideas on mesosiderite origins and to develop better models for large impacts.

*3.6.3. Ureilite achondrites*. Ureilites, which probably formed at depth in a partly melted asteroid, consist largely of coarse-grained olivine and pyroxene grains with minor interstitial metal and graphite. If these phases were in equilibrium, ureilites must have formed at depth in a body that was at least 100 km in radius (*Mittlefehldt et al.,* 1998). One of the most remarkable features of ureilites is that they all cooled rapidly from 1250° to <650°C at ~10°C/h (see *Goodrich et al.,* 2001, 2002). To cool in a few days, the hot rock must have been broken into meter-sized pieces. Fragmentation of impact debris into such tiny pieces may have been aided by formation of $CO$-$CO_2$ gas in grain boundaries on pressure release (*Keil et al.,* 1994).

A large number of the ureilites contain shock-formed diamonds and other shock metamorphic features. The high proportion of shocked ureilites and their unusual thermal history suggest that they are derived from near the point of impact. Since ureilite regolith breccias are made from similar material, it seems likely that ureilites are derived from one member of a family of asteroids that accreted a few days or more after the catastrophic breakup of the first ureilite body. Since the catastrophic impact probably occurred 4.5 G.y. ago, the asteroid family may no longer be recognizable.

## 4. IMPLICATIONS

The meteorite record contains a wealth of information about the origin and evolution of asteroids and the critical role of impacts at all stages. Meteorite breccias and features can be identified that reflect impacts during accretion; during melting, metamorphism, and alteration of asteroids; and during the erosion and disruption of cold asteroids. However, many meteorites do not fit comfortably into our simple models for understanding asteroid accretion and evolution. This probably results from the complexity of geological processes on asteroids and our inadequate understanding of what impacts do to hot and cold asteroids during and after accretion.

New meteorites and better constraints on the chronology, impact, and thermal history of chondrites and differentiated meteorites have greatly helped to advance our understanding of asteroid formation and evolution since the review by *Scott et al.* (1989). But they have also emphasized the urgent need for fieldwork on main-belt and near-Earth asteroids and laboratory study of returned samples. Without these we cannot hope to understand fully how meteorites, asteroids, and planets formed; how asteroids and planets interact; and how the harmful effects of such interactions can be minimized.

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