

Meteorites: An Overview

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Meteorites come from numerous parent bodies with a wide variety of geological histories. A few (~0.5%) come from Mars or the Moon; the rest are impact debris from collisions between asteroids orbiting between Mars and Jupiter. Unlike terrestrial, Martian, and lunar rocks, the asteroidal meteorites contain minerals that formed before the Sun and the Solar System, during the growth of planetesimals and planets from the disk of dust and gas around the Sun (“the solar nebula”), and during the first half-billion years of Solar System evolution.

Meteorites from unmelted asteroids are called chondrites; they are cosmic sediments composed of particles that were present in the solar nebula (Fig. 1). The most abundant particles are millimeter-sized objects called chondrules, which are solidified droplets of silicate magma. The chondrules, associated grains of Fe–Ni metal, and a few volume percent or less of calcium–aluminum-rich inclusions (CAIs), which were the first solids to form in the solar nebula, are embedded in a fine-grained matrix. The matrix initially contained a mixture of chondrule fragments, presolar and solar nebular grains, and organic materials. However, most chondrites were aqueously altered or thermally metamorphosed so that only a handful of chondrites have preserved presolar grains and pristine chondrules.

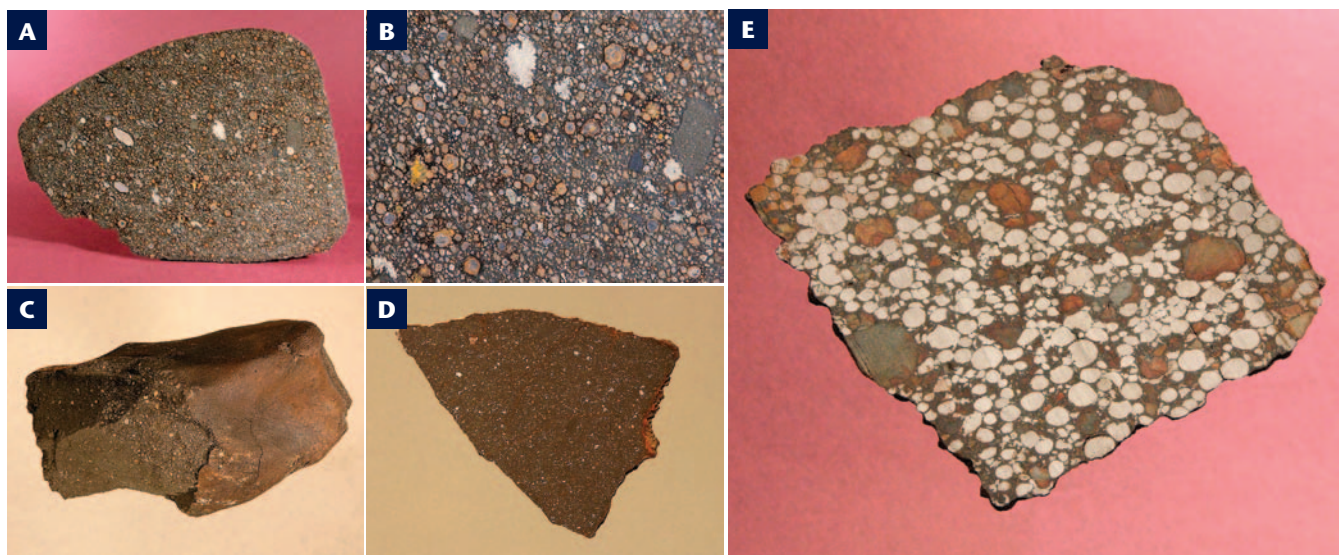
The three major classes of chondrites—carbonaceous, ordinary, and enstatite—are divided into 13 major groups. Ordinary chondrites, which make up 85% of meteorite falls, include three groups, called H, L, and LL chondrites. Carbonaceous chondrites, which are generally richer in carbon and matrix, are divided into CI, CM, CO, CV, CK, CR, CH, and CB groups. Enstatite chondrites contain virtually Fe-free enstatite and are divided into the EH and EL groups. Nearly all chondrites were metamorphosed or aqueously altered in their parent bodies to a degree that is indicated by their “petrologic type.” Type 3, or “unequilibrated,”

chondrites are the most pristine, type 6 are the most metamorphosed, and type 1 are the most aqueously altered.

Asteroids that melted supply us with three major classes of meteorites: irons, which are Fe–Ni samples from the cores of asteroids; metal-free silicate rocks from asteroidal mantles and crusts, which are called achondrites as they lack chondrules; and stony irons, which are impact-generated mixtures of achondrites and Fe–Ni metal (Fig. 2). Most irons (85%) are divided into thirteen groups (called IAB, IIAB, IIC, etc.), which come from separate parent bodies. The remaining ~15% probably come from another 50-odd parent bodies. There are two major types of stony irons: pallasites, which are olivine–metal mixtures from at least 5 different bodies, and mesosiderites, which are mixtures of metal and basaltic material.

The four largest groups of achondrites are the howardite–eucrite–diogenite group (abbreviated HED), aubrites, ureilites, and angrites. Eucrites are basalts and gabbros that have been modified by metamorphism and impacts,

FIGURE 1 Four kinds of chondrites. (A) A polished slice of the Axtell CV3 chondrite showing abundant millimeter-sized chondrules and several white Ca–Al-rich inclusions (CAIs). (B) Close-up view of Axtell. (C) The Murchison CM2 chondrite with a fusion crust (right), showing small chondrules embedded in a dark matrix, which contains organic compounds and presolar grains. (D) A slice of the Kaufman L5 chondrite showing white grains of Fe–Ni metal enclosed in black silicates. (E) The CB3 chondrite Gujba contains ~70 vol% globules of Fe–Ni (white) metal and chondrules with diverse sizes. Long dimensions of samples: (A) 12 cm, (B) 5 cm, (C) 6 cm, (D) 18 cm, (E) 11 cm. ALL PHOTOS BY GEOFFREY NOTKIN©, OSCAR E. MONNIG METEORITE COLLECTION, TEXAS CHRISTIAN UNIVERSITY



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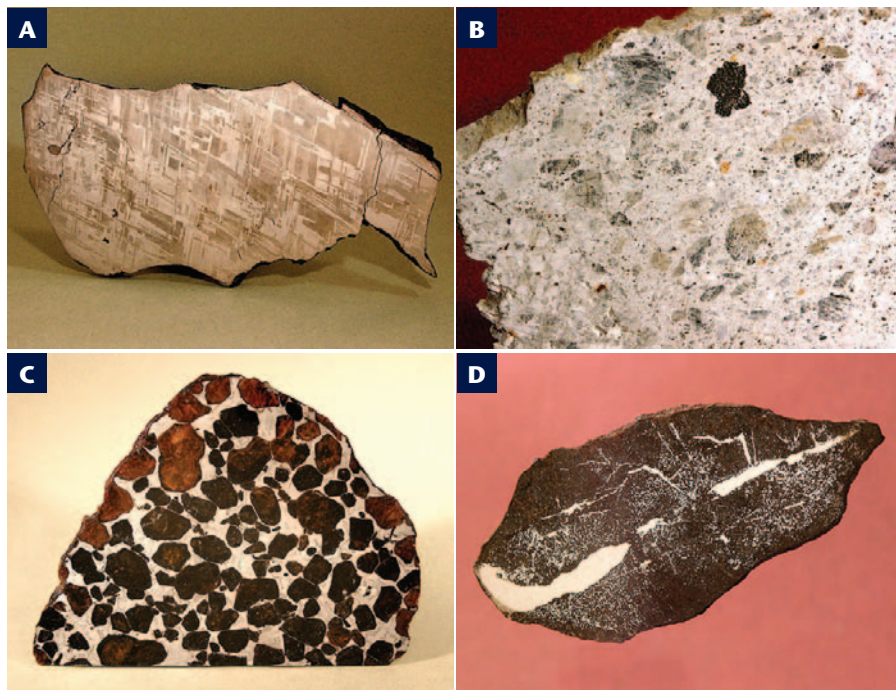


FIGURE 2 Four kinds of differentiated meteorites from asteroids that melted. (A) A slice of the San Angelo IIIAB iron etched to show the Widmanstätten pattern of oriented kamacite crystals (body-centered cubic Fe–Ni), which exsolved from a single crystal of taenite (face-centered cubic Fe–Ni). (B) A slice of the Peña Blanca Spring aubrite—an achondritic breccia composed largely of enstatite fragments. (C) A polished and etched slice of the Ahumada pallasite showing olivine fragments enclosed by Fe–Ni metal. (D) Monument Draw is a so-called “primitive achondrite” containing rare chondrules and metallic veins; it formed in an asteroid that was hot enough to melt Fe–Ni metal and iron sulfide. Long dimensions of samples: (A) 20 cm, (B) 9 cm, (C) 17 cm, (D) 6 cm. ALL PHOTOS BY GEOFFREY NOTKIN©, OSCAR E. MONNIG METEORITE COLLECTION, TEXAS CHRISTIAN UNIVERSITY

diogenites are composed of orthopyroxenite, and howardites are eucrite–diogenite breccias. Except for a handful of eucrites with aberrant oxygen isotope compositions, the HED meteorites are probably derived from the brightest asteroid, Vesta, which will be orbited by the Dawn spacecraft for a year starting in July 2011. Aubrites, which are the most reduced achondrites, are breccias consisting of fragments of virtually Fe-free enstatite. Ureilites are composed of olivine and pyroxene with interstitial graphite and formed as residues from partial melting. Angrites are basaltic rocks composed largely of Al–Ti–diopside.

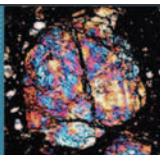
The diverse nature of meteorites reflects the wide range of formation times and locations of their parent bodies and their different impact histories. Meteorites formed through igneous processes probably come from bodies that accreted early, possibly less than 2 astronomical units (AU) from the Sun, when heat from the radioactive decay of ^{26}Al could readily melt asteroids. Chondritic asteroids accreted a few million years later, probably in the asteroid belt (>2 AU from the Sun), when ^{26}Al was no longer abundant enough to melt asteroids. Impacts increased the diversity of rock

types by creating bizarre mixtures of metal and silicate when the asteroids were partly molten (e.g. pallasites, Fig. 2C). After the asteroids had solidified, impacts pulverized their surfaces, mixed fragments, and welded them into new types of rocks, like the aubrite (Fig. 2B) and howardite breccias.

RESOURCES

The Meteoritical Bulletin Database, which is run by the Meteoritical Society, is the authoritative source of information about the 40,000 approved meteorites. The database includes their classification, discovery details, size, and constituent minerals (www.lpi.usra.edu/meteor/metbull.php). For an excellent review of meteorite classification and properties, read chapter 6 in *Cosmochemistry* by Hap McSween and Gary Huss (Cambridge University Press, 2010). Recent discoveries about meteorites are succinctly summarized and explained for non-experts on the NASA-supported website called Planetary Science Research Discoveries (www.psr.d.hawaii.edu) run by my colleagues at the University of Hawai‘i Jeff Taylor and Linda Martel. ■

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