Sears, D.W.G. (1985b) Meteorites are clues to the early solar system. *Geotimes*, June issue, 12-14 (Conference report).

of chondrites, chondrules & other things

Meteorites are clues to the early Solar System

The primitive solar nebula contained a bewildering array of solid material. Much of it eventually found its way into the planets or was swept out of the system, but a small and tantalizing fraction of the solid residue survived its 4,600 million years in space to find its way, ultimately, to Earth. Several sessions of the 16th Lunar & Planetary Science Conference were devoted to meteorites and meteoritic components and much of the discussion centered on the diversity and complexity of early Solar System material and processes.

The major components of the chondritic classes, those 4,600-million-years old, and with essentially solar composition, are the matrix, the metal and sulfide grains, chondrules and calcium-aluminum rich inclusions. The matrix has been regarded commonly as a fine smoke that condensed directly from the gases of primitive solar nebula. K. Tomeoka and Peter Buseck (Arizona State University) and Bob Housley (Rockwell International) argued that certain petrologic trends and compositional inhomogeneities refute that theory. They contend that the matrix consists of a finely crushed mixture of chondrules and various aggregates, which in some instances has undergone aqueous alteration and low-temperature reactions. Similarly, Jeff Grossman (U.S. Geological Survey, Reston) argued that the matrix of the particularly primitive Semarkona ordinary chondrite, the largest chondrite class, appeared to have excess sodium and potassium, a property he attributed to recondensation of those elements after evaporation from other components.

Views on the origin and history of chondrules have become complex in recent years. Chondrules are beads of silicates that appear to have had an independent existence before their incorporation into the meteorite. At one time it was thought that chondrules had condensed directly from the nebula as liquid droplets. That view gave way to the idea that the liquid droplets were produced by an unknown flash melting event, and recently to the idea that some of the chondrules, perhaps many, contain grains that have survived the melting event; they are 'relic' grains. The variety of textures shown by chondrules has attracted considerable interest for many decades, and experimental synthesis experiments by Gary Lofgren and W.T. Russell (Johnson Space Center) showed that the presence of nucleation centers, as well as the cooling rate following the flash melting, influences the structures. Some authors have recently argued that chondrules were identical regardless of the class they came from, but Alan Rubin and John Wasson (University of California, Los Angeles) reported that chondrules in the CM class of chondrites show compositional-mineralogical trends dissimilar to chondrules from the major classes. The processes that can occur during the chondrule-formation event appear to be highly diverse, as reflected in the six chondrules examined by Gero Kurat and his co-workers (Naturhistorisches Museum, Vienna). There were indications of vapor loss, direct condensation from the nebula and element redistribution. Several alumina-bearing chondrules from the unusual Karoonda chondrite also appear to have suffered a multi-stage, complex history, according to Joe Delaney and co-workers (American Museum of Natural History, New York). In fact, some of the larger chondrules contain grains that, although petrographically unlike the relic grains, were unaltered by chondrule formation and may be sites of some of the unusual isotopic ratios found in certain chondrites.

Chondrules and CAI are millimeter- to centimeter-size aggregates of a variety of calcium and aluminum-rich minerals. They are host to many unusual isotopic and elemental properties. Since their discovery in the early 1970s, the major question for CAI studies is whether they are condensates that formed in the nebula before the condensation of the more volatile elements, or whether they are the residues remaining after evaporation of the more volatile elements. It has also been argued that they may be supercooled liquid condensates. J.M. Paque (Smithsonian Astrophysical Laboratory, Cambridge) described a CAI particularly rich in relatively volatile vanadium and argued that it was probably a distillation residue on which volatile elements had recondensed. Ed Stopler and his associates (Cal Tech) used the pyroxene-melilite mineral pair in other CAI to calculate equilibration temperatures and found them close to the solidus (1,200 to 1,400°C), inferring an igneous origin.

In the last year or so, attention has been given to how the mineralogic and textural properties of CAI reflect parent-body processes, such as metamorphism. Last year, petrographic data were used to argue that five CAI from the Allende meteorite had experienced metamorphism, some being thoroughly altered, and some only slightly affected. At the meeting, Janet Teshima and Gerry Wasserbrug (Cal Tech), members of the research group responsible for the suggestion of metamorphic alteration of CAI, showed that the extent of homogenization of the mineral compositions varied with the metamorphic sequence previously proposed. In another paper, John Armstrong and others (Cal Tech) were able to estimate metamorphic temperatures of about 600°C from the mineral chemistry of metal and sulfide grains in CAI. Andy Davis (University of Chicago) surveyed CAI in the CO chondrites and concluded that they too show signs of alteration before and after their incorporation in the meteorite. CAI in meteorites may therefore turn out to have a history as complex and diverse as the chondrules and matrix.

In addition to petrologically observed components, there may be others present in amounts too small to see under the microscope. Some of the isotopic properties of chondrites may reflect exotic components of that sort. In 1983, Ed Anders' group (University of Chicago) and Colin Pillinger's group (the Open University) discovered that a tiny residue left after extensive acid treatment of the Murchison CM meteorite contained

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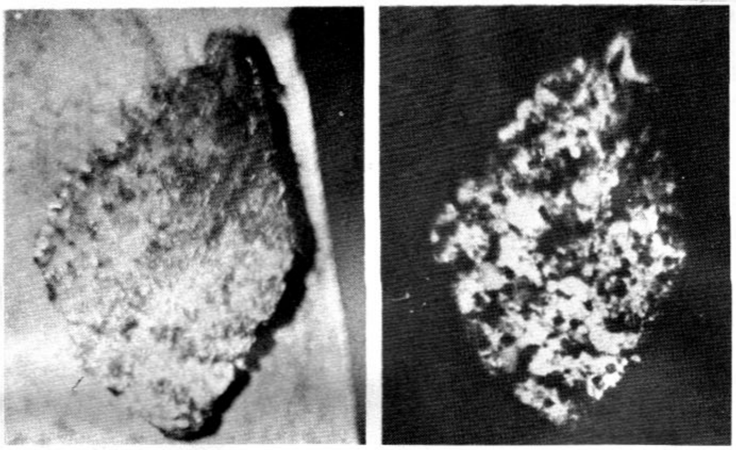

A 1-mm-thick slice of the Holbrook meteorite (1 cm long) lies on a heating strip before being heated to about 300°C in the dark (left). The thermoluminescent grains irregularly distributed through the slice are feldspar, and thermoluminescence is acutely sensitive to the nature and the amount of feldspar. Thus the phenomenon provides a uniquely quantitative way to study phenomena such as shock and metamorphism, which profoundly affect the feldspar. (Photo by Derek W.G. Sears, University of Arkansas)

carbon with twice as much carbon-13 as observed normally. They suggested that the source was grains that had formed in the shell of red giant stars. At the meeting, Halbout and co-workers (University of Chicago) discussed stepwise heating experiments on bulk samples of four chondrites in which the carbon released at high temperatures (1,200°C) contained two-fold enrichments of carbon-13.

Perhaps a third of the chondrite studies reported at the meeting dealt with processes experienced by the meteorite as a whole, rather than components. Usually such studies were aimed at quantifying various aspects of meteorite history. Using the distribution of Mg and Fe between olivine, spinel and Mg-ilmenite, Frank Wlotzka (Max Planck Institute, West Germany) obtained some new paleotemperatures for the ordinary chondrites. The scheme of Van Schmus and Wood divides the ordinary chondrites into types 3 to 6, according to the metamorphic alteration experienced, and type 3 has been further divided into types 3.0 to 3.9. Wlotzka found that a type-3.9 chondrite had equilibrated at 600 to 700°C and type 4 to 5 at about 800°C, while the minerals in a type-3.5 chondrite were too unequilibrated for paleothermometry. The most promising method of paleothermometry for the unequilibrated chondrites is by thermoluminescence, since the technique uses phase changes in a single mineral. The thermoluminescence sensitivity of ordinary chondrites shows a 100,000-fold increase in going from type 3 to type 6, while type 3 alone shows a 1,000-fold increase with metamorphism. It has been suggested that the thermoluminescence-metamorphism relationship was due to the formation of the phosphor (feldspar) during metamorphism by crystallization of glass. Kyle Guimon and Derek Sears (University of Arkansas, Fayetteville) and Gary Lofgren (Johnson Space Center) showed that annealing a type-3.4 chondrite in a way that caused crystallization in synthetic glasses, resulted in an increase in the thermoluminescence sensitivity.

It has never been clear whether the type-3 to type-6 sequence represents a single genetic sequence or whether it represents the accretion of material equilibrated to various extents in the nebula. Ed Scott and his co-workers (University of New Mexico) summarized current data on the question. Mineral chemistry is consistent, but oxygen isotopes and siderophile-element differences are inconsistent, with a single genetic sequence.

A few meteorites result from planetary, rather than nebula, processes. Those meteorites, called achondrites or differentiated meteorites, are rare but very diverse in origin and history. Among them are the three meteorites found in Antarctica that almost certainly came from the Moon. J.H. Chen and Gerry Wasserbrug (Cal Tech) added to the already substantial data base indicating a lunar origin for the Allan Hills A81005 meteorite. The chondrites also include eight meteorites that many authors believe originated on Mars, the so-called SNC meteorites. Highlights of talks on the SNC meteorites included Paul Pellas's assertion (Musée d'Histoire Naturelle, Paris) that the Martian-origin conclusion for SNC was premature and a discussion prompted by John Jones (University of Arizona), who argued that the 180-million-year Rb-Sr age reflects an igneous event rather than the shock event advocated by many groups.

Other differentiated meteorite classes attracted attention, especially the ureilites, an intensely shocked class containing high concentrations of inert gases and volatile elements in carbon-rich veins. All but one of the ureilites contain shock-produced diamond, which U. Ott and his co-workers (Max Planck Institute, West Germany) found to be the host for the inert gases. Veins seem to have been introduced during impact on an already hot body, so that magmatic and redox trends are superimposed. The unusual thermochemistry that resulted was explored in four papers by Cynthia Goodrich (University of New Mexico) and John Berkely (SUNY, Fredonia), and by H. Takeda and coworkers (University of Tokyo). From olivine zoning, the Japanese group calculated post-shock cooling rates for ureilites of 3 to 20 C/h.

If there was a single theme running through the meteorite papers at this year's meeting, it was the great diversity of processes occurring in the early solar nebula, whether at the meteorite, clast, grain or even atomic level. Meteorites and their components came from a wide variety of locations, and have experienced various processes before and after coming together as a single rock. It is widely assumed that the chondritic meteorites came from the asteroid belt, but, as Dieter Heymann (Rice University) stated, that assumption should not go untested.

Meteorites have much to tell us about the early Solar System. However, the situation is too complicated without considering data from other sources. Now multiple spacecraft missions to asteroids are needed, to sort out the meteorite-asteroid connection and to help decipher the message that meteorites have to tell about the rest of the early Solar System.

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