THE ENDURING LEGACY OF THE ALLENDE METEORITE

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The Earth is a very geologically active planet. Rocks are recycled through erosion, burial, and melting, which makes it difficult to learn about the origin of the Solar System by analyzing samples from Earth. In order to understand the earliest processes in the Solar System, we have to study meteorites—specifically, chondrites, which are over 4.5 billion years old and contain the first solids to have formed in the Solar System. The Solar System formed from a cloud of gas and dust called the solar nebula, and its bulk chemical composition is known because about 99.8% of the mass of the solar nebula ended up in the Sun and we know the Sun's composition from spectroscopic analysis of its light. From this composition, the sequence of minerals that should form by gas-to-solid condensation at high temperatures from the cooling solar nebula can be predicted. These very minerals, Ca–Al-rich oxides and silicates, can be found in refractory inclusions within carbonaceous chondrites. However, this was scarcely appreciated until the fall of the Allende meteorite in Mexico on February 8, 1969, because until then very little material had been available for study.

Within a few months of the fall, two tons of specimens of the Allende meteorite were recovered from a 50 km long strewnfield, and many specimens were distributed for study. Preliminary reports were published within a year of the fall (e.g. King et al. 1969), and an extensive report on the fall, recovery, and classification was published within two years (Clarke et al. 1970). A view of a slab surface of Allende (Fig. 1) shows that, typical of CV-type carbonaceous chondrites, the meteorite is a jumble of refractory Ca–Al-rich inclusions (CAIs) and round objects called chondrules set in a dark, carbonaceous matrix. The chondrules and inclusions are not related to each other. Before becoming enclosed in the matrix, they formed individually as discrete objects in space. They have been preserved since the formation of the Solar System because they were incorporated into a parent body that was too small to have a geologically active surface.

At a time when geochemical laboratories were being modernized and equipped in anticipation of the first return of lunar samples, scientists suddenly had several tons of unique, extraterrestrial material to study. Allende provided the material for several important advances, including a classification scheme for refractory inclusions in Type 3 carbonaceous chondrites (Grossman 1975), which is still in use today, and the discovery that the oxygen isotope compositions of refractory inclusions are ^{16}O-rich and do not fall on the terrestrial fractionation line (Clayton et al. 1977). Allende's inclusions (e.g. Fig. 2) were found to have an average enrichment factor among the refractory elements of 17.5 relative to bulk Solar System abundances (Grossman et al. 1977), strong evidence for their formation at high temperatures.

Figure 1 View of a sawn and polished slice of the Allende meteorite, showing numerous white Ca–Al-rich refractory inclusions (CAIs) and round chondrules in a dark, carbonaceous matrix. Field of view is about 8 cm across. Photo by Linda Welzenbach, courtesy of the Smithsonian Institution

The first refractory inclusions shown to have excess ^{26}Mg due to the decay of ^{26}Al (Gray and Compston 1974; Lee et al. 1976) were from Allende, and the first studies of the distinctive rim layer sequences on refractory inclusions (Wark and Lovering 1977), indicative of processing in the nebula after they formed and before they were enclosed in the meteorite matrix, were also based on Allende samples. In addition, the first report of trivalent Ti in a refractory inclusion was based on the analysis of Ti–Al-rich pyroxene from Allende by Dowty and Clark (1973), who termed the phase "fassaite"; the presence of Ti^{3+} is strong evidence for formation under very oxygen-poor (reducing) conditions, as would be expected for a system of solar composition. Note that all of these major breakthroughs in the understanding of refractory inclusions occurred within ten years of the fall of the Allende meteorite. In following years it was shown that CAIs were not simply condensates but that some had been molten at least once (MacPherson and Grossman 1981; MacPherson et al. 1984) or even twice (Simon et al. 2005). The study of

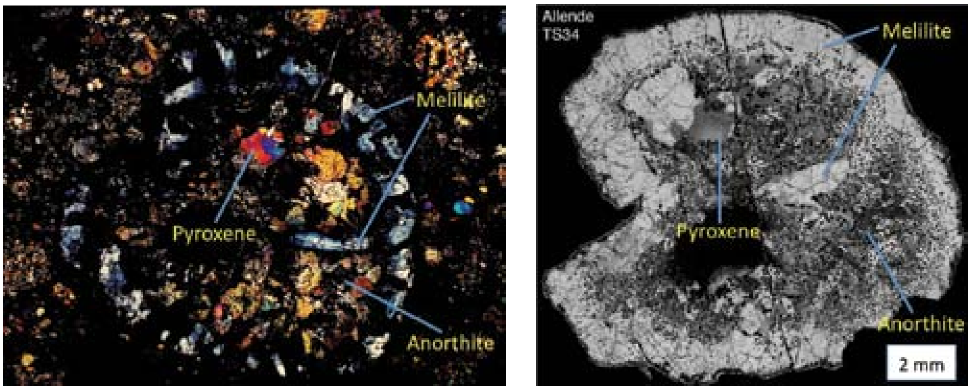

Figure 2 Two views of one of the most-studied refractory inclusions from Allende, Type B1 inclusion TS34. Transmitted light, crossed polars (left), backscattered electron image (right). Lines point to the same melilite and fassaite grains in both views.

Cont'd on page 176

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ALLENDE METEORITE *Cont'd from page 174*

Allende still results in discoveries; through work done at high magnification, nine new minerals have been found in Allende by C. Ma and coworkers since 2007 (Table 1). Allende was also the source of the first presolar diamonds to be identified (Lewis et al. 1987).

Table 1 MINERALS DISCOVERED IN ALLENDE SINCE 2007

Mineral name	Formula
Allendeite	$Sc_4Zr_3O_{12}$
Hexamolybdenum	Mo,Ru,Fe alloy
Monipite	MoNiP
Tistarite	Ti_2O_3
Davisite	$CaScAlSiO_6$
Grossmanite	$CaTi^{3+}AlSiO_6$
Hibonite-(Fe)	$(Fe,Mg)Al_{12}O_{19}$
Panguite	$(Ti,Al,Sc,Mg,Zr,Ca)_{1.8}O_3$
Kangite	$(Sc,Ti,Al,Zr,Mg,Ca,[])_2O_3$

The research that has been done on Allende is far too vast and varied to be adequately summarized in this brief article. Suffice it to say that this meteorite has been a valuable source of pieces to the puzzle of the formation of the Solar System, and it will continue to be one for the foreseeable future.

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THE NEW TISSINT METEORITE

It's a well-known secret that meteorites fall to Earth all the time, but rarely does such an event happen in a place where people see the fireball and then find space rocks on the ground. July 18, 2011, marks a remarkable event, rare even among meteorite falls—for only the fifth time, a piece of Mars was witnessed to fall to Earth. The fireball and associated sonic booms that marked the rock's atmospheric entry occurred in Morocco, a fortuitous coincidence for two reasons: many people in Morocco are experienced meteorite hunters, and the arid environment makes it one of the best places on Earth for the preservation of meteorites. Beginning in October, nomads began to find fresh, fusion-crusted stones in a remote area about 48 km from Tissint village, and over 10 kg have been recovered thus far. The meteorite was classified as a shergottite by Tony Irving and Scott Kuehner (University of Washington, Seattle), and its name, Tissint, was approved by the Nomenclature Committee on January 17, 2012 (search "Tissint" at www.lpi.usra.edu/meteor/index.php).

58 g Tissint specimen from the University of Alberta Meteorite Collection, Department of Earth and Atmospheric Sciences, Edmonton, Canada

As the freshest fall of a Martian meteorite since 1962, Tissint is currently the subject of intense scientific scrutiny: it is a typical Martian basalt, consisting of olivine phenocrysts in a pyroxene–plagioclase groundmass, with accessory oxides, sulfides, and phosphates. Many (if not all) specimens are crosscut by glassy veins and pockets that formed as a result of shock during an impact on Mars, likely the impact that lofted the meteoroid from the surface of Mars. The shock melt pockets are similar to those in another famous Martian meteorite, Elephant Moraine 79001, in which trapped Martian atmosphere was found, providing the crucial piece of evidence for a Martian origin. But beyond the insights that will be gained into Martian igneous and shock processes, Tissint represents a unique opportunity to test curation and handling methods for future sample return (from Mars or elsewhere). Analyses to determine what contaminants the meteorite picked up in the Moroccan desert are underway, in order to establish a baseline to test whether Tissint preserves any Martian organic matter. Regardless of the outcome, Tissint is sure to become one of the most studied Martian meteorites—at least until the next one falls!

Chris Herd, University of Alberta