CARBONACEOUS CHONDRITE IMPACT MELTS

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Collisions between planetary bodies (such as asteroids colliding with one another or with planets) have played a role in the geologic evolution of our Solar System since the formation of planetesimals, the earliest kilometer-scale bodies. Shock damage from collisional impacts leaves evidence on surviving planetary materials that range in scale from kilometer-sized craters to nanometer-sized mineral structural defects.

Impact shock-induced melting is thought to be a common consequence of collisions throughout the Solar System. While ordinary chondrites, martian, and lunar meteorites all exhibit signs of having been melted by impacts, until very recently, no impact melts of primitive carbonaceous chondrites had been recognized (Lunning et al. 2016a).

CARBONACEOUS CHONDRITES

Carbonaceous chondrites include the most primitive known Solar System materials and hold important clues for understanding the origin of the Solar System. Some of their primitive components formed as small objects (≤ cm-scale) in the protoplanetary disk and experienced minimal modification after the accretion of their parent planetesimals (Fig. 1). The primitive nature of carbonaceous chondrites is part of the motivation for the ongoing *Hayabusa 2* (JAXA) and *OSIRIS-REx* (NASA) spacecraft missions, which will return samples from carbonaceous chondrite-like asteroids. The samples carried back to Earth by these spacecraft will be the most pristine (i.e. will have experienced the least amount of terrestrial alteration) primitive Solar System materials ever studied by scientists on Earth.

Figure 1 NASA image of the Robert Massif (RBT) 04143 carbonaceous chondrite (CV3) found in Antarctica by the U.S. Antarctic Search for Meteorites (ANSMET) program. The cube pictured is 1 cm along each edge and the ruler is in cm. The light-colored object in the piece below the * is an impact melt pocket that formed by in situ melting of this carbonaceous chondrite.

Carbonaceous chondrites are a class of meteorites defined by their similarity in volatile elemental abundance and refractory lithophile elemental abundance. The shared elemental and isotopic signatures of this meteorite class suggest they originated from the same or similar geochemical reservoirs in the protoplanetary disk. However, the 8 known groups (CI, CM, CV, CR, CO, CK, CB, CH) within the carbonaceous chondrite class originated from separate parent bodies.

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The term "carbonaceous" in their name is a bit of a misnomer. Although a few groups within this meteorite class are somewhat carbon-rich (e.g. CI and CM chondrites contain up to wt% quantities of elemental carbon), carbonaceous chondrites do not consistently contain more carbon than other stony meteorite classes (Krot et al. 2003; Scott and Krot 2003).

MISSING IMPACT MELTS

Scott et al. (1992) called attention to the dearth of impact melted carbonaceous chondrite material. The lack of carbonaceous chondrite impact melts might be explained by the meteorites higher volatile concentrations which may prevent the formation of cohesive melts. Many researchers have been searching for these melt features to little avail.

CARBONACEOUS CHONDRITE IMPACT MELTS – FOUND!

Recently, in three separate meteorites, five objects have been identified that appear to be carbonaceous chondrite impact melts. These objects were found by the systematic petrographic examination of the CV chondrites in the Smithsonian Institution's (USA) thin section library and through the petrological characterization of howardites found in the Grosvenor Mountains (GRO) field area in Antarctica in 1995 (Lunning et al. 2016a,b).

The objects all contain signs that they had rapidly cooled from melts. For example, they contain >60% olivine microphenocrysts, which are strongly zoned with Mg-rich cores and comparatively Fe-rich rims (Fig.

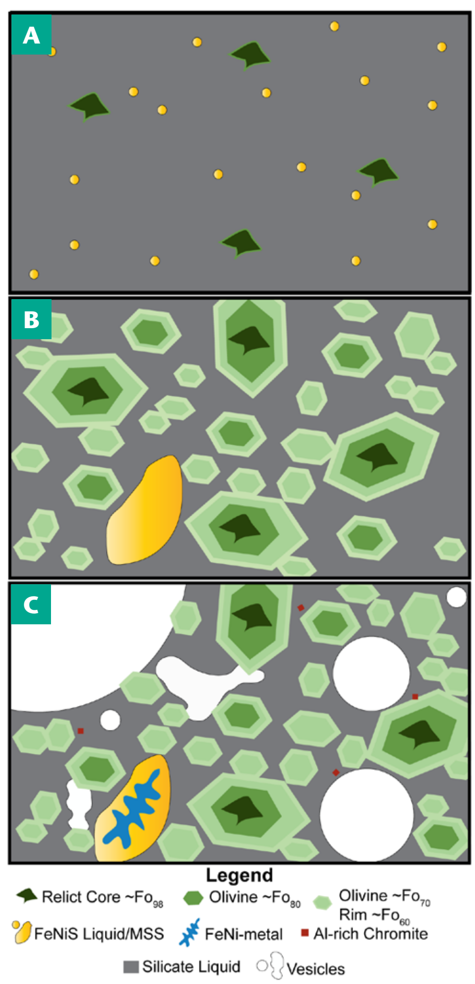

Figure 2 Schematic illustrating a generalized scenario for impact melt formation. (**A**) Impact-induced bulk melting. Only very Mg-rich relict olivine (dark green) is not melted. Immiscible silicate (grey) and FeNiS (yellow) liquids are formed. (**B**) Olivine rapidly crystallizes from the silicate liquid and FeNiS liquid globules and coalesce into larger globules. (**C**) Olivine continues to crystallize. The five objects referred in the main text were arrested around this point, thereby quenching the silicate liquid into glass and trapping vesicles (if present). Images of the slight variations on the texture between separate objects are illustrated in Lunning et al. (2016a).

2). Fe-Mg zoning in minerals, such as olivine, indicates they solidified too quickly for solid-state diffusion to homogenize these elements within individual crystals. Some of the olivine microphenocrysts contain relict cores, which are likely the only portion of these objects that remained solid when the rest of the source material melted. All objects contain accessory FeNiS globules, and within those are cellular or skeletal FeNi-metal consistent with rapidly cooled materials. In four of the five objects, the groundmass is vitric glass, indicating they were rapidly cooled and effectively froze before further crystallization could proceed. Several of the objects contain vesicles, which are notably rare in meteoritic materials. To freeze gas bubbles in place and form vesicles, cooling must have occurred more rapidly than the time required for gas bubbles to migrate out of the molten impact melt. These rapid cooling features contributed to the interpretation that these objects are solidified impact melts.

These five objects all have metal- and sulfide-free bulk elemental lithophile element ratios that are consistent with carbonaceous chondrites. This is evidence these objects are impact melts because most other melting processes (on Earth and on planetesimals) fractionate or change the composition of magmas relative to their source material. Additional contextual evidence for each object (see Lunning et al. 2016a) led to the interpretation that four of these objects are CV chondrite impact melts and one is a CM chondrite impact melt. These objects include three fragmental clasts, a melt pocket that formed in situ (Fig. 1), and a melt droplet incorporated after solidification into a breccia primarily composed of achondritic material (specifically a howardite, which is a meteorite breccia possibly from the asteroid 4 Vesta).

ORIGIN OF THE CM CHONDRITE MELT DROPLET

Measurements of all three stable isotopes of oxygen (^{16}O, ^{17}O, ^{18}O) obtained through secondary ion mass spectrometry analyses are a powerful tool for assessing the distinct provenance of planetary materials (e.g. Greenwood et al. 2016). The oxygen three-isotopic signature of olivine in the melt object found in the howardite meteorite provided evidence that the object is a CM chondrite impact melt. The nonrelict olivines in this melt object have oxygen three-isotope signatures that overlap the bulk CM chondrite range and do not overlap the ranges of any other known Solar System materials. The relict olivine core in this object has an oxygen three-isotope signature that falls slightly above the carbonaceous chondrite–anhydrous mineral (CCAM) line (Fig. 3) and coincides with the primitive chondrule mineral (PCM) line (Ushikubo et al. 2012). These results further support that this object did not form by impact melting of its howardite host or another member of the howardite, eucrite, diogenite (HED) meteorite clan (generally thought to originate from the asteroid 4 Vesta). Rather, the melt object is composed of CM chondrite impactor material. A CM chondrite was melted upon impact with the parent HED body, ejected a melt droplet, which was solidified in-flight. It was subsequently incorporated into the HED regolithic sediments, which were later collectively lithified to form its host breccia. This CM chondrite melt droplet bears some textural similarity to impact derived crystal-bearing spherules/droplets identified in lunar and martian regolithic samples (Symes et al. 1998; Ruzicka et al. 2000; Udry et al. 2014).

RELEVANCE TO CURRENT ASTEROID EXPLORATION

The newly discovered carbonaceous chondrite impact melts have olivine-dominated mineral assemblages, which are notably different from their unmelted precursors. Thus, impact melt-rich regions on carbonaceous chondrite-like asteroidal surfaces may be identifiable using high-resolution mapping during spacecraft missions. JAXA's *Hayabusa 2* spacecraft and NASA's *OSIRIS-REx* spacecraft are currently heading toward asteroids that are thought to be composed of carbonaceous chondrite material. These recently discovered carbonaceous chondrite impact melts may inform site selection for these spacecraft to collect samples and aid in distinguishing impact-modified material from other regolith components in future samples returned via spacecraft missions to these and other Solar System bodies.

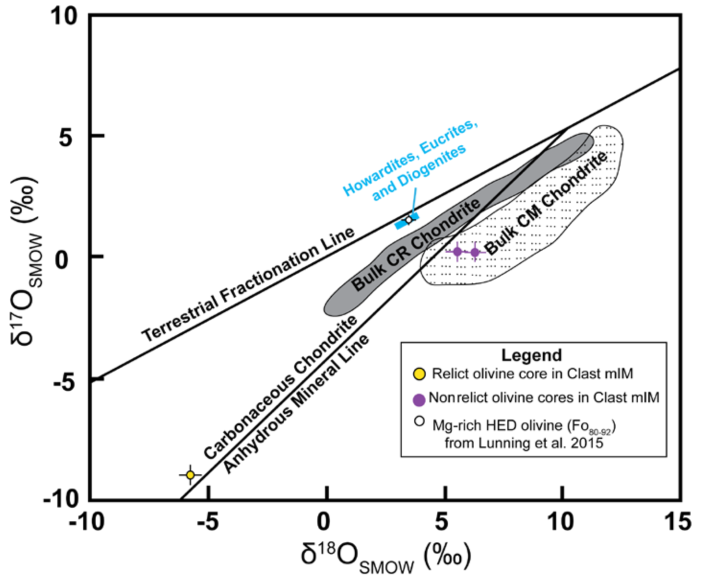

Figure 3 Oxygen three-isotope plot of olivine in Clast mIM in the regolithic howardite GRO 95574,17. The composition of the olivine relict core (yellow circle) falls slightly above the carbonaceous chondrite–anhydrous mineral (CCAM) line. Oxygen three-isotope compositions of common meteorite groups are from Krot et al. (2003) and references therein. Known achondrite groups plot close to the howardites/eucrites/diogenites or on the terrestrial fractionation line (lunar rocks) or above (martian rocks). Modified from Lunning et al. (2016a).

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