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Chondrules in the CB/CH-like carbonaceous chondrite Isheyevo: Evidence for various chondrule-forming mechanisms and multiple chondrule generations

Alexander N. Krot[a,*], Marina A. Ivanova[b], Alexander A. Ulyanov[c]

[a]*Hawai'i Institute of Geophysics and Planetology, School of Ocean and Earth Science and Technology, University of Hawai'i at Manoa, Honolulu, HI 96822, USA*
[b]*Vernadsky Institute of Geochemistry and Analytical Chemistry, Kosygin Street 19, Moscow 119991, Russian Federation*
[c]*M.V. Lomonosov Moscow State University, Moscow 119992, Russian Federation*

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Abstract

The recently discovered metal-rich carbonaceous chondrite Isheyevo consists of Fe, Ni-metal grains, chondrules, heavily hydrated matrix lumps and rare refractory inclusions. It contains several lithologies with mineralogical characteristics intermediate between the CH and CB carbonaceous chondrites; the contacts between the lithologies are often gradual. Here we report the mineralogy and petrography of chondrules in the metal-rich (~70 vol%) and metal-poor (~20 vol%) lithologies. The chondrules show large variations in textures [cryptocrystalline, skeletal olivine, barred olivine, porphyritic olivine, porphyritic olivine-pyroxene, porphyritic pyroxene], mineralogy and bulk chemistry (magnesian, ferrous, aluminum-rich, silica-rich). The porphyritic magnesian (Type I) and ferrous (Type II) chondrules, as well as silica- and Al-rich plagioclase-bearing chondrules are texturally and mineralogically similar to those in other chondrite groups and probably formed by melting of mineralogically diverse precursor materials. We note, however, that in contrast to porphyritic chondrules in other chondrite groups, those in Isheyevo show little evidence for multiple melting events; e.g., relict grains are rare and igneous rims or independent compound chondrules have not been found. The magnesian cryptocrystalline and skeletal olivine chondrules are chemically and mineralogically similar to those in the CH and CB carbonaceous chondrites Hammadah al Hamra 237, Queen Alexandra Range 94411 (QUE94411) and MacAlpine Hills 02675 (MAC02675), possibly indicating a common origin from a vapor–melt plume produced by a giant impact between planetary embryos; the interchondrule metal grains, many of which are chemically zoned, probably formed during the same event. The magnesian cryptocrystalline chondrules have olivine–pyroxene normative compositions and are generally highly depleted in Ca, Al, Ti, Mn and Na; they occasionally occur inside chemically zoned Fe, Ni-metal grains. The skeletal olivine chondrules consist of skeletal forsteritic olivine grains overgrown by Al-rich (up to 20 wt% Al_2O_3) low-Ca and high-Ca pyroxene, and interstitial anorthite-rich mesostasis. Since chondrules with such characteristics are absent in ordinary, enstatite and other carbonaceous chondrite groups, the impact-related chondrule-forming mechanism could be unique for the CH and CB chondrites. We conclude that Isheyevo and probably other CH chondrites contain chondrules of several generations, which may have formed at different times,

*Corresponding author. Tel.: +1 808 956 3900; fax: +1 808 956 6322.
E-mail address: sasha@higp.hawaii.edu (A.N. Krot).

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places and by different mechanisms, and subsequently accreted together with the heavily hydrated matrix lumps and refractory inclusions into a CH parent body. Short-lived isotope chronology, oxygen isotope and trace element studies of the Isheyevo chondrules can provide a possible test of this hypothesis.

Keywords: Metal-rich chondrites; Chondrules

1. Introduction

The metal-rich CH and CB chondrites are among the most primitive (unmetamorphosed, unaltered), but controversial meteorites; both nebular and asteroidal models have been proposed to explain the origins of their high-temperature components – chondrules and metal grains (Grossman et al., 1988; Scott, 1988; Weisberg et al., 1988; Wasson and Kallemeyn, 1990; Bischoff et al., 1993; Meibom et al., 1999, 2000, 2001; Campbell et al., 2001, 2002; Petaev et al., 2001; Rubin et al., 2003; Campbell and Humayun, 2004; Krot et al., 2000a, b, 2001a, b, 2002a, 2005, 2006a).

In addition to porphyritic chondrules and rare refractory inclusions, the CH chondrites contain a high abundance (~20 vol%) of metal and dominant cryptocrystalline chondrules of small sizes (20–70 μm). Based on the unusual mineralogical and chemical (high enrichment in siderophile elements and extreme depletion in volatile elements) characteristics and the rarity of metal-rich chondrites (the only known CH chondrite at that time was ALHA85085), Wasson and Kallemeyn (1990) proposed that ALHA85085 is a modified "subchondritic" meteorite containing chondrules and metal grains produced during a highly energetic asteroidal collision. However, based on the condensation origin of zoned metal grains (Meibom et al., 1999, 2000) and ^{16}O-enriched isotopic compositions of chondrules and refractory inclusions (Sahijpal et al., 1999; Krot et al., 2001b, 2002a; Kobayashi et al., 2003; Yoshitake and Yurimoto, 2004), it has subsequently been concluded that refractory inclusions, chondrules and zoned metal grains in CH chondrites are in fact the most pristine nebular products.

The CB chondrites have much higher abundances of metal (~70 vol%) and larger chondrules (0.1–7 mm) than CH chondrites (Weisberg et al., 2001); most chondrules have non-porphyritic [cryptocrystalline (CC) and skeletal olivine (SO)] textures (Krot et al., 2001a, 2002a). Largely based on the sizes of chondrules and metal grains, Weisberg et al. (2001) subdivided CB chondrites into two subgroups – CB_a (Bencubbin, Gujba, and Weatherford) and CB_b (Hammadah al Hamra 237 and QUE94411 paired with QUE94627). Similar to CH chondrites, the CB_b chondrites contain chemically zoned metal condensates (Meibom et al., 2001; Petaev et al., 2001; Campbell et al., 2001) and rare refractory inclusions (Krot et al., 2001b); the former, however, are much more abundant than in CH chondrites. Based on the young chondrule ages (4562.7 ± 0.5 Myr), lack of evidence for the recycling of chondrules and metal condensates, and paucity of interchondrule, fine-grained matrix material, Krot et al. (2005) concluded that chondrules and metal grains in both CB subgroups formed from a vapor–melt plume produced by a giant impact between planetary embryos after dust in the protoplanetary disk had largely dissipated, supporting the earlier conclusions of Rubin et al. (2003) and Campbell and Humayun (2004).

The presence of mineralogically and chemically similar chondrules and metal grains in the CH and CB chondrites, which are virtually absent in ordinary, enstatite and other known chondrule-bearing carbonaceous chondrite groups (CM, CR, CV, CO, CK) and ungrouped carbonaceous chondrites (Acfer 094, Adelaide, LEW85332), may indicate possible genetic relationship between these meteorites: they may have either formed by a similar mechanism or formed during the same event and subsequently experienced size sorting.

The recently discovered metal-rich chondrite Isheyevo contains metal-rich (>70 vol%) and metal-poor (<20 vol%) lithologies, which show mineralogical, chemical and isotopic similarities to both CH and CB chondrites (Ivanova et al., 2006). Since this meteorite can potentially provide a clue for a genetic relationships between CH and CB chondrites and for the origin of metal-rich chondrites in general, we initiated detailed mineralogical and isotopic studies of its components. Here, we describe the mineralogy and petrography of chondrules in the metal-rich and metal-poor lithologies of Isheyevo. The preliminary results of this study have been described by Krot et al. (2006b).

2. Analytical procedures

Two polished sections of Isheyevo of ~3 cm^2 were mapped in Ca, Al, Mg, Ti, Na, Si, Ni, and Co K_α X-rays using a fully focused electron beam, 15 kV accelerating voltage, 100 nA beam current, 20–30 ms per pixel acquisition time and resolution of ~8–10 μm per pixel with a Cameca SX-50 electron microprobe at the University of Hawai'i. The elemental maps in Mg, Ca and Al K_α were combined using a RGB-color scheme