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# Relict chondrules in primitive achondrites: Remnants from their precursor parent bodies

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**Abstract**

We studied the petrography, analyzed the chemical compositions, constrained the closure temperatures (via geothermometry), and determined the oxidation states of relict chondrules in Campo del Cielo (IAB iron meteorite), Graves Nunataks (GRA) 98028 (acapulcoite), and Netschaëvo (IIE iron meteorite) to constrain their formation conditions and investigate links to known meteorite groups. Despite having been thermally metamorphosed, mineral phases within relict chondrules retain information about their precursor compositions. The sizes and textures of relict chondrules, and silicate and chromite compositions indicate that Campo del Cielo, GRA 98028, and Netschaëvo had distinct parent bodies that were similar to, but different from, known chondrite groups. To determine the utility of relict chondrule sizes in thermally metamorphosed meteorites, we determined the chondrule size distributions in the LL chondrites Semarkona (LL3.00), Soko-Banja (LL4), Siena (LL5), and Saint-Séverin (LL6), and the H chondrites Clovis (No. 1) (H3.6), Kesen (H4), Arbol Solo (H5), and Estacado (H6). As expected, mean chondrule diameters increase with degree of thermal metamorphism.

We find that Campo del Cielo and GRA 98028 were reduced during thermal metamorphism, consistent with previous studies, indicating that their precursors were initially more FeO-rich than their current compositions. In contrast to previous studies, we find no evidence for reduction of silicates in Netschaëvo. Normal zoning of olivine in Netschaëvo is consistent with crystallization and suggests its silicates are near their primary FeO-contents. The presence of elongated chromite grains along olivine grain boundaries in Netschaëvo indicates formation during thermal metamorphism under oxidizing conditions. Due to the absence of reduction and the composition of chromite being distinct from that of metamorphosed H chondrites, we conclude that Netschaëvo, and by extension the IIE iron meteorites, are not from the H chondrite parent body.


*Keywords:* Relict chondrule; Primitive achondrite; Iron meteorite; Ordinary chondrite; Carbonaceous chondrite; Chromite; Closure temperature; Oxygen fugacity; Reduction

## 1. INTRODUCTION

Primitive achondrites and partially differentiated meteorites have been thermally modified since accretion, but did not melt completely. As a result, the study of primitive achondrites and partially differentiated meteorites, and their precursors, is paramount to understanding the earliest stages of asteroidal differentiation (e.g., McCoy et al., 1996; Bogard et al., 2000; Benedix et al., 2005). Relict chondrules in meteorites provide an invaluable opportunity to investigate both the range of thermal metamorphic processes that modified asteroids and the compositions of their precursors. Relict chondrules are chondrules that were subjected

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to thermal metamorphism that was extensive enough to modify their morphologies and compositions but not so extensive as to make them unrecognizable. In meteorite groups with both unequilibrated and equilibrated members, such as the ordinary chondrites, the initial precursor materials are preserved in unmetamorphosed samples, while relict chondrules are used as indicators of degree of thermal metamorphism in equilibrated members. However, in meteorite groups without unequilibrated members relict chondrules provide the best indication of the nature of their precursor material.

Relict chondrules have been observed in several primitive achondrite groups and silicate-bearing iron meteorites (e.g., Olsen and Jarosewich, 1971; Bild and Wasson, 1977; Yanai and Kojima, 1991; McCoy et al., 1996; Benedix et al., 1998; Rubin, 2006; Schrader et al., 2010; Gardner-Vandy, 2012; Van Roosbroek et al., 2012, 2013, 2015, 2016). While relict chondrules have been identified in the winonaites Dhofar 1222, Pontlyfni, Mount Morris, Northwest Africa (NWA) 725, NWA 1052, and NWA 1463 (Benedix et al., 1998; Rubin, 2006, 2007; Greenwood et al., 2012), none have been reported in the related IAB iron meteorites (e.g., Benedix et al., 2000; Tomkins et al., 2013; Ruzicka, 2014). Relict chondrule-bearing acapulcoites include Allan Hills (ALH) 77081, Graves Nunataks (GRA) 98028, Monument Draw, and Yamato (Y) 74063 (Schultz et al., 1982; Yanai and Kojima, 1991; McCoy et al., 1996; Rubin, 2007). Relict chondrules have also been noted in the IIE iron meteorites Netschaëvo (Olsen and Jarosewich, 1971; Bild and Wasson, 1977) and Mont Dieu (Van Roosbroek et al., 2012, 2013, 2015, 2016).

The parent asteroids of the winonaite–IAB iron meteorites, the acapulcoites, and the IIE iron meteorites have varied metamorphic histories. It has been proposed that the winonaite–IAB parent body underwent partial melting (Wlotzka and Jarosewich, 1977) and incomplete differentiation, during which it was catastrophically disrupted and reaccreted (Benedix et al., 2000). A study of winonaites and silicate-bearing IAB iron meteorites determined that while their two-pyroxene closure temperatures (900–1200 °C) were higher than those determined via olivine-spinel geothermometry (590–700 °C), the oxygen fugacity stayed relatively constant although modest reduction likely occurred during cooling (Benedix et al., 2005). Closure (i.e., equilibration) temperatures also varied between samples, indicating heterogeneous heating on the centimeter scale, which was attributed to the catastrophic breakup and reassembly of the winonaite–IAB parent asteroid (Benedix et al., 2005). The acapulcoites have been argued to form via internal thermal metamorphism and/or heating via impacts (McCoy et al., 1996; Rubin, 2007). The cause of the partial differentiation of the IIE parent body is also complex; it has been suggested that internal heating led to partial melting and differentiation ~4.5 Gyr ago, followed by localized impact heating ~3.6 Gyr ago (Bogard et al., 2000).

Chondrule formation conditions and precursors vary between chondrite groups (e.g., Rubin, 2010; Berlin et al., 2011; Jones, 2012). Depending on the degree of thermal metamorphism relict chondrules may retain indicators of their initial formation conditions and compositions. We conducted a study of a chondrule-bearing primitive achondrite (i.e., acapulcoite) and two silicate-bearing iron meteorites (IIE and IAB) to determine (1) any similarities with, and/or genetic links to, known chondrite groups, and (2) their oxidation histories during cooling.

## 2. ANALYTICAL PROCEDURE

### 2.1. Mineralogy and petrology

Thin sections of Campo del Cielo USNM 5615-2 (IAB iron meteorite), GRA 98028,1 (acapulcoite), and Netschaëvo USNM 494-1 (IIE iron meteorite) were initially characterized via optical microscopy to identify relict chondrules (Electronic Annex 1; EA-1). Backscattered electron (BSE) image collection and mineral identification via energy dispersive X-ray spectroscopy (EDS) were conducted on an FEI Nova NanoSEM 600 scanning electron microscope (SEM) at the Smithsonian Institution (SI) National Museum of Natural History, Department of Mineral Sciences. Modal abundances of select mineral phases were measured within each thin section by pixel (i.e., point) counting (n.b., area% determined by point counting is equivalent to volume%; Eisenhour, 1996).

Chondrule diameters in thin sections and polished mounts were determined using Adobe Photoshop® by measuring chondrules in full section BSE images and X-ray element maps (Fig. EA-2, Table 1 and EA-3). Chondrule diameters were measured in the following sections: Campo del Cielo USNM 5615-2, GRA 98028,1, Netschaëvo USNM 494-1, Semarkona USNM 1805-17 (LL3.00), Soko-Banja USNM 3078-1 (LL4), Siena USNM 3070-3 (LL5), Saint-Séverin USNM 2608-3 (LL6), Clovis (No. 1) ASU 168_A_2 (H3.6), Kesen ASU 362_C_1 (H4), Arbol Solo ASU 1046_C_1 (H5), and Estacado ASU 44_A_4 (H6). Sections of witnessed falls were selected when possible. BSE images and X-ray element maps were obtained with the SEM at SI (Campo del Cielo, GRA 98028, and Netschaëvo; LL chondrites from Schrader et al., 2016), and the Cameca SX-100 electron probe microanalyzer (EPMA) at the University of Arizona (UA) for the H chondrites. Mean chondrule diameters were determined by measuring both the major and minor axes of each chondrule, and group means, standard deviations (σ), and standard error of the mean (SE) were determined from these average diameters (Table 1).

The major element abundances within olivine, pyroxene, plagioclase, chromite, metal, and sulfide were measured with a JEOL 8900 Superprobe EPMA at SI. Additional silicate analyses of Campo del Cielo were obtained on the EPMA at UA. Polished and carbon-coated thin sections were analyzed with a focused beam by individual point and line-scan measurements (operating conditions: 15 kV and 20 nA). A ZAF correction method (a Phi-Rho-Z correction technique; Armstrong, 1988) was used, and peak and background counting times were varied per element to optimize detection limits. Only stoichiometric silicate analyses with totals between 98.0 and 102.0 wt.%, chromite analyses with totals between 97.0 and 102.0 wt.%, and Fe,