

GROVE MOUNTAINS (GRV) 020043: ACAPULCOITE-LODRANITE GENESIS FROM THE VIEW OF THE MOST PRIMITIVE MEMBER. T.J. McCoy¹, C.M. Corrigan¹, T.L. Dickinson², G.K. Benedix³, D.L. Schrader⁴ and J. Davidson⁴, ¹Dept. of Mineral Sciences, National Museum of Natural History, Smithsonian Institution, Washington, DC 20560-0119 USA (mccoyt@si.edu), ²Science Matters Consulting, LLC, Washington DC 20016 USA, ³Curtin University, Bentley, WA 6102, Australia, ⁴Arizona State University, Tempe AZ 85287-1404 USA.

Introduction: The formation of acapulcoites and lodranites by partial melting of a chondritic precursor has long been recognized from their broadly chondritic mineralogy and bulk composition. Rarely, relict chondrules have been observed in these meteorites [1–5]. In a recent survey of acapulcoites and lodranites, [6] highlighted Grove Mountains (GRV) 020043, which was reclassified by [7] as a possible chondritic precursor to acapulcoites. The meteorite is remarkable for the abundance of chondrules and chondrule fragments (~62 vol.%; [7]) and mineral compositions (Fa_{10.7}, Fs_{10.8}) intermediate between enstatite and ordinary chondrites. [7] reported isotopic compositions for oxygen and chromium that fall within the field of acapulcoites and lodranites. Our primary motivation in studying GRV 020043 is examining several long-standing questions in acapulcoite-lodranite petrogenesis that can be uniquely addressed by such a primitive member of the group. In particular, we discuss the relative roles of modification during heating and partial melting versus inheritance from the chondritic precursor(s) in establishing the distinctive properties of acapulcoites and lodranites.

Results: The most dramatic feature of GRV 020043 is a distinctly chondritic texture (Fig. 1) unlike other acapulcoites. The estimate of ~62 vol.% chondrules and chondrule fragments (Li et al., 2018) is consistent with our observations of abundant chondrules with a matrix rich in metal and sulfide and determination of 39 vol.% matrix of mixed silicate mineralogy.

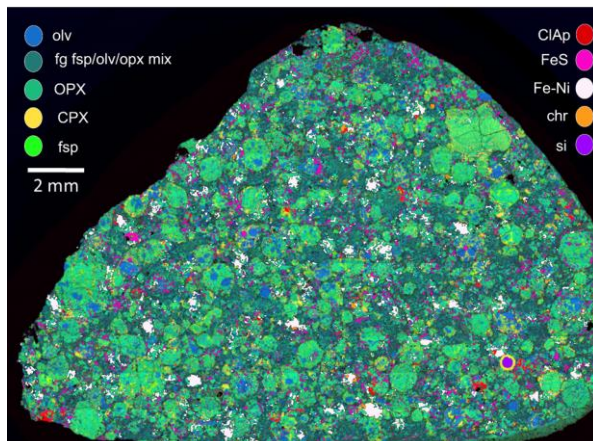


Figure 1. Elemental map of GRV 020043,2 exhibiting numerous well-defined chondrules in a matrix rich in metal and sulfide.

An unusual, well-defined radial chondrule (Fig. 2) consists of a core of low- and high-Ca pyroxene rimmed by SiO₂ and mantled by low- and high-Ca pyroxene and plagioclase. Chondrules range in diameter from ~200 to ~2000 μm, with the mode between 400 and 500 μm and the mean diameter is 690 μm, essentially identical to the results of [7].

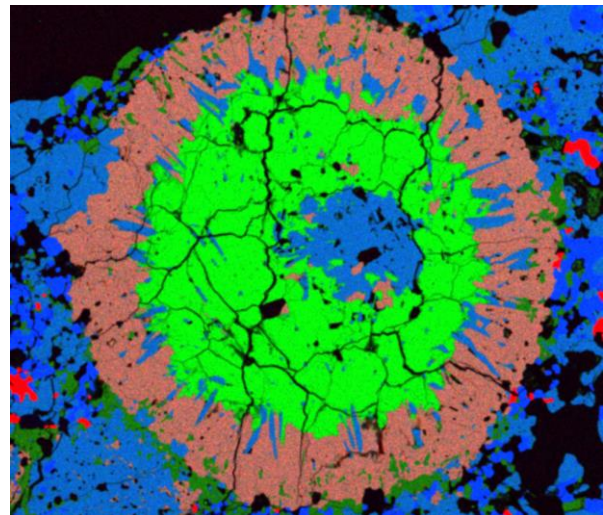


Figure 2. RGB (Ca-Si-Mg) composite elemental map of ~500 μm diameter radial chondrule with a core of low- and high-Ca pyroxene rimmed by SiO₂ and surrounded by a mantle of low- and high-Ca pyroxene and plagioclase.

A notable feature in GRV 020043 is the presence of Fe,Ni metal and sulfide inclusions commonly observed in orthopyroxene. Greater than 90% of chondrules contain orthopyroxene with inclusions of metal and sulfide, sometimes as composite inclusions. Metal inclusions in GRV 020043 orthopyroxene are Ni-bearing (4.5–32.1 wt.% Ni), similar to compositions for metal inclusions reported by [8] in Acapulco.

GRV 020043 consists of dominant low-Ca pyroxene (Fig. 1) with lesser abundances of olivine, high-Ca pyroxene, feldspar, metal and troilite. Minor amounts of phosphate are present. Mafic silicates are homogeneous; grain-to-grain and core-to-rim variability were not observed in olivine, low-Ca pyroxene or high-Ca pyroxene. Average mineral compositions are within uncertainty of those reported by [7] and similar to those of other acapulcoites. Olivine is Fa_{10.3±0.2}, with Fe/Mn of

20.7±0.9. Low-Ca pyroxene is $\text{Fs}_{10.4\pm0.2}\text{Wo}_{1.3\pm0.1}$ and high-Ca pyroxene is $\text{Fs}_{3.9\pm0.2}\text{Wo}_{45.6\pm1.4}$. Calculated mineral equilibria temperatures are consistent with relatively modest metamorphism of GRV 020043. The calculated two-pyroxene equilibration temperature for GRV 020043 using average compositions consistent with the equilibrated nature of these phase is $924\pm15^\circ\text{C}$ ($\pm 1\sigma$). Calculated oxygen fugacities are consistent with the overall FeO-poor nature of silicates in GRV 020043 and the acapulcoites. The calculated oxygen fugacity at the olivine-spinel equilibration temperature is iron-wüstite (IW) -2.2 log units. At the two-pyroxene equilibration temperature, the oxygen fugacity is IW -3.5 log units. Relative to the iron-wüstite buffer, these values are essentially identical to those determined for GRA 98028 by [5] and for five acapulcoites and lodranites by [9].

Discussion. Linkage between GRV 020043 and the acapulcoite-lodranite clan was convincingly presented [7]. Evidence includes mineral compositions; the bulk chemical composition; similarity in cosmic-ray exposure age; the oxygen isotopic composition; and the chromium isotopic composition. Additional evidence from our study includes the orthopyroxene-dominant silicate mineralogy, dominance of kamacite in metal phase, similarity in Fe/Mg ratio between olivine ($\text{Fa}_{10.3}$) and orthopyroxene ($\text{Fs}_{10.4}$) which is typical of acapulcoites and lodranites, dominance of chlorapatite relative to whitlockite/merrillite, and the presence of ubiquitous Fe,Ni metal and sulfide inclusions in orthopyroxene grains. Our observations are entirely consistent classification as a type 4 chondrite [7]. Olivine and low-Ca pyroxene compositions are homogeneous. Chondrules are well-delineated from the matrix. Importantly, chondrule mesostasis is microcrystalline, plagioclase is slightly heterogeneous, and polysynthetically striated low-Ca pyroxene is present. Together, these suggest that evidence for partial melting and/or melt migration is not an essential feature for classification in the acapulcoite-lodranite clan.

[6] suggested that the chondrule-bearing GRV 020043 and GRA 98028, coupled with evidence of partial melting of ≥ 35 wt.% in Frontier Mountain (FRO) 93001 at temperatures of $\sim 1250^\circ\text{C}$ [10], are consistent with a range of temperatures on the acapulcoite-lodranite parent body of $\sim 650^\circ\text{C}$. This temperature is similar to the total range of temperatures in the ordinary chondrites (~ 400 - 950°C). While the total temperature range may be similar, acapulcoites and lodranites are shifted to systematically higher temperatures compared to ordinary chondrites. This shift to higher temperatures may reflect earlier accretion of the acapulcoite-lodranite parent body compared to that of ordinary chondrites

[11] and, thus, incorporation of an increased concentration of heat-producing ^{26}Al .

Numerous authors have argued for reduction at or near the peak temperature during partial melting of acapulcoites and lodranites. A generalized reaction of FeO-bearing mafic silicates reacting with graphite to produce more magnesian mafic silicates, Fe metal and CO/CO₂ has been suggested [4]. However, as noted by [5], graphite reduction of FeO to Fe⁰ is a high-temperature process, typically occurring at temperatures of $>1200^\circ\text{C}$. This temperature is well in excess of that experienced by GRV 020043, either as evidence by two-pyroxene and olivine-chromite temperatures or petrologic and mineralogic indicators of thermal history. Yet, GRV 020043 shares most of the properties of other acapulcoites that have been attributed to reduction, including high low-Ca pyroxene/olivine, high kamacite/taenite, magnesian silicate compositions ($\text{Fa}_{10.3}$, $\text{Fs}_{11.4}$), subequal Fs and Fa, and low Fe/Mn ratio (20.7) relative to ordinary chondrites. The mineralogy and mineral compositions of the type 4 acapulcoite GRV 020043 strongly suggest that the reduced nature of acapulcoites and lodranites was largely inherited from the precursor chondritic material.

Evidence for partial melting in acapulcoites and lodranites is unequivocal. A long-standing dispute is whether Fe,Ni metal and troilite blebs that are ubiquitous in the cores of low-Ca pyroxene formed during partial melting and whether that melting, if it occurred, was the result of incipient partial melting and crystallization or injection as shock melts [4,8,12]. The presence of metal-sulfide inclusions in the orthopyroxenes in GRV 020043 suggests that these phases were, in fact, trapped during chondrule crystallization. We note that these inclusions are quite unlike those in other chondrite groups and may suggest a different chemical and/or physical history for the chondrules in the acapulcoite-lodranite precursors. Given the low shock stage of GRV 020043 (S2), these inclusions could not have been injected via shock with shock effects subsequently annealed.

References: [1] Yanai K. and Kojima H. (1991) *Ant. Met. Res.* 4, 118–130. [2] Schultz L. et al. (1982) *EPSL* 51, 23–31. [3] McCoy T.J. et al. (1996) *GCA* 60, 2681–2708. [4] Rubin A.E. (2007) *GCA* 71, 2383–2401. [5] Schrader D.L. et al. (2017) *GCA* 205, 295–312. [6] Keil K. and McCoy T.J. (2018) *Geochemistry* 78, 153–203. [7] Li S. et al. (2018) *GCA* 242, 82–101. [8] Zipfel J. et al. (1995) *GCA* 59, 3607–3627. [9] Righter K. et al. (2016) *Am. Min.* 101, 1928–1942. [10] Folco L. et al. *MAPS* 41, 1183–1198. [11] Touboul M. et al. (2009) *EPSL* 284, 1568–178. [12] Takeda H. et al. (1994) *Meteoritics* 29, 830–842.