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Early metal-silicate differentiation during planetesimal formation revealed by acapulcoite and lodranite meteorites

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Abstract

In order to establish the role and expression of silicate-metal fractionation in early planetesimal bodies, we have conducted a highly siderophile element (HSE: Os, Ir, Ru, Pt, Pd, Re) abundance and ^{187}Re-^{187}Os study of acapulcoite-lodranite meteorites. These data are reported with new petrography, mineral chemistry, bulk-rock major and trace element geochemistry, and oxygen isotopes for Acapulco, Allan Hills (ALHA) 81187, Meteorite Hills (MET) 01195, Northwest Africa (NWA) 2871, NWA 4833, NWA 4875, NWA 7474 and two examples of transitional acapulcoite-lodranites, Elephant Moraine (EET) 84302 and Graves Nunataks (GRA) 95209. These data support previous studies that indicate that these meteorites are linked to the same parent body and exhibit limited degrees (<2–7%) of silicate melt removal. New HSE and osmium isotope data demonstrate broadly chondritic relative and absolute abundances of these elements in acapulcoites, lower absolute abundances in lodranites and elevated (>2 × CI chondrite) HSE abundances in transitional acapulcoite-lodranite meteorites (EET 84302, GRA 95209). All of the meteorites have chondritic Re/Os with measured ^{187}Os/^{188}Os ratios of 0.1271 ± 0.0040 (2 St. Dev.). These geochemical characteristics imply that the precursor material of the acapulcoites and lodranites was broadly chondritic in composition, and were then heated and subject to melting of metal and sulfide in the Fe-Ni-S system. This resulted in metallic melt removal and accumulation to form lodranites and transitional acapulcoite-lodranites. There is considerable variation in the absolute abundances of the HSE, both among samples and between aliquots of the same sample, consistent with both inhomogeneous distribution of HSE-rich metal, and of heterogeneous melting and incomplete mixing of silicate material within the acapulcoite-lodranite parent body. Oxygen isotope data for acapulcoite-lodranites are also consistent with inhomogeneous melting and mixing of accreted components from different nebular sources, and do not form a well-defined mass-dependent fractionation line. Modeling of HSE inter-element fractionation suggests a continuum of melting in the Fe-Ni-S system and partitioning between solid metal and sulfur-bearing mineral melt, where lower S contents in the melt resulted in lower Pt/Os and Pd/Os ratios, as observed in lodranites. The transitional meteorites, EET 84302 and GRA 95209, exhibit the most elevated HSE abundances and do not follow modelled Pt/Os and Pd/Os solid metal-liquid metal partitioning trends. We interpret this to reflect metal melt pooling into domains that were sampled by these meteorites, suggesting that they may originate from deeper within the acapulcoite-lodranite parent body, perhaps close to a pooled metallic 'core' region. Petrographic examination of transitional samples reveals the most extensive melting, pooling and networking of metal among the

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acapulcoite-lodranite meteorites. Overall, our results show that solid metal-liquid metal partitioning in the Fe-Ni-S system in primitive achondrites follows a predictable sequence of limited partial melting and metal melt pooling that can lead to significant HSE inter-element fractionation effects in proto-planetary materials.

Keywords: Highly siderophile elements; Metal partitioning; Acapulcoites; Lodranites; Core formation; Planetesimals

1. INTRODUCTION

Metal-silicate segregation is a fundamental process in the evolution of differentiated planetary bodies, leading to the formation of metal cores and silicate mantles and crusts. These processes occurred quite early in Solar System history (e.g., Jones and Drake, 1986; Righter and Drake, 1996; Rushmer et al., 2000; Kleine et al., 2002; Righter, 2003), such as in the case of the acapulcoite-lodranite body, which accreted ~1.5–2 Ma after CAI formation (Touboul et al., 2009) under reduced conditions (~2 log units below the iron-wustite buffer; Righter and Drake, 1996). Investigating core formation processes is important for understanding the present distribution of elements within planetary bodies, particularly the siderophile (e.g., Fe, W) and highly siderophile elements (HSE: Os, Ir, Ru, Rh, Pt, Pd, Au, Re; cf., Brenan et al., 2016; Day et al., 2016a). Such studies also have implications for quantifying light element abundances in the core (e.g., Poirier, 1994) and large-scale volatile element inventories of planetary bodies (Righter, 2003). Fully differentiated bodies that have experienced core-formation, such as Earth or Mars, do not retain information on the earliest stages of core formation and metal-silicate differentiation. Improved knowledge of early metal-silicate differentiation processes during planetary evolution is therefore valuable for understanding the timing and nature of core formation processes in the Solar System.

Within the available collection of meteorites there are a number of ‘primitive’ achondrites that ‘bridge the gap’ between undifferentiated ordinary, carbonaceous and enstatite chondrites, and differentiated achondrites, and so have the potential to yield information on early metal-silicate differentiation. These primitive achondrites include ureilites, brachinites, winonaites-IAB-IIICD iron meteorites, and the acapulcoite-lodranite meteorites (e.g., Weisberg et al., 2006; Day, 2015). Of these samples, acapulcoites and lodranites have experienced some of the least apparent metal and silicate melt-loss; they represent high-grade metamorphosed rocks to incipient residues of chondrite-like precursors (McCoy et al., 1996, 1997a,b). These meteorites also include *transitional* acapulcoite-lodranite samples, which have characteristics of both acapulcoites and lodranites, with evidence for silicate melting and high FeNi abundances (McCoy et al., 2006). These features of acapulcoite and lodranite meteorites make them useful for understanding early core-formation processes in planetesimals, as they preserve the earliest stages of metal segregation and, possibly, metal accumulation. Acapulcoite-lodranite meteorites are characterized by early-formation ages (^{182}Hf-^{182}W model ages of ~4563 ± 1 Ma; Touboul et al., 2009), with similar mineralogy, mineral compositions, thermal histories and exposure ages, and origins on the same parent body (McCoy et al., 1996, 1997a,b; Mittlefehldt et al., 1996; Weigel et al., 1999). Refractory lithophile and siderophile element abundances in acapulcoites have previously been suggested to be most similar to those in CI chondrites (Rubin, 2007). However, measurements of C and N isotope ratios of graphite grains in the archetype meteorite, Acapulco, indicate distinct source compositions of precursor material (El Goresy et al., 1995, 2005), as well as incomplete melting on the acapulcoite-lodranite parent body, including within FeNi grains.

The range of oxygen isotopic compositions in acapulcoite and lodranite meteorites (Clayton and Mayeda, 1996; Greenwood et al., 2012) is also consistent with incomplete differentiation and mixing in their parent body (McCoy et al., 2006; c.f. winonaites, Hunt et al., 2017); although some of the O-isotope variability may be explained by aqueous alteration prior to metamorphism (Greenwood et al., 2012). These observations provide evidence for a protracted thermal history, resulting in the preservation of different degrees of partial melting and thermal equilibration regimes. Acapulcoites experienced lower temperatures of equilibration than lodranites, with only FeNi-FeS cotectic melting, and so these meteorites generally retain chondritic modal abundances of troilite and plagioclase. In contrast, lodranites experienced larger degrees of partial melting and show evidence of both FeNi-FeS cotectic melting and silicate melting, including more extensive melt migration and associated troilite depletion (McCoy et al., 1997a,b) (Fig. 1). Estimated thermal conditions experienced by lodranites for silicate melting are in the range of ~1050–2000 °C (~5–20% partial melting, 300 MPa), compared to acapulcoites, at ~950–1000 °C

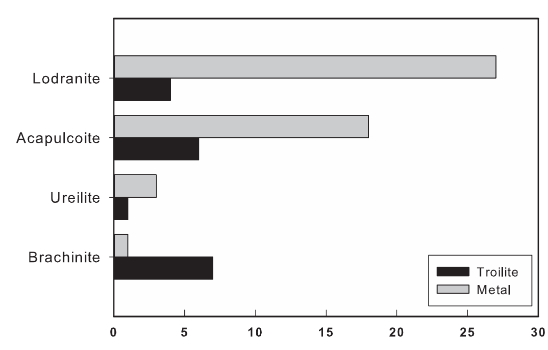

Fig. 1. Metal and troilite abundances in primitive achondrites: acapulcoites, lodranites, ureilites and brachinites. Data from Goodrich et al. (1987), Nehru et al. (1992), Mittlefehldt et al. (1996), McCoy et al. (1996, 1997a,b) and Rubin (2007).