MINERAL CHEMISTRY AND OXYGEN ISOTOPE ANALYSIS OF A CHONDRITIC PROJECTILE IN LUNAR METEORITE PECORA ESCARPMENT 02007.

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Projectile Relics on the Moon: Fragments of meteoritic debris found in the lunar regolith provide direct evidence of the sources of projectiles delivered to the inner Solar System. Such examples include an enstatite chondrite fragment (Hadley Rille [1]), a carbonaceous chondrite fragment (Bench Crater [2]), silicate mineral debris from primitive chondritic projectiles (UMMFs [3]), and stony-iron fragments in soils. Here, we characterise chondritic projectile debris found within lunar meteorite Pecora Escarpment (PCA) 02007 [4].

PCA 02007: PCA 02007 is a feldspathic regolith breccia [4-6] with a 3 Ma (<1 cm burial) lunar regolith exposure age [7]. A minor KREEP compositional component indicates that the sample likely contains impact ejecta from the Imbrium basin-forming event [5]: the sample was, therefore, probably consolidated from a regolith to a breccia after ~3.85 Ga [8]. The meteorite, thus, likely records post-basin-forming epoch regolith processes. Day et al. [4] report a 0.6 × 0.4 mm chondrule-like fragment in thick section PCA 02007,24 and named it clast T8 (Fig. 1). We have re-examined this fragment in detail to better understand its meteorite affinities.

Methods: The PCA 02007,24 thick section was imaged using the NASA JSC ARES JEOL 5910LV SEM. Mineral composition was determined using the NASA JSC ARES Cameca SX100 electron microprobe (EMP). The oxygen isotopic compositions of olivine grains was analysed *in situ* with the UH Cameca IMS-1280 ion microprobe in a technique similar to that described by Makide et al. [9]. Instrumental fractionation was corrected using a San Carlos olivine.

Petrography: Clast T8 is located within a consolidated lunar feldspathic regolith matrix (containing clasts of lunar mineral fragments, impact melt and melt breccias, and anorthositic igneous lithics) (Fig. 1a). The fragment does not contain any melt veins or pockets, and only has minor cross-cutting fractures indicating that little remelting or shock deformation occurred during the impact delivery process.

Mineral Chemistry: The fragment is composed of small (<35 µm) single grains and aggregates of magnesian olivine (Fo_{98-99}) (Fig. 1b). The olivine has FeO/MnO ratios of 6-12, which are distinct from lunar phases, and are most similar to those in type-1 carbonaceous chondrite chondrules. The forsteritic olivine is typically mantled by more ferroan olivine (Fig. 1b). The ferroan olivine also occurs as subhedral to blocky groundmass grains. Many of the smaller ferroan olivine grains display normal zoning from Mg-rich cores to thin (<5 µm) Fe-rich rims (Fo_{74-86}, with some outliers at Fo_{54-69}). Some of the larger ferroan grains also have subtle reverse and oscillatory zoning (Fig. 1c); the largest of these groundmass ferroan grains is ~30 × 60 µm. The more ferroan olivine, regardless of location within the clast (interior or exterior), has lunar-like FeO/MnO ratios of 66-141, clearly different from the more forsteritic olivine FeO/MnO ratios (6-12). The olivine is subophitically enclosed within a groundmass of plagioclase (An_{77-83}, Al_{18-22}, $Or_{0-0.4}$) and an interstitial Fe-rich (Mg#5) glass. Minor blebs of FeNi metal and FeS are scattered throughout the clast groundmass and some FeNi blebs occur within the olivine grains. Large (100 µm) assemblages of sulphide and metal also occur within the clast (Fig. 1a). Two type of sulphide are present: an Fe-richer variety with 58.9-61.4 wt% Fe, 35.0-35.7 wt% S, 1.9-6.6 wt% Ni and 0.22-0.32 wt% Co, which is compositionally akin to a Ni-bearing pyrrhotite, and an Fe-poorer variety with 42.4-43.5 wt% Fe, 31.6-33.4 wt% S, 22.1-23.0 wt% Ni, 0.48-0.64 wt% Co and 0.1-0.3 wt% Cu, which is compositionally akin to pentlandite (see also [4]). Small (<10 µm) prismatic grains of taenite (43 wt% Fe, 50.7 wt% Ni and 1.6-1.7 wt% Co) are scattered within the sulphide masses.

Day et al. [4] used mineral chemistry data, and the presence of Ni-rich metal, pentlandite and pyrrhotite as evidence that the fragment is meteoritic (*e.g.*, non-lunar). They argued that the clast is CV-chondrite-like in composition and may have been reworked in the lunar regolith to account for the more fractionated ferroan lunar-like olivine compositions.

Oxygen Isotopes: We measured the oxygen isotopic compositions of both the forsteritic and ferroan olivine to constrain isotopic similarities to primitive meteorite groups (Fig. 2). The forsteritic olivine has extremely ^{16}O-enriched compositions ($\delta^{18}O$ -41.9 to -44 ‰, $\delta^{17}O$ -43.3 to -44.7 ‰; $\Delta^{17}O$ -21.5 to -21.8 ‰), similar to compositions reported in ^{16}O-rich calcium-aluminium-inclusions (CAIs) in primitive chondrites and in forsterite within amoeboid olivine aggregates (AOAs). Ferroan olivine, both from within the interior and close to the exterior of the fragment, has $\delta^{18}O$ 4.1 to 5.7 ‰, $\delta^{17}O$ -0.5 to 1.1 ‰ and $\Delta^{17}O$ -1.8 to -2.3 ‰; these values all lie on the CCAM (carbonaceous chondrite anhydrous minerals) line, intermediate to bulk CR and CM chondrite meteorites (Fig. 2). These observations demonstrate that the fragment is not from a differentiated body, as differentiation would isotopically homogenize the body. The ferroan olivines are isotopically distinct from the terrestrial fractionation line (TFL) and lunar olivines (also measured in our study, Fig. 2). This demonstrates that the whole fragment has a non-lunar origin, and has not undergone any isotopic equilibration with lunar melts.

Fragment Origin: As noted by Day et al. [4], clast T8 is fragmentary and texturally unlike most plagioclase-rich chondrules. Olivine major and minor element abundances indicate that the Mg-rich olivines (Fig. 1b) in T8 are most similar in composition to forsterites in type-1 chondrules in CV, CR, CH and CB groups, but dissimilar from forsterite in K, CO, CI and E-chondrites. Their ^{16}O-rich compositions (Fig. 2) indicate a similarity to olivines in the CV meteorites and other AOA-bearing carbonaceous chondrites, suggesting that they were formed in high-temperature regions of the solar nebula, below forsterite condensation temperatures. It appears that these grains then underwent mixing with a different reservoir, with oxygen isotopic compositions akin to chondrules in carbonaceous chondrites (Fig. 2). The ferroan groundmass olivines have similar FeO/MnO ratios to type-2 chondrules from the CO meteorite group [10]. Their oscillatory zoning suggests that these grains might have nucleated from relict (Fo-rich) cores, or underwent several stages in crystal growth; possibly indicative of a relatively slow cooling rate. Ca-rich plagioclase crystallised between the olivine grains, and late-stage liquid was trapped as an interstitial component.

Summary: Clast T8 provides direct evidence of asteroid projectile fragments being delivered to the lunar surface. The particle illustrates the value of the NRC [11] objective 7d, which is to separate and study rare materials (like meteorites) in the lunar regolith.

References: [1] Rubin A.E. (1997) *Meteoritics and Planetary Science* 32, 135-141. [2] Zolensky M.E. (1996) *Meteoritics and Planetary Science* 32, 15-18 [3] Joy K. H., et al. (2011) *Annual Meeting of the Lunar Exploration Analysis Group*. Abstract #2036. [4] Day et al. (2006) *Geochimica et Cosmochimica Acta* 70, 5957-5989. [5] Korotev et al., (2006) *Geochimica et Cosmochimica Acta* 70, 5935–5956. [6] Joy et al., (2010) *Meteoritics and Planetary Science*. 45, 917-946. [7] Nishiizumi et al., (2006) LPSC *XXXVII*. Abstract #2369. [8] Stöffler et al., (2006) Chapter 5. *Reviews in Mineralogy & Geochemistry*. 60, 519-596. [9] Makide et al., (2009) *Geochimica et Cosmochimica Acta* 73, 5018-5050. [10] Berlin et al., (2011) *Meteoritics and Planetary Science* 46, 513-533 [11] NRC (2007) The Scientific Context for the Exploration of the Moon. [12] McKeegan et al., (2011) *Science* 332, 1528-1532 [13] Mittlefehldt et al., (2008) *Reviews in Mineralogy & Geochemistry*, 68, 399-428.

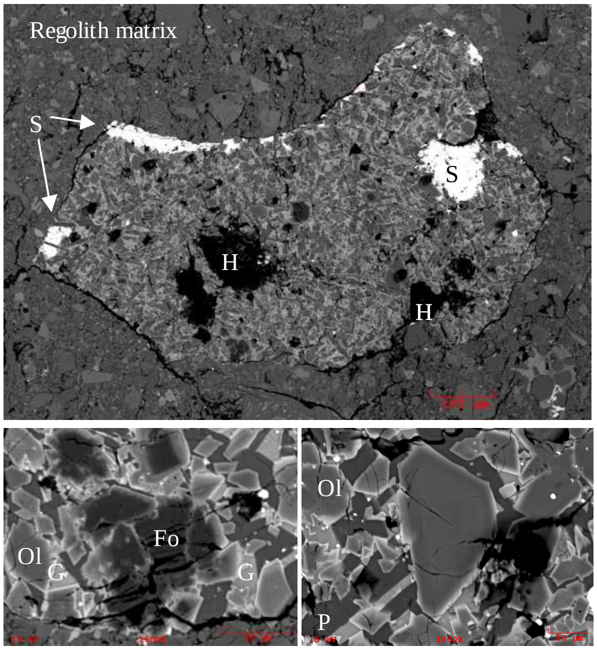

Figure 1. Backscattered electron images of clast T8 in PCA 02007,24. (a) Complete view of particle surrounded by feldspathic lunar matrix. (b) Close up of aggregate of forsteritic and (b) more ferroan (note subtle oscillatory zoning in largest grain at centre) olivines. Denoted phases: P = plagioclase, G = glass, H = hole, S = sulphide assemblage, Fo = forsteritic olivines, Ol = ferroan olivines.

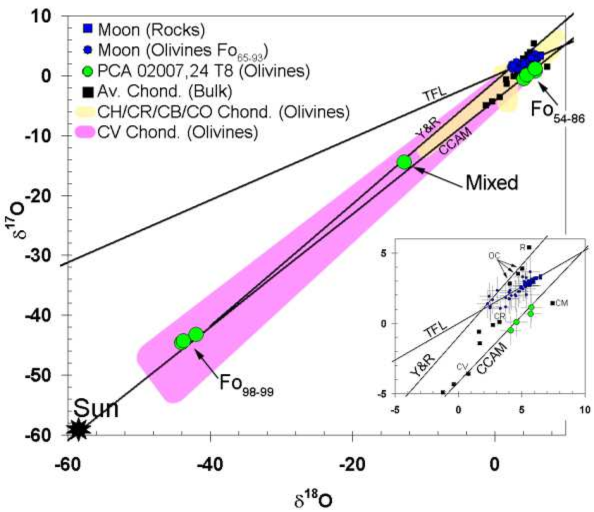

Figure 2. Oxygen three-isotope diagram showing olivine grains in PCA 02007,24 Clast T8 compared with lunar bulk rock analysis (literature), lunar olivines (this study), distribution of olivines from the Allende CV3 meteorite and CH/CR/CB/CO carbonaceous chondrites (literature). Solar oxygen data from [12] and average chondrite groups (black squares – some types are labelled) taken from data compilation of [13]. Inlay shows close up of the top-right corner of the diagram, depicting the composition of the more ferroan clast T8 olivines. Errors bars represent 2σ analytical uncertainty including both the internal measurement precision and the external reproducibility for San Carlos olivine measurements during a given analytical session.