OLIVINE AND PLAGIOCLASE OXYGEN ISOTOPE SIGNATURE OF NON-LUNAR MATERIAL IN APOLLO REGOLITH BRECCIAS WITH CLOSURE AGES ~1.79 TO 1.70 GA.

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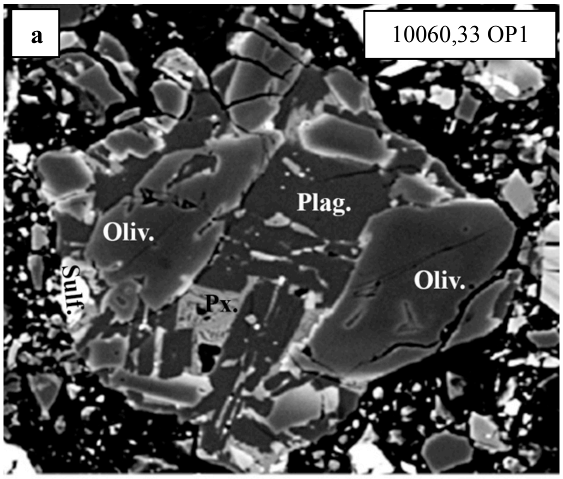
Introduction: The lunar regolith preserves a record of the temporally changing bombardment history of the Earth-Moon system in the form of relic fragments of asteroid debris. Such relics include the Hadley Rille enstatite chondrite [1], the Bench crater carbonaceous chondrite [2], Ultra-mafic Magnesian Fragments (UMMFs) that represent primitive chondritic material [3], and metallic iron fragments sourced from iron meteorites [4].

Potential relic clasts have been identified [5] in lunar regolith breccias with formation (closure) ages (t_c) 1.92 to 1.76 Ga [6]. Two of the relic types [5] are: (1) olivine- and plagioclase-bearing and (2) olivine- and glass-bearing clasts; these clasts are compositionally distinct from lithic lunar material and appear to be texturally similar to fragments of chondrules (Fig. 1). In order to better constrain the origin of this material, we have performed *in situ* oxygen isotope analyses on 6 selected clasts and compared the results with those of other planetary material.



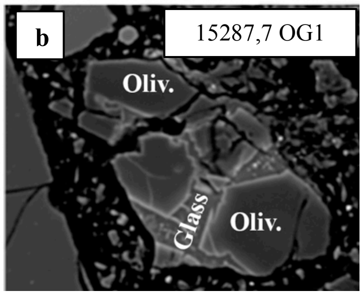


Fig. 1. Examples of the (a) olivine and plagioclase-bearing and (b) olivine and glass-bearing clasts. Phases are labeled.

Selected Samples: Three olivine- and plagioclase-bearing clasts (OP, Fig. 1a) were selected for oxygen isotope analyses along with 3 olivine- and glass-bearing clasts (OG, Fig. 1b) from 10021,35 (t_c~1.79 Ga); 10060,33 (t_c~1.76 Ga); and 15287,7 (t_c~1.76 Ga). OP clasts consist of forsteritic olivine (Fo_{67-89}, Fig. 2) and anorthitic plagioclase (An_{79-91}). The olivine have non-lunar FeO/MnO ratios of ~41 to 66 (Fig. 2). In contrast, OG clasts consist of forsteritic olivine (Fo_{56-85}, Fig. 2) set in a glass matrix (Fig. 1b). Many of the olivine have distinctly non-lunar FeO/MnO ratios (~53 to 69, Fig. 2), whereas others exhibit FeO/MnO zonations that stray into the lunar field (~ 70 to 93, Fig. 2).

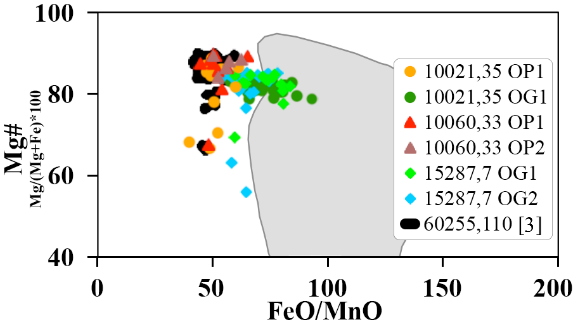


Fig. 2. Olivine compositions from lithic clasts in this study in comparison to lunar olivine (light grey field) and an olivine-phyric relic from Apollo 16 regolith breccia 60255,110 [3].

Analytical Methods: Potential relic material was first identified from thin-sections of selected regolith breccias using an optical microscope as well as qualitative element and backscattered electron maps (see [7] for details of element mapping technique) generated by the NASA JSC JEOL-7600F Field Emission-Scanning Electron Microscope. Clasts were then analyzed using the NASA JSC Cameca SX100 electron microprobe to determine mineral compositions.

Oxygen isotopic analyses were performed on olivine and plagioclase grains within 6 lithic clasts. Analyses were conducted *in situ* with the UH Cameca ims-1280 ion microprobe using a technique similar to that described by Joy et al. [3]. The primary beam was rastered over a 3×3 µm area and the overall spot size was ~8 µm. Instrumental fractionation was corrected using a San Carlos olivine and a Miyake-Jima anorthite for olivine and plagioclase analyses, respectively.

Results and Discussion: Olivine and plagioclase analyses from lithic clasts all lie close to the terrestrial fractionation line (TFL), but many of the δ^{18}O and δ^{17}O analyses from this study are higher than published lunar material (Fig. 3). Two clasts (10021,35 OG1 and 10060,33 OP2) are petrographically and compositionally similar to others in their respective groups, but these clasts are isotopically indistinguishable, in terms of oxygen, from lunar material.

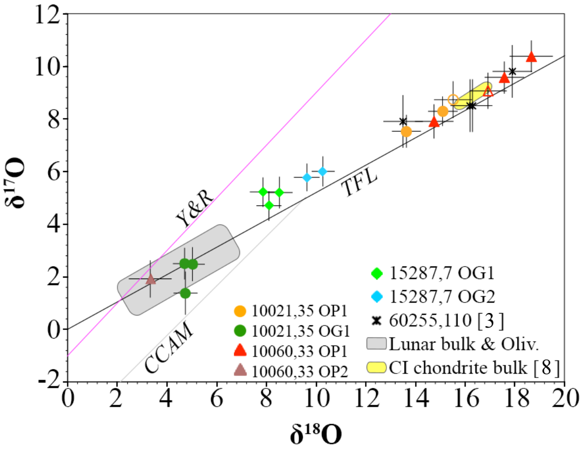


Fig. 3. Oxygen three-isotope diagram showing olivine (filled symbols) and plagioclase (open symbols) grains in this study compared with lunar (bulk rock and individual olivine grains [3 and refs. therein]) and CI (bulk rock, [8]) data. Error bars represent 2σ analytical uncertainty including the internal measurement precision, the external reproducibility for the standards during the analytical session, and a drift correction.

OP Relic Clasts: Olivine from two of the OP clasts (10021,35 OP1 and 10060,33 OP1) have higher δ^{18}O and δ^{17}O values (δ^{18}O 13.6 to 18.7‰, Δ^{17}O 0.2 to 0.7) than lunar values, but are indistinguishable from the TFL (Fig. 3). Plagioclase is isotopically similar to the olivine (δ^{18}O 15.5 to 16.9‰, Δ^{17}O 0.3 to 0.7, Fig. 3). Remarkably, the olivine in these clasts is isotopically (Fig. 3) and compositionally (Fig. 2) similar to olivine from a relic clast within Apollo 16 regolith breccia 60255,110 [3], which also has a similar closure age (t_c~1.70 [9]) to the Apollo 11 samples. Such similarities suggest that the clasts may have a similar origin, but few materials in the present meteorite collection have such high δ^{18}O and δ^{17}O values.

OG Relic Clasts: Olivine from the 15287,7 OG clasts have oxygen isotopic concentrations that lie between the two OP groups (δ^{18}O 7.9 to 10.3‰, Δ^{17}O 0.5 to 1.1, Fig. 3). In contrast to the OP clasts, which are indistinguishable from the TFL, these OG clasts are statistically resolvable from the TFL, and therefore are clearly distinct from lunar material.

These OG olivine have compositional similarities (Mg#, FeO/MnO ratio) to a CC-relic in lunar meteorite PCA 02007,24 (t_c<3.85, [3]), but the textural and isotopic data are distinct. In contrast, the OG clasts are isotopically similar to olivine from several different meteorite groups (e.g., LL3.6, CH, CH/CB chondrites [10,11 and references therein]), but these groups are petrographically and mineralogically distinct from the OG clasts. Further work is required to constrain the source material.

Implications: Although the oxygen isotopes of some of the OP clasts are similar to the CI chondrites in the present day meteorite collection, the relics are petrographically dissimilar from CI chondrite material: the silicate assemblages of the OP clasts are dominated by olivine, whereas neither olivine nor chondrules are abundant in most CI chondrites, which have been pervasively aqueously altered (e.g., [12]). Where olivine is present in CI chondrites, it is typically more forsteritic [13] than the relic olivine in this study (Fig. 2) and, although the database for comparison with CI olivine is limited, the OP clasts are ^{16}O-poorer than most CI olivine [14]. Thus, CI chondrites are unlikely to be the source for the OP material. As there are no other isotopically similar materials in the current meteorite collection, or sampled from comet Wilde-2, it is possible that the relics are sourced from an ancient projectile type.

Olivine from the Apollo 11 OP and Apollo 16 60255,110 relic clasts have very similar mineral compositions, oxygen isotope signatures, and closure ages despite their collection from different missions. These relics could represent material from a single impact event of a ^{16}O-poor projectile or several isotopically similar projectiles that bombarded the Moon and Earth over a period of time. These relics illustrate the potential for a population of impactors with oxygen isotopic signatures similar to CI chondrites, but with distinct mineral chemistry and texture, that may represent material with no analogue in the current meteorite sample collection.

References: [1] Rubin A.E. (1997) *Meteorit. and Planet. Sci.,* **32**, 135-141. [2] Zolensky M.E. (1996) *Meteorit. and Planet. Sci.,* **32**, 15-18. [3] Joy K.H. et al. (2012) *Science*, **336**, 1426-1429. [4] Jolliff B.L. et al. (1993) *LPSC* 24, Abst. #729. [5] Fagan A.L. et al. (2015) *LPSC* 46, Abst. #1405. [6] Fagan A.L. et al. (2014) *Earth, Moon, and Planets*, **112**, 59-71. [7] Joy K.H. et al. (2011) *Ann. Meet. Lunar Exp. An. Group*, Abstract #2007. [8] Clayton R.N. & Mayeda T.K. (1999) *Geochim. Cosmochim. Acta,* **63**, 2089-2104. [9] Joy K.H. et al. (2011) *Geochim. Cosmochim. Acta,* **75**, 7208-7225. [10] Ruzicka A. et al. (2007) *Geochim. Cosmochim. Acta*, **257**, 274-289. [11] Krot A.N. et al. (2010) *Geochim. Cosmochim. Acta*, **74**, 2190-2211. [12] King A.J. (2015) *Geochim. Cosmochim. Acta*, **165**, 148-160. [13] Frank D.R. et al. (2014) *Geochim. Cosmochim. Acta*, **142**, 240-259. [14] Leshin L.A. et al. (1997) *Geochim. Cosmochim. Acta*, **61**, 835-845.