FRAGMENTS OF MULTIPLE IMPACTORS PRESERVED IN LUNAR METEORITE LYNCH 002.
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Introduction: Systematic study of meteoritic debris in regolith breccias with different closure ages indicates the nature of lunar impactors varied over time, with more primitive material impacting earlier in the Moon's history [1-2]. Fragments of iron meteorites [3], carbonaceous chondrites [1,4-5], enstatite chondrites [6], and ultramagnesian, primitive chondritic material [1] have all been identified thus far in lunar samples. During our study of a recently described lunar meteorite, Lynch 002 [7-9], we identified three potential meteoritic fragments. Here we present mineralogic and isotopic evidence that one of those fragments is the first reported ordinary chondrite (OC) fragment in a lunar breccia.

Lynch 002 is a small (~36 g), heavily weathered, moderately mafic lunar regolith breccia discovered on the Nullarbor Plain, Western Australia, in 2012 [7-9]. Lynch 002 is fine-grained, with no clasts larger than 1 mm. It contains fragments of very low-Ti and low-Ti mare basalt, KREEP-rich clasts, smaller breccias, mineral fragments, and impact melt spherules [7,9]. Lynch 002 contains several cross-cutting impact melt veins that indicate the breccia was modified by one or more impact events after assembly [7,9]. The presence of KREEP-rich fragments suggests Lynch 002 most likely originated from within the Procellarum-KREEP terrane on the lunar nearside [7-10].

Methods: One epoxy-mounted, polished thick slab of Lynch 002 was available for this study. X-ray elemental maps of the section were acquired at the Natural History Museum, London (NHM). Clasts of interest were identified and examined using SEM and EMPA at both the Open University (OU) and the NHM. Mineral chemistry was determined with the Cameca SX100 electron microprobes at the OU and NHM, using well-characterized glass, metal, and mineral standards [7,9].

Oxygen three-isotope measurements of olivine in selected clasts were obtained with the Cameca ims 1280 ion microprobe at the University of Hawaii, using a similar setup as [1]. A ~800 pA primary beam was rastered over ~7 × 7 μm for a 30 cycle measurement using Faraday cups for ^{16}O and ^{18}O, and an electron multiplier for ^{17}O. San Carlos olivine was used to correct for instrumental mass fractionation. Data were also corrected for ^{16}OH interference on the ^{17}O peak (typically less than ~0.1 ‰).

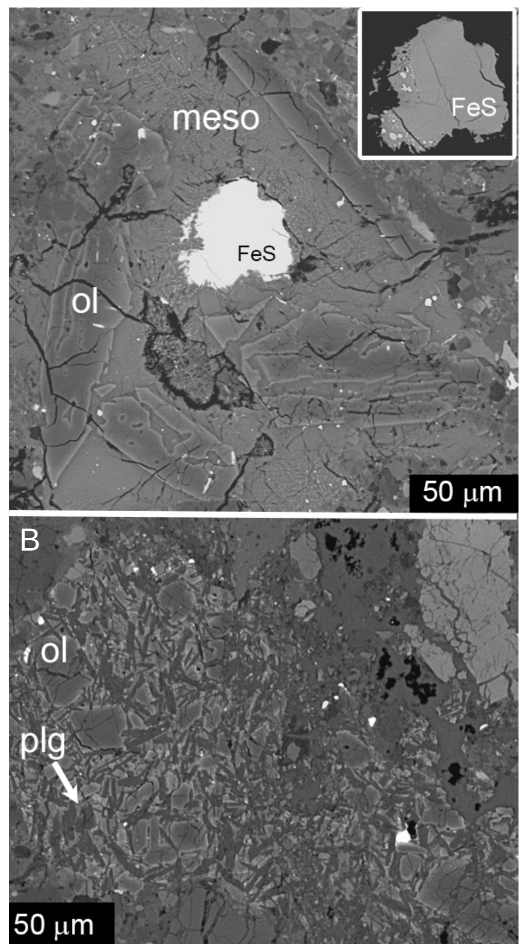

Fig 1. BSE images of olivine-rich fragments in Lynch 002. (A) Fragment L38. Zoned olivine is surrounded by glassy mesostasis containing microcrystallites. The inset shows tiny blebs of Fe,Ni within the central FeS grain. (B) Olivine-phyric clast L17, consisting of zoned olivine and small plagioclase needles.

Clast Descriptions: We identified three potential meteoritic fragments labeled Lithics 38, 17, and 12.

Lithic 38 (L38). This 190 μm-long clast was noted as unusual by C. Smith and A. Kearsley during an initial reconnaissance of the Lynch 002 section. L38 is a porphyritic olivine melt fragment (Fig. 1A). It consists of four zoned skeletal olivine grains (Fo_{72-85}) in a microcrystallite-bearing glassy mesostasis. A large FeS grain containing very small Fe,Ni-metal blebs sits roughly in the center of the fragment. The presence of glass and zoned olivine indicates L38 is a texturally and chemically unequilibrated fragment [9].

Lithics 12 and 17 (L12 & L17). Lithics 12 and 17 are texturally identical, and are located in relatively close proximity to each other in the Lynch 002 section. They may, thus, be fragments of the same parent rock. L12 and L17 have olivine-phyric textures, with larger zoned subhedral olivines (Fo_{70-86}) separated by smaller tabular plagioclase crystals (Fig. 1B). Both fragments contain small FeS grains. L12 and L17 are texturally and compositionally similar to olivine-phyric fragments identified as meteoritic relics in Apollo samples by Joy et al. [1] and Fagan et al. [2].

Results and Discussion: The Fe/Mn ratio of olivine varies with parent body (e.g., [11]) and is a useful petrogenetic indicator for determining the source of planetary samples. Olivine FeO/MnO data for L38, L12, and L17 are plotted against olivine Mg# in Fig. 2 [1]. L38 is clearly outside the lunar field. L12 and L17 fall near the edge of the lunar field. This indicates that they could all potentially have non-lunar sources.

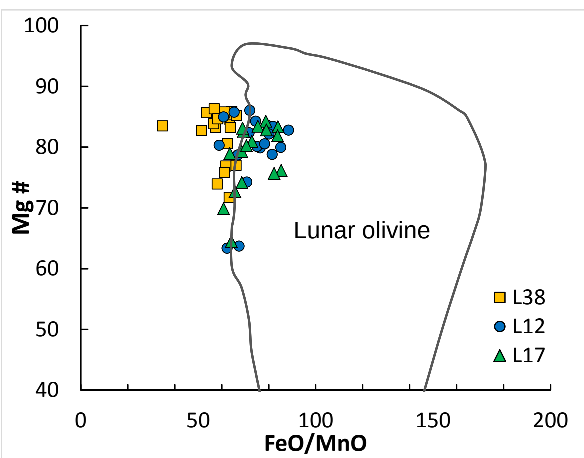

Fig. 2. Olivine Mg# versus FeO/MnO of clasts in Lynch 002. L38 falls outside the lunar field defined in [1], suggesting a non-lunar origin. L12 and L17 fall partially within the lunar field and are, thus, more ambiguous.

Oxygen isotope compositions, which are another provenance indicator, are shown for multiple olivine crystals in each clast in Fig. 3. Olivine in L38 is distinct from the terrestrial fractionation line (TFL) and falls within the ordinary chondrite (OC) range with average $\delta^{18}O$ ~5.6 ‰ and $\Delta^{17}O$ ~1.1 (±0.7). The uncertainty of the measurements is large enough to prevent us from resolving H, L, or LL material in this sample with O isotopes, but the Fe content of the olivine (Fa_{15}) is indicative of an H chondrite source [12]. While O isotopes in L12 and L17 are largely unresolved from the TFL (Fig. 3), they are isotopically much heavier than the accepted lunar range. Lunar olivine has $\delta^{18}O$ ~3 to 6 ‰ [1], while olivine in L12 and L17 has $\delta^{18}O$ ~11 to ~12 ‰ and average $\Delta^{17}O$ of ~0.5. Similar olivine-phyric clasts reported by Joy et al. [1] and Fagan et al. [2] also show elevated $\delta^{18}O$ with little deviation from the TFL (Fig. 3). L12 and L17 may represent an additional detection of impactor fragments with oxygen isotope compositions similar to CI chondrites that are not present in the current meteorite sample collection [2]. Thus, Lynch 002 contains at least two types of meteoritic relics.

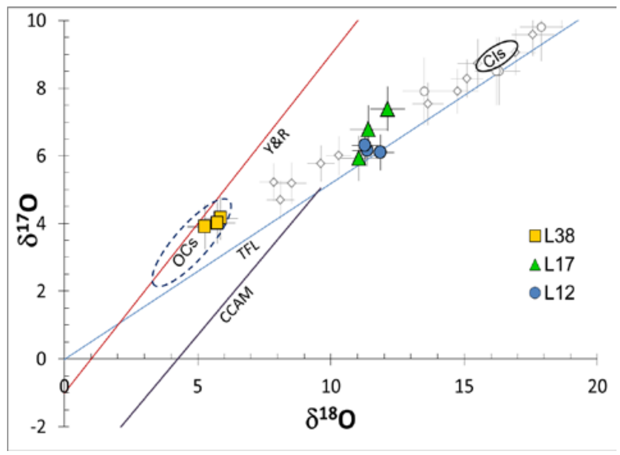

Fig. 3. Three oxygen isotope plot for olivine-rich clasts in Lynch 002. The O isotope composition in L38 is consistent with ordinary chondrites [14-15]. L12 and 17 fall along the TFL, but have nonlunar signatures similar to previously reported olivine-rich material [1-2] (open symbols) and bulk CI chondrites [13].

References: [1] Joy K.H. et al. (2012) *Science*, 336, 1426–1429. [2] Fagan A.L. et al. (2016) *LPS LXVII* Abstract #2789. [3] Quaide W., Bunch T. (1970), *Proc. LPS*, *1*, 711–729. [4] Zolensky M.E. (1997) *MaPS*, *32*, 15–18. [5] Day J.M.D. et al. (2006) *GCA*, *70*, 5957–5989. [6] Rubin A.E. (1997) *MaPS*, *32*, 135–141. [7] Smith C.L. et al. (2012) *75th MetSoc* abst. 5137. [8] Korotev R.L. (2013) *76th MetSoc abst.* 5021. [9] Robinson K.L. et al. (2016) *LPS LXVI* Abstract #1470. [10] Jolliff B.L. et al. (2000) *JGR*, *105*, 4192–4216. [11] Papike J.J. et al. (2009) *GCA*, *73*, 7443–7485. [12] Van Schmus W.R. and Wood J.A. (1967) *GCA*, *31*, 747–765. [13] Clayton R.N. & Mayeda T.K. (1999) *GCA*, *63*, 2089–2104 [14]. Clayton R.N. et al. (1991) *GCA*, *55*, 2317–2337. [15] Greenwood R.C. et al. (2017) *Chemie der Erde*, *77*, 1–43.