PROJECTILE FRAGMENTS IN ANCIENT LUNAR REGOLITH BRECCIAS: EXPLORING THE SOURCES AND TEMPORAL RECORD OF LUNAR IMPACTS. K. H. Joy[1,2], D. A. Kring[1,2], M. E. Zolensky[2,3], D. K. Ross[3,4], D. S. McKay[2,3]. [1]CLSE, LPI/USRA, 3600 Bay Area Blvd., Houston, Texas 77058, USA (joy@lpi.usra.edu). [2]NASA Lunar Science Institute. [3]ARES, NASA Johnson Space Center, Houston, TX 77058, USA. [4]ESCG-Jacobs Technology, 2224 Bay Area Blvd. Houston TX 77058, USA.

Introduction: A key lunar and planetary science goal is to understand the sources of projectiles that formed the large (>300 km) lunar basins. Resolving the sources of these basin-forming impactors will help to provide constraints for models of Solar System dynamics, understand the delivery of volatiles to the early Earth-Moon system, and to explain the causes of possible spikes in the ancient impact record [1].

A direct geochemical record of impactor origin is recorded by several meteorites that survived collision with the lunar surface. For example, a carbonaceous-chondrite (Bench Crater meteorite [2]) and an enstatite-chondrite (Hadley Rille meteorite [3]), have been previously reported in lunar soils. However, it is not known exactly at what time these meteorites impacted the lunar surface, and if they were involved in crater-forming events; so these samples provide only a limited perspective on the sources of impactors striking the Moon through time.

Regolith breccia time-capsules: Regolith breccias, which are consolidated samples of the lunar regolith (soil), were closed to further impact processing at the time they were assembled into rocks [4]. They are, therefore, time capsules of impact bombardment at different times through lunar history.

Here, we present a study of regolith breccias collected by the Apollo 16 mission from the Cayley Plains Formation.We used a revised calibration (after [5]) of the ratio of trapped $^{40}Ar/^{36}Ar$ ('parentless' ^{40}Ar derived from radioactive decay of ^{40}K, ratioed to solar wind derived ^{36}Ar) to semi-quantitatively calculate the timing of the assembly of the Apollo 16 regolith breccias (see Joy et al. [6] for more details, where the Apollo 16 $^{40}Ar/^{36}Ar_{Tr}$ values were taken from McKay et al. [4]). Our revised calibration indicates that the Apollo 16 ancient regolith breccia population was assembled between 3.8 and 3.4 Ga, consistent with regoliths developed and closed after the Imbrium basin-forming event (~3.85 Ga), during the time of declining basin-forming impacts.

Methods: We have used optical microscope and FEG-SEM techniques to identify non-lunar compositionally 'exotic' rock and mineral fragments within thin sections of these samples (see Joy et al., this meeting [7] for details, and Fig. 1a here). Samples are then analysed using the NASA JSC Cameca SX100 electron microprobe (EMP) to derive mineral (1 µm beam) and bulk fragment (10-20 µm beam) compositions.

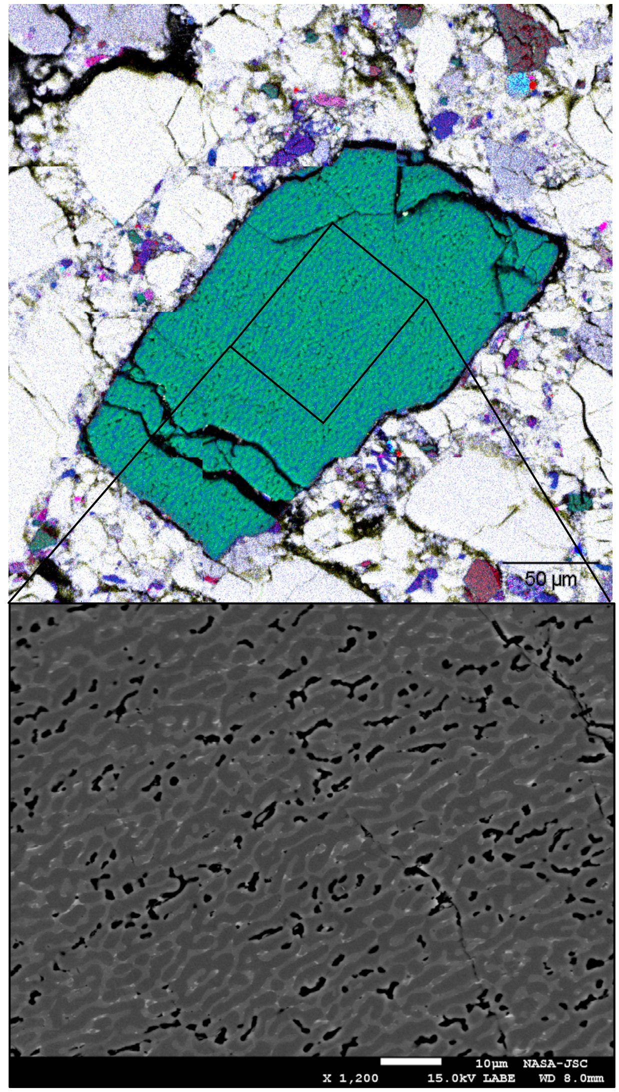

Figure 1. (a) Top: False-colour image (where Al=white, Mg=green, Si=blue, Fe=red, Ti=pink, Ca=yellow, K=cyan [7]) of large (~475 × 325 µm) cryptocrystalline UMMF fragment in 66035,13 (see also [13]). (b) Bottom: Close-up BSE image of UMMF with ultrafine grained intergrowth of forsteritic olivine (dark grey) and enstatitic pyroxene (medium grey). Porous texture is clearly seen.

Results: In ancient (~3.8-3.5 Ga) regolith breccias 60016, 60019, 61135, 66035 we have identified a suite of ultra-magnesian mafic fragments (UMMFs). These fragments contribute 0.02 to 0.25 % to the surface area of the fine fraction (<2 mm) regolith component in each thin section.

The UMMFS have different textures: (1) Microcrystalline fragments are formed of forsteritic olivine grains ($Fo_{95\text{-}98}$ Fig. 2a), sometimes enclosing near end-member enstatitic pyroxene ($En_{90\text{-}96}Fs_2Wo_{2\text{-}8}$). MnO concentrations in the forsteritic olivine are variable, with FeO/MnO ratios of 40-70 in some grains and up to 122-190 in others (Fig. 2a). The clasts sometimes also contain small (<5 µm) irregular interstitial phases (glass?), including an Al, Ca, Na, P and K component. (2) Cryptocrystalline fragments are fine grained clasts consisting of intergrowths between forsteritic olivines and enstatitic pyroxenes (<3 µm too fine grained to be compositionally determined by EMP). They are frequently porous, with small (<5 µm) pores often aligned throughout a fragment to give a mottled texture (Fig. 1). They also include microcrsyts (<1 µm) of an Al-richer phase (Fig. 1). (3) Barred fragments and (4) amorphous fragments exhibit poor or no crystal habit, and are formed of material with a composition intermediate to magnesian olivine and pyroxenes.

Interpretation: The olivine and pyroxene phases in the UMMFs are more magnesian than any lunar indigenous mafic minerals previously analysed (Mg-Suite lithologies typically have olivine with $Fo_{80\text{-}93}$, whilst some are magnesian dunites that extend those compositions to Fo_{95} [8]: Fig. 2a). The mafic phases are also compositionally distinct from experimentally produced and theoretically calculated minerals from the early mantle cumulates of the lunar magma ocean [9,10]. The bulk composition of all of the UMMFS are highly magnesian (bulk Mg# 93-99: Fig. 2b) compared with known lunar rocktypes (Fig. 2).

The bulk composition and olivine compositions of the UMMFS are as magnesian (Fig. 2a) as chondrules [11] and chondrule olivines from carbonacous chondrite groups. This compositional evidence suggests that the UMMF are non-lunar, and possibly originate from a primitive chondritic meteoritic source. In comparison with primitive carbonaceous chondrite chondrules [11], the UMMFs have similar Al_2O_3, Na_2O and Mg# compositions, but lower Cr_2O_3 and MnO (higher FeO/MnO ratios: Fig. 2b), and are typically TiO_2-richer.

Summary: In ancient (~3.8-3.4 Ga) regolith breccias 60016, 60019, 61135 and 66035 we have identified a suite of ultra-magnesian fragments that are consistent with material delivered to the Moon by primitive (carbonaceous) projectiles during the last stages of the basin-forming epoch.

Our investigation demonstrates how detailed analytical studies can be employed to search the lunar regolith for meteoritic material; helping to address several key scientific objectives for the exploration of the Moon [1].

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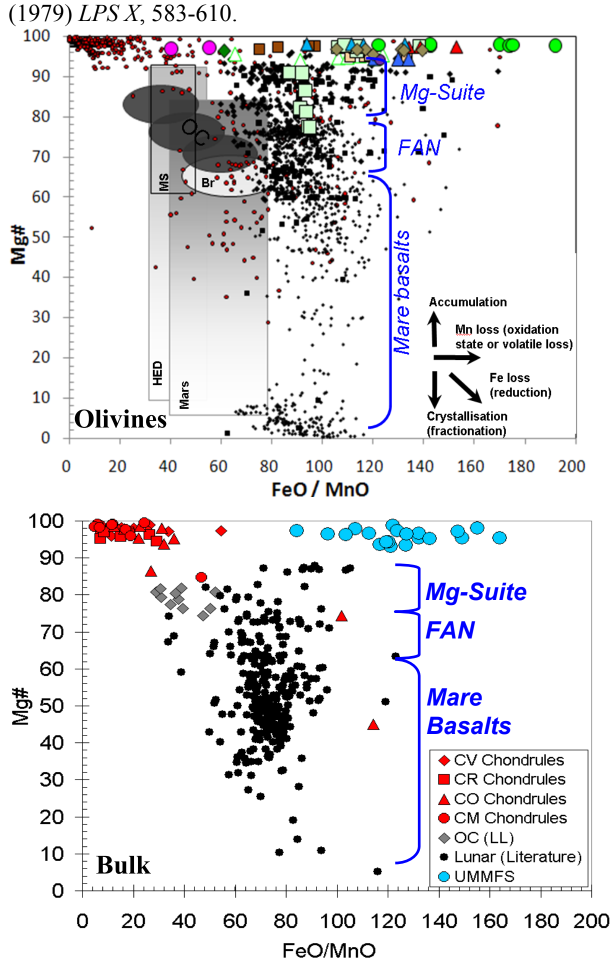

Figure 2. (a) Top: Olivine compositions in UMMFS analysed in our study (large coloured symbols) compared with lunar olivines (black symbols), carbonaceous chondrite olivines (small red symbols) and other groups of meteorites (martian, HED, mesosiderite, ordinary chondrite and bracinite). Data compiled from many sources. (b) Lower: Average bulk composition of UMMF fragments in 60016,83, 60016,93, 60016,95, 60019,176, 61135,36 and 66035,13 compared with lunar bulk rock compositions (taken from various literature sources) where the main lunar rock suites are shown,