DIRECT DETECTION OF PROJECTILE RELICS ON THE MOON. K. H. Joy[1,2], M. E. Zolensky[2,3], D. K. Ross[3,4], D. S. McKay[2,3], D. A. Kring[1,2]. [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 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]. Comparing these records to post-basin forming impactor populations will illustrate how source regions and delivery mechanisms of projectiles evolve with time.

Chemical signatures of material accreting to the Moon have been detected in the past, generally in the form of highly-siderophile elements (HSE) in impact melt rocks and bulk soils. A more direct method of identifying the projectiles is to locate relics that survived collision with the lunar surface.

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 [2]. 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 (A16) mission from the Cayley Plains Formation. We used a revised calibration (after [3]) 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. [4] for more details, where the Apollo 16 $^{40}Ar/^{36}Ar_{Tr}$ values were taken from McKay et al. [2]). Our revised calibration [4] 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.

We compare ancient regolith breccia archive to younger regolith breccias and soils from A16 and other Apollo landing sites. The A16 young regolith breccia population was closed between the time of Imbrium (3.85 Ga) and ~2.3 Ga [4]. A16 Soil-like regolith breccias include samples that were closed by 1.7 Ga until more recent times [4].

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 sample. 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.

Ancient breccia projectile relics: In ancient (~3.8-3.4 Ga) regolith breccias 60016, 60019, 61135, 66035 and 66075 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 igneous textures: (1) Microcrystalline (porphyritic olivine and pyroxene POP: Fig. 1b) and (2) barred olivine (BO) fragments (Fig. 1c) are formed of forsteritic olivine grains (Fo_{95-98}), sometimes enclosing near end-member enstatitic pyroxene ($En_{90-96}Fs_2Wo_{2-8}$). 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 The clasts sometimes also contain small (<5 µm) irregular interstitial phases, including an Al, Ca, Na, P and K component. (3) Cryptocrystalline fragments (Fig. 1a) are fine grained clasts consisting of intergrowths between forsteritic olivines and enstatitic pyroxenes (<3 µm; too fine grained to be compositionally determined by EMPA). They are frequently porous, with small (<5 µm) pores often aligned throughout a fragment to give a mottled texture (Fig. 1a). They also include microcrsyts (<1 µm) of a felsic and Ti-rich phase. They have a bulk a composition intermediate to forsterite and enstatite. (4) Radial olivine fragments are also compositionally intermediate to forsterite and enstatite.

The olivines and pyroxenes in the UMMFs are more magnesian than any lunar indigenous mafic minerals previously analysed (Mg-Suite lithologies typically have olivine with Fo_{80-93}, whilst some are magnesian dunites that extend those compositions to Fo_{95} [5]). The mafic phases are also compositionally distinct from experimentally produced and theoretically calculated minerals from the early mantle cumulates of the lunar magma ocean [6,7]. The bulk composition of all of the UMMFS are highly magnesian (bulk Mg# 93-99) compared with known lunar rocktypes.The bulk composition and olivine compositions of the UMMFS are as magnesian (Fig. 2a) as chondrules [8] and chondrule olivines from carbonaceous chondrite groups. This compositional evidence suggests that the UMMF are non-lunar, and possibly originate from a primitive chondritic meteoritic source.

Post-basin forming projectile population:

Fragments in A16 young regolith breccias. Examples of post-basin forming projectiles include an (~200 × 320 µm) ultramafic magnesian olivine (Fo_{96-97}) fragment within the splash coat of 60275 (2.3 Ga) that is similar to the composition of UMMFs found in the ancient Apollo 16 regolith breccias: it likely represents silicate (chondrule) material from primitive carbonaceous chondrite projectile. In sample 60255 (1.7 Ga) we have identified at least three different projectile relics. One is a small (<50 µm) ultramafic magnesian fragment, with a bulk composition (Mg# 99, FeO/MnO ratio of 35) similar to Type-1 chondrules in carbonaceous chondrites. Another small fragment (<20 µm) represents reworked fragments of a Type-1 carbonaceous chondrite assemblage (magnesian pyroxene and olivine fragments surrounded by a groundmass of melted sulphide-rich material). A third fragment is a larger (~250 × 120 µm) olivine-phyric basalt (Fig. 1e) that has a porphyritic texture with phenocrysts of olivine (Fo_{86-90}), with non-lunar compositions (FeO/MnO 44-60), in an interstitial mesostasis, formed of radiating laths of plagioclase (An_{65-72}) and a mafic Si-rich phase (pyroxene?) and small grains of Cr-rich spinel. The fragment also has troilite (FeS) enclosing grains of taenitic (high-Ni) metal, indicating that it originates from a reduced parent body. The fragment is potentially an impact or magmatic melt from an asteroidal source.

Fragments in soils and regolith breccias of unknown age. Other examples of projectiles delivered to the Moon after the basin-forming epoch include a CM carbonaceous-chondrite fragment found in soil 12037 (Bench Crater meteorite [9]: Fig. 1g), an enstatite-chondrite in soil 15601 (Hadley Rille meteorite [10]: Fig. 1d), a potential mesosiderite fragment in soil 10084 [11] and iron meteorite (bronzite-bearing) fragment in soil 10085 [12].

Two additional meteorite fragments found in lunar samples have uncertain delivery times, but probably were delivered after the formation of the Imbrium basin at 3.85 Ga. An Ir-rich micrometeorite fragment was found in Apollo 16 drive-tube 60014 [13]. A chondrule fragment (Fig. 1f) is present in feldspathic lunar meteorite regolith breccia Pecora Escarpment (PCA 02007) [14].

Summary: In ancient (~3.8-3.4 Ga) regolith breccias 60016, 60019, 61135, 66075 and 66035 we have identified a suite of ultra-mafic magnesian fragments that are consistent with material delivered to the Moon by primitive chondritic projectiles during the last stages of the basin-forming epoch. In young regolith breccias 60255 and 60275 we have also located primitive chondritic debris. In 60275 we have also located an asteroidal crystalline impact/magmatic melt clast.

Our investigation demonstrates that 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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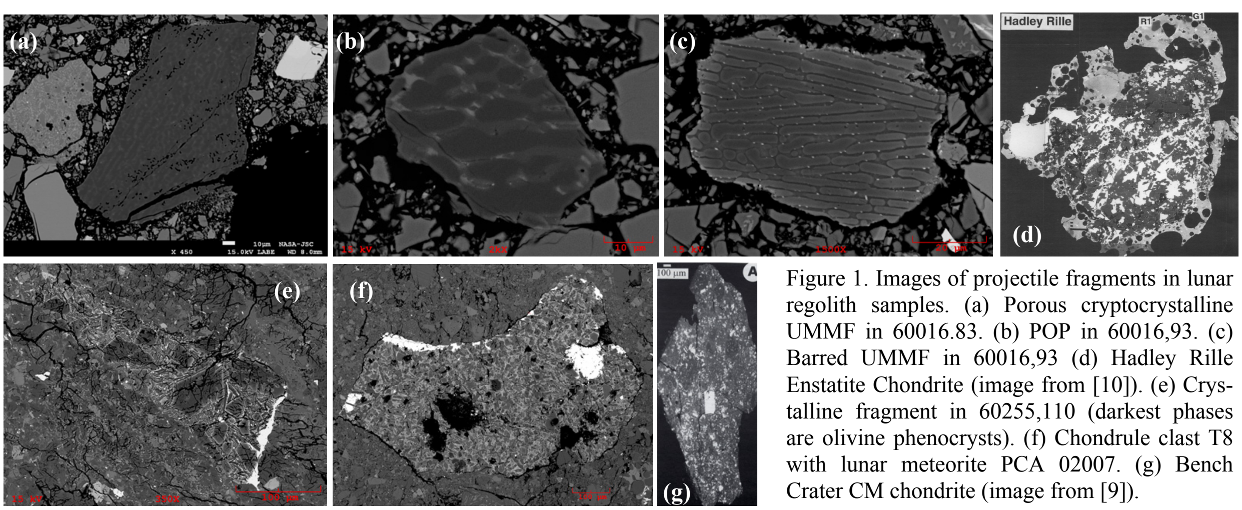

Figure 1. Images of projectile fragments in lunar regolith samples. (a) Porous cryptocrystalline UMMF in 60016.83. (b) POP in 60016,93. (c) Barred UMMF in 60016,93 (d) Hadley Rille Enstatite Chondrite (image from [10]). (e) Crystalline fragment in 60255,110 (darkest phases are olivine phenocrysts). (f) Chondrule clast T8 with lunar meteorite PCA 02007. (g) Bench Crater CM chondrite (image from [9]).