**INVESTIGATING THE SOURCES AND TIMING OF PROJECTILES STRIKING THE LUNAR SURFACE.** K. H. Joy[1,2] D. A. Kring[1,2], M. E. Zolensky[2,3], D. S. McKay[2,3] and D. K. Ross[3], [1]Center for Lunar Science and Exploration, Lunar and Planetary Institute, 3600 Bay Area Blvd. Houston, Tx, USA (joy@lpi.usra.edu), [2]The NASA Lunar Science Institute, [3]ARES, NASA Johnson Space Center, Houston, Tx, USA.

**Introduction:** The lunar surface is exposed to bombardment by asteroids, comets, and debris from them. Surviving fragments of those projectiles in the lunar regolith provide a direct measure of the sources of exogenous material delivered to the Moon. Constraining the temporal flux of their delivery will directly address key questions about the bombardment history of the inner Solar System.

Regolith breccias, which are consolidated samples of the lunar regolith, were closed to further impact processing at the time they were assembled into rocks [1]. They are, therefore, time capsules of impact bombardment at different times through lunar history. Here we investigate the impact archive preserved in the Apollo 16 regolith breccias and compare this record to evidence of projectile species in other lunar samples.

**Temporal Archive of the Apollo 16 Regolith Breccias:** McKay *et al.* [1] presented Ar-isotopic evidence that the Apollo 16 regolith breccias were assembled either prior to 4 Ga (the ancient regolith breccias) or after 4 Ga (the young regolith breccias).

We used a revised calibration (after [2]) 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 (initial results were presented in [3]).

Our revised calibration indicates that the Apollo 16 ancient regolith breccia population was assembled between 3.77 and 3.35 Ga (after [3]), consistent with regoliths developed and closed after the Imbrium basin-forming event (~3.85 Ga), during the time of declining basin-forming impacts. We also find that young regolith breccias were assembled in the Eratosthenian period between 2.51 and 2.16 Ga, providing a window to the sources of post-basin bombardment.

**Methodology:** Thin sections of Apollo 16 regolith breccias are studied optically, and then carbon coated, and examined with the NASA JSC JEOL field-emission scanning electron microscope to collect qualitative element and back-scatter electron (BSE) maps. Phases and rock fragments of interest are then examined using a Cameca SX100.

**Ancient regolith breccia 60016:** The 60016 sample is a $B_2$-type breccia (light matrix with dark clasts [4]). In thin sections ,83 ,93 and ,95 we find a range of clasts (<2 cm) including mafic and feldspathic impact melt and melt breccias, ferroan anorthosites, and mineral fragments in a comminuted mineral, glass, and polymict rock matrix. Although devitrified and homogenous glassy impact melt spheres occur, we do not observe any agglutinates. This is consistent with the observation of [1] that 60016 is very immature (0.5 $I_s$/FeO) and had limited surface exposure.

The breccia has a trapped $^{40}Ar/^{36}Ar$ ratio of 12.2 [1] suggesting assembly at ~3.74 Ga (after [2,3]). The material contained within this ancient regolith breccia, therefore, provides evidence of impactors delivered to the Moon in the Late-Imbrian epoch, and may also sample impactor populations during the basin-forming epoch itself. In three different thin sections of 60016 (,83, ,93, and ,95) we have identified several clasts with atypical lunar mineral chemistries. These include:

*Ultra Magnesian Mafic Fragments (UMMF).* Eight small (<250 µm) fragments found in all three sections (*e.g.*, see Fig. 1) are formed of forsteritic olivine grains ($Fo_{95-98}$: Fig. 2a), often enclosing near end-member enstatitic pyroxene ($En_{90-96}Fs_2Wo_{2-8}$: Fig. 2b). 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.

The olivine and pyroxene phases in the UMMF are more magnesian than any lunar indigenous mafic minerals analysed previously (Mg-Suite lithologies typically have olivine with $Fo_{80-93}$, while some magnesian dunites extend those compositions to $Fo_{95}$ [5,6]). The 60016 mafic phases are also compositionally distinct from experimentally produced and theoretically calculated minerals from the early mantle cumulates of the lunar magma ocean [7,8]. However, the olivine has FeO/MnO and Mg# similar to that in Mn-poor matrix olivine from carbonaceous chondrites (CC Trend 1 [9]: Fig. 2a). We, therefore, propose that the UMMF are non-lunar, and possibly originate from a primitive meteoritic source.

*Olivine-sulphide Assemblage*. An unusual ~40×40 µm clast in section 60016,83 consists of disseminated troilite (61-62 wt.% Fe, 36-37 wt.% S), an Si-rich phase, and reverse-zoned olivine ($Fo_{53-64}$: Fig. 2a). The fragment is associated with two types of pyroxene with compositions that are unusual for the Moon (OPX: $En_{33}Fs_{65}Wo_2$: Fig. 2b and CPX $En_{28-29}Fs_{26-27}Wo_{45-46}$: Fig. 2b). FeO/MnO ratios in the olivine phase are non-lunar (45-54: Fig. 1a), are similar to olivine from Martian basalts, and have Mg# variation that is indicative of melt fractionation rather than reduction processes

(Fig. 2a). This suggests the clast either originated in a comparatively more volatile (*e.g.*, lower FeO/MnO ratio) achondritic parent body, or that the clast is of unique lunar origin. The latter interpretation requires the Moon to have much more variable Fe/Mn ratios than has previously been suggested (see also [10]).

*Fe-Oxide Fragment.* A 90×60 µm breccia in section 60016,83 is composed of Fe-oxide found in association with FeS (troilite) and clasts of plagioclase ($An_{95-97}$) and pyroxene ($En_{74-75}$ $Fs_{21-22}$ $Wo_{3-4}$: Fig. 2b) of typical lunar composition. Fourteen analyses of the Fe-oxide phase result in 69.5±0.69 (1 st. dev.) wt. % Fe equivalent to hematite with 99.4±0.98 wt. % $Fe_2O_3$. Hematite has been previously sought before, but not found as large fragments in Apollo samples, and we are in the process of fully characterising the fragment to determine crystal structure. The phase has irregular banding suggesting that it surrounded, and included, the other phases during deposition. Hematite on the Moon could be attributed to interaction with oxidising gases from cometary or carbonaceous chondrite impacts, lunar fumarolic activity, or low temperature gas-solid exchange processes [11].

**Summary.** In ancient regolith breccia 60016 we have located several lithic fragments with mineral chemistries that are not consistent with known types of lunar lithologies. We suggest that the fragments have a meteoritic origin, and our results point to both primitive and differentiated projectiles being delivered to the lunar surface prior to ~3.74 Ga. Other work also suggests that projectiles with both chondritic [12] and non-chondritic (*i.e.*, samples 14321 and 72395 [13]) asteroid affinities were delivered to the Moon between 3.85-3.98 Ga. Locating and classifying additional fragments of meteorites in ancient regolith breccias may, therefore, help to identify these types of ancient basin-forming impactor populations.

**Acknowledgements:** Thanks to A. Pelsier and G. A. Robinson for analytical assistance. C. Meyer's Apollo Sample Compendium has been an invaluable resource.

**References:** [1] McKay D. S. et al. (1985) *JGR, 91,* D277–303 [2] Eugster O. et al. (2001) *Meteoritics & Planet. Sci., 36,* 1097-1115. [3] Joy K. H. et al. *Meteoritics & Planet. Sci., 45, Supp. 1,* A99. [4] Wilshire H. G. et al. (1981) *Geological Soc. Professional Paper 1048,* Part E. [5] Shearer C. K. and Papike J. J. (2005) *Geochim. Cosmochim. Acta, 69,* 3445-3461. [6] Papike et al. (1998) Planetary Materials. *Reviews in Mineralogy, 36.* [7] Elardo S. M. (2010) Master's Thesis, The University of New Mexico. [8] Longhi J. (2010) *Geochim. Cosmochim. Acta, 74,* 784-798. [9] Steele I. M. (1993) *LPS XXIV* Abstr. 1345. [10] Gross J. and Treimen A. H. (2010) *Goldschmidt 2010*, Abstr. 2557. [11] Williams R. J. and Gibson E. K. (1973) *Earth and Planet. Sci. Lett., 17,* 84-88. [12] James O. B. (2002) LPS. XXXIII. Abstr. 1210. [13] Puchtel I. S. et al., (2008) *Geochim. Cosmochim. Acta, 72,* 3022-3042.

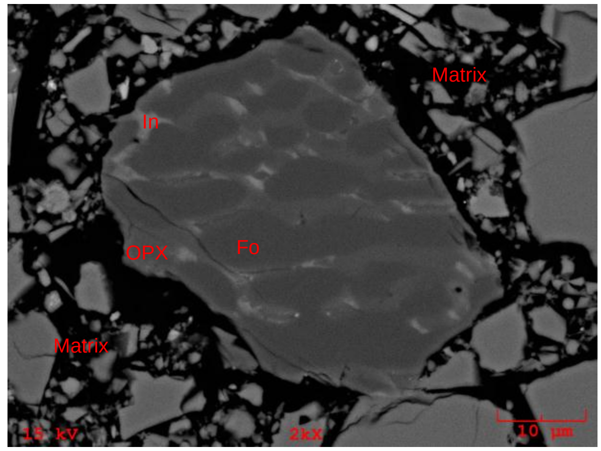


Figure 1. BSE image of 'Mg-Fragment 1' in 60016,93, composed of $Fo_{98}$ olivine (Fig. 2a), enstatitic pyroxene (Fig. 2b) and an interstitial component (In).

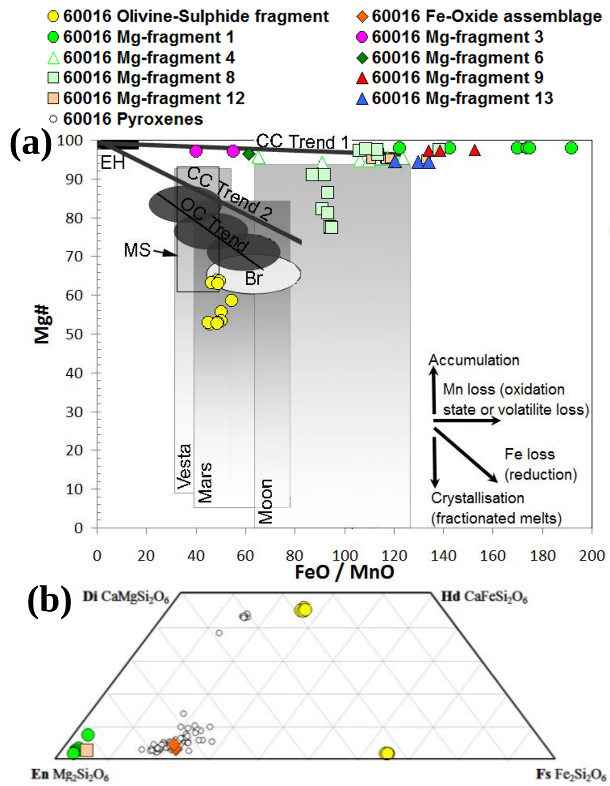


Figure 2. (a) Olivine FeO/MnO vs. Mg# of unusual clasts in 60016 (sections 83, 93 and 95) compared with olivines in Apollo samples and different meteorite groups. OC = ordinary chondrites, CC = carbonaceous chondrites, EH = enstatite chondrite, Br = brachinites, MS = mesosiderites. Meteorite data taken from range of sources including [6]. Mn values in several of the 60016 clasts are very low (<0.03 MnO), but long instrument count times (300 s) and high beam current (20 KeV, 40 nA) were used to analyse these phases to ensure low detection limits. Note that Mg-fragment 8 has a very magnesian core with zoned rim with more typical lunar olivine compositions. (b) Pyroxene compositions in unusual clasts in 60016. Key is the same in both diagrams.