A SUMMARY OF GEOLOGICAL, GEOCHEMICAL, PETROLOGICAL, AND ISOTOPIC EVIDENCE OF IMPACTOR SOURCES.

David A. Kring[1], [1]Center for Lunar Science and Exploration, USRA-Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston, TX 77058, [2]NASA Solar System Exploration Research Virtual Institute (kring@lpi.usra.edu).

Introduction: The cover of a *Science* issue [1] with the initial Apollo 11 results features a picture of meteoritic metal discovered in a lunar regolith sample. From the moment that particle was found, efforts to assess the types of impactors striking the Moon (and, thus, Earth) have been underway. The last decade has blossomed with several new advances in the field, which are summarized here.

Geological Signatures: Measured impact crater size frequency distributions (SFD) have long been an analytical staple of lunar geology, providing the foundation for crater counting chronologies. In parallel, analytical pi-scaling has been used to calculate the sizes of impactors that produced observed impact craters. In a novel approach, Strom et al. [2] integrated those two techniques to determine the SFD of impactors that shaped the ancient lunar highlands. Their results indicated asteroids dominated the impact flux and that they may have been perturbed by resonances sweeping through the asteroid belt as Jupiter's orbit shifted.

Geochemical Signatures: Kring and Cohen [3] used lunar impact melt siderophile abundances to argue that asteroids, not comets, dominated the impactors during the basin-forming interval 4.0–3.9 Ga. New analytical techniques for determining highly siderophile element concentrations, along with $^{187}Os/^{188}Os$ isotopic compositions, have been developed by Walker's group [4-6] and others. Their data are broadly consistent with a diverse set of chondritic impactors and an additional contribution from a fractionated core-composition impactor. Fischer-Gödde and Becker [7] suggest the diversity is, instead, a mixing trend between a carbonaceous chondrite component and a type IVA iron meteorite component.

If the compositions of Liu et al. [6] reflect multiple impactors rather than mixing, then compositions change from carbonaceous chondrite affinities at 4.2 Ga to ordinary and enstatite chondrite affinities at 3.75 Ga (**Fig. 1**), which might be reflecting sweeping of resonances as postulated by [2] from the outer to inner portions of the asteroid belt. In the midst of that sweep, impactors with iron meteorite affinities occur, which could have been scattered from the terrestrial zone and deposited in the midst of the asteroid belt before the resonances moved.

Petrological Signatures: New electron microprobe imaging techniques made it feasible to conduct micron-scale surveys of lunar regolith breccias to locate relict particles of impactors. When combined with regolith closure ages, one can extract how the compositions of impactors changed with time. Joy et al. [8] reported carbonaceous chondrite particles in regolith breccias consolidated during the final phase of the basin-forming epoch (3.8–3.4 Ga) and a more diverse population of impactors over the last 2 billion years. Fagan et al. [9] showed that the younger population still includes carbonaceous chondrite components as late as 1.7 Ga.

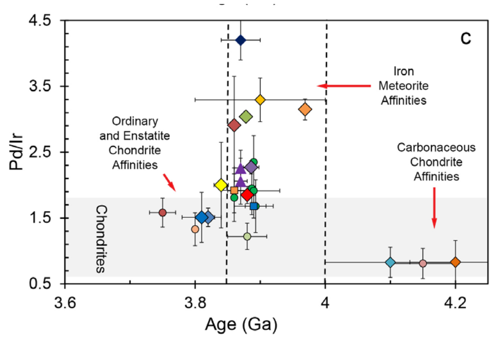

Fig. 1. *Values of Pd/Ir in lunar impact melts as a function of their age. Annotated version of Fig. 9c of [6].*

Isotopic Signatures (and the Future): New techniques are being developed by Bermingham et al. [10] using Mo and Ru isotope signatures that suggest EH chondrites could not have been the dominant component of the final 10% of accretion. Barnes et al. [11] are developing a completely different method using [H_2O] and δD in lunar samples to assess the origin of lunar interior water. Those results indicate that most water was delivered by material with carbonaceous chondrite-like compositions, not comets, during a 200 million year period after the Moon formed.

Conclusions: Asteroids at all stages of lunar accretion appear to dominate. Carbonaceous material may have dominated the earliest phases, to be replaced in part by ordinary and enstatite chondrites towards the end of the basin-forming epoch. Afterwards, asteroids continued to dominate the impactor population, but their compositions became more diverse.

References: [1] *Science*, 30 January 1970. [2] Strom R. G. et al. (2005) *Science*, *309*, 1847–1850. [3] Kring D. A. and Cohen B. A. (2002) *JGR*, *107*, 6p. [4] Puchtel I. S. et al. (2008) *GCA*, *72*, 3022–3042. [5] Sharp M. et al. (2014) *GCA*, *131*, 62–80. [6] Liu J. et al. (2015) *GCA*, *155*, 122–153. [7] Fischer-Gödde M. and Becker H. (2012) *GCA*, *77*, 135–156. [8] Joy K. H. et al. (2012) *Science*, *336*, 1426–1429. [9] Fagan et al. (2016) *LPS XLVII*, Abstract #2789. [10] Bermingham K. R. (2016) *LPS XLVII*, Abstract #1488. [11] Barnes J. J. et al. (2015) *LPS XLVI*, Abstract #2159.