GEOCHEMICAL AND GEOCHRONOLOGICAL CONSTRAINTS ON EARLY LUNAR BOMBARDMENT HISTORY. B. A. Cohen, Hawai'i Institute of Geophysics and Planetology, School of Earth and Ocean Science and Technology, University of Hawai'i, Honolulu HI 96822 (bcohen@higp.hawaii.edu).

Introduction: The aim of this abstract is to acquaint the reader with the major geochemical and geochronological properties of lunar rocks formed or affected by impact events, and thus how these rocks constrain lunar bombardment history, with particular emphasis on constraints upon the proposed Lunar Cataclysm or Late Heavy Bombardment [1]. To this end, the focus is on clast-poor impact melt rocks and crystalline melt breccias as products of large impacts (>1 km craters) and basins (>300 km craters) Though micrometeorite impacts and secondary craters are create agglutinitic glass and impact melt splashes, they are not considered here.

What we might expect the data to look like

Geochemical: Chemically homogeneous, completely crystallized impact melt is one product of large (>10 km) terrestrial craters [2]. Less-equilibrated melt mixes with clasts as it moves along the transient crater and is thrown out around the impact site. Thus, we expect to be able to find clast-free lunar impact melt samples forming geochemical groups based on their crater of origin. Mixing models should be able to show what rocks were the targets. Since impacts are distributed evenly over the entire lunar surface, all types of lunar terranes are expected to be represented.

During the impact process, the impactor is largely vaporized and expelled in a plume [3], but a small amount can be mixed with the target material. Because the lunar crust is heavily depleted in siderophile elements while asteroidal or cometary impactors retain their siderophile abundances, the mixing of only a small amount of impactor should create a trace siderophile signature in impact melts. If comets or other volatile-rich impactors were important in bombardment history, as has been proposed for the Earth, then water vapor from the impactor might also be a trace constituent of the impact melt.

Geochronological: The spectrum of impact-created or –reset ages in the lunar regolith should be proportional to the time, frequency, and size of impacts, modified by the destruction (by comminution or remelting) of older rocks as the lunar surface is saturated by craters. The volume of impact melt scales logarithmically with crater diameter [4]. Using the observed crater size-frequency distribution from 1-300 km, scaling it back to 4.0 Ga (i.e. increasing the flux by a factor of 500) [5] and comparing with the melt volume created in the ~40 mapped lunar basins >300 km [6], it is calculated that basin-formed impact melt is volumetrically dominant. Thus, given statistically significant sampling of the regolith, the impact melt age distribution should mirror the basin-forming impact rate prior to 3.85 Ga.

What the data are

Geochemical: Large lunar melt sheets appear to be chemically homogeneous. Some Apollo 15 and 17 impact melt samples are identical in composition and age [7], implying that they were derived from a single, homogeneous melt sheet. Impact melts can be grouped based on trace elements, particularly siderophiles [8]. Remote sensing of the Orientale melt sheet shows no radial variation in major-element chemistry [9].

Lunar impact melts are often a mixture of well-known lunar rock types. The nearside KREEP-rich terrane [10] is easily recognized as a contributor to impact melt samples. Impact melts in highland lunar meteorites, on the other hand, are KREEP-poor and plagioclase-rich. Statistically, impact melts from Apollo, Luna, and meteorite samples represent both lunar hemispheres [11]. Impact melts from mare basalt surfaces have not been positively identified [12, 13].

Siderophile element signatures of impact melts at the Apollo landing sites (Fig. 1) suggest that some had compositions similar to ordinary chondrites and others are similar to iron meteorites and enstatite chondrites [14-17]. None of them resemble CI and CM chondrites, which are good proxies for comets [18].

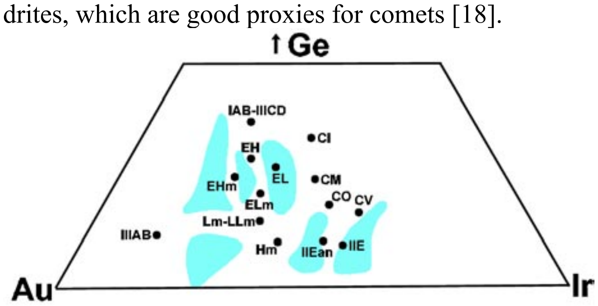

Fig. 1: Apollo site siderophile signatures, from [19]

There is no evidence for lunar in-situ water vapor interaction with impact melts or any other lunar rock. The only evidence for water in the Apollo samples is FeOOH, a product of rapid oxyhydration of lunar $FeCl_2$ in the terrestrial atmosphere [20]. Weathering products in lunar meteorites, usually Ca- and Sr- carbonates, are confined to veins and bubbles originating at the surface of the meteorite.

Geochronological: Crystalline impact melt samples, found as fragments or breccia matrix, are the most reliable indicators of impact age, yielding concordant ages with multiple chronometers. The ^{40}Ar-^{39}Ar method is most sensitive to thermal events such as melting and metamorphism but resistant to shock [21]. Only material which is completely melted and cooled relatively slowly has time to fully degas Ar. Glassy fragments, veins, coatings, and spherules are quenched melt, which may not have time to fully degas. Impact melt breccias contain clasts which may or may not have time to degas, and thus often show a range of ages [22]. Essentially no cold ejecta or basement involved in an impact records the impact age.

Representative Apollo and Luna sample impact melt ages [23] are shown in Figure 2a. Based on the physical characteristics of the Apollo samples, impact melts in lunar meteorites (Fig. 2b) could be identified and dated [24-26], though with much lower precision. Because of their small size, glass spherules (Fig. 2c) may have completely degassed and now record their creation age in an impact [27]. Fig. 2a is not comprehensive, and differs from similar histograms [28] in that it shows only impact melts, not inferred impact-reset or degassed lithic clasts or breccias.

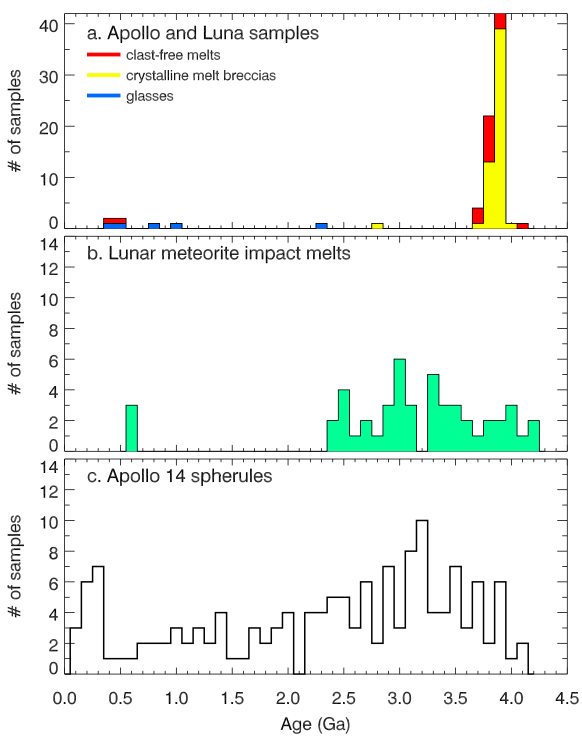

Fig. 2: Impact-reset lunar rock histograms.

Implications and outstanding issues

Geochemical: The physics of the impact process as they relate to the chemistry of the impact melt are poorly understood. Exogeneous siderophile abundances in impact melts imply that CI/CM asteroids or comets did not produce the major nearside basins. However, large amounts of volatiles may help projectile material to escape and high impact velocities for comets may impart even more energy to the plume. Thus, siderophile evidence for cometary impacts may not be retained. The possible detection of ice at the lunar poles [29] implies that not all water is lost from volatile-rich impacts, yet no evidence of water has been seen in hand sample.

Geochronological: The most striking feature of the Apollo and Luna sample age histogram is its sharp peak at 3.9 Ga rather than an increase of melt samples with age. This is the most compelling fact supporting a cataclysmic scenario in which all the sampled lunar basins, and by inference, many other basins, were formed within the ≤200 Myr period defined by the histogram. Lunar meteorite impact melts and spherules do not have the same pronounced peak, but none is older than ~4.0 Ga. The persistent lack of pre-3.9 Ga impact melt has been used by [30] to argue for a low bombardment rate prior to 3.9 Ga, such that no impact melt was created, and by [31] to argue for a flux so high that evidence of older impact events has been obliterated.

The younger ages in the meteorites and spherules must represent small, local impact events. Given the inferred volumetric paucity of young impact melt, there may be a bias favoring the sampling of recent impact melts. Impact melt volume and vertical distribution in the regolith is poorly understood and yet to be fully modeled.

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