LUNAR METEORITE IMPACT MELT CLASTS AND LESSONS LEARNED FOR LUNAR SURFACE SAMPLING.

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Introduction: One of the important outstanding goals of lunar science is understanding the bombardment history of the Moon and calibrating the impact flux curve for extrapolation to the Earth and other terrestrial planets. Obtaining a sample from a carefully-characterized interior melt sheet or a ring massif is a surefire way to tell a single crater's age. A different but complementary approach is to use extensive laboratory characterization (microscopic, geochemical, isotopic, geochronological) of float samples to understand the integrated impact history of a region. Both approaches have their merits and limitations. In essence, the latter is the approach we have used to understand the impact history of the Feldspathic Highland Terrain (FHT) as told by lunar feldspathic meteorites [1]. Here, I report on impact-melt clast composition and ages in five new lunar meteorites, and then draw on our experience with this work as an example of how this approach is valid for understanding regional lunar bombardment history of areas such as the South Pole-Aitken Basin (SPA).

New lunar meteorite impact-melt clasts: Yamato 86032, Dhofar 910, Dhofar 911, and Kalahari 008 are feldspathic breccias with varying amounts of regolith and impact-melt components [2]; both Dhofar meteorites may be paired with other Dhofar meteorites. Impact-melt clasts in these meteorites are high in Al_2O_3 and have compositions within the range of Apollo 16 feldspathic breccias, consistent with an origin in the feldspathic lunar highlands either prior to, or far away from, the nearside KREEP-rich terrane that produced mafic impact-melt rocks. Sayh al Uhaymir (SaU) 169 [3] is mostly a KREEP-rich mafic impact melt breccia, probably originating from the near-side KREEP terrane. The SAU 169 rock also contains adhering regolith breccia, a sample of which was used for this study. Impact-melt clasts within SAU 169 include both feldspathic and KREEPy clasts, likely derived from the lunar nearside. Impact-melt clasts these meteorites were identified using the petrographic microscope and backscattered-electron imaging and their major-element compositions were obtained on the electron microprobe [4]. Clasts were extracted from the meteorites using a Medenbach microcorer for ^{40}Ar-^{39}Ar analysis using laser step-heating at the New Mexico Geochronology Research Laboratory in Socorro.

Characteristics of the microcores are shown in Table 1. The sample ages were derived by isochron analysis; most samples had well-defined isochrons with multiple heating steps and small uncertainties. In two cases (Dho 911 and Y86032), samples had two well-defined isochrons; both are reported but further interpretation is required to understand their meaning. The feldspathic meteorite impact-melt ages range from 3.7 Ga to younger ages. This distribution is consistent with previous results for feldspathic lunar meteorites, showing the clasts' origin in multiple impact craters into compositionally similar bedrock or megaregolith. The impact-melt clast ages in the regolith component of SaU 169, on the other hand, cluster around 1.4 Ga. There appear to be resolvable differences in age and composition among these clasts, but further work is needed to evaluate the possibility that a single event (possibly the breccia formation event) is responsible for resetting the clasts.

Sampling strategies for dating lunar craters: The age recorded by the slowly-cooled impact-melt sheet that lines the floors of large craters gives the most reliable date for the formation of the crater (e.g., Sudbury, Manicouagan). Extensive geologic fieldwork is usually employed to positively link the impact-melt formations to the crater of origin. Many other craters have reliable ages found by dating impact melt blebs that are ejected from the crater and mixed into breccias in the ejecta (e.g., Ries). In the lunar case, many, if not most, random breccia melt clasts may never be positively linked with their source crater. Nevertheless, this does not preclude their use in understanding the impact history of the area in which they are found. In the case of the lunar feldspathic meteorites, the compositional signature of the impact-melt clasts in the meteorites links them to the FHT and precludes their origin in other geochemical terrains. Therefore, these products reflect the composition and age of craters in the this particular region (Fig. 1). In this approach, a large number of samples must be studied with terrestrial laboratory techniques to build meaningful statistics and correlations.

Several important lunar craters such as Tycho are young, not filled with lava flows, and probably preserve impact melt, if not as lining sheets, at least as extensive melt pools in the bottom of the crater. These craters have well-constrained stratigraphic ages and therefore serve as key benchmarks in defining the lunar flux curve. Such sites are probably less geologically complex than a large old basin such as SPA and it has been suggested that they would need less intensive fieldwork to either retrieve, or possibly date in situ. The young end of the lunar flux curve is more tightly constrained than the old end, but still, in situ dating may be achievable with extensive ongoing instrument development and would be sufficient to constrain the young lunar flux curve better than at present. However, the impact-melt rocks even at a geologically simple location are not likely to be simple themselves. A smaller crater means that the impact-melt rocks have the same composition as the bulk crust at that location and it may be difficult to distinguish the impact melt of interest from locally-contributed ejected melt from nearby craters. Smaller craters also may cool more quickly than is needed to totally reset radiometric systems in the melt rocks themselves.

At the other end of the lunar flux curve, the South Pole–Aitken Basin is the stratigraphically oldest identifiable lunar basin and is therefore the most important target in understanding whether ancient lunar bombardment history smoothly declined or was punctuated by a cataclysm. The interior of SPA retains an anomalously mafic compositional signature relative to the surrounding feldspathic terrain, despite billions of years of vertical and lateral mixing from smaller and younger impact basins both internal and external to SPA. SPA near-surface materials are almost certainly a broken-up mixture of original SPA rocks, reworked material from interior basins, and exogeneous material. On the lunar near side, mixing of ejecta and local bedrock has led to some ambiguity in the origin of specific impact-melt rock groups, because we do not have definitive information on the composition of the basin floors. In contrast, the unique geochemical signature of SPA materials serves as a proxy to link impact melt rocks found in the region to the SPA basin and subsequent interior basins and craters, giving context to the rocks even without extensive human field activity.

Conclusions: Our collection of impact-melt rocks from the extensive FHT has been limited to the lunar meteorites so far. The impact-melt clasts in the meteorites have not yet been linked with specific source craters, but their petrologic identification as impact-created, geochemical affinity to remotely-sensed lunar regions, and age by radiometric techniques provides a statistical knowledge of the impact history of these areas. This experience can be translated to other areas where combinations of techniques such as orbital and regional remote sensing and extensive laboratory analysis of a large number of samples can link samples to specific goals, such as understanding the age distribution of impact craters. This approach is not useful everywhere but is a completely valid approach to one of the most important science goals – understanding the impact history of the SPA basin.

Table 1. Characteristics of impact-melt clasts.

Clast	Texture	Feldspar (%)	Mg#	Weight (μg)	Age ± 1σ (Ma)
Dhofar 910					
F1	poikilitic	67	68	210	3219 ± 100
F2	lathy	89	62	140	2650 ± 130
F3	microporphyriric	93	59	80	3670 ± 150
F4	lathy to microporphyriric	91	59	20	1770 ± 110
Dhofar 911					
I1	feldspathic clast			350	3500 ± 400
I2	groundmass	89	76	200	2700 ± 200
I2[1]	groundmass	89	76	200	3720 ± 110
Kalahari 008					
G2	microporphyritic	78	71	110	2050 ± 40
G5	basaltic(?)			220	2080 ± 50
SAU 169					
H3	fine quench	67	70	40	1380 ± 20
H9	poikilitic			100	1547 ± 8
H12	microporphyritic			90	1300 ± 20
H13	microporphyritic			<10	1658 ± 5
H14	microporphyritic/breccia			20	1290 ± 40
H15	microporphyritic				1423 ± 18
Yamato 86032					
J1[1,2]	glass vein	85	68	90	4340 ± 1302
J2	glass vein	85	68	220	500 ± 250
J3	glass vein	85	68	420	
J4	glass vein	85	68	330	

[1] Two ages were resolved in these samples; both are reported.

[2] All subsamples of Y86032 were added to create a single isochron

References: [1] Cohen, B.A., *et al.* (2005) *MAPS* 40, 755. [2] Korotev, R.L., *http://meteorites.wustl.edu/lunar/moon_meteorites.htm* [3] Gnos, E., *et al.* (2004) *Science* 305, 657–659. [4] Cohen, B.A. (2005) *MAPS* 40, 42. [5] Daubar, I.J., *et al.* (2002) *MAPS* 37, 1797. [6] Fernandes, V.A., *et al.* (2000) *MAPS* 35, 1355. [7] Fernandes, V.A., *et al.* (2004) *LPSC* 35, abstract #1514. [8] Cohen, B.A., *et al.* (2002) *LPSC* 33, abstract #1252. [9] Cohen, B.A., *et al.* (2005) *LPSC* 36, abstract #1481.

Fig. 1: Impact-melt clast ages in lunar meteorites [1, 4-9].