IMPACT MELT PRODUCTION DURING THE BASIN-FORMING EPOCH.

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Introduction: The top three lunar science priorities are to (i) test the lunar cataclysm hypothesis, (ii) anchor the early Earth-Moon impact flux curve by determining the age of the oldest lunar basin, and (iii) establish a precise absolute chronology for the remainder of lunar history. All three tasks involve measurements of impact melt ages.

We have, thus, developed an integrated program that is grounded in (a) analyses of the ages of existing impact melt samples with advanced techniques [e.g., 1]. Because interpretations of those ages and plans for collecting future samples depends on impact melt volumes, we have been (b) developing new analytical expressions for calculating those volumes as a function of several impact parameters [2] and (c) evaluating the size distribution of craters and the impactors that produced them [3,4]. To further prepare for future sampling, we have been (d) mapping specific sites on the lunar surface where new impact melt samples can be collected [e.g., 5] and (e) developing the means to collect them [e.g., 6,7]. In this paper, we calculate the melt volumes produced during the basin-forming epoch and discuss how they may influence interpretations of existing impact melt age distributions and prospects for making further progress with future sample return missions.

Methods: Impact melt volumes were calculated (equation 12 of [2]) for the population of craters identified by [3] for the ancient lunar highland terrain. That population corresponds to a global inventory of 45 to 50 basins with diameters in excess of 300 km. We assumed the target had average highland properties (i.e., specific internal energy of melting, E_m=3.42 MJ/kg, and ρ_t=2940 kg/m^3) and that the projectile was chondritic (i.e., ρ_p=3320 kg/m^3). We used the scaling relationship of [8] to estimate transient crater diameters from observed crater dimensions. We also used 45° as the impact trajectory, because it is the average for the large number of impact craters in size bins from 8 to 300 km diameter and the most probable impact trajectory for the small numbers of craters in larger crater diameter size bins. In this initial study, craters smaller than 8 km were ignored, because that population is overprinted by a significant number of secondary craters and the melt volume produced by them is relatively small. The largest size bin captures the largest resolvable impact crater on the Moon, the ~2500 km diameter South Pole-Aitken (SPA) Basin.

Results: The melt volume produced by populations of craters of different sizes is shown with dark blue symbols in Fig. 1. The cumulative melt volume is shown in bright pink symbols, both in terms of km^3 (left axis) and percent of total melt volume (right axis).

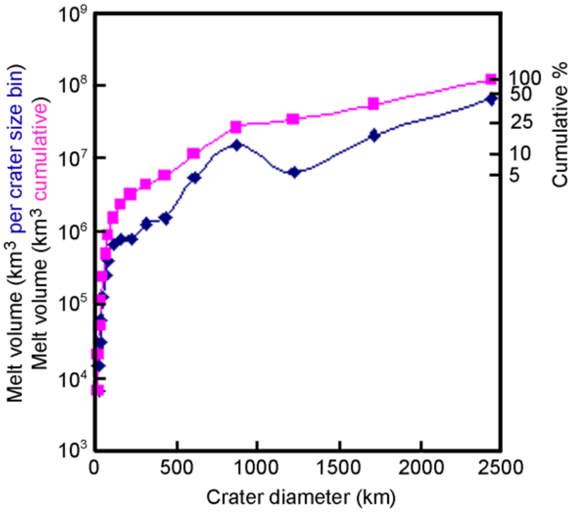

Fig. 1. Melt volumes for ancient lunar highland crater populations in crater size bins ranging from 8 to 2500 km.

Melt volumes for the smaller crater size bins are robust, because the average impact properties assumed in the calculations are assured by the thousands of cratering events reflected in each of those crater size bins. The largest three crater size bins only contain single craters, however, so actual melt volumes may be sensitive to the details of those impact events (e.g., the precise density of the projectile and its trajectory). The melt volumes for the basin-size events also are minimum values, because they do not include the effects of a geothermal gradient in the lunar target. Both analytical [2] and hydrocode [e.g., 9] modeling indicate melt volumes are enhanced by increased pre-impact temperatures at depth.

With those caveats in mind, the melt volumes in Fig. 1 indicate that craters smaller than basins produce substantial volumes of melt, but their melt volume is less than 5% of the total. This disparity is slightly larger than that previously inferred [10]. The melt volume produced by simple and complex craters is comparable to that produced by a single, Nectaris-size basin-forming impact event. Melts produced by these smaller craters (of both simple and complex morphologies) will be widely distributed over the surface of the Moon and near the surface.

Among the intermediate-size basins, the three that dominated the Apollo missions (Nectaris, Serenitatis, and Imbrium) are responsible for ~8% of the total impact melt volume produced during the basin-forming epoch. The melt volume in the youngest basin, Orientale, is about 60 times greater than that in the subsequent mare.

Approximately half (if not more) of the impact melt volume was produced by the largest basin-forming event (that of the South Pole-Aitken Basin). The largest fraction of the melt stayed within the central melt pool. If we cautiously extrapolate from studies of smaller complex craters [11], then 25 to 45% of that melt may have been ejected. Most of that ejected material was distributed over the lunar surface, although the results of [12], assuming a chondritic projectile of diameter 150 to 220 km hitting at 18 km/s, imply that 3 to 12% of the melt was ejected with escape velocities.

Discussion: The equation for calculating melt volumes is not affected by changes in impact velocity, as it is scaled entirely to the size of the observed craters. This is important, because recent work [4] suggests the impact velocity may have doubled during the basin-forming epoch. The time of that transition is still uncertain, but appears to have preceded the formation of Nectaris. Thus, it is plausible that the youngest 1/3 to 1/2 of the basins were produced at higher velocities (~20 vs. 10 km/s). However, any increase in impact velocity and its effects on melt volume is already incorporated into our equations. Thus, the results in Fig. 1 should be robust regardless of changes in the impact velocity, because they are based on observed crater diameters throughout the basin-forming epoch, at least from the time of SPA to that of Orientale. This conclusion can only be undermined if the scaling relationship between final and transient craters is sensitive to impact velocity. The results of [8] and [13] suggest the velocity dependence is weak to non-existent.

If that is errant, however, then we can calculate the maximum consequence by examining the projectiles rather than the resultant craters. A doubling of impact velocity produces 3.25 times more melt for the same size impactor. If we assume the size distribution of projectiles remained the same throughout the basin-forming epoch, then ~60 to ~75% more impact melt was produced by the faster (younger) impactors in the latter 1/3 to 1/2 of the basing-forming epoch. While ages of the oldest crating events should still be accessible, there will be a strong prevalence of younger impact melts. This emphasizes the need for a future strategy that targets samples linked to specific impact events that are distributed geographically and temporally and, ideally, are large enough events to have significantly large surfaces that can be used to calibrate crater-counting chronologies [14].

Implications: Impact melt volumes for both small (i.e., simple and complex) craters and large basins are substantial and widespread. Thus, the foundation for previous tests of the lunar cataclysm [e.g., 1,10] is substantiated by the calculations here.

The work of [3] suggests the asteroid belt was sampled in a size-independent manner. Observations of the ancient lunar highlands also indicate large basin-forming events were distributed in time and were occurring simultaneously with smaller impact events. Thus, ages from populations of either small-crater or large-basin melts should reflect the duration of the basin-forming epoch. The latter, however, produce broad surfaces suitable for relative chronologies and, thus, will provide better benchmarks for the cadence of impacts during the basin-forming epoch.

In a regolith setting, where the production, excavation, and transport of impact melts produces mixtures of melts from many events, impact melt clasts that are coarse-grained and, thus, cooled slower and represent large melt volumes, are more likely to be derived from larger craters. Impact melts with lithologic and mineralogical remnants (clasts) or chemical signatures of a complex mixture of target lithologies, including deep-seated target lithologies, are also better targets for defining the ages of large impact events.

It will be best, however, if landing and sampling sites are selected because the melts at those locations can be linked to specific craters. To fully address the two highest lunar science priorities, those target sites should be geographically and temporally representative of the entire basin-forming epoch [14]. To address the third highest lunar science priority, the same site selection rationale applies to younger craters.

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