IMPACT MODIFICATION OF THE LUNAR HIGHLANDS CRUST DURING THE BASIN-FORMING EPOCH.

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Introduction: The lunar crust was heavily modified by impact events during the basin-forming epoch. Here I examine the chronology of those events, discuss how they modified the crust (e.g., by wholesale remelting), and how those same events can be used to probe relatively unaltered portions of the lower crust.

Chronology of Basin-Forming Modification: Ages of thermally altered Apollo samples indicate impact cratering was particularly severe in the Earth-Moon system during the first billion years of its evolution. A concentration of ages circa 3.9-4.0 Ga suggests there may have been a spike in the impact flux in an event called the lunar cataclysm [1,2], but the total duration of the basin-forming epoch is still uncertain. Thus far, we only have one solid age and five tentative ages for the 15 basins produced during the Nectarian and Early Imbrian periods of time. The ages of the final two basin-size events (Schrödinger and Orientale) are among those still uncertain. Based on the available data, estimates for the duration of the lunar cataclysm range from a few tens to a few hundred Ma. We have no ages for ≥29 older, pre-Nectarian basins and, thus, little idea if they are part of a lunar cataclysm or are instead part of an extended period of bombardment that may have lasted as long as 700 million years.

This period of bombardment is also seen among impact-modified samples from planetesimals that existed between the orbits of Mars and Jupiter (now the main asteroid belt). Thus, the lunar cataclysm is sometimes called the inner solar system cataclysm [3]. Based on age spectra among meteorites (e.g., [4-6]), we have detected collisions (e.g., [7]) during the epoch of planetary accretion between ~4.4 and 4.5 Ga. After many of those small planetary relicts were consumed by large collisions or ejected from the solar system, there was a significant decline or absence of impact degassed samples produced between ~4.4 and 4.1 Ga. At ~4.1 Ga, however, the orbits of asteroids were pumped up by resonances sweeping through the belt (e.g., [8,9]), causing a large number of impact-reset ages ~4.1 to 3.5 Ga. The bulk of the excited population was eventually consumed, leaving relatively quiet conditions that produced very few impact ages between ~3.5 and 1 Ga.

Collectively, the existing lunar and meteoritical data reveal a dramatic series of events in the collisional evolution of the early solar system. Yet, the precise chronology of the events that shaped the Moon is still vague. We do not know the duration or magnitude of the terminal cataclysm. Nor can we confidently define the pace of basin-forming events at the tail end of the accretional epoch and during the interval between accretion and the terminal cataclysm.

To determine the tempo of impacts during the basin forming epoch, we need to recover impact melt samples from basins that are representative of the flux in both space and time [10]. As discussed elsewhere [11,12], the highest priority target is unaltered impact melt from the South Pole-Aitken (SPA) basin. Because SPA is the oldest and largest basin, it will define the beginning of the basin-forming epoch. If this basin is part of the cataclysm, then the magnitude of the lunar cataclysm event is far greater than previously proposed, involving ~3 times the number of basin-forming impact events. If SPA has instead a much older age (say 4.4 Ga), then pre-Nectarian basins with successively younger relative ages need to be sampled to determine if a cataclysm began in the pre-Nectarian and, if so, when it began in that basin-forming sequence. The best location for an SPA sample may be within the Schrödinger basin [13], because we could obtain samples of both the oldest and the second youngest basins at that locality, effectively bracketing the entire basin-forming epoch.

Those same impact melt samples can be used to determine the source of projectiles and their chemical compositions. This will, in turn, test proposed mechanisms for the impact flux. These data can also be used to calculate the delivery of biogenic elements during the bombardment and the environmental consequences of the impact events, particularly on neighboring Earth.

Resurfacing the Moon: Geologic mapping [14] indicates that the basin-forming epoch resurfaced most of the Moon. Those processes also dramatically altered topography. The collisional processes excavated large topographic lows (e.g., the floor of South Pole-Aitken basin is ~13 km deep), while producing stacked layers of ejecta kilometers thick that partially buried the original igneous crust of the Moon.

Modifying the Composition of the Crust: The basin-forming processes excavated material from all depths within the crust and created a megaregolith that apparently has a noritic composition created by mixing lower and upper crustal components [15].

Those same events melted immense volumes of the Moon's crust and, in some cases, the underlying mantle. A recent calculation [16] indicates that ~10^8 km^3 of impact melt was produced (Fig. 1). Approximately half (if not more) of the impact melt volume was produced by the largest basin-forming event (that of the SPA basin). The largest fraction of the melt stayed within the central melt pool. If we cautiously extrapolate from studies of smaller complex craters [17], then 25 to 45% of that melt may have been ejected.

Differentiating Impact Melt Pools: Melt remaining in the largest basins may have differentiated, producing a new series of layered lithologies. To illustrate the processes involved, let's continue to examine SPA. In this case, impact melting may have been dominated by mantle lithologies [18]. If the surface of the central melt pool cooled to form a "lid" like the surfaces of the central melts sheets at the Chicxulub and Sudbury basins on Earth, it would have a composition similar to that of the bulk melt; i.e., it would have crystallized to form an olivine- and pyroxene-rich rock. As the underlying melt pool cooled, olivine may have crystallized and settled downward (see the illuminating work of [19]). Progressive crystal fractionation would drive the remaining liquid towards noritic compositions. Those magmas may have occasionally pierced the solidified top of the melt pool, erupting to form noritic lava flows. Potentially, rafts of the olivine- and pyroxene-rich roof of the melt pool may have been mobilized and re-exposed on the surface (e.g., potentially like mafic mound). Plagioclase may have eventually crystallized and floated to the top of the melt pool, where it may have been largely trapped as an anorthositic horizon beneath the solidified roof of the melt pool. These differentiation processes may have mimicked those associated with the older, lunar magma ocean (LMO), and partially erased the signatures of the LMO in places like the center of SPA.

Probing the Deep Crust: As outlined above, basins will be the target of future sample return missions, because they provide a means of testing the lunar cataclysm hypothesis and determining the age of the oldest basin on the Moon [e.g., 6].

Impact basins are also excellent probes of the entire lunar crust. Normal faults in the modification zones and along the walls of the basins expose subsurface lithologies and their stratigraphic relationships. Uplifted peak rings in the centers of the basins expose even deeper levels in the Moon's crust. Furthermore, clasts of subsurface lithologies are entrained in impact melt breccias deposited within the basins and beyond the basin rims. Thus, by combining observations of modification zones, central uplifts, and impact breccias, one can generate a cross-section of the lunar crust that may be kilometers to 10's of kilometers deep. The volume of material beneath an impact site that is melted extends to an even deeper level than the material that is excavated. Because that melt is mixed, samples of it will provide an average chemical composition of the crustal (and potentially upper mantle) volume affected by an impact event. Consequently, while collecting samples to determine the impact flux to the lunar surface, one is also collecting samples of the deep lunar crust and potentially the underlying mantle.

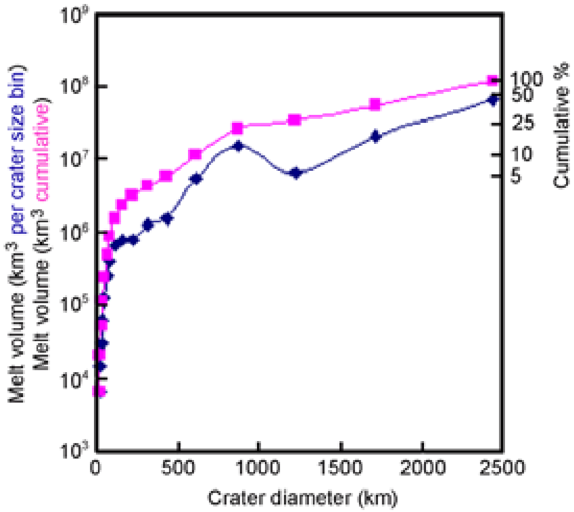

Fig. 1. Melt volumes for ancient lunar highland crater populations in crater size bins ranging from 8 to 2500 km. From [15].

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