WHICH SAMPLES ARE NEEDED FOR IMPROVED CALIBRATION OF THE LUNAR CRATERING CHRONOLOGY?

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Introduction: Recent lunar sample-return mission concepts and proposals focus on the goal of returning samples that represent either the oldest of the lunar basins (South Pole-Aitken basin, [e.g., 1,2]) or some of the youngest lunar mare basalts (P60 basalt [e.g., 3-7]; Mons Rümker [8]). Indeed, studies of in situ dating mission payloads also propose locations that would provide access to materials from ancient basins and young basalts [e.g., 9,10]. Here, we examine how each type of sample would help improve the calibration of the lunar cratering chronology.

Background: The lunar cratering chronology is based on (1) empirical measurement of the size-frequency distribution of craters produced on the Moon – termed the "production function" [11-13], and (2) construction of a chronology curve that relates Apollo and Luna sample ages to crater spatial densities, here N_{cum} (D≥1 km), measured at the sample sites (***Fig. 1***, [11,13-16]). The curve allows the assignment of absolute model ages (AMAs) to unsampled geological units across the Moon via crater size-frequency distribution (CSFD) measurements.

As there are no samples from other planetary bodies which have known provenance, and therefor measureable crater spatial densities for a body-specific calibration, the lunar crater chronology is modified and used for many terrestrial bodies throughout the Solar System. Consequently, the accuracy of the AMA determinations for the Moon and other planetary bodies depends on the quality of the lunar calibration, in addition to the assumptions made in translating the chronology to the other bodies.

One approach for improving the lunar cratering chronology and its wider application is to test and improve the existing calibration points [e.g., 15-17], as well as to examine which samples could be collected from the Moon that would improve our understanding of the distribution of sample ages versus $N(1)$ (***Fig. 1***).

Current Status: The chronology currently depends on samples of Imbrium basin ejecta (Descartes and Fra Mauro Formations, radioisotopic ages of ~3.9 Ga), mare basalts (radioisotopic ages of ~3.2-3.7 Ga), ropey glasses from the Apollo 12 landing site that have been interpreted as Copernicus ejecta (radioisotopic age of

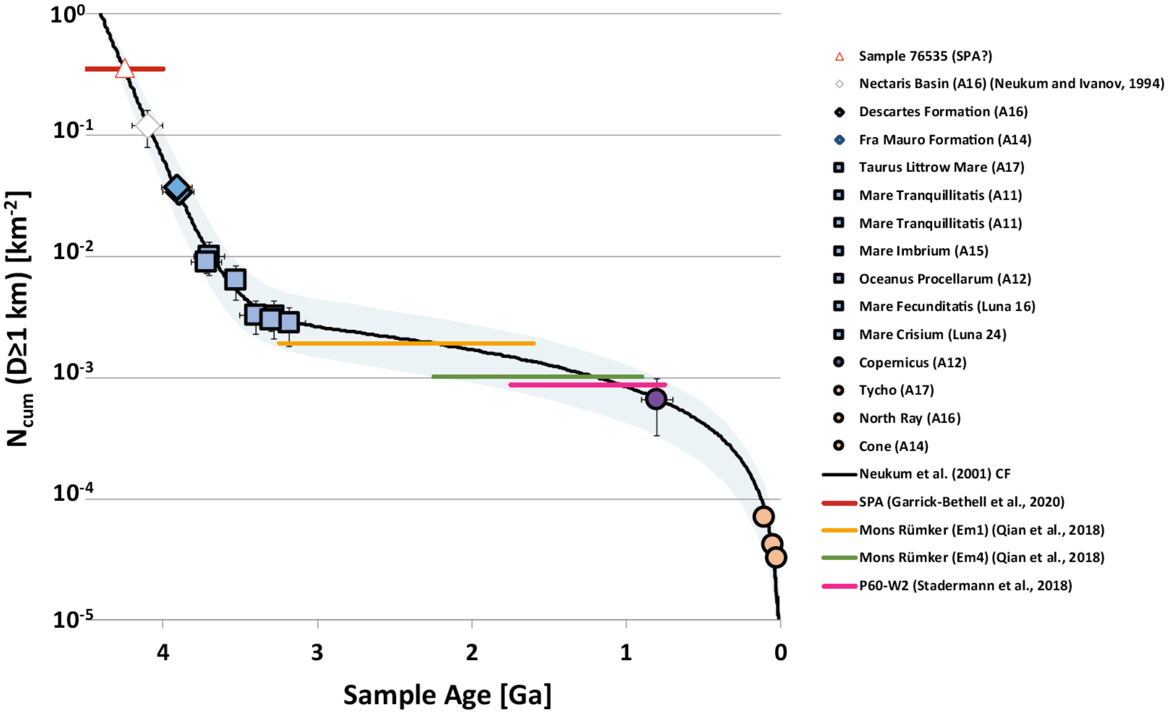

Figure 1. *The lunar cratering chronology curve (black) of Neukum et al. (2001)[14], where the shaded blue region shows the range of proposed chronology functions to illustrate the absence of a precise fit for the 1-3 Ga time frame. There are no calibration points for ages >3.9 Ga. The colored lines mark N(1) values determined via crater size-frequency distribution measurements for proposed sample regions. Sample 76535 is proposed to originate from the South Pole-Aitken basin [18]. The age of Nectaris basin is not well-constrained – we use [13] as a reference.*

~850 Ma), and cosmic-ray exposure ages of ejecta and secondary crater materials of the Tycho, North Ray, and Cone craters [e.g., 19].

Mind the Gap: The current sample set does not contain materials of indisputable provenance with ages between 3.2 Ga and the age of Copernicus crater. This means that various workers have estimated the vertical position of the chronology curve differently (blue shaded region, ***Fig. 1***)(See also [17]). Because the curve is flat across this time frame, small differences in measured crater spatial densities result in large differences in resultant AMAs (***Fig. 1***). For example, the most recently measured $N(1)$ values for the P60 site [20] could give AMAs that could range from ~0.75 to ~1.75 Ga (pink line, ***Fig. 1***). $N(1)$ values for two basalt units in the Mons Rümker region [8] also could give largely different AMAs depending on which chronology function is used (green and orange lines, ***Fig. 1***). Thus, a sample from any of these or other young basalts are critical for pinning the position of the chronology function in this age range more accurately. This exercise is necessary for more clearly understanding the duration/extent of lunar volcanism since 3.2 Ga.

Catastrophism or Uniformitarianism: The chronology function has been extrapolated beyond ~3.9 Ga, because there are no older samples of known provenance. Here, further calibration of the chronology is necessary to make progress on questions about the possibility and nature of a lunar cataclysm or late heavy bombardment.

A sample unambiguously originating from the South Pole-Aitken basin would fix the age of the oldest known basin on the Moon. If Apollo 17 sample 76535 represents a piece of the SPA basin, its age of 4.25 Ga would support the absence of a spike in the early bombardment of the Moon, and support the accretion tail model proposed by Morbidelli et al. (2018)[18,21]. However, the geophysical arguments required to show this sample's provenance in SPA could be put aside if a sample was collected directly from SPA.

Additional samples from basins that formed between the Imbrium and SPA basins are also needed to fully investigate the stability of the impact rate change over time. Nectaris basin is proposed to have an age of ~4.1 Ga [13, 22] or to have a younger age of ~3.9 Ga [18], but it has a CSFD that places it in between Imbrium and SPA [e.g., 23]. Thus, samples of the Nectaris basin, or other basins with ages of 4.1-4.2 Ga would add granularity to the calibration of the oldest lunar regions. The Crisium basin has also been examined as a potential sample site due to the presence of potential impact melt deposits [24-26], with CSFD measurements suggesting an age >3.9 and <4.1 Ga [25,23].

The current calibration cannot exclude periodic excursions in recent times from the modeled impact flux [e.g., 27] due to an absence of granularity. This is because the lunar cratering chronology from ~1 Ga to present is calibrated with only one radiometric age (Copernicus crater) and three exposure ages (Tycho, North Ray, and Cone craters). Additional sample ages in this time frame would allow assessment of the recent stability of the impact rate.

Lunar Chronology Site Requirements: To improve the lunar chronology, it is not enough to collect samples of well-established provenance. Indeed, it is also critical that the sample sites exhibit a surrounding region where robust CSFD measurements can be conducted. This requires a geologically homogeneous unit with little topography, minimal secondary crater contamination, and few to no other secondary features (e.g., wrinkle ridges). These requirements mean that it will be more straightforward to select appropriate calibration sites for young basalts than for ancient, heavily cratered basins. Unfortunately, the extremely young irregular mare patches [28] generally do not cover enough area to provide good counting areas, and the ejecta and impact melt deposits of young craters tend to be rugged – causing challenges in measuring their CSFDs [e.g., 29]. Nevertheless, a sample return or in situ age measurement could resolve questions about the self-secondary craters and strength-scaling effects on CSFDs [30-32].

Facet: An improved calibration of the lunar chronology will allow a clearer and more granular interpretation of the geological history of the Moon and other bodies where the lunar chronology is applied. New returned samples or in situ age determinations are thus required.

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