

DETERMINING THE IMPACT HISTORY OF THE EARTH-MOON SYSTEM AS A PART OF LUNAR EXPLORATION. T. D. Swindle, Lunar and Planetary Laboratory, University of Arizona, 1629 E. University Blvd., Tucson AZ 85721-0092, USA, tswindle@u.arizona.edu.

Introduction: The impact history of the Earth-Moon system is of interest from the points of view of geology, planetary science, and evolutionary biology. The Moon preserves a far better record of that history than does the Earth. Our understanding has increased dramatically as a result of our access to the well-documented Apollo and Luna samples, followed by the lunar meteorites from largely unknown lunar locations. However, we have now reached a stage where we have questions that can not be answered without more lunar samples collected in geologic context from non-Apollo locations. From single locations to large suites of locations, sample return as a part of lunar exploration could provide the materials to answer a steady stream of questions.

The impact history as we now know it: Impacts as a geological process on any body were not widely recognized until the spacecraft exploration of the Moon in the 1960s. Then, although more and more impact craters were identified on Earth, their importance was not truly appreciated until the discovery and understanding of the end-Cretaceous impact at Chicxulub. Now, we understand that in at least in that one case, an impact dramatically affected the course of evolution of life on Earth.

Meanwhile, study of returned lunar samples led to the suggestion that there was a lunar “cataclysm” ~3900 Ma ago, with a much higher impact flux than occurred after [1, 2]. In particular, rock-based ages of all basins dated so far fall in a very narrow window of time. Although it has been suggested that this simply represents the end of a long period of high impact flux, there are very few old impact melt samples [3]. Furthermore, recent theoretical models provide a mechanism for having a sudden increase in the impact flux after 600 Ma of relative quiescence, by having resonances with the giant planets sweep through the asteroid belt as a result of relatively small changes in Jupiter’s and/or Saturn’s orbits [4, 5]. Since this also corresponds to the earliest surviving rocks on Earth, with the earliest evidence for life shortly after, the “cataclysm” may be tied into the origin of life on Earth, either providing energy or nutrients for life to start [6], or establishing an evolutionary barrier through which only the common ancestor of modern terrestrial life passed.

At the other end of the scale, we have directly determined ages for only a few small craters from the Apollo sites, and indirectly determined ages from Tycho and Copernicus, assuming certain events at

Apollo landing sites are related to those more distant craters [7]. We do not know how the cratering flux has changed, if at all, since the days of the lunar maria, we do not know whether there is any periodicity in impacts, and we do not know whether any particular impacts are the result of something like comet showers [8] as opposed to random asteroid collisions (which might affect our approach to protection of Earth from impacts). Finally, although many asteroidal impacts can leave chemical signatures, we are unable to test for this on any lunar impacts more recent than those of the cataclysm.

Specific approaches to addressing specific questions: We can address many of these questions, in ways that would not have been possible in the past, by combining the excellent lunar stratigraphy and global orbital lunar chemistry now available with targeted sample returns.

In the context of a lunar base, these could be accessed either through brief sorties by astronauts or through robotic sample collection, presumably directed by astronauts via telepresence. In either case, the samples would not need to be analyzed on the Moon, but could be returned to Earth to make use of the extensive laboratory facilities here. Ideally, we would like drill cores that penetrate to crater melt sheets. Assuming that the use of km-length drills is decades in the future, however, we can make use of nature’s drill cores, the smaller, more recent impacts that penetrate into the melt sheets.

Particular questions we would like to address, and the samples we would need to do so, follow. Conveniently enough, the simplest target is probably also the most interesting:

Pre-basin impact flux 1. One of the most important questions is that of the impact flux in the period from the formation of the Moon (~4500 Ma) to the formation of the dated basins at ~3900 Ma. It is widely agreed that the oldest visible impact feature on the Moon is the South Pole-Aitken (SPA) basin. If it formed at ~4000 Ma or later, then ~40 basins must have formed in ~150 Ma or less, a true cataclysm. If it formed in the interval between accretion and the “cataclysm”, at ~4300 Ma, for example, the idea of a cataclysm becomes much less likely, although dating some of the basins of intermediate stratigraphic age then becomes crucial. Since SPA is huge, and has vast expanses that have not been restructured by later impacts, it should be the simplest pre-Nectarian basin to access.

In fact, the planning for the proposed “Moonrise” mission (M. Duke, PI), which would have returned samples from SPA, can be used to target specific locations. However, if a base is at the South Pole, that region is actually within the outer rim of the basin [9], so typical regolith there might actually contain a significant amount of SPA melt breccia [10].

Pre-basin impact flux 2. If SPA is much older than the nearside basins dated by Apollo, the next obvious thing to do is to test another of the basins that is very low in the stratigraphic column. There are several candidates, beginning with Australe, a basin in the southern hemisphere on the eastern limb, extending south to ~65°S [9]. None of the pre-Nectarian basins are north of 10°S on the Near Side, where are current returned samples come from.

Calibrating the cratering flux for the last 3000 Ma. Though not crucial to understanding the origin of life on Earth, the detailed shape of the cratering rate curve for the last 3000 Ma is really just assumed, not measured. The most obvious targets are probably the craters for which ages have been inferred from Apollo data, Copernicus (800 Ma) and Tycho (100 Ma). However, there are other Eratosthenian and Copernican craters sprinkled across the surface of the Moon, and there would almost certainly be some within a few hundred km of any lunar base. For example, the 30-km Copernican crater Schomberger-A is ~300 km from the South Pole, and two >100-km Eratosthenian craters, Hausen and Moretus, are roughly twice that far. As long as the craters are large enough to have generated a significant amount of melt (and simply looking for samples would give a better answer about what that size is), they could begin to fill in the gaps in the curve.

Periodicity, showers, impactor composition. The questions of whether there is a periodicity, or occasional spikes, in the recent (last 1000 Ma) cratering history can best be addressed simply by the acquisition of large amounts of data. There are unlikely to be enough 10- or 20-km craters to begin to address these questions from a lunar base, but even small craters produce impact glass that will mix into the local regolith. Sieving and analyzing regolith from a variety of sites can add to the database being built from the Apollo sites [11-13], and potentially lead to answers to these questions. As long as there are sorties to any locations around the Moon, simply picking up a few kg of regolith in each location would supply more than enough material for this. Finally, detailed trace-element chemistry of any melt samples that are collected is sufficient to attempt to address the question of the origin of the impactors [e.g., 8].

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