TARGETING COMPLEX CRATERS AND MULTI-RING BASINS TO DETERMINE THE TEMPO OF IMPACT BOMBARDMENT WHILE SIMULTANEOUSLY PROBING THE LUNAR INTERIOR. David A. Kring[1,2], [1]Center for Lunar Science and Exploration, USRA Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston, TX (kring@lpi.usra.edu), [2]NASA Lunar Science Institute.

Introduction: 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 *c*. 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]. Hints of impact events at that same time among meteoritic samples of several planetesimals and Mars suggest the lunar cataclysm is really an inner solar system cataclysm [3,4]. Not only may the bombardment have affected the geologic evolution of terrestrial planets, it may have also influenced the origin and evolution of life on the Earth and potentially Mars [*e.g.*, 5]. Because the impact flux to the inner solar system is both accessible and uniquely preserved on the lunar surface, additional samples to further evaluate the impact flux are among the highest lunar science priorities [6].

Target Requirements: To determine that flux and any variations in it, we need to

- Target impact craters and multi-ring basins that are representative of the flux in both time and geographic location on the lunar surface.

To provide a temporally broad chronometer, we also need to

- Target impact craters that provide surfaces (*e.g.*, crater floors) that can be used to calibrate crater counting chronologies and/or
- Target impact craters that provide stratigraphic horizons (*e.g.*, ejecta blankets) that can be used for relative chronologies, even for events that may occur too close in time to be discernable using radiometric techniques.

I have applied these targeting requirements to an inventory of complex craters and multi-ring basins on the lunar surface [7] and identified a subset of those impact sites as potential landing sites for sampling. To better evaluate that potential, this subset of impact sites should be integrated into the imaging campaign by the Lunar Reconnaissance Orbiter.

Exploring the Basin-forming Epoch: The most intense period of bombardment produced dozens of >300 km-diameter impact basins. The duration of this activity is 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. Based on those ages, estimates for the duration of a lunar cataclysm range from 20 to 200 Ma. We have no ages for ≥29 older, pre-Nectarian basins and, thus, no idea if they are part of a lunar cataclysm or are instead part of an extended period of bombardment that may have lasted ~500 million years.

As discussed elsewhere [6,8], 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. Candidate targets include the ***Nubium Basin*** (middle pre-Nectarian), ***Smythii Basin*** (slightly younger), and ***Apollo Basin*** (the last of the pre-Nectarian basins).

The timing of the latter third of the basin-forming events is better understood because of the availability of Apollo and Luna samples, but links between samples of known ages with specific basins is still fraught with uncertainty. For that reason, better documented samples of impact melt or impact-metamorphosed samples from the ***Nectaris***, ***Serenitatis***, ***Crisium***, ***Schrödinger***, and ***Orientale*** basins are recommended. Orientale Basin is a particularly attractive target because it is the youngest basin and exquisitely preserved, so that the geological relationships between target rocks and impact lithologies can be mapped. That clarity will dramatically assist with investigations of samples from older basins.

Determining the Post-basin Impact Flux: After the formation of Orientale, the impact flux declined at a still-uncertain rate. To quantify the flux we need precise analyses of impact ages from a moderate number of post-3.8 Ga impact craters and an accurate determination of the relative number of impact events that occurred between those absolute benchmarks. We currently have no ages for Late Imbrian and Eratosthenian impact craters. To begin constraining the Late Imbrian, samples are needed from craters that meet target requirements, such as ***Humboldt***, ***Tsiolkovskiy***, ***Antoniadi***, and ***Archimedes***. Eratosthenian craters that meet target requirements include ***Hausen***, ***Pythagoras***, ***Theophilus***, ***Eratosthenes***, and ***Maunder***.

The ages of younger impact events during the Copernican Period are also ill-defined, although tentative ages of 1.29 Ga, 0.8 Ga, and 0.1 Ga have been suggested for Autolycus (or Aristillus), Copernicus, and Tycho, respectively, based on samples that are interpreted to be distal ejecta and an impact-generated landslide. To confirm those ages and to further refine the flux during the Copernican, well-documented impact melt samples from ***Kepler***, ***Aristarchus***, ***King***, ***Copernicus***, and ***Tycho*** are recommended.

Scientific Multipliers: In addition to solving several chronological problems, these same impact melt samples can be used to (i) determine the source of projectiles and their chemical compositions. This will, in turn, (ii) test proposed mechanisms for the impact flux. These data can also be used to (iii) calculate the delivery of biogenic elements during the bombardment and (iv) the environmental consequences of the impact events. In many cases, sampling sites associated with the craters identified above will also (v) provide access to impact melt samples from additional craters. For example, samples of pre-Nectarian Nubium Basin melt may coexist with samples from the younger (Nectarian) Humorum Basin.

Complex craters and multi-ring basins are also excellent probes of the lunar interior. Normal faults in the modification zones of these craters (vi) expose subsurface lithologies and their stratigraphic relationships. Uplifted central peaks and peak rings in the centers of these craters (vii) expose even deeper levels in the Moon's crust. Furthermore, (viii) clasts of subsurface lithologies are entrained in impact melt breccias deposited within the crater and beyond the crater rim. Thus, by combining observations of modification zones, central uplifts, and impact breccias, one can (ix) 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 (x) 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 lunar interior.

Many of the impact craters that satisfy the target requirements above are also associated with other geological processes. The floors of impact craters were often flooded by mare basalts (*e.g.*, Nubium, Nectaris, Serenitatis, and Tsiolovskiy). Thus, missions designed to collect impact melt from those craters can also (xi) provide access to volcanic samples that help clarify the magmatic evolution of the lunar interior.

As outlined recently [9], the ***Schrödinger Basin*** is an example of a location where the impact flux can be evaluated while also uncovering information about magmatic activity and the lunar interior. Schrödinger Basin is ~320 km in diameter and is the second youngest basin on the Moon. It is located, however, within the SPA, the oldest basin on the Moon. Because the Schrödinger event excavated and uplifted impact melted material from the SPA event, one may be able to collect samples at a single landing site that provides the ages of both events. That outcome would virtually bracket the entire basin-forming epoch.

In addition, the floor of the Schrödinger Basin is partially covered with several younger volcanic units [10] that appear to be Eratosthenian and/or Copernican in age. Because the style of eruption varies, the volcanic units may have tapped sources from different depths in the lunar interior. Thus, collectively, by targeting the impact melts in Schrödinger Basin, one might simultaneously bracket the duration of the entire basin-forming epoch, expose upper crustal units in the walls of the basin, expose deeper crustal units in the peak ring, expose fragments of crustal units in impact breccias, provide an average chemical composition of the crust (and potentially upper mantle) beneath the point of impact, provide magmatic products from several episodes of volcanic activity, and provide a mineralogical and chemical window into subsurface magmatic processes.

Imaging Guidelines: Wide-angle imaging of the targets described above will often be sufficient for evaluating the gross distribution of impact melt-bearing lithologies. Narrow-angle camera imaging will be required, however, for specific landing site selection and traverse planning. The locations for that type of spatially-focused imaging can be deduced from existing imaging and from preliminary studies of potential landing sites. For example, the recent study of the Schrödinger Basin described above identified three specific locations for a possible landing site that are sufficiently precise to guide narrow-angle camera targeting.

References: [1] Turner G. et al. (1973) *Proc. 4th Lunar Sci. Conf.*, 1889-1914. [2] Tera F. et al. (1974) *Earth & Planet. Sci. Letters, 22*, 1-21. [3] Bogard D. D. (1995) *Meteoritics, 30*, 244-268. [4] Kring D.A. and Cohen B.A. (2002) *J. Geophys. Res., 107*, doi: 10.1029/2001JE001529. [5] Kring D.A. (2000) *GSA Today*, *10*(8), 1-7. [6] NRC (2007) *The Scientific Context for Exploration of the Moon*, 107p. [7] Losiak A. et al. (2009) *LPS XL*, Abstract #1532. [8] Kring D.A. (2008) *LPS XXXIX*, Abstract #1251. [9] Kohout T. et al. (2009) *LPS XL*, Abstract #1572. [10] Shoemaker E.M. (1994) *Science*, *266*, 1851-1854.