TESTING BOMBARDMENT MODELS WITH HUMAN-ASSISTED ROBOTIC MISSIONS AND WELL-TRAINED ASTRONAUTS ON THE LUNAR SURFACE.

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Introduction: The Apollo sample return missions revealed the Moon is a differentiated body that once harbored a magma ocean, that plagioclase crystallizing from that magma ocean buoyantly rose to form a solidified anorthositic crust, and that impacting objects, particularly early in Solar System history, dramatically modified that crust. Today we see the remnants of that period of bombardment in the form of immense basins, some of which are of order 1000 km in diameter.

The samples returned to Earth revealed a surprising pattern. A concentration of *c*. 3.9-4.0 Ga ages suggest there may have been an intense period of bombardment [1] or lunar cataclysm [2] that may be reflective of collisions throughout the entire inner Solar System [3,4]. Not only did the bombardment affect the geologic evolution of terrestrial planets, it may have also influenced the origin and evolution of life on the Earth, potentially on Mars, and potentially on water-rich bodies in the outer Solar System. Because the impact flux to the inner Solar System is both accessible and uniquely preserved on the Moon, additional samples to evaluate the impact flux are among the highest lunar science priorities [5].

Impact Cratering Science during the Apollo Era: The Apollo results emerged when the geologic community's understanding of impact cratering processes was in its infancy. It was not understood, for example, the amount of target melting that could occur. Many photogeologically-observed features, such as melt flows in Tycho crater, were errantly interpreted to be post-impact volcanic products. We now understand that such deposits are likely a direct result of crustal melting produced by the intense kinetic energy of impacting objects.

Our interpretation of the samples was (and remains) challenging because they were collected around basins (Imbrium, Nectaris, and Serenitatis) that have been overprinted by younger impact events. Thus, when trying to evaluate the ages of complex breccias that may have incompletely reset radiometric systems and subsequently been overprinted by younger incompletely reset radiometric systems, interpretations of ages extracted from the samples can be difficult.

Collecting New Samples: Potential landing sites to test the lunar cataclysm hypothesis have been identified (e.g., [6]). Two of the most important sites are the Orientale and Schrödinger impact basins, the youngest and second youngest impact basins on the Moon. For that reason, the lithologies exposed there are nearly pristine. If collected, they will provide an opportunity to measure the age of each basin and, just as importantly, illuminate the nature of melt rocks and melt-bearing breccias produced by single basin-forming events. Once armed with that knowledge, we will be better able to assess the samples in the Apollo collection and samples collected from other, intermediate-age basins.

The second highest priority is to determine the age of the South Pole-Aitken (SPA) basin, the largest and oldest basin on the Moon. Missions to the SPA basin have been proposed (e.g., [7]). Potentially that age can also be determined with a mission to the Schrödinger basin, because it sits within the SPA basin and may have exposures of SPA impact melt within it [8].

Robotic and Human-assisted Robotic Missions: Landing sites, rover traverses, and sample stations have been identified within the Schrödinger basin for robotic mission that last from 14 days [9] to 3 years [10] in duration. These are compelling missions because they also address most of the other NRC objectives for lunar exploration [9,10] and several *in situ* resource utilization objectives. The shorter duration mission can be conducted entirely from Earth, assuming a communication relay to the farside exists, or with crew in the Orion vehicle. The longer duration mission can be conducted with crew in the Orion vehicle and within an orbiting Gateway [11].

Humans on the Lunar Surface: Landing sites, rover traverses, and sample locations for astronauts have been identified for simple sortie-type missions to the Schrödinger basin [12,13]. The Schrödinger basin is also an integral part of 5 human missions [11] recently outlined for the International Space Exploration Coordination Group, of which NASA is a member. In this scenario, two rovers are deployed at the first landing site. Crew then land, conduct up to a 42-day-long mission, collecting samples, before returning to Earth. The rovers are tele-robotically driven to the second landing site, where crew rendezvous with the vehicles. Crew conducts another 42-day-long mission, returning to Earth with a second suite of samples. The mission cadence is once per year and begins at the Malapert massif, followed by landings at Shackleton crater, the

Schrödinger basin, Antoniadi crater, and the center of the SPA basin.

Training: To complete those tasks, crew and the science staff supporting them in mission control will need to study analogue sites (Fig. 1) to learn about crater morphology, associated structural elements, the distribution of impact lithologies, and how to locate samples suitable for determining the ages of craters [14-16].

Figure 1. Kring training 2009 class of astronauts in Meteor Crater in a program that also involved studies in the nearby San Francisco Volcanic Field.

Astronauts and supporting science staff can also be taught to use complex craters and multi-ring basins as probes of the lunar interior. Normal faults in the modification zones of these craters expose subsurface lithologies and their stratigraphic relationships. Uplifted central peaks and peak rings expose even deeper levels in the Moon's crust. Furthermore, clasts of subsurface lithologies are entrained in impact melt breccias deposited within the crater and beyond its rim. Thus, by combining observations of modification zones, central uplifts, and impact breccias, one can generate cross-sections 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. Thus, while collecting melt samples to determine the impact flux, crew will also be collecting samples of the lunar interior.

Large craters may have formidable crater walls, so some missions may be limited to the crater interior, while others may be limited to the crater ejecta blanket. Learning how to conduct radial sampling of an ejecta blanket to probe the subsurface stratigraphy exposed in the crater interior will be another key training objective at terrestrial craters.

In addition to basic geologic training, it will be essential to conduct mission-style simulations (Fig. 2). Good examples of the simulations were developed by the DRATS program, wherein crew in Lunar Electric Rovers conducted 3-, 14-, and 28-day long missions.

Figure 2. Mission simulations in the San Francisco Volcanic Field north of Flagstaff.

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