DEVELOPING AN INTEGRATED, MULTI-INSTITUTIONAL APPROACH FOR STUDIES OF FUNDAMENTAL PLANETARY PROCESSES ON THE MOON: THE GIANT IMPACT, LUNAR MAGMA OCEAN, AND LUNAR CATACLYSM HYPOTHESES. David A. Kring[1] and the Center for Lunar Science and Exploration Team, [1]Lunar and Planetary Institute, Universities Space Research Association, 3600 Bay Area Blvd., Houston, TX 77058 (kring@lpi.usra.edu).

Introduction: The LPI-JSC Center for Lunar Science and Exploration, along with its collaborators at the University of Arizona, University of Houston, University of Maryland, University of Notre Dame, Rice University, and its international partners, is a founding member of the NASA Lunar Science Institute (NLSI). The NLSI has created an opportunity for the Center to (i) develop a core, multi-institutional lunar science program that addresses the highest science priorities identified by the National Research Council for NASA (2007); (ii) provide scientific and technical expertise to NASA that will infuse its lunar research programs, including developing investigations that influence current and future space missions; (iii) support the development of a lunar science community that both captures the surviving Apollo experience and trains the next generation of lunar science researchers; and (iv) to use that core lunar science to develop education and public outreach programs that will energize and capture the imagination of K-14 audiences and the general public.

Science Objectives: At the core of the Center's activities is a series of studies to test the giant impact hypothesis for the Moon's origin; the lunar magma ocean hypothesis and its implications for differentiation of all terrestrial planets; and the lunar cataclysm hypothesis, which has become a critical measure of events involved in the accretion and orbital evolution of planetary bodies in both the inner and outer solar system. To illustrate our integrated approach, we outline here a subset of the results obtained thus far regarding our investigation of the earliest collisions to have affected the Moon.

We begin with the discovery of a surviving fragment of a collision among planetesimals that occurred during the accretion of Earth and prior to the origin of the Moon [e.g., 1]. After the Moon accreted, collisions continued to modify its crust and upper mantle. Hydrocode modeling of the formation of the oldest and largest basin on the Moon, the South Pole-Aitken Basin, indicates a significant amount of mantle material was melted and incorporated into a central melt zone [2], thus providing a compositional parameter for the identification of impact melts associated with that event and its age. Similar modeling of other basins is underway [3], which is providing the input needed to evaluate post-basin evolution of the lunar crust [e.g., 4]. Interestingly, the integration of hydrocode and thermal evolution models can test the cadence of impacts during the basin-forming epoch while also providing new tools for evaluating lunar topography and gravity and their implications for the evolution of the lunar crust. We have found that basins may have influenced stresses in the lithosphere and the eventual eruption of basalts on the lunar surface [5]. In parallel, we are testing models of basin-formation, with a specific structural study of the Orientale Basin, which is the youngest and best preserved basin on the Moon. That study suggests the formation of the outer rings of the basin formed along normal faults [6] and, thus, in a manner similar to that seen at the Chicxulub impact crater on Earth.

During the basin-forming epoch, the Moon's crust and upper mantle were repeatedly affected by impacting asteroids and, to a lesser extent, comets [e.g., 7, 8]. We had previously developed a tool to evaluate the sources of projectiles using the size distribution of lunar craters [8]. We used that tool to probe the most ancient lunar terrains in more detail and discovered a shift in the size distribution of craters that implies a shift in the impact velocities of impacting asteroids [9]. At some point between the formation of the South Pole-Aitken and Nectaris basins, impact velocities appear to have roughly doubled. This is consistent with a shift in the orbits of Jupiter and other outer solar system planets that has previously been implied [e.g., 10, 8]. It is also consistent with the Apollo-era view that all Nectarian and Early Imbrian basins were produced during a cataclysmic surge of impactors. It also implies, however, that some of the pre-Nectarian basins, including the South Pole-Aitken Basin, were produced independently through other collisional mechanisms.

We are continuing to probe the source of debris hitting the Moon during the basin-forming epoch and compare it to more recent times using newly developed techniques to measure highly siderophile elements and Os-isotopes. Applying that approach to mantle-derived samples has revealed new evidence [11] of the late accretion of siderophiles to the Earth-Moon system. Applying that approach to individual Apollo impact melt samples has also been used to detect the chemical signatures of the impactors in specific impact events [12, 13]. While some of the impact melts contain the remnants of known meteoritic sources, others contain the remnants of projectiles that are not represented in the current inventory of meteorite analogues, although they still seem to have an asteroidal, rather than cometary, origin.

The lunar regolith contains a complementary record of impacting debris and has the potential of revealing how that flux of material has changed with time. Thus, we began an examination of ancient regolith breccias from the Apollo 16 landing site and recalibrated an existing technique for determining their ages [14]. We then studied a subset of the breccias for remnant impactors. In a series of exciting discoveries [e.g., 15; and this conference), relic grains of impactors have been found in breccias ranging from 3.8 to 3.4 Ga, spanning the final phase of the basin-forming epoch. These impactor relics confirm a contribution of chondritic material to the Moon, although, interestingly, it has affinities to carbonaceous chondrites rather than ordinary and enstatite chondrites.

We also continue to test the lunar cataclysm hypothesis with a series of geochronologic studies of lunar samples. This includes traditional Ar-Ar analyses [e.g., 16] and the development and application of detailed U-Pb analyses of single zircon crystals and associated phosphates in impact melt breccias and related impact lithologies [e.g., 17, 18].

It is critical for those geochronologic studies to be integrated with updated geologic assessments of the Apollo landing sites and the geologic context of the samples. In a new photogeologic assessment of the Apollo 17 landing site on the margin of the Serenitatis Basin, significant deposits of Imbrium ejecta have been mapped [19]. Thus, we are now sorting through the chemistry and ages of impact melts from the Apollo 17 site to determine which are associated with Imbrium and which are associated with Serenitatis.

Crucial to the success of our assessment of the early collisional evolution of the Earth-Moon system has been the multi-disciplinary and multi-institutional integration that a program like NLSI can produce. That program also provides a platform for integrating lunar science with exploration.

Exploration Objectives: As the community develops the architecture and hardware to return to the lunar surface, our team has developed a series of studies to determine where on the lunar surface the NRC's highest science objectives can be achieved. For example, we have determined that one of the best sites for testing the lunar cataclysm hypothesis is Schrödinger Basin [e.g., 20, 21]. At that one locality, we should be able to determine the age of the oldest basin (South Pole-Aitken) and that of the second youngest (Schrödinger), thus bracketing nearly the entire basin-forming epoch. Interestingly, Schrödinger also contains volcanic deposits of Eratosthenian and Copernican age, thus providing two additional benchmarks in the evolutionary stratigraphy of the Moon. Because the collection of impact melts during and after the basin-forming epoch will be needed to evaluate the collisional flux throughout lunar history, we are also mapping the locations where those impact melts are accessible to robotic and human exploration assets [e.g., 22].

Training Objectives: Our Center and the NLSI are committed to developing a healthy lunar science community. For that reason, our Center sponsors the (a) Lunar Exploration Summer Intern Program, which provides an opportunity for teams of students to identify lunar landing sites where the NRC (2007) objectives can be accomplished; the (b) Field Training and Research Program at Meteor Crater, which provides an opportunity for students to study impact cratering processes and how they modified the Moon; and (c) the development of material that teachers and university faculty anywhere in the world can use to incorporate lunar science into their classrooms. The latter material is accessible through the Lunar Science and Exploration portal (http://www.lpi.usra.edu/lunar/) and the Center's web site http://www.lpi.usra.edu/nlsi/.

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