PROBLEMS IN LUNAR SCIENCE: GALILEO RESULTS AND THE PROMISE OF FUTURE EXPLORATION: James W. Head, Dept. of Geological Sciences, Brown University, Providence, RI 02912

Background: Apollo and Luna orbital and surface exploration data, and results from Earth-based observations have provided a first-order understanding of the major stages in the formation and evolution of the Moon. The Moon is known to have formed a primary crust (1) in its early history (the lunar highlands), and a secondary crust (the lunar maria) primarily in the latter part of the first half of its history. Impact craters at all scales have modified the primary and secondary crust and the largest basins have perhaps excavated through the crust into the mantle. Exploration of the other terrestrial planetary bodies has shown the many similarities of Mercury and Mars to the Moon and demonstrated that the Moon is a cornerstone to the understanding of the evolution of one-plate planets (2). The recently emerging view of Venus has shown that despite their similarities in size, density and position in the Solar system, Earth and Venus differ in fundamental ways (3). This has brought renewed interest in the implications of the formation of the Earth's Moon from the impact of a Mars-sized object into a proto-Earth (4), and the effects on the subsequent evolution of the Earth, relative to Venus. All of these factors indicate that the Moon is a baseline and a cornerstone in planetary exploration in reference to such fundamental questions as planetary origin, the impact record, and the formation and evolution of primary and secondary planetary crusts.

Scientific Problems and the Significance of the Moon: The history of the Earth and Moon appear to be inextricably linked. The Moon may be Earth's progeny, having originated from the Earth; this event would set the stage for the subsequent evolution of the Moon, and cause fundamental, but largely unknown effects on the proto-Earth and its evolution. The Moon gives insight into the Earth's formative years; the period of formation of the lunar primary crust is largely missing on the Earth, and the record of impact basin formation and effects for this period are preserved on the Moon. The record of onset of the formation of secondary crust on the Moon provides clues to the nature of internal melting and its surface manifestation. The Moon provides fundamental data on impact crater formation processes and on impact flux throughout Earth history, including relatively recent periods. The Moon is also a keystone for the understanding of the family of Earth-like planets. It is a laboratory for primary and secondary crustal formation processes and for crustal modification processes, including volcanism, tectonism, and impact cratering. The cratering chronology linked to returned samples collected in context makes it a foundation for establishing elements of planetary history. The globally continuous lithosphere provides important clues to the tectonic evolution of one-plate planets and to the phenomenon of vertical tectonics. The combination of these data and geophysical data provide important insight to the gravity field, internal structure, and level of internal activity.

The Lunar Exploration Paradox and Future Exploration Requirements: Despite the well-known general stages of lunar history (5), and the significance of the study of the Moon to the Earth and other terrestrial planets, there is an immense amount that we do not know about the characteristics and configuration of the basic crustal elements and the processes that were responsible for their formation and evolution. The history and nature of lunar exploration has brought fundamental insight into lunar and planetary science but it has also produced a "lunar exploration paradox": we know a lot about a few places on the Moon but little about most places on the Moon. Apollo and Luna sites are known in relative detail, and the lunar nearside is much better known than the lunar farside. We have important Apollo orbital geochemical data for about 20% of the Moon, but we lack significant geochemical and mineralogic information for much of the rest of the Moon. There is better systematic image coverage for Mars and Venus than for the Moon, and the topography of Venus is becoming relatively better known than that of the Moon. In addition, much of these data were collected with old technology. That the majority of lunar exploration was completed more than two decades ago is illustrated by the fact that the only spacecraft digital image data for the Moon was obtained by Mariner 10 on its way to Mercury in 1974 and most recently by the Galileo SSI experiment in 1990!

Clearly what is presently required to maximize the scientific return from this 'lunar laboratory' is a more global view of the fundamental aspects of the Moon; e.g., its chemistry, mineralogy, geology, topography, gravity, magnetic field and atmosphere. Acquisition of these data would then provide an important baseline for the further scientific exploration of the Moon by all-purpose landers, sample return missions from sites shown to be of primary interest from the global orbital data, micro-rover exploration of sites of significant interest, etc. These data in turn would provide the basis for the intelligent selection of sites for exploration by astronauts and for the establishment of lunar base sites for long-term scientific exploration. This sequence is the same as that which has recently been proposed for the first stages of the Space Exploration Initiative, and it is clear that there is a large degree of commonality in the scientific requirements, and engineering and exploration requirements of SEI.

Recent Exploration Applied to Scientific Problems: Recent and upcoming exploration of the Moon by the Galileo spacecraft provide examples of what could be derived from global coverage of the Moon. During the
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December 1990 encounter the Galileo Solid State Imaging System (SSI) obtained multispectral imaging data for the western part of the nearside, the western limb including the Orientale basin region, and parts of the farside including the South Pole-Aitken Basin (6). These data, although of limited resolution (several up to about 20 km at Orientale and the farside), provided important new data on questions of the homogeneity and heterogeneity of the highland and mare crust and the depth of excavation of lunar basins. Lunar mare basalt deposits cover about 17% of the lunar surface, occur preferentially in topographic lows on the nearside, and have a total volume estimated at 1 x 10^7 km^3. The affinity of limb and farside mare basalts to those on the nearside and at the Apolo and Luna sites is poorly known (7). SSI multispectral image data has permitted a census of mare deposits along the western margins of Oceanus Procellarum, in the patches along the western limb of the nearside, in the Orientale Basin, and in the farside South Pole-Aitken Basin, and the establishment of the affinities of these deposits to mare basalts on the nearside (8, 9). Analysis of returned samples and photogeologic and remote sensing studies show that mare volcanism began prior to the end of heavy bombardment, in pre-Nectarian times (the period of cryptomare formation (10)). The SSI multispectral image data has confirmed the presence of the Schiller-Schickard cryptomare and permitted the more detailed mapping of its configuration beneath the Orientale ejecta deposit (11). This, together with the documentation of an additional cryptomare in the Mendel-Rydberg region (12), contributes to an understanding of the areal significance of mare-like volcanism in the period of basin formation. Stratigraphic analyses show that the volcanic flux was not constant, but peaked in early lunar history, during the Imbrian Period (which spans the period 3.85-3.2 Ga); these data provide important information on the volumetric significance of early mare volcanism. In addition, mixing models of Orientale ejecta and the cryptomaria can provide information on ejecta emplacement dynamics (11). The compositional data on mare diversity is also providing additional insight into the existence of planet-wide mantle heterogeneity and the development of diversity and trends in single volcanic complexes such as the Marius Hills (9). Fundamental issues remain in understanding the lateral and vertical homogeneity and heterogeneity of the lunar highlands crust and its implications for models of initial crustal formation and evolution. Comparison of the deposits of major impact basins provides evidence for vertical crustal heterogeneity and depth of excavation; Galileo SSI multispectral image data show the distribution of highland and ejecta units around and within the 900 km diameter Orientale basin and suggest that excavation largely came from upper to middle crustal levels (12). Galileo SSI multispectral image data for the farside lunar crust show a major and widespread mafic anomaly primarily within the ~2000 km diameter South Pole-Aitken basin region (6, 13); this major anomaly may be related to deep crustal or mantle excavation, impact melt, or ancient cryptomare activity (13). Fresh impact craters show additional regional compositional diversity below the megagregolith (13) and their characteristics can be used to map the ages of craters (14). Correlation of the Galileo SSI multispectral image data and Apollo x-ray spectrometer data shows the synergism of these two approaches and permits the extension of Al/Si ratios over broader parts of the farside. The Galileo spacecraft will encounter the Moon again in December, 1992, flying over the North Pole and obtaining additional data.

Plans for the Future: These examples of the scientific return from low resolution (several up to about 20 km) Galileo SSI multispectral imaging data demonstrate that global multispectral imaging coverage at resolutions of 200 meters would provide fundamental scientific return. These examples further underline the importance and synergism of global data sets (chemistry, mineralogy, geology, topography, gravity, magnetic field and atmosphere) in order to properly utilize the unique and accessible 'lunar laboratory' and prepare for further exploration of the Moon.


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