Future Lunar Science Opportunities – What's Left to be Done? C. R. Neal[1], [1]Department of Civil Engineering & Geological Sciences, University of Notre Dame, Notre Dame, IN 46556, USA (neal.1@nd.edu).

Introduction: The past (and present) exploration of the Moon begs the question "what's left to be done?" The public and to some degree political perception is that, in terms of the Moon, we have "been there – done that". With the renewed focus on the Moon, now that it is in the pathway for the exploration of Mars (and beyond) a similar question has been raised – what should the astronauts do on the Moon? Before addressing this question, here is a brief history of lunar exploration.

Lunar Exploration: Unmanned missions to the Moon began in 1959 with the January 3 Soviet Luna-1 fly-by mission, passing within 5995 km of the lunar surface. Since then, there have been a further 66 missions to the Moon either as fly bys, orbiters, robotic returns (either from orbit or the lunar surface), as well as crewed return missions from both orbit and the lunar surface. Each mission collected a variety of data although 16 of these failed to meet their mission objectives. There have been a total of 9 successful sample return missions: six Apollo spacecraft + astronauts landed on the Moon between 1969 and 1972, each returning lunar samples to Earth (Apollo 11, 12, 14, 15, 16, 17). Between 1970 and 1976, three Soviet robotic Luna spacecraft landed and also returned lunar samples (Luna 16, 20, 24). In addition, lunar meteorites have been recognized and while the locations of these meteorites cannot be precisely pinpointed, these samples extend the diversity of such samples. As of the summer of 2007, 48 lunar meteorites have been recognized [1,2]. Since 1976, there have been 6 missions that have flown by, orbited, or impacted the Moon: Galileo, Hiten, Clementine, AsiaSat/HGS-1, Lunar Prospector, Hayabusa-MUSES-C, and SMART-1.

The President's speech in January of 2004 [3] opened a new era of lunar exploration for the USA, although other nations had already begun their own lunar exploration initiatives. At the time of writing, two missions have been successfully launched to the Moon. The Japanese SELENE and the Chinese Chang'e 1 missions are currently in orbit around the Moon. In addition, the Chandrayaan-1 (India) and the Lunar Reconnaissance Orbiter (United States) missions scheduled for launch to the Moon in 2008.

Remaining Lunar Science Questions: The synthesis of 45+ years of data of various forms presented by [4] not only highlighted what we have learned since 1959, but maybe more importantly it brought sharp focus on those areas we know little about and presented many unanswered questions. Within the USA, the NRC [5] and LEAG [6] have been working on the science aspects of returning to the Moon. These publications fed into the initial Lunar Architecture Team deliberations and were followed by the NASA Advisory Council (NAC) sponsoring a workshop in Tempe, Arizona, entitled "Science Associated with the Lunar Exploration Architecture" [7]. Both the LEAG and NRC reports break down into various themes that are somewhat overlapping, but can be used as a basis for grouping lunar science questions that still remain to be addressed. These questions have been crafted and presented in a wide variety of reports and papers from the early 1970s until the current LEAG and NRC reports (e.g., [8-15]) and summarized by [16]. They are presented here under six themes.

<u>1. Investigate the geologic evolution of the Moon and other terrestrial bodies.</u>

What were the initial thermal state and the early thermal evolution of the Moon?

What role did early (i.e., > 4Ga) volcanism play?

What is the composition and depth of origin of the farside and young (i.e., < 3 Ga) nearside basalts?

What is the nature of the Moon's global-scale crustal asymmetry, what caused it, and what are the implications for the Moon's internal evolution and present-day distribution of materials?

What is the cause of the center-of-mass/center-of-figure offset?

Is the offset related to convection and density inversion dynamics, early giant impacts, asymmetric crystallization of the magma ocean, or Earth-Moon tidal effects?

What is the vertical and lateral structure of the lunar crust and how did it develop?

What is the provenance of the Magnesian Suite rocks?

What is the composition and origin of the lower crust?

What are the characteristics of the core (size, composition), and did the Moon ever support a dynamo-driven magnetic field? What are the origins of lunar paleomagnetism?

Was there a significant late veneer of accretion (post core formation/early differentiation)?

Are the Apollo geophysical measurements representative of the whole Moon or are they only valid for the small regions encompassed by the Apollo landing sites?

What is the origin and lateral extent of the 500-km seismic discontinuity?

Is there an undifferentiated lower mantle (limited or no involvement in magma ocean melting)? If so, what was its role in lunar magmatism?

Did at least some of the volcanic glasses come from a deep, garnet-bearing region beneath the cumulate mantle?

What was the extent of lunar magma ocean differentiation?

Is the surface distribution of KREEP representative of the underlying crust?

What were the sources and magnitude of heating to drive secondary magmatism?

How was heat transferred from Th-U-K-rich crustal reservoirs to the mantle? What was their role in large-scale crustal insulation?

How are the different suites of plutonic rocks related to specific or localized geologic terranes and to the global geochemical asymmetry?

How is the surface expression of lunar materials related to the Moon's internal structure and evolution (or where exactly do the different rock types come from?)?

2. Quantification of impact processes and histories of the solar system.

What were the timing and effects of the major basin-forming impacts on lunar crustal stratigraphy? What is the nature and composition of the South Pole-Aitken Basin, did it penetrate the lunar mantle, and how did it affect early lunar crustal evolution?

What was the impactor flux in the inner Solar System and how has this varied over time? Was there a terminal cataclysm at ~3.9 Ga?

What are the absolute ages of the large rayed craters that are assumed to be Eratosthenian and Copernican in age (e.g., Autolychus, Copernicus, Tycho)?

What are the unequivocal ages of the large multi-ring basins (i.e., Nectaris, Imbrium, and Orientale)?

Why are there no impact melts older that ~4.2 Ga in the sample collection? Is this a sampling problem or is it because they simply don't exist?

3. Characterization of regolith and mechanisms of regolith formation and evolution.

What is(are) the origin(s) of lunar swirls, the light and dark colored "swirl-like" markings up to 100 km across (e.g., Reiner Gamma in Oceanus Procellarum)?

How do the physical/geotechnical properties of the lunar regolith differ between measurement on Earth and in its natural environment on the lunar surface?

How does the process of space weathering occur?

How has the solar wind flux changed over time?

4. Development and implementation of sample return technologies and protocols.

What technology development is needed to be able to collect, transport, and curate samples from permanently shadowed regions of the Moon (i.e., samples containing H deposits)?

What technology is currently (commercially) available to aid in (a) robotic (b) astronaut sampling of lunar lithologies, including contextual information for each sample?

5. Study of endogenous and exogenous volatiles on the Moon and other planetary bodies.

What volatiles are (were) present in the deep lunar interior and what was their role in magmatic processes and eruptive styles?

What happens to elemental species volatilized during impact?

What and where are the most concentrated, extensive, and readily extractable deposits of H and ^{3}He?

What are the origin and mineralogical or physical form, thickness, and concentration of H or H_2O ice deposits in permanently shadowed craters at the poles?

6. Processes involved with the atmosphere and dust environment of the Moon are accessible for scientific study while the environment remains in a pristine state.

What elemental and molecular species make up the lunar exosphere and how has it changed with time?

Are there seasonal fluctuations in the lunar exosphere?

How quickly does the lunar exosphere recover from (a) a meteoroid impact, and (b) landing of a spacecraft?

Addressing the Questions: The new era of lunar exploration offers a vehicle to address many of these questions through human and robotic exploration. Careful planning will be required in order to maximize the science obtained from each mission, whether it be orbital or landed, human or robotic. Many of these questions require data gathered over a long period of time (years to decades) through global networks. Others will use orbital data to target sample returns. Such sample returns could deploy a network node before sample collection. Still others require detailed sampling of the lunar regolith after careful manipulation through trenching. Technology developments in instrumentation to send to the Moon will also be necessary. Such developments will need to miniaturize systems and minimize the power requirements. Other technological advancements will be needed for sample collection. Several advancements that immediately spring to mind are deep coring of the lunar regolith, robotic sampling, and sampling and preservation of material from lunar cold traps.

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