TEN YEARS OF THE LUNAR RECONNAISSANCE ORBITER: ADVANCING LUNAR SCIENCE AND CONTEXT FOR FUTURE LUNAR EXPLORATION. N. E. Petro[1], J. W. Keller[1], B. A. Cohen[1], T. P. McClanahan[1], [1]NASA Goddard Space Flight Center, Solar System Exploration Division, Greenbelt, MD 20771 (Noah.E.Petro@nasa.gov).

Introduction: In the leadup to the Apollo program there was a critical need for images of selected landing sites, a need that led to the development of the Lunar Orbiter program [1]. Having demonstrated the ability to hit the Moon with Ranger missions, and land on the Moon with Surveyor, Lunar Orbiter offered a final piece of data. With those data, safe, geologically compelling landing sites were identified for the early Apollo missions, and set in motion the scientific revolution realized by Apollo. For nearly 40 years those data offered the best perspective on the Moon and provided much of the geologic context for studies of the lunar surface [2].

Now, 50 years after the first human landing on the Moon (Figure 1), 10 years since the Lunar Reconnaissance Orbiter (LRO) began mapping the Moon, and with lunar exploration once again on the horizon, it is timely to review the accomplishments of LRO and look to future science enabled by LRO discoveries. LRO data encompasses a broad range of datatypes, from visible images revealing intriguing morphologies and young volcanics [3], to radiation data critical for planning extended operations in deep space [4]. In that sense, LRO data is not only telling us where to go on the Moon, but how to survive there.

In the near term LRO will support the identification and characterization of landing sites for commercial enterprises and use these landings as opportunities for science observations [e.g., 5, 6]. This new era of lunar exploration is fundamentally enabled by LRO's data, creating a period of lunar exploration on the shoulders of LRO, GRAIL, Kaguya, and the other recent missions [7].

LRO Accomplishments: Summarizing the successes of an ongoing mission is difficult, especially with a mission as productive as LRO is. In the past three years there have been no fewer than three special issues in various journals highlighting the science from the LRO mission [8, 9]. These are publications that feature data from multiple instruments and are authored by both LRO team members and scientists from outside the mission. Here we briefly discuss accomplishments of the mission in the main areas of study for the mission; volatiles, the regolith and impact cratering, and volcanism and interior processes.

Volatiles: The evolution in understanding of lunar volatiles over the past decade is perhaps most similar to the rapid advance in understanding of the impact process in the 1960s [10] or the interpretation of the lunar magma ocean in the 1970s [11]. While the initial detection of water in lunar samples [12] and the widespread distribution on the lunar surface [13-15] occurred as LRO was in development, the LRO instrument suite is robust [16], having been selected to map and measure hydrogen and volatiles. Despite the rapid pace with which our understanding of lunar volatiles has evolved, LRO remains at the leading edge in our understanding and interpretation of volatiles [17, 18].

Going forward, LRO will focus on the diurnal variability of surface volatiles, the composition of the lunar exosphere and its role in the transport of volatiles, and the changing state of the space environment and how it may or may not control surface volatiles [17, 18]. These studies rely on the entire suite of LRO instruments, from purely mapping the current state of hydrogen to placing constraints on the amount of hydrogen in the exosphere. A benefit of a long-lived mission such as LRO is that we have consistent set of data with which to compare over ~10 years.

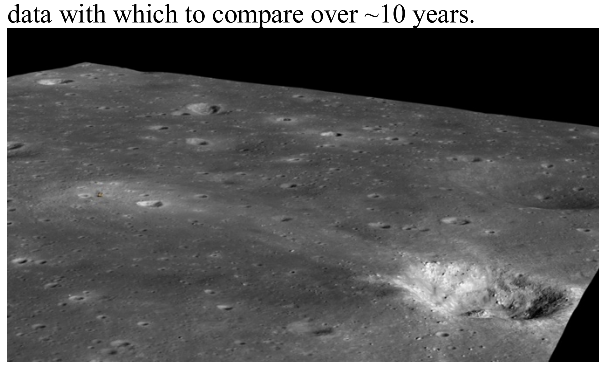

Figure 1. View of the Apollo 11 landing site, generated by LROC NAC image M175124932R and a NAC-derived topographic model. West Crater is at bottom right, Little West Crater is at left. The increased albedo surrounding the landing site is visible to the left of Little West Crater [e.g., 6].

Lunar Regolith and Impact Cratering: The ubiquitous regolith, its evolution, and how impact cratering (over a range of spatial scales) is a key area of study for LRO as well as for extending our results to other airless bodies in the Solar System [19]. Using multiple instruments, we are able to probe the regolith in 4-dimensions, not only studying the surface with LROC, LAMP, and LOLA but also probing the near-surface of the regolith with Diviner and Mini-RF.

We will focus on understanding how impact craters modify the surface, specifically on the distribution of impact melts within and around young craters and large basins. We can also use the identification of new, LRO-era impact craters to characterize not only distributions of ejecta, but also the flux of small objects in the Earth-Moon system [20]. Additionally, studies of the photometric properties of the regolith at multiple wavelengths allows for a unique opportunity to evaluate space weathering at a range of wavelengths. We will specifically focus on a subset of young craters, the so-called "cold spots" identified in Diviner data [21]. These features appear to be young (>0.5 Myr) [22] and allow for focused studies of how solar wind interacts with geologically young material.

Volcanism and Interior Processes: The surface expression of ancient crustal compositions and mantle melts enables studies of the lunar interior *via* remote observations. Additionally, tectonic features such as lobate scarps and graben provide insight into the thermal and stress history of the lunar crust [23]. LRO observations have constrained volcanic features of a range of emplacement styles, from silicic volcanism [24, 25], pyroclastic deposits [26, 27], to young volcanic features [3]. Using both image data and compositional data from LROC and Diviner, we evaluate the distribution, morphology, and compositional variation of these features.

The recent observations of "pure anorthosite" (PAN) on the lunar surface enables detailed measurements of the small-scale variability of these features and their association with surround lithologies. These presumably ancient compositions offer insight into the products of magma ocean differentiation, first identified in those initial studies of Apollo 11 sample studies [11].

The global distribution of tectonic features and the imaging of those features at small (>1m per pixel) scales allows for the detection of potential surface changes, or geologically recent changes. Models of the stress-state of the Moon suggest that tidal forces may trigger Moon-quakes, which may manifest themselves at lobate scarps [28].

Landing Site Characterization for Commercial Landers: The new era of cooperation with private missions to the lunar surface allows LRO to 1) support the characterization of landing sites and 2) coordinate on potential observations of lunar landings and their effects on the lunar regolith. LRO has, by definition, been supporting lunar landing site characterization since its inception, however now there is a coordinated effort from NASA HQ to work directly with the companies to work at all levels of identification of landing sites (from the initial identification to detailed characterization).

This new era of lunar surface exploration also enables a new age of coordinated lunar science between an orbital asset and surface assets. During Apollo, coordinated measurements of surface magnetic fields and the deep space environment by Explorer 35 [29], during this period of lunar exploration we may offer similar coincident measurements that benefit both LRO and the surface asset.

The Value of LRO- Providing a Context for Lunar Exploration: In the 50 years since Apollo 11 provided the first samples and established surface experiments on a planetary body, lunar and planetary science has leveraged those samples and surface measurements to broadly understand the entire Moon. Prior to LRO much of the local geologic context for samples collected was provided by limited high-resolution Apollo and Lunar Orbiter images and Clementine compositional data [30]. LRO data allows the Apollo samples and data to be placed in a 21st Century context, both in terms of where the samples were collected [31] and where the surface experiments were deployed [32] (Figure 1).

The next decade of lunar exploration may see not only landers but possible human exploration of the lunar surface. Just as the robotic precursor missions of the 1960s enabled the 1970s to be the decade of Apollo Science, the 2020s have the promise to be a decade where science questions defined by LRO are answered by surface assets.

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