8. Discussion

8.1. Lessons from the Constellation Program

As part of the Constellation Program, the LPI provided NASA with an analysis and recommendations for astronaut training and mission simulations (Kring, 2007a). The report noted:

- All lunar surface activities will occur in impact-cratered and volcanic terrains and, thus, crew should be given basic geologic training and conduct EVA simulations in appropriate analogue terrains.
- EVA training in analogue terrains should involve the integrated expertise of a broad group: the astronaut office, astronaut trainers, field geology trainers, site selection teams, geologists involved in surface operations planning, lunar sample analysts, in-situ resource specialists when appropriate, equipment designers, flight controllers, and management (SMD, ESMD, SOMD).
- Field mobility is needed for crew and robotic assistants.
- Integration of human and robotic exploration components should be tested in analogue terrains with realistic simulations of lunar surface operations. Likewise, all tools to be used by crew in lunar surface operations should be tested in realistic simulations.
- Initially, missions will be of relatively short duration and, thus, traverse-dominated with backroom support, which requires training similar to that for the Apollo J missions.
- Training for extended duration missions will need to develop greater crew independence, because they will be operating in an exploration mode that (i) more closely mirrors terrestrial field work and (ii) takes advantage of the human ability to analyze in real time. Backroom assistance will still be important, but the crew will not require constant consultation over long durations (*e.g.*, 30 to 180 day expeditions).
- Four-person crews should include mission specialists with advanced training in subjects like geology, resource recovery, and engineering. These individuals could potentially be involved in pre-mission scientific research and engineering trade studies associated with lunar surface operations.

Several of those findings were implemented during the Constellation Program, while others evolved as trade studies were completed as part of the Constellation Program.

To address the first finding, LPI helped JSC and several university partners develop a new training program for astronauts who were selected with the Moon as a potential exploration destination. That program was initiated with the 2009 class of astronauts, with the understanding that we were preparing the class to walk on the Moon. To introduce impact cratering processes, a lecture series was developed (Kring & Hörz), with a complimentary laboratory exercise that used terrestrial impact crater samples (Kring & Hörz) and another complimentary laboratory exercise that used Apollo impactites (Kring & Lofgren), followed by a 3-day field exercise at Meteor Crater, Colton Crater, SP Mountain, and Lava River Cave (Kring, Hörz, & Eppler). Training that compared and contrasted impact cratered terrains with volcanic terrains addressed the scope of the Constellation Program: while initial landing sites were being planned for the impact-cratered highlands of the lunar south polar region, global access to the lunar surface – and, thus, to volcanic terrains – was being preserved.

The exercises were designed to show astronauts the linkage between good field observations, smart sample selection, and important scientific outcomes once the samples were analyzed on Earth. The revised training activities were also designed to provide astronauts the skills needed (Kring, 2010a, 2018) to address the highest scientific priorities identified by the National Research Council (NRC, 2007) for lunar exploration.

LPI's representative (Kring) in the Constellation-era astronaut training program conducted forward planning for more advanced training at the Sierra Madera impact crater, the Nevada Test Site explosion craters, the Sudbury crater, the Ries crater, and the Stillwater, Duluth, and Marcy anorthositic field sites. Unfortunately, the Constellation Program was cancelled before more advanced geologic training and mission-specific training could be implemented.

LPI helped NASA address the second finding by assisting with integrated training and mission simulations in a rock yard at JSC; at Moses Lake, Washington (2008); and in the vicinity of the SFVF Black Point Lava Flow (2008-2011), Arizona, including Colton Crater and SP Mountain (2010). Those simulations were coordinated with the development of lunar mission architectures being developed by NASA's Lunar Surface Systems (LSS), including a dual-rover 28-day-long mission in the vicinity of the Moon's Malapert massif, and deployed as part of NASA's Desert RATS program.

LPI helped NASA address the third and fourth findings by participating in the development and testing of crew rovers (Chariot and Lunar Electric Rover) and hosting a blue-sky meeting for the development of a second generation small pressurized rover that would be the immediate predecessor to the flight model for Constellation, which was notionally to be delivered to KSC for launch in 2015. That blue-sky meeting led to the modified Space Exploration Vehicle (SEV) cabin. LPI also developed, installed, and tested a ground penetrating radar (GPR) system that was integrated into the chasis of the Lunar Electric Rover, demonstrating a new capability for Constellation (Kring, 2017b; Kring & Heggy, 2020) that did not exist for Apollo.

LPI helped NASA address the fifth finding through a revised curriculum for newly selected astronauts and additional training provided in support of the lunar mission simulations. NASA requested evaluations after each mission simulation, which LPI provided in a series of short reports with observations, findings, and recommendations.

LPI helped NASA address the sixth finding by developing a lunar south polar mission traverse plan (Kring, 2010b; Kring *et al.*, 2020j) that contained two 14-day-long loops in the vicinity of Malapert massif (for a 28-day or 42-day-long mission). LPI helped the agency expand its SFVF test site (Kring, 2008b) to accommodate a simulation of that type of mission. The institute then helped the agency test a simulation of that mission using dual small pressurized rovers (Abercromby *et al.*, 2013). That simulation was a success. We were not able to develop and test longer mission capabilities, however, because the Constellation Program was cancelled.

The agency implemented the seventh finding by ensuring each crew of two in Constellation mission simulations included a flight astronaut (EV1 = Commander) and a geologist astronaut (EV2). EV1 always involved a senior astronaut with flight experience. EV2 was generally an early career planetary scientist, including a graduate student, in lunar mission simulations. LPI's representative (Kring) was asked to be a crew member, but it was decided it better he continue in a SCILEAD role in preparation of a Constellation-era lunar surface mission.

The lunar mission simulations revealed several additional findings. While we will not list all of those LPI provided NASA here, we note those findings that are most relevant to training for, and operations in, lunar impact-cratered terrains: (i) Astronauts participating in the lunar mission simulation crews need additional geologic training in suitable terrains; (ii) The geologists participating in the lunar mission simulation crews need communication training, to learn how to package a lot of information into a few words; (iii) The science operations team needs flight operations training, so that they can better communicate with flight operations staff and function at a level required for human flight operations; (iv) rovers dramatically enhance lunar surface science productivity (and – by inference – *in situ* resource utilization (ISRU) activities); (v) a small pressurized rover, compared with an unpressurized rover, greatly enhances science productivity while reducing risk to crew; (vi) a system of rapid egress and ingress (approximately 10 to 15 minutes), like suitports, is necessary to take advantage of small pressurized rovers; (vii) it is possible to integrate instruments (*e.g.*, GPR) into the chassis of a small pressurized rover to provide data not otherwise obtainable by crew; (viii) rovers should have a waist-high surface that astronauts can use to sort samples, equipment, etc; and (ix) that communication between crew and science ops staff is more difficult in low-light and dark EVA situations, so that type of EVA needs an additional training effort.

Many of those findings were shared with the lunar community through a series of meeting presentations (Kring, 2017b,c; 2019a; 2020b,d; Kring *et al.*, 2021d,f).

8.2. Implications for Artemis Astronaut Training

The initial Artemis exploration zone and future location of a planned base camp (NASA, 2020a, b) is an impact-cratered terrain. Thus, it is important to provide astronauts with the skills necessary to operate in that type of terrain. The revised training for new classes of astronauts that was developed for the Constellation Program is a good start. However, more advanced geologic training and mission-specific training in impact cratered terrains, which were never implemented for Constellation due to its cancelation, should be developed for Artemis. That three-part training sequence is being labeled as (i) initial training, (ii) proficiency training, and (iii) assigned crew training by the agency (Graff *et al.*, 2020).

One of the challenges of Artemis missions will be the topography of the impact-cratered south polar terrain. Elevation changes and slopes within the thirteen candidate Artemis III landing regions may affect EVA workload (Kring *et al.*, 2023) and, in some cases, will be physical barriers to exploration. For example, in the vicinity of site 001 (NASA, 2020a) within the 'Connecting Ridge' landing region, slopes are generally <10° along a ridge towards Shackleton crater, although intervals have slopes approaching 20° and the ridge is bounded by flanks with slopes >20°. Moving away from Shackleton crater from site 001, the slope exceeds 10° within 1,000 m. The relief within 2,000 m (the walking EVA limit) of site 001 is ~500 m, while a maximum elevation change along a potential traverse is ~140 m. Introducing astronauts to the topography of terrestrial impact craters will help them develop an intuitive understanding of how to navigate that type of terrain.

As outlined above (**Section 2**), Meteor Crater is the ideal location to initiate training. That training is very effective if – at the same time – the features of Meteor Crater are contrasted with those of the Colton volcanic explosion crater, as LPI (Kring) and JSC (Hörz) collaboratively developed for the Constellation Program. That basic training can be augmented with exercises in the nearby Cinder Lake crater fields, which are crafted analogues for a cratered lunar surface. Subsequent training at several other impact sites (Sierra Madera and Odessa; **Sections 6 & 7**) and explosion craters (Nevada Test Site; **Section 5**) in the United States can follow, with additional training possible at Germany's Ries Crater (**Appendix Q**) and Canada's Sudbury and Manicouagan impact structures (**Appendix R**) (*e.g.*, Kring *et al.*, 2020a). One can also utilize volcanic explosion craters (maars, such as those in the Pinacate Volcanic Field (**Appendix P**)) as training sites to further address the geographical constraints of a cratered terrain. Importantly, because Shackleton crater in the Artemis exploration zone appears to have excavated anorthosite (Yamamoto *et al.*, 2012; Gawronska *et al.*, 2020; Halim *et al.*, 2020), astronauts should probably be exposed to anorthosite at locations such as the Duluth Complex and Stillwater Complex (*e.g.*, Kring et a., 2020a), as was done during Apollo.

As the Artemis exploration effort advances, we have also come to better understand the role impact cratering processes have on the distribution of lunar resources that may be needed to meet one of NASA's objectives: to produce a sustainable exploration program (NASA, 2020a). We now realize that impact cratering is the single most important geologic processes affecting ISRU prospects (Kring, 2020a). The topography of impact craters in the polar regions produces the permanently shadowed regions (PSRs) where volatiles can be trapped. Impacting asteroids and comets were a source of the volatiles that could be trapped in those PSRs. The largest impact events altered the spin axis of the Moon and, thus, the locations of PSRs where volatiles could accumulate. The largest impact basins thinned the crust, allowing large volumes of magma to reach the surface and vent volatiles, providing another source of volatiles that could be trapped in PSRs. Impact ejecta from cratering events covered (and potentially reworked via ballistic sedimentation) horizons of ice deposited in PSRs, producing a stratigraphic succession. Ancient impact basins provided catchments for flood basalts (mare) that contain ilmenite that can be chemically modified to produce oxygen. Ongoing impacts, including micrometeoritic impacts, have infused the regolith with meteoritic-derived volatile abundances. Those volatiles, when combined with volatiles from the solar wind, provide a recoverable reservoir everywhere on the Moon. They have also infused the soil with meteoritic metal, which is another potential resource for a sustainable exploration program. The largest of the impact events produced melt sheets that may have differentiated, potentially forming ore deposits of metal and sulfide. Thus, astronauts, while training to operate in an impact cratered terrain like that in the Artemis exploration zone, will also be learning how to recognize those lunar surface attributes that may lead to a better assessment of resource availability.

When a south polar landing site was announced in March, 2019 (White House, 2019), LPI and USRA suggested (April, 2019) that training begin immediately. We continued to point out (Kring, 2019a; Kring, 2020c) that Armstrong and Aldrin and the science staff supporting them had 5 years 4 months to develop surface science plans before the first Apollo landing; and Cernan and Schmitt and the science staff supporting them had more than 8 years to develop surface science plans for the final Apollo landing. At that moment, we had a 5 year time-scale to prepare for a lunar south pole landing in 2024. As of this moment (December 2022), the landing has been shifted to the end of 2025, leaving 3 years to prepare. The same urgency to begin training was articulated by Apollo 17 astronaut Harrison 'Jack' Schmitt during the Constellation Program: "In this context, it is imperative for field training of future lunar and Martian crews begin sooner rather than later" (Schmitt *et al.*, 2012). Additional training methods feeding from Apollo experience can be found in Schmitt and others (2012) and Hodges and Schmitt (2012).

8.3. Training Objectives and Rewards

Rationales for training were outlined in **Section 1.4** and training objectives specific to certain geologic locations were outlined in **Sections 2 through 7**. Here we expand our discussion of those training objectives and how they can support positive mission outcomes.

It is important to understand that field geology is a discipline that requires a skill set as distinct as isotope geochemistry and other types of geology, and is complementary to them. Sophisticated laboratory analyses are, for example, only as good as are the field studies that led to sample collection (Sharp, 1988). It should, thus, be apparent that trainers should have a well-documented record of field geology triumphs.

One of the keys to field geological success is the ability to make observations, sift through those that are relevant and those that are not, and connect the relevant observations to generate an understanding of the spatial and temporal evolution of a geologic terrain and, once done, determine which samples should be collected to address mission priorities.

A well-trained astronaut can make outstanding observations, as illustrated by Apollo. Astronauts are generally very good at absorbing information from a scene before them and drawing meaningful conclusions. Indeed, an astronaut who was an Air Force pilot deduced a finding in a Meteor Crater field exercise faster than any previous planetary scientist in our training programs. And an astronaut who was a Marine deduced a finding in a volcanic terrain exercise faster than any planetary scientist in our training programs.

Two keys to field geology success are observation and the ability to process those observations. Kastens and others (2009) drew a similar conclusion, noting that "Across geoscience specialties, the human mind is arguably the geoscientist's most important tool. It is the mind that converts colors and textures of dirt, or blotches on a satellite image, or wiggles on a seismogram, into explanatory narratives about the formation and migration of oil, the rise and fall of mountain ranges, the opening and closing of oceans."

They went on to say that “Professional vision can be developed through guided apprenticeship, as an expert watches and corrects a novice’s iterative efforts to segment the observed world into meaningful categories (*e.g.*, cloud types or rock units) and to identify features of interest (*e.g.*, rip tides or faults) amid visual complexity. Such mentorship extends beyond the development of observational skill and include guidance on the use of observational data to test hypotheses. The interplay between observation and testing of ideas is a central feature of a geoscientist’s reasoning, and field experiences may play a critical role in developing this habit of mind.”

When training for lunar surface science EVAs, one has to be mindful of issues specific to that environment. Schmitt and others (2012) summarized this point well: “A terrestrial geologist may commonly return to a location again and again, each time generating and testing hypotheses. In contrast, a lunar field geologist must always be aware that time is relentless, that consumables are limited, that fatigue can be fatal, and that, usually, returning to a location is unlikely. These cognitive realities add to the normal intellectual workload of doing field work. In addition, most of the normal terrestrial tasks will take longer in a space suit, if they can be done at all.”

To help mitigate the challenges of lunar surface science EVAs, crews will be supported by science operations teams. The integration of those teams with crew activities relies strongly on good communication. In the case of Apollo training, that communication was improved by post-traverse debriefings. As Apollo 15 trainer Gary Lofgren wrote (2008), “The most important part of this training exercise was the face-to-face debriefing where the crew, together with the capcoms and the science backroom geologists, walked over the entire traverse and discussed the degree to which the crew had been able to communicate the geology they were seeing in the field.”

As Lofgren went on to note, “These debriefings forced everybody to recognize their deficiencies and to eliminate them.” That ethos is central to the ***Space Flight Resource Management Training for Science Operations*** program that LPI developed with FOD.

Bill Muehlberger (2005), the PI of the Apollo 16 and 17 “Field Geology Experiment,” wrote “This time of training was key to the success of the Apollo missions.” If done well, an Apollo 17 astronaut noted that “geological field training of astronauts …will reduce operational risk to crews as well as increase crew and ground team productivity” (Schmitt *et al.*, 2012). Another important outcome of crew training can be crew ownership of a mission, enhancing the dedication astronauts devote to the scientific success of a mission (Lofgren, 2008).

Because field observations are an important component of geologic outcomes, samples collected by well-trained crew should be returned with crew, rather than stockpiled. That strategy will ensure the field geology team (the crew) and the EVA science operations team are still available to provide the geologic context of samples when they are analyzed. Separating those activities in time may diminish the scientific return of a mission. Although robotic sample return missions have not been addressed in this report about crew training, the same philosophy applies to them. Samples collected robotically on the Moon should be returned to Earth as soon as possible, so that the science team involved in the robotic traverse is available to provide the geologic context of the samples when they are analyzed. Science may be lost if geologic context is lost or ignored when interpreting sample analyses.

Crews on the lunar surface will sometimes be asked to deploy instrumentation, such as a solar wind collector and a seismometer. Such activities require task-specific training, like that used to support current activities on the International Space Station. In contrast, geological surface science requires skill-based training. Moreover, mechanical demands where resupply is difficult and timelines may need to be replanned also require skill-based training (Ney & Looper, 2006). Collectively, the training paradigm for astronauts will need to evolve as lunar surface operations expand (Kring *et al.*, 2020a).

The best and most advanced capability that we can deploy is a well-trained astronaut.