9. Summary

This report illustrates how geologic sites have been used to train astronauts how to explore impact-cratered planetary surfaces and how they can be used to prepare Artemis astronauts and supporting lunar surface operational teams for future missions.

While the report outlines how to best use those geologic sites, it does not provide answers to the types of questions that instructors will be expecting to hear from crews and the scientific teams that will support lunar surface operations. That is, reading this guidebook is not a fast track to a trainee's success. Nor would it be prudent for a potential instructor without years of experience in the analogue terrains to take this guidebook and attempt to lead exercises. There are hundreds of unwritten field-based and sample-based geologic details that should be included in any successful training program. The need for that type of expertise was recognized during the Apollo program (*e.g.*, Lofgren, 2008; Schmitt *et al.*, 2012). As Apollo 17 astronaut Harrison Schmitt wrote, "Instructors should be the best teachers who are also at the top of their fields of specialization." For operations in impact-cratered lunar terrains, trainers should have extensive field experience with that type of terrain, analytical experience with lunar samples from that type of terrain, and be a high-quality teacher.

Several general statements about astronaut training can be made based on the experiences described in **Sections 1 through 7 and several appendices**:

- The first key to success is to learn how to observe. Most astronauts already have a well-developed capability for observation, so training should be designed to focus attention on geologic details. Perhaps unique to geological sciences, astronauts need to put those observations in a three-dimensional spatial context and along an evolutionary timeline.

- The second key to success is to learn how to describe observations to other crew members and science operations staff. This needs to be practiced, so that the crew and ops staff understand each other and to build a level of trust needed for efficient and productive EVAs.

- The third key to success is to learn how to critically analyze those observations in the context of mission objectives and, when warranted, identify unanticipated opportunities. It is important for astronauts to be comfortable making independent observations, thinking about them in real time, making decisions about sample collection, and, if necessary, discussing modifications of an EVA with science operations staff.

Observe and connect the dots is the informal way we describe the practice in the field.

The Artemis exploration zone is an impact-cratered terrain. The highest science priorities for lunar exploration (NRC, 2007) also involve impact cratering: to determine impact chronologies to test the lunar cataclysm hypothesis, anchor the impact flux curve with the age of the South Pole-Aitken basin, and calibrate the entire impact flux curve, including that for the post-basin-forming epoch. To successfully address those science objectives, crew training at lunar analogue sites on Earth should include lessons about crater morphology, associated structural elements, the distribution of impact lithologies, and the identification of samples in the field that are suitable for determining the ages of craters. Some of the insights about impact lithologies and crater chronology used by crew during the Apollo missions were wrong and should be improved in a new training program that has the advantage of five additional decades of research at terrestrial impact craters and laboratory analyses of lunar samples.

Well-trained astronauts familiar with mission objectives will collect the samples needed to address those objectives and nothing extraneous. Thus, the sample collection has already been high-graded and no further descoping of samples may be necessary. If we invest large amounts of time and money training astronauts, sending them to the Moon, and supporting their field work, then it seems reasonable to conclude the samples they collect should be returned to Earth.

It is important to emphasize that lunar samples are the key to transformative lunar science and should be a part of every lunar surface mission (*e.g.*, Pieters *et al.*, 2018; Kring, 2020b). Because the Moon has a relatively small gravity well and is close to the Earth, and because lunar rocks and soils are complex geologic materials, returning samples to Earth will be preferred to analyses *in situ* or on an orbiting platform (Kring et al., 2021f). During Apollo, the recovery rate of sample mass was a constant 2.3 kg/EVA hr/crew member from Apollo 12 through 17 (Kring, 2007c; **Appendix S**). Interestingly, sample mass recovery rates during mission simulations (**Appendix G**) are 1.01 – 2.49 kg/EVA hr/crew member (Gruener *et al.*, 2013), similar to those of Apollo. Plans for adequate geologic sample mass should be made (*e.g.*, Kring, 2007c; Shearer *et al.*, 2007; Kring, 2020b). On the other hand, volatile materials may lend themselves to *in situ* analyses, particularly when transport may alter important physical/chemical properties. Techniques that provide elemental and isotopic information about volatile constituents will be needed to address National Research Council (NRC, 2007) objectives.

Well-trained astronauts will be our most important asset on the lunar surface. Missions may be supplemented with complementary instrumentation and robotic assets, but those should be deployed and used in ways that do not undermine the productivity of astronauts. Any additional instrumentation should augment an astronaut's observational skills and capabilities. It should not distract astronauts from making field observations and collecting samples, or require an inordinate amount of maintenance. Also, instrumentation should be avoided that makes measurements that an astronaut can make visually (*e.g.*, the identification of lithologies) or that will be made better once samples are returned to Earth (*e.g.*, the chemical compositions of samples).

While it will remain necessary to conduct task-oriented training (*e.g.*, to deploy a seismometer), as lunar surface stay times and the complexities of surface activities increase, the amount of skill-based training needed will also increase (Ney & Looper, 2006; Kring *et al.*, 2020a).

Training should engage flight and science operational teams. Apollo Flight Director Gerry Griffin emphasized the need for flight operations staff to deploy with astronauts and scientists in field training exercises (Kring *et al.*, 2020a). Likewise, science operations staff need to learn how to work in a human exploration environment. LPI's ***Space Flight Resource Management Training for Science Operations*** program was designed to help meet that need. In this twoweek-long program, participants are taught space flight resource management (SFRM) skills, learn to develop and share situational awareness in a complex mission environment, learn to develop better active listening skills, learn communication protocols, how to package comm-loop calls, and problem-solving skills relevant to a human mission environment.

Science operations staff may also need enhanced geological training. The Apollo field geology teams were drawn from the geologic community, which, at that time, had a strong field training component in university curricula. From the success of Apollo emerged a planetary science community that, in the post-Apollo era, relied on robotic spacecraft for exploration. During Constellation it was recognized that few members of the planetary science community have the same field geology experience as the Apollo generation.

Moreover, impact cratering processes are not taught in most geology departments. Likewise, very few lunar and planetary scientists have significant field-based experience in impact-cratered terrains. (And less than a handful of those scientists are also Apollo sample PIs.) That gap in training is why, during the Constellation Program, the LPI developed field training programs for graduate students and postdoctoral researchers at Meteor Crater, the Sudbury impact structure, and elsewhere. LPI continues to operate those programs, versions of which can be used to train members of an Artemis geology team.

Per recommendations of Apollo personnel and Constellation lessons (summarized in Kring *et al.*, 2020a), integrated lunar mission simulations are also required. At this stage we are training the entire team, not just the astronauts. Flight operations personnel will be learning how EVAs in a geologic terrain work. Science operations personnel will be learning how to conduct EVA operations. Everyone will be learning how to communicate. Geologic tools and other hardware and software elements can be tested and sequentially improved through the Desert Research and Technologies Studies (D-RATS) program or similar activities in facility test sites (*e.g.*, the Neutral Buoyancy Laboratory). A snapshot of that tool-development process has been presented in abstract form (Naids *et al.*, 2020a,b, 2021).

As part of its training activities, the LPI developed several resources for astronauts. And, as is LPI tradition, those resources were made available to the entire academic community. Supporting products are:

- Astronaut's Guide to Terrestrial Impact Structures
- Landsat Images of Meteor Crater
- Space Shuttle and International Space Station Imagery of Meteor Crater
- Integrated ArcGIS-compatible Meteor Crater Map Package
- Atlas of STS and ISS Images of Earth's Impact Craters
- Video Simulations of Impact Cratering
- Lunar Impact Cratering Simulator
- Digital version of Apollo experiment Mare Exemplum (illustrating the consequences of a lunar surface subjected to multiple impact events)
- Laboratory Exercise: Measuring the Depth of Meteor Crater & Height of its Rim
- SEBASS Data for Meteor Crater
- MODIS Satellite Imagery of Meteor Crater

- LPI Library of Classroom Illustrations
- LPI Lunar sample Atlas (including Apollo Thin-Sections and a Virtual Microscope)

The LPI developed several other resources for astronauts, their instructors, and others in the lunar community who are engaged in lunar exploration. Those resources were made available online and include the:

- LPI Lunar South Pole Atlas
- Lunar Surface Flyovers
- Apollo-era Documents
- Lunar Surface Data
- The Consolidated Lunar Atlas
- Lunar Orbiter Photo Gallery
- Ranger Photographs of the Moon
- Digital Lunar Orbiter Photographic Atlas of the Moon
- The Apollo Image Atlas
- Apollo Surface Panoramas
- Atlas of Lunar Sinuous Rilles
- The Lunar Map Catalog
- South Pole-Aitken Basin Landing Site Database
- ALSEP (Apollo Lunar Surface Experiments Package)
- Lunar Impact Crater Database
- Lunar Mission Summaries
- Exploration Strategies
- Computational Tools
- Educational Resources

Those lunar resources are augmented further with an extensive collection of online resources related to Meteor Crater and the Chicxulub Crater.

The distribution of lunar and impact-related resources to anyone with internet access supports LPI's objective to provide opportunities for more diverse participation in exploration of the lunar surface. That effort began in 2006 with the institute's Lunar Exploration Initiative and the creation of the LPI-JSC Center for Lunar Science and Exploration. The institute remains committed to its support of lunar science and exploration as the Artemis program ramps up.