Planetary and Space Science 58 (2010) 920–930

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Scientific field training for human planetary exploration

D.S.S. Lim [a,b,*], G.L. Warman [c], M.L. Gernhardt [d], C.P. McKay [a], T. Fong [a], M.M. Marinova [e], A.F. Davila [a,b], D. Andersen [b], A.L. Brady [f], Z. Cardman [g], B. Cowie [h], M.D. Delaney [i], A.G. Fairén [a,b], A.L. Forrest [j], J. Heaton [k], B.E. Laval [j], R. Arnold [d], P. Nuytten [k], G. Osinski [l], M. Reay [k], D. Reid [j], D. Schulze-Makuch [m], R. Shepard [n], G.F. Slater [o], D. Williams [p]

[a] NASA Ames Research Center, Mail-Stop 245-3, Moffett Field, 94035 CA, USA
[b] SETI Institute, 515N. Whisman Road, Mountain View, 94043 CA, USA
[c] ExperiencePoint, 800 West El Camino Real, Ste 180, Mountain View, 94025 CA, USA
[d] NASA Johnson Space Center, 2101 NASA Parkway, Houston, TX 77058, USA
[e] Planetary Science, California Institute of Technology, MC 150-12, Pasadena, CA, USA
[f] Department of Biological Sciences, University of Calgary, 2500 University Drive NW, Calgary, Alberta, Canada
[g] University of North Carolina at Chapel Hill, Department of Marine Sciences, 340 Chapman Hall, CB 3300, Chapel Hill, NC 27599-3300, USA
[h] Applied Geochemistry Group, University of Calgary, 2500 University Drive NW, Calgary, Alberta, Canada
[i] The Edge Diving Centre, 973 Marine Drive, North Vancouver, B.C., Canada
[j] Department of Civil Engineering, University of British Columbia, Vancouver, B.C., Canada
[k] Nuytco Research, 241A East 1st Street, North Vancouver, B.C., Canada
[l] Department of Earth Sciences, University of Western Ontario, London, Ontario, Canada
[m] School of Earth and Environmental Sciences, Washington State University, Pullman, WA, USA
[n] Geology Department, University of California, One Shields Avenue, Davis, CA USA
[o] School of Geology and Geography, McMaster University, Hamilton, Ontario, Canada
[p] McMaster Centre for Medical Robotics, McMaster University, Hamilton, Ontario, Canada

ARTICLE INFO

Article history:
Received 6 May 2009
Received in revised form
20 February 2010
Accepted 24 February 2010
Available online 2 March 2010

Keywords:
Field science
Planetary exploration
Astronaut
Training
Pavilion lake

ABSTRACT

Forthcoming human planetary exploration will require increased scientific return (both in real time and post-mission), longer surface stays, greater geographical coverage, longer and more frequent EVAs, and more operational complexities than during the Apollo missions. As such, there is a need to shift the nature of astronauts' scientific capabilities to something akin to an experienced terrestrial field scientist. To achieve this aim, the authors present a case that astronaut training should include an Apollo-style curriculum based on traditional field school experiences, as well as full immersion in field science programs. Herein we propose four Learning Design Principles (LDPs) focused on optimizing astronaut learning in field science settings. The LDPs are as follows:

(1) LDP#1: Provide multiple experiences: varied field science activities will hone astronauts' abilities to adapt to novel scientific opportunities
(2) LDP#2: Focus on the learner: fostering intrinsic motivation will orient astronauts towards continuous informal learning and a quest for mastery
(3) LDP#3: Provide a relevant experience—the field site: field sites that share features with future planetary missions will increase the likelihood that astronauts will successfully transfer learning
(4) LDP#4: Provide a social learning experience—the field science team and their activities: ensuring the field team includes members of varying levels of experience engaged in opportunities for discourse and joint problem solving will facilitate astronauts' abilities to think and perform like a field scientist.

The proposed training program focuses on the intellectual and technical aspects of field science, as well as the cognitive manner in which field scientists experience, observe and synthesize their environment. The goal of the latter is to help astronauts develop the thought patterns and mechanics of

---

[*] Corresponding author at: NASA Ames Research Center, Mail-Stop 245-3, Moffett Field, 94035 CA, USA. Tel.: +1 650 604 0098; fax: +1 650 604 6779.
E-mail address: darlene.lim@nasa.gov (D.S.S. Lim).

doi:10.1016/j.pss.2010.02.014

an effective field scientist, thereby providing a broader base of experience and expertise than could be achieved from field school alone. This will enhance their ability to execute, explore and adapt as in-field situations require.

1. Introduction

Gene Shoemaker[1] advocated astronauts be "instruments of scientific discovery". His opinion was formed during the Apollo era, which focused on proofing technologies, as well as collecting lunar rocks and visual data for post-mission scientific analyses. Apollo Moon missions were characterized by short stays and geographically restricted extra-vehicular activities (EVAs). As such, scientific training efforts were designed to ensure that Apollo astronauts were versed in geological methods, terminology and techniques relevant to their exploration of the Moon (see Wilhelms, 1993 for overview). Training evolved as the Apollo program moved from the G to the J class missions, which involved longer, more complex EVAs, and an increased emphasis on scientific return. Instruction to prepare the astronauts included both classroom and field activities, the latter of which took them to locales around North America such as Meteor Crater in Arizona, Kilauea Volcano in Hawaii, and the Sudbury Impact Crater in Ontario, Canada. These sites were chosen for their relevance as lunar analogs where astronauts could enhance their scientific knowledge, and ultimately possess the ability to act as proxy scientists on the Moon. The training efforts were deemed a success. Indeed, NASA's Apollo era astronauts demonstrated a high degree of sophistication in real-time and post-mission scientific activities.

Shoemaker's philosophy still resonates today as we enter a new era of human space exploration. It is reasonably anticipated that NASA's Exploration Architecture for the next round of human planetary exploration will include increased demand for scientific return both during and after the mission, longer surface stays, greater geographical coverage, more frequent and lengthy EVAs, and more operational complexities to test and ground truth preliminary conclusions reached from remote-sensing experiments, and to explore previously unsurveyed regions.

These factors will allow for and demand a greater degree of intellectual, physical and operational autonomy for the astronauts relative to what occurred during the Apollo missions. Harrison "Jack" Schmitt was the only formally trained field scientist to take part in the Apollo missions. In the future, predominantly selecting experienced field scientists as astronauts would be one mechanism to ensuring a high degree of scientific return, innovation and discovery on the Moon, Mars, and other targets such as Near Earth Objects (NEOs). Realistically, however, astronauts will be chosen from a variety of backgrounds, both scientific and non-scientific, and crews will comprise a mixture of expertise. This creates both an opportunity and a need to shift the nature of astronauts' scientific capabilities to something akin to an experienced terrestrial field scientist. A summary of past and present scientific exploration circumstances is summarized in Table 1.

To achieve this aim, we propose that training include an Apollo-style curriculum based on traditional field school experiences, as well as full immersion in field science programs. Herein we propose four Learning Design Principles (LDPs) focused on optimizing astronaut learning in field science settings. The proposed training program would focus on the intellectual and technical aspects of field science, as well as the cognitive manner in which field scientists experience, observe and synthesize their environment. The goal of the latter is to help astronauts develop the thought patterns and mechanics of an effective field scientist. This will offer them a broader base of experience and expertise to draw upon in order to hone their ability to execute, explore and adapt as the situation requires. This field science training could be used to train both individual astronauts and pre-determined teams of astronauts.

In effect, astronauts can become both *instruments* and *innovators* of scientific discovery, and we expect large scientific gains to result. A recent Field Exploration Analysis Team (FEAT) white paper (Schmitt et al., in review) describes the need to develop astronauts with the field science know-how to be able to "interpret the unexpected," or at least collect the data that can eventually be used to interpret the "unexpected." The purpose of this paper is to present ideas on how to connect on-going and future exploration and science activities, and to use this synergy to prepare astronauts so that they can face the unforeseen, unexpected scientific circumstances that are commonly encountered by terrestrial field scientists, and which will undoubtedly be encountered on a variety of planetary settings.

Table 1
Comparison of Apollo era versus future human planetary exploration opportunities and astronaut training needs. The additional opportunities and training needs for future missions are in BOLD.

Apollo	Future human planetary exploration activities
Opportunity: Proofing of technological innovations on the Moon and the application of well-established field methods in geology and geophysics to the collection of rock and visual data for post-mission scientific analyses by extended (terrestrial) science team	Opportunity: Proofing of technological innovations on the Moon/**Mars/other planetary bodies** and the application of well-established field methods in geology and geophysics to the collection of rock and other data for **real-time** and post-mission scientific analyses by **immediate (astronaut)** and extended (terrestrial) science team **More in-depth scientific discovery and innovation while conducting on-site planetary exploration**
Astronaut science training requirements: Grounding in relevant geological and field techniques, including data collection, nomenclature, and sample triage	Astronaut science training requirements: Grounding in relevant geological and field techniques, including data collection, nomenclature, and sample triage **Experience and expertise in field science techniques, including cognitive, operational, and team science components of field science**
Training method: *Field school*—Classical geological field school activities, including classroom and field learning	Training method: *Field School*—Classical geological/biological field school activities, including classroom and field learning ***Field science*—immersion in real field science activities**

---

[1] Eugene M. Shoemaker created the research field of planetary science, and was affiliated with the US Geological Survey and the California Institute of Technology (Caltech). Among many legendary accomplishments, he was also involved with Apollo astronaut field training. More information about Dr. Shoemaker can be found at http://astrogeology.usgs.gov/About/People/GeneShoemaker/.

We thus present a case for this developmental training, and put forward four LDPs for a training program that would enable the development of adaptive, scientifically minded, exploration field scientist–astronauts. These are as follows:

1) LDP#1: Provide multiple experiences: varied field science activities will hone astronauts' abilities to adapt to novel scientific opportunities;
2) LDP#2: Focus on the learner: fostering intrinsic motivation will orient astronauts towards continuous informal learning and a quest for mastery;
3) LDP#3: Provide a relevant experience—the field site: field sites that share features with future planetary missions will increase the likelihood that astronauts will successfully transfer learning; and,
4) LDP#4: Provide a social learning experience—the field science team and their activities: ensuring the field team includes members of varying levels of experience engaged in opportunities for discourse and joint problem solving will facilitate astronauts' abilities to think and perform like a field scientist.

2. Distinguishing field school from field science

Science and engineering objectives during the Apollo missions were focused on the collection of rock and visual data for post-mission scientific analyses and proving technological innovations. To prepare astronauts for the science objectives, carefully crafted classroom lectures along with field excursions to lunar analog sites were designed. The classes and field excursions were typically taught by well-respected and highly experienced field geologists, who in many cases had been intimately involved with the characterization of the field sites and their subsequent analytical juxtaposition to locations on the Moon. Trainees were exposed to the disciplined field ethic that enables the deciphering of our Earth's dynamic history from observations of static rocks.

In any field school, the answers to questions posed to the trainees are usually known and the Apollo sessions were no exception. That is, when presented with a field site that has been previously characterized there is a safety net of known facts and understandings that will catch and reset misconceptions and scientific missteps. This type of field experience is important, and one which every professional field scientist has had to undergo to ensure that they have a solid academic grounding in relevant terminology and field techniques. In essence, field school is an extension of the classroom experience. However, it is the process of conducting hands-on field science, as part of ground-breaking research activities that ultimately leads to the ability to innovate in new situations and formulate new hypotheses.

Future human planetary exploration will present an opportunity for real-time and post-mission scientific analyses by the immediate (astronaut) and extended (terrestrial) science teams, as well as the opportunity for scientific discovery and innovation while still on site. The key here is to ensure that the astronauts possess adaptive field expertise such that they are trained to reconstruct and reassemble knowledge so that it can be applied in new and novel situations. Replicating skills and knowledge is very different from adapting and innovating in novel situations. Schwartz et al. (2007) present an extensive study of the various academic solutions to ensuring knowledge transfer in learning environments, and their conclusion states that "the ability to transfer and innovate grows from experiences where people gain insight into important environmental structures and their possibilities for interaction." While *field school* can provide a solid grounding in classical geological techniques, the experiences necessary for an astronaut to be able to effectively transfer knowledge from terrestrial settings to those of other planetary bodies will need to also stem from real *field science*.

In field science programs, the answers to scientific questions are not known, and there precise sample collection, handling and post-processing is critical. Task loading is real in field science settings, and must be properly managed to ensure that the scientific and exploration objectives of the research team are being met. Placing the astronauts in real science and exploration training environments will help them develop habits of thinking such that when the unpredicted is encountered, there are innovative and reliable thought processes based on experiences, which can be drawn upon to ensure that discoveries are not missed along the way. This will help to enhance their classical field school training and give them a real-world, field science breadth of experience that will result in EVAs with high scientific return. As well, these activities will engender a deeper commitment to the scientific process and will ensure that the highest level of scientific integrity is strived for throughout the mission.

3. Execution versus discovery—the 'exploration method'

As part of a field science training program, each real-field excursion should contribute towards a broad base of experience, and each initiative should help develop strong observational scientists for future human planetary missions. Osinski et al. (2009) discuss operational guidelines for conducting science on the Moon and Mars, making note of the need for EVA planning that allows for science discovery. Here, we discuss how best to equip astronauts with the necessary experience to make those discoveries. We recommend that the best approach is to facilitate the negotiation of two seemingly incompatible modalities of thought: (1) Discovery Mode and (2) Execution Mode. Both are important to the success of an EVA, however, while the latter can be taught in Apollo-like training curriculums, the former is best taught, learned and refined in real scientific exploration scenarios.

In support of these statements, we begin by examining and comparing the two thought modalities. Characteristics associated with each are listed in Table 2.

Both intellectual modalities are essential to gaining a contextual understanding of one's environment and to being a successful field/observational scientist. Depending upon the goals of a field excursion, one mode of operation might be employed more than the other. It is the seamless movement between modalities by the field scientist that allows for both disciplined science and seminal discoveries to occur. In *Execution* mode, the scientist will prioritize established protocols, objectives and methods when exploring. Should something unplanned or out of the ordinary occur, protocols and if–then considerations are used to reason through the situation. In *Execution* mode, convergent thinking, which emphasizes recognizing the familiar and reapplying set techniques, is used to derive the single best answer to a clearly defined question. By comparison, in *Discovery*

Table 2
Characteristics of Discovery and Execution modalities.

Discovery	Execution
Curiosity trumps efficiency	Efficiency trumps curiosity
Push boundaries	Optimization within boundaries
Reasoning through analogies	Reasoning through protocols
Divergent thinking	Convergent thinking

mode, the scientist will still use the scientific method to explore, however, they will prioritize the unusual above a set task. In this modality, divergent thinking dominates. As such, hypotheses will be generated from across disciplines in order to better understand and contemplate the new and unknown.

We argue that there are two types of exploration: the 'Treasure Hunt' and the 'Tour.' In the case of the former, a clear discovery goal is defined for the activity (e.g. to find groundwater), whereas in the latter, the only goal is to observe one's environment and the discoveries are defined as they are found or even after subsequent review of the exploration (e.g. reconnaissance of a new, unexplored region).

In both cases, discovery is the overarching goal of the exercise. However, in the case of the Treasure Hunt scenario, it is easy to overemphasize Execution over Discovery in terms of a method of exploration. The identification of a set target or goal is most efficiently accomplished by using Execution mode to focus on cues in their environment, which lead to the target. However, it is important that the scientist is cognizant of being able to process their environment in both modalities so as to not miss discoveries that were unplanned and possibly equally if not more impactful to the scientific understanding of the environment than those that were earmarked as goals. By comparison, in the Tour scenario, the scientist may overemphasize the need to operate in the Discovery modality. In this situation, the scientist might, for example, spend an inefficient amount of time at one site of interest as a consequence of underestimating the need to optimize these finds within reasonable operational boundaries, that is, in Execution mode.

The interplay and balance of both exploration modalities is intuitive to an experienced field scientist. The ability to operate in both modalities requires: (1) academic training, (2) hours spent in the field conducting both 'Treasure Hunt' and 'Tour' type of exploration, (3) constructive mentorship, and (4) analysis and reflection upon the success of their field observations in accomplishing the set task and in maximizing science return.

4. The Learning Design Principles

The opportunity for scientific return in future missions is unprecedented. Consequently, tomorrow's astronauts do not simply need to better understand field science, they need to become field scientists. As discussed, field science exemplars approach their work with a unique mindset that enables appropriate and seamless movement between the two unique thought modalities of Discovery and Execution.

Cultivating thinking patterns is a significant challenge and is significantly different from pure knowledge transfer. Educational researchers have explored numerous methods for engendering conceptual change, and current theories are best expressed from the situative perspective on learning and development.

The situative view of learning focuses on engaged participation (Greeno et al., 1996). Learners become more adept at contributing to a domain area and can derive identity by becoming involved in environments that demand certain interactions and personal investment. Therefore, for astronauts to become proficient field scientists, they must engage as full participants in field science teams working on actual research. Moreover, the adherence to key Learning Design Principles (LDPs) in shaping these learning experiences can build meaningful field science expertise with maximum efficiency.

Our LDPs in combination address the learning system holistically. An overarching LDP is the need for astronauts to engage in multiple field experiences that differ in research goals, techniques, sites, and teams. We then focus on the field site (select many appropriate sites (LDPs 1 and 3)), the Learner (LDP 2), and the participating field team and its specific activities of engagement (LDP 4). The LDPs are focused, but flexible and therefore can provide guidance and be applicable to any field site in the world. Ideally, a community of learning will form around these LDPs and their manifestation in different field research projects. This community will share best practices to improve the overall effectiveness of the astronauts' training.

In all cases, it will be the responsibility of the science and exploration personnel working with the astronauts to use the following LDPs to develop a training program that fits their field site and their field/research goals. It will also be incumbent upon the research group to have a clear science plan in place that should be communicated to the astronaut participants. If complications, unexpected discoveries, technical setbacks, or the like are encountered during the field session, a clear scientific field objective will ensure that the entire team has a vision upon which to rely as they reorganize, reprioritize and mobilize.

4.1. LDP#1: provide multiple experiences

4.1.1. Providing experience in varied field science projects will hone astronauts' ability to adapt to novel scientific opportunities.

It is through multiple, relevant and varied field science experiences that one can develop the ability to innovate and adapt to novel situations. By engaging in multiple field projects, astronauts will experience how different field researchers *approach* a variety of scientific opportunities. "Approach" constitutes both the Discovery and Execution methods and sensibilities used by field scientists in the performance of their work. It is expected that this experience will increase the likelihood that astronauts on other planetary bodies, assisted by remote science teams on Earth, will be able to adapt their scientific research according to the opportunities presented *in situ*.

As was the case in the geological training for the Apollo missions, field science experience will result in the explicit learning of relevant scientific techniques and language. Fluency in these areas will have a direct payoff in extra-planetary sample identification, collection, and analysis. *Multiple* experiences necessarily increases "time-on-task", the absolute amount of cognitive investment the learner makes in the material. Time-on-task is directly correlated with increased learning (Brophy, 1988). Beyond these gains, there are also significant benefits associated with multiple experiences from the perspective of implicit learning.

It is known that multiple, varied experiences can improve people's ability to appropriately transfer knowledge into novel scenarios for at least two reasons. The first is that multiple applications of an approach in environments that offer different surface features (i.e. those elements we can perceive on the surface), engenders a better understanding of the "deep structure" of the approach than multiple forms of traditional instruction (Gick and Holyoak, 1983). For example, performing sample collection in an underwater environment and again in a polar desert environment confers fundamentals about collection methods (e.g. criticality of extracting without compromising the structural integrity of the sample). The second reason relates to the implicit comprehension of the scope of applications for a piece of knowledge. It is theorized that the brain attends to and encodes variability in surface features when experiencing instantiations of a concept. The greater the variability in surface features, the more readily people can identify opportunities for applying a concept. For example, a simple operational heuristic for mission planning that is introduced in one research project, may resurface as an operational heuristic for sample collection in another project. The two vastly different scales of the applications (i.e. one mission, the other tactically oriented) implicitly confer multiple opportunities for applying the heuristic.

There are sites and field programs the world over that would be able to contribute to the development training of astronauts, as well as benefit from their inclusion in the science and exploration. These field programs could range from short (<2 weeks) to long (>2 weeks) duration field stays, and range from small (<10) to large (>10) groups. These science and exploration activities could be found throughout the year *as well as in a wide variety of locations and environments,* thus providing ample opportunity to form insights about environmental structures and their potential for interaction.

4.2. LDP#2: focus on the learner

4.2.1. Fostering intrinsic motivation will orient astronauts towards continuous informal learning and a quest for mastery.

The field science and exploration program should engender a sense of intrinsic motivation in the astronaut by stressing the need for a commitment to not only field science and exploration objectives, but also personal development objectives. This is an important factor in ensuring that (a) the individual is intrinsically motivated to learn and (b) that learning is focused on specific outcomes.

Goal Theory focuses on learner motivation and suggests learners approach new domains with a mixture of two types of goals: (1) Performance Goals, and (2) Mastery Goals. Performance Goals are tied to a learner's desire for external rewards such as praise or the avoidance of criticism. Mastery Goals reflect a learner's desire to become proficient and is associated with deeper engagement and greater perseverance in the face of setbacks. A Mastery orientation enhances the depth of learning and willingness to engage in the subject matter even after formal learning structures are removed.

Although a learner may bring a particular goal bias to learning experiences, it has been demonstrated that certain techniques can induce a Mastery orientation (Malone and Lepper, 1987). For example, the abilities to personalize elements in the learning experience and to choose different aspects of the learning activity can increase intrinsic motivational appeal (Cordova and Lepper, 1996). Therefore, we recommend that choice and personalization enter into the design of astronauts' involvement in field research.

Choice at a macro level involves an astronaut choosing to participate in this learning program. The next choice relates to which field research projects an astronaut wishes to join. Finally, an astronaut may also be asked to make choices about the specific activities he or she chooses to engage in as part of a research project. Personalization may take many forms, however, most relevantly would be to have astronauts take full responsibility for a part of the data gathering, analysis and synthesis, such that ultimately their results form part of a peer-reviewed manuscript, for example.

4.3. LDP#3: the field site

4.3.1. Selecting field sites that share features with future planetary missions will increase the likelihood that astronauts successfully transfer learning

It is clear that knowledge does not exist absent from the context in which that knowledge was acquired. The brain encodes the conscious and subconscious perceptions that occur coincident with learning something. Therefore, memory and the subsequent ability to transfer knowledge successfully are heavily reliant on perceptual cues.

A specific aspect of this phenomenon that has direct bearing on the design of field science learning experiences for astronauts relates to the definition of "context", meaning not only the physical surface features of an environment (sight, sound, smells), but also the mental and emotional state of the learner at the time of knowledge acquisition. A learning environment that reflects the context of future missions will increase the likelihood that astronauts correctly transfer learning.

Therefore, we recommend that in the near future, training programs are established at sites where (a) there are on-going scientific exploration activities, (b) the site or activity has some first-order features similar to the planetary body of interest and (c) the environment has an element of operational complexity in order to provide a degree of emotional fidelity to their experience. Moreover, Lee and McKay (2008) suggest the following key factors be considered in the evaluation of a field site or activity for relevance to lunar or Mars exploration: (1) aspects of interest, (2) applications, (3) functions, (4) fidelity and (5) value. The following is a general list of environments that would, in our opinion, be prime target regions for on-going scientific programs in which astronauts could be embedded as field scientists:

Underwater environments are well-suited analogs as safety and 100% reliance upon technology for survival is at the forefront of all operations. The underwater environment provides a useful analog for studies of (1) human performance in intrinsically lethal environments, (2) optimization of human and robotic interactions in an environment where human mobility is encumbered, (3) comparison of teleoperated and robotic assistant modes, (4) testing and operational use of scientific instrumentation and tools for augmenting human senses in an environment where the normal human senses are impaired, and (5) the effects on humans and robots in distinctive varieties of extreme life support limited environmental conditions from altitude considerations, to overhead ice to extreme temperature variations. An example of science and exploration activities in an underwater environment is the Pavilion Lake Research Project (www.pavilionlake.com).

Cold and hot desert environments subject the explorer to the constant pressures of the elements and of logistically challenging locales in which to conduct science. While the level of dependence upon technology for human survival is significantly lower than in the underwater environment, the hostile weather of the High Arctic, the Antarctic Dry Valleys or the Atacama Desert present their own challenges for human survival. These environments provide the closest visual analog to the surface of Moon and Mars, and feature a large diversity of geologic landforms that the astronauts will encounter during their EVAs. As well, there are many fascinating and unexplored scientific questions related to physical and biological aspects of these environments. An example of an ideal polar desert training environment is the Haughton Mars Project, which operates in the Canadian High Arctic.

Deep mines and other underground environments provide the opportunity to gain field science and exploration experience with the added risk factors associated with operating in these dangerous settings. These field settings have relevance to our understanding of life in extreme environments. Field scientists who work in underground environments must contend with tight operational constraints on their field activities to minimize risk and maximize safety. Simultaneously they must carefully gather data to limit sample contamination and loss of information. The confluence of astrobiologically relevant science and challenging operational constraints make these field settings relevant and analogs to conducting human science and exploration on other planetary environments such as the Moon and Mars (e.g., within lava tubes). As such, real scientific experience in these environments stands to have an important impact on the field capabilities of astronauts.

Impact craters are one of the most widespread and abundant geologic features on the surface of the Moon and Mars, and are considered important targets for future robotic and human missions. The complexity of impact craters, not only in terms of their geologic features and mineralogy, but also accessibility, will require that the astronauts become familiar with this type of environments on Earth. Numerous sites, such as Meteor (Barringer) Crater and the Haughton impact structure (Devon Island), have already been used for astronaut field training and field science campaigns.

Volcanic structures have been widely used for astronaut field geology training, ranging from active sites (e.g., Kilauea) to old lava flows (e.g., Black Point Lava Flow). These environments provide many similar geologic features to those found on the lunar surface (Schaber, 2005).

4.4. LDP#4: the field science team and their activities

4.4.1. Ensuring the field team includes members of varying levels of experience engaged in opportunities for discourse and joint problem solving will facilitate astronauts' abilities to think and perform like a field scientist

Traditional perspectives on learning postulate that it is the interaction between the learner and the material that results in the acquisition of knowledge. This view also suggests that learning "has a beginning and an end; that it is best separated from the rest of our activities" (Wenger, 1998).

The situative perspective, however, highlights both the social and informal nature of learning. Researchers Jean Lave and Wenger (1991) have coined the term "Communities of Practice" to describe dynamic groups that build collective knowledge through shared passion, regular interaction and domain specialization. New community members acquire and contribute to this collective knowledge in time through social situations of co-participation.

Opportunities for co-participation are therefore critical in the learning design of field science for astronauts. Activities such as science meetings based on the daily findings of the research team and mission planning for new excursions should involve astronaut participants. It is anticipated that astronauts will be able to engage fully in such activities as they become increasingly familiar with the field team and their practices.

We also hypothesize that if the field team is composed of both seasoned field scientists and graduate students of varying levels of experience, astronauts will be able to more quickly become active participants. Graduate students are typically eager to learn and to gain experience, and as such their participation in "sense-making" through contribution and inquiry will inherently help astronauts learn about the methods and sensibilities of field scientists.

One of the main goals of social learning is to work to close the knowledge gap between experts and non-experts through group participation. Another goal is to allow the students to grow and develop their skills at their own comfort level. Revisiting the importance of context to learning, if the student is uncomfortable or stressed, for example, learning will be more difficult. As such, it is important for the project leads to ensure that the astronauts are (a) actively integrated into the field team's activities by providing pre-, during and post-field activity learning opportunities, (b) trained in the necessary scientific and exploration skills to become an active, contributing field participant, and (c) provided many opportunities for dialog with experts to share their personal thoughts and questions.

4.4.2. Integration

During their inclusion with the research team, the astronaut should be working jointly with experienced field scientists on activities that will enhance the astronaut's scientific knowledge and field experience. As part of this process, the field team must ensure that the trainees are not treated as guests, VIPs, or passengers, but rather truly as members of the science and exploration team. Prior to the field season, they should be given the scientific and exploration training necessary to allow them to contribute to the entire process. In the field, they should eat, work, play and sleep as the rest of the team, and contribute to data recovery, synthesis and other discussion. After the field season, ideally their integration should continue by involving them in sample and data analyses, and ultimately the publication of a peer-reviewed manuscript. This will work to ensure that the astronauts gain a holistic understanding of field science, as it is typically the case that most if not all of the data analysis and synthesis occurs after the research team has returned from their field work. Understandably this final component might get truncated given the scheduling demands of an astronaut's life. As such, it truly falls to the research team to create opportunities for continued interaction and involvement.

To ensure that astronaut integration into the research team occurs, the astronauts should be allocated science tasks and responsibilities that are similar to other field team members and that are equally as important to the final scientific and exploration success of the mission as those of other field participants. As an example, they could actively participate in (1) the mapping and exploration of unknown environments by collecting and synthesizing data, (2) the collection, handling and preparation of field samples from environmentally sensitive environments, (3) *in situ* or *in field* sample analyses, or (4) the deployment of field instrumentation for data collection. If daily science discussions are held, then they should be given the opportunity to participate, first as observers and then as their comfort and knowledge increases, as active contributors to the discussion. Furthermore, their logistics and support role in the field camp must be similar to those of the other participants as well. This will mean that astronauts are involved in such activities as daily operations, traverse planning, equipment maintenance, and education and public outreach events. This level of integration will lead to the most value for each party, and help to create a team environment that will have training, and more importantly, scientific and exploration benefits to the research team, as well as to the human scientific exploration of various planetary bodies.

We also stress the importance of allowing the astronauts to participate as an observer at different stages of the field science activity. It is during these periods of training where it is likely that they will be afforded the opportunity to observe the application of the Execution and Discovery thought modalities. They will be able to synthesize and reflect upon those skills and qualities that they see in the field experts that they find most important in developing their field science experience. They will be able to draw personal learning from the group as a whole.

4.4.3. Pre-season training

To adequately prepare the astronaut for their upcoming field science experience, we suggest that some pre-season training is provided to them. Essential components of the pre-field season training should involve classroom lectures, individual study and other preparatory work to ensure that each trainee is well grounded in the information necessary to be an effective and productive member of the field team. As a consequence of these preparatory exercises, there will be a higher likelihood of commitment to the project and integration into the field team of the trainee. This will have benefits to both the trainee, in terms of their development as a field/observational scientist, and to the field/research team, in terms of scientific and exploration return. Depending upon the field site, the length of these pre-season activities will vary. Appendix A lists preparatory exercises to consider in the pre-season training curriculum.

4.4.4. One-on-one time

Finally, one-on-one communication between the astronaut and a field expert is a necessary component to creating a safe and nurturing learning environment. For any scientist, this type of dialog can be one of the most important influencing factors in long-term success. A lack of communication can lead to potential that is never realized, while caring, thoughtful dialog can lead to the development of original, cutting-edge thinkers. Ideally, this more intimate social learning interaction should continue between the expert and the astronaut from pre- to post-season field activities. With personalized input and direction from field team participants, each astronaut will have the opportunity to critically analyze their own progress, check their assumptions, and ensure that they are working in the appropriate thought modality in any given situation.

5. A case study: Pavilion Lake Research Project—example of a relevant underwater learning context for human planetary exploration

As addressed in Section 4, there are many well-suited terrestrial analogs for preparing humans and supporting technology for the rigors of space exploration both through field school (simulation) and field work (science and exploration) activities. As an example, activities at the Pavilion Lake Research Project (PLRP) present a relevant and unique learning opportunity for astronauts to take part in science and exploration field activities in an underwater setting (the first field setting mentioned). Underwater environments present the opportunity to experience unplanned, unexpected happenings and discovery in an extreme setting where individuals are forced to depend on their equipment.

The PLRP is an underwater field science project that is focused on Safety, Environmental Stewardship, the Advancement of Science and the Advancement of Exploration. A synopsis of PLRP scientific exploration activities and results can be found in Lim et al. (in review). With these principles in mind, the PLRP has been conducting scientific research to understand the factors influencing the formation, morphogenesis, and associated biological signatures (biosignatures) in Pavilion Lake, B.C., Canada (50°51′N, 121°44′W) (Fig. 1). The PLRP is made up of a multidisciplinary team of experienced field scientists, and in 2008 was joined by their first astronaut trainee. The PLRP's science and exploration goals directly address Mars science questions pertaining to the identification and characterization of mineralized biosignatures. PLRP research participants have been: (1) exploring the physical and chemical limnological properties of the lake, especially as these characteristics pertain to microbialite formation (Lim et al., 2009; Forrest et al., 2008), (2) using geochemical and molecular tools to test the hypothesized biological origin of the microbialites (Brady et al., 2009), and (3) using geochemical and microscopic tools to characterize potential biosignature preservation in the microbialites (Brady et al., accepted for publication). To address these goals, the PLRP established the DeepWorker Science and Exploration (DSE) program in 2008. At the heart of this program are two DeepWorker, single-person submersibles (Fig. 2) that offer Scientist Pilots (SP) an opportunity to study the lake in a 1-atmosphere (atm) environment. The increased range, life support duration, and depth capabilities of the DeepWorker subs have allowed project members to (a) map Pavilion Lake to gain a contextual understanding of microbialite distribution and the environmental influences affecting their placement throughout the lake, and (b) sample microbialites from the deepest regions of the lake (60 m).

Many of the challenges associated with the human scientific exploration of underwater environments such as Pavilion Lake are analogs to those we will encounter on the Moon, Mars and other planetary bodies. The physical, mental and operational rigors associated with the SCUBA diving and DeepWorker operations at Pavilion Lake are directly relatable to astronaut EVA scenarios using spacesuits and pressurized rovers, respectively. Underwater, humans must, as they do in space, contend with limited connection to colleagues, protection/isolation from the environment, and life support systems (LSS), all while exploring and conducting science in variable and unfamiliar terrains. These working constraints are not simulated, but real and inextricable from the PLRP's activities. Moreover, the PLRP researchers must ensure that they accomplish their science objectives, and shift and balance through Discovery and Execution modalities while exploring the lake to ensure the highest science and exploration return on each submersible or SCUBA dive.

The PLRP DSE program was deployed in both June 2008 and July 2009 to map Pavilion Lake. High-definition (HD) video was used to document Science Pilot (SP) audio and visual observations. The SPs were also tasked with collecting microbialite samples below safe science diving depths (i.e. greater than 40 m). Results from the 2008 and 2009 DSE campaigns (Marinova et al., in prep.) have shown a high level of success in providing insights into the environmental factors influencing microbialite

Fig. 1. From left to right: Pavilion Lake, British Columbia, Canada (*Source*: N. McDaniel); Microbialite formation in Pavilion Lake (*Source*: D. Reid).

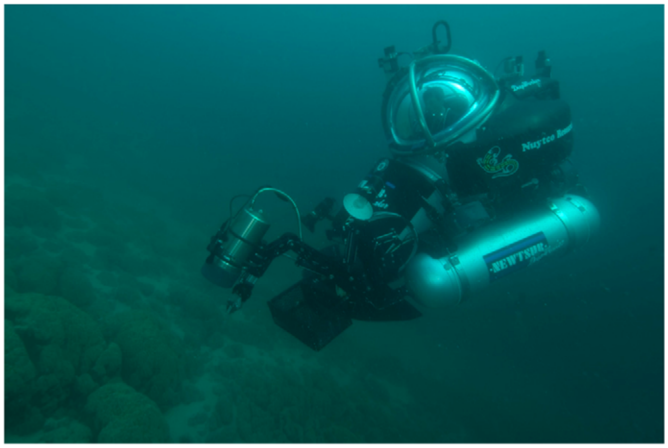

Fig. 2. Human scientific exploration of Pavilion Lake using DeepWorker, single-person submersible built by Nuytco Research Incorporated (*Source*: D. Reid).

distribution and morphology, and the geochemical variability of microbialites throughout the lake.

Given the relevance of the Pavilion Lake experience to human scientific exploration of planetary bodies, the PLRP broadened their goals to include several exploration foci as well. This resulted in the inclusion of NASA astronauts in the 2008 and 2009 PLRP DSE field activities. The astronauts were fully immersed in the program and trained as DeepWorker submersible SPs alongside the rest of the research team (Fig. 3). After training, the astronauts participated as SPs and completed science and exploration submersible dives, along with other activities such as traverse planning, sample triage and SCUBA dives to help meet the research program's goals of mapping and deep microbialite sampling in the lake (Fig. 4). The SPs had to complete set flight plans that either targeted deep (>30 m) microbialite sampling, or extensive mapping. While piloting the submersibles, the SPs were required to act as the main data recording tool, capturing observations through audio and video recordings. The guiding philosophy was that, above all else, the visual and audio observations of the SPs were prioritized. The on-board HD video camera was considered a back-up tool for documenting what the SPs were seeing. Descriptions had to include morphologies, substrate, transition states, biological characteristics, water quality, as well as "targets of opportunity" (TOPS). TOPS were identified prior to the field deployment and were characterized as those targets worth deviating from the flight plan to describe, visually document using video, and sometimes sample (Forrest et al., 2010). When needed, the SPs sampled microbialites using hydraulic manipulators attached to the subs, and placed them in a sample basket attached to the subs.

The 2008 field session was considered a pilot program for the DSE activities, where the LDPs presented herein were developed and partially implemented. In 2009, the LDPs were fully applied to a more developed training program. Video data collected by the astronaut SPs were both useful and impactful to the mapping of Pavilion Lake microbialites (Marinova et al., in prep.). The data collection success from the astronaut SP can be attributed to adequate preparatory submersible and scientific training, as well as 100% immersion in the end to end process of planning, executing and discussing/synthesizing submersible dives and data collection activities. The astronaut SPs were an intrinsic part of the research team. They actively contributed to scientific discourse and traverse planning activities while at Pavilion Lake (Fig. 4A). Without the astronauts' data collections the Pavilion Lake map would not have been completed.

Fig. 3. PLRP DeepWorker Science and Exploration (DSE) DeepWorker submersible training activities in Vancouver, Canada. 2008 training activities (top photo; *Source*: L. Stang), 2009 training activities (bottom photo; *Source*: D. Lim).

The PLRP DSE program is at one end of the spectrum of research programs that not only provide a science and exploration experience, but also human and environmental risk factors that are analogs to those encountered in space. This degree of fidelity does not always have to be in place for a field science and exploration activity to provide useful training opportunities to astronauts. Once again, the most important aspect of our suggestions is to provide a breadth of science and exploration experiences of varying degrees of direct operational analogy to astronauts, such that they have a broad base to draw upon when faced with new and novel situations on various planetary bodies, such as Mars.

6. Conclusions

The planetary bodies within our solar system are natural environments with undiscovered complexity, and as such field science will be intrinsic to the process of exploring these worlds. There will be no shortage of discoveries to be made in these environments—we will never exhaust the scientific potential as there will always be new questions to answer. This is the case on Earth, and will most certainly be the case on other vastly unexplored planetary environments. In our preparation for human planetary missions it will therefore be essential to develop

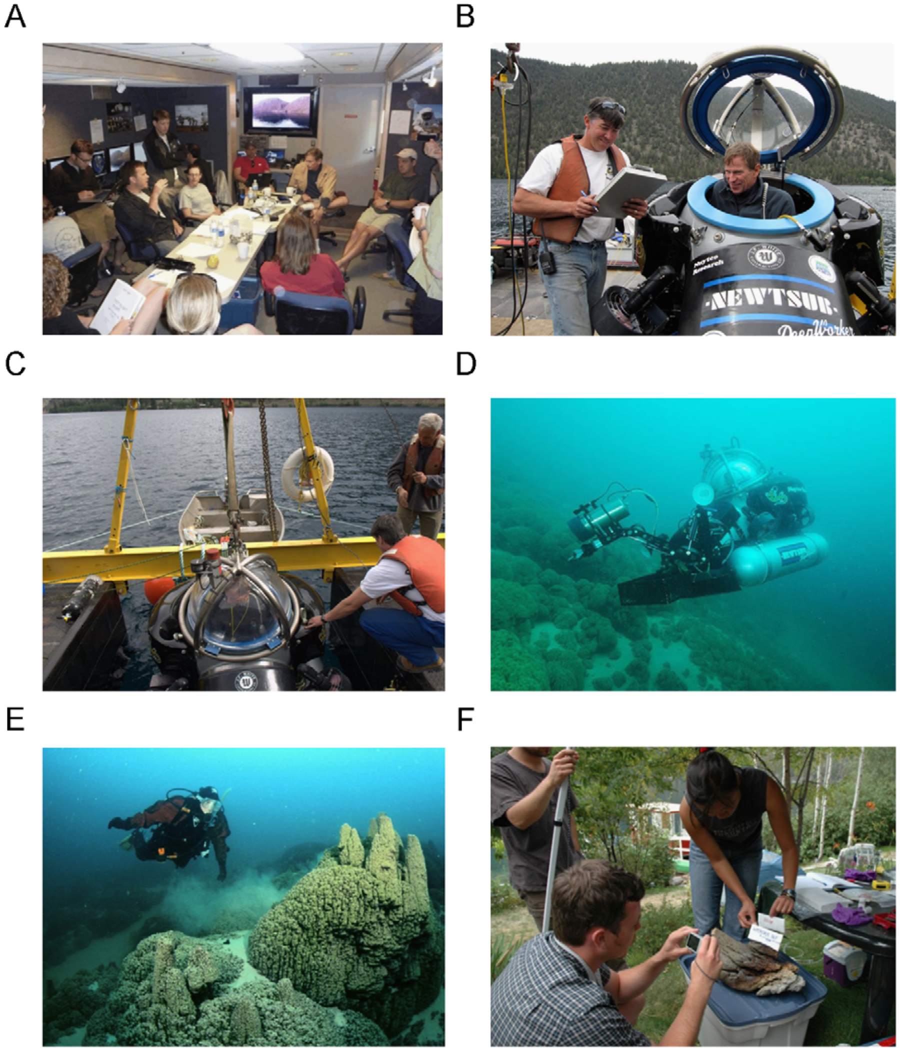

Fig. 4. (A) Flight planning discussion with scientist pilots (SPs) prior to morning DeepWorker (DW) submersible flights (*Source*: D. Lees); (B) SP DW pre-flight preparations and safety checks with DW engineer and SP (*Source*: D. Lim); (C) DW launching from barge in Pavilion Lake, Canada (*Source*: D. Lim); (D) SP conducting mapping and sample collection activities in Pavilion Lake. Manipulator arm with mounted HD video capture system is seen here extended from the DW (*Source*: D. Reid); (E) All SPs participate in science diving activities including microbialite surveys and sample collections (*Source*: D. Reid); (F) Example of sample triage activities in which all SPs participate at Pavilion Lake (*Source*: N. McDaniel).

experienced astronaut field scientists such that the potential for discovery is realized to the highest degree possible.

The application of the LDPs to astronaut training in field science and exploration settings will engender a mindset and build a skill set that will ultimately result in better scientific return from human planetary missions. To summarize, the four LDPs are:

1. LDP#1: Provide multiple experiences: varied field science activities will hone astronauts' abilities to adapt to novel scientific opportunities;
2. LDP#2: Focus on the learner: fostering intrinsic motivation will orient astronauts towards continuous informal learning and a quest for mastery;
3. LDP#3: Provide a relevant experience—the field site: field sites that share features with future planetary missions will increase the likelihood that astronauts will successfully transfer learning; and,
4. LDP#4: Provide a social learning experience—the field science team and their activities: ensuring the field team includes members of varying levels of experience engaged in opportunities for discourse and joint problem solving will facilitate astronauts' abilities to think and perform like a field scientist.

These LDPs are meant as guidelines, and are to be further developed, refined and perfected by the science and exploration community. The execution of this training does not have to be financially, nor logistically intensive as there are numerous field science and exploration activities that are on-going throughout the world, and which are well suited, in varying ways, to contributing to the development of astronauts as experienced, and effective field scientists.

The LDPs can be applied to training individual astronauts or a team of astronauts, and in the future including remote science backroom teams in appropriate field science activities would provide a greater degree of operational complexity to the astronauts' experience. On Earth, field scientists typically operate in co-located teams, however on other planetary bodies such as the Moon and Mars astronauts will be supported by a remote science team with access to a wealth of *a priori* data (e.g. remote-sensing data) as well as real-time data streams from the crews, their instruments, and their vehicles. This will impact the way crews will operate and affect their problem-solving methods in the field. As such, including science backroom interactions on both sides of the link, i.e., working as part of the team and being remotely supported by the team as part of the astronauts' field science experience should also be considered in appropriate settings.

In the future, a mechanism to facilitate these activities would be to allow research groups to offer the training opportunities through supplemental funding opportunities to existing federal grants. Each real field experience will be unique, given the differing settings, research goals and personnel. However, with the aid of the guidelines outlined in this paper, each experience will consistently afford the astronaut opportunities to develop their field skills in new and important directions. When these astronauts finally reach their planetary destination they will not just be proxy scientists, but rather field scientists, with a commitment to the integrity of the scientific exploration of these environments.

Acknowledgements

The authors would like to thank the Canadian Space Agency's 'Canadian Analog Research Network' Program and NASA's Moon and Mars Analog Mission Activities (MMAMA) program for their continued support. We also thank the NASA ASTEP and Spaceward Bound program, NASA ESMD Analogs, the Natural Sciences and Engineering Research Council (NSERC) of Canada's Discovery Grant program, and the National Geographic Society. We are most grateful to all of the members of the PLRP for their continued field and intellectual support. We also thank the Ts'Kw'aylaxw First Nation, British Columbia Parks, Linda and Mickey Macri, and the Pavilion Community. This is PLRP publication number 09-03.

Appendix A. Suggestions for field science pre-season training topics

A.1. Relevant scientific and exploration literature review

Classroom lectures covering the scientific and exploration literature relevant to the field site should be presented to trainees well in advance (e.g. >1 month) prior to departing for the field site. These lectures should be given by experts in the science at hand. Trainees could also be given take home reading and allowed enough time prior to the field season to synthesize and reflect upon their classroom learning. As well, they could be provided with a direct line of communication to resident experts so that their questions and concerns can be addressed.

A.2. Science and exploration goals review

A solid grounding in the field/research team's goals is essential to ensuring that the trainee is focused and motivated from the get-go. This review will overlap with the scientific and exploration literature review, as the research goals will undoubtedly represent a knowledge gap in our understanding of certain natural processes. Included in this overview should be a clear statement of the scientific and exploration hypotheses that support each goal. For each hypothesis, the field experiments and methods, as well as the post-field work data analyses and experiments that are to be performed to test these hypotheses should be clearly described. Depending upon the field group, this step-by-step scientific and exploration road map could be fairly complex. As such, while a complete contextual understanding of the field/research team's goals is important for the trainee to comprehend, it is also recommended that more time is spent on those goals, hypotheses, experiments and analyses that directly impact the field work that the trainee will undertake.

A.3. Remote sensing and other visual data review

For most field sites on Earth, remote sensing data (visible and multi-spectral imagery, radar maps, terrain maps, mineralogical maps, etc.) will be available. Ironically, on the Moon and Mars, for example, these data might be more widely available and in higher resolution than what is available terrestrially. No matter which planetary body, such data will be an important component of not only the pre-field season training, but also the scientific research planning process. Essentially any data that can provide insight into mission/exploration planning will be used by the research and planning teams alike to organize and optimize scientific and exploration activities. In addition, such information can provide the trainees with the ability to better understand the environmental and operational context of their field site, and as such should be carefully reviewed.

A.4. Overview of relevant field science methods, experiments and tools

The scientific methods, experiments and tools to be used at each site should be presented to trainees well in advance of field deployment. Ideally, in addition to classroom lectures on these matters, the astronauts should also be given the chance to practice relevant techniques and skills in field school prior to the field science campaign. Sterile sample collection technique is an example of training that will be essential to future space missions to search for the evidence of life, as well as being intrinsic to many terrestrial research projects. This technique is one of many examples that could be taught and practiced prior to heading into the field. This section of the curriculum is important to the integration of each astronaut into the field activities. If the trainees are not given field science and exploration tasks that are intrinsic to the success of the research project, the full potential of their experience will not be realized. The key will be to ensure that the astronauts are developing their experience in scientific field exploration through full immersion in real science and exploration activities—they should not be treated as merely passengers.

A.5. Relevant exploration methods and tools

Similar to their grounding in scientific methods, experiments and tools, the astronauts should also be well versed in exploration methods and tools that are relevant to each field campaign. As an example, for survey-based excursions, exploration training would include protocols and techniques associated with conducting disciplined and refined site surveys, such as driving or walking techniques, map reading, visual documentation requirements, and human factors issues related to exposure, fatigue and dehydration, for example. Traverse planning tools and other related applications would also be discussed in this section of the pre-season preparation.

A.6. Characteristics of an effective field/observational scientist

This portion of the pre-season training will involve a discussion of

(1) The purpose and application of the field science training to human planetary exploration,
(2) The characteristics of a highly successful field/observational scientist,
(3) The Scientific method,
(4) The Exploration method
(5) The field science experiences of the research team that could benefit the development of the astronaut trainees.
(6) Environmental stewardship

A.7. Wrap up

It will be at the discretion of each research PI to allocate tasks such as reading, relevant academic or technological exercises, and operational planning. However, the authors propose that a final and important component to the pre-season preparatory training should include a session that once again relates what they have learned back to both the goals of the specific field/research endeavor and the goal of helping the astronauts develop their science exploration experience and skill set. Although this may seem straightforward and obvious, in many circumstances the context of the training is not always revisited and as such, the true goals are lost in the details. In all cases, it is truly the science, the exploration and the role of the humans in these endeavors that should take center stage in all participants' minds at the end of this pre-season training.

References

Brady, A.L., Slater, G.F., Lim, D.S.S., Laval, B.E., 2009. Constraining carbon sources and growth rates of freshwater microbialites in Pavilion Lake using ^{14}C analysis. Geobiology 7, 544–555.

Brady, A.L., Slater, G.F., Omelon, C.R., Southam, G., Druschel, G., Andersen, D.T. , Hawes, I., Laval, B., Lim, D.S.S. Photosynthetic isotope biosignatures in laminated micro-stromatolitic and non-laminated nodules associated with modern, freshwater microbialites in Pavilion Lake, B.C. Chemical Geology (accepted for publication).

Brophy, J.E., 1988. Educating teachers about managing classrooms and students. Teaching and Teacher Education 4 (1), 3.

Cordova, D.I., Lepper, M.R., 1996. Intrinsic motivation and the process of learning: beneficial effects of contextualization, personalization, and choice. Journal of Educational Psychology 88, 715–730.

Forrest, A.L., Laval, B.E., Lim, D.S.S., Williams, D.R., Trembanis, A.C., Marinova, M.M., Shepard, R., Brady, A.L., Slater, G.F., Gernhardt, M.L., McKay, C.P., 2010. Performance evaluation of underwater platforms in the context of space exploration. Planetary and Space Science 58, 706–716.

Forrest, A.L., Laval, B.E., Pieters, R., Lim, D.S.S., 2008. Convectively driven transport in temperate lakes. Limnology and Oceanography 53, 2321–2332.

Gick, M.L., Holyoak, K.J., 1983. Schema induction and analogical transfer. Cognitive Psychology 15, 1–38.

Greeno, J., Collins, A., Resnick, L., 1996. Cognition and Learning. In: Berliner, D., Calfee, C. (Eds.), Handbook of Educational Psychology. MacMillan Library Reference, USA, pp. 15–45.

Lave, J., Wenger, E., 1991. Situated Learning—Legitimate Peripheral Participation. University of Cambridge Press, Cambridge.

Lee, P., McKay, C.P., 2008. Planetary Analogs: An Evaluation Standard. STAIF-2008, Albuquerque, New Mexico, USA, 10–14 February 2008.

Lim, D.S.S., Abercromby, A.F., Andersen, D., Andersen, M., Arnold, R.R., Bird, J.S., Bohm, H.R., Brady, A.L., Cady, S.L., Cardman, Z., Chan, A.M., Chan, O., Chénard, C., Cowie, B.R., Davila, A., Deans, M.C., Dearing, W., Downs, M., Fong, T., Forrest, A., Gernhardt, M.L., Hawes, I., Hansen, J., Imam, Y., Laval, B.L., Lees, D., Leoni, L., Looper, C., Marinova, M.M., McCombs, D., McKay, C.P., Mullins, G., Nuytten, P., Pendery R., Pike, W., Pointing, S.B., Pollack, J., Raineault, N., Reay, M., Reid, D., Sallstedt, T., Schulze-Makuch, D., Seibert, M., Shepard, R., Slater, G.F., Sumner, D.Y., Suttle, C.A., Trembanis, A., Turse, C., Wilhelm, M., Wilkinson, N., Williams, D., Winget, D.M., Winter, C., in review. The Pavilion Lake Research Project—A Deep Dive towards the Moon and Mars. Geological Survey of America Special Paper: Analogs for Planetary Exploration.

Lim, D.S.S., Laval, B.E., Slater, G.F., Antoniades, D., Forrest, A., Pike, W., Pieters, R., Saffari, M., Reid, D., Andersen, D., McKay, C.P., 2009. Limnology of Pavilion Lake B.C.—characterization of a microbialite forming environment. Fundamental and Applied Limnology 173 (4), 329–351.

Malone, T.W., Lepper, M.R., 1987. Making learning fun: a taxonomy of intrinsic motivations for learning. In: Snow, R.E., Farr, M.J. (Eds.), Aptitude, Learning and Instruction: III. Cognitive and Affective Process Analyses (. Erlbaum, Hillsdale, NJ, pp. 223–253.

Marinova, M., Lim, D.S.S., et al. Relationship between microbialite morphology and physical characteristics in Pavilion Lake, British Columbia, in preparation.

Osinski, G.R., Lee, P., Cockell, C.S., Snook, K., Lim, D.S.S., Braham, S. 2009. Field geology on the Moon: some lessons learned from the exploration of the Haughton impact structure, Devon Island, Canadian High Arctic. Planetary and Space Science doi:10.1016/j.pss.2009.10.004.

Schaber, G.G., 2005. The US Geological Survey, Branch of Astrogeology—A Chronology of Activities from Conception through the End of Project Apollo (1960–1973). Open-File Report 2005-1190.

Schmitt, H.H., Eppler, D., Dickerson, P., Rice, J., Swann, G., in review. Field Exploration Analysis Team (FEAT)—Planetary field exploration project white paper. Geological Survey of America Special Paper: Analogs for Planetary Exploration.

Schwartz, D., Varma, S., Martin, L., 2007. Dynamic transfer and innovation. In: Vosniadou, S. (Ed.), Handbook of Conceptual Change. Erlbaum.

Wenger, E., 1998. 'Communities of practice. Learning as a social system', Systems Thinker 〈http://www.co-i-l.com/coil/knowledge-garden/cop/lss.shtml〉. Accessed 5 May 2009.

Wilhelms, D.E., 1993. To a Rocky Moon: A Geologist's History of Lunar Exploration, 477pp.