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A historical overview of the Pavilion Lake Research Project—Analog science and exploration in an underwater environment

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ABSTRACT

As humans venture back to the Moon, or onward to near-Earth objects and Mars, it is expected that the rigors of this exploration will far exceed those of *Apollo*. Terrestrial analogs can play a key role in our preparations for these complex voyages, since in addition to their scientific value, analogs afford the exploration community a means to safely prepare and test exploration strategies for future robotic and human planetary missions. Many relevant analog studies exist, and each is focused on a particular aspect of strategic development. Some analog programs such as the Pavilion Lake Research Project (PLRP) present the opportunity to investigate both real scientific and real exploration scenarios in tandem. The activities of this research program demand the use of techniques, tools, and strategies for underwater scientific exploration, and the challenges associated with the scientific exploration of Pavilion Lake are analogous to those human explorers will encounter on other planetary and small solar system bodies. The goal of this paper is to provide a historical synopsis of the PLRP's objectives, milestones, and contributions to both the scientific and exploration community. Here, we focus on detailing the development and deployment of an integrated science and exploration program with analog application to our understanding of early Earth systems and the preparation for future human space exploration. Over a decade of exploration and discovery is chronicled herein.

INTRODUCTION

The Pavilion Lake Research Project (PLRP) is a multidisciplinary science and exploration endeavor that focuses on understanding the morphogenesis of modern microbialites in Pavilion Lake, Canada, while providing an important analog for optimizing human exploration missions. Over the years, the PLRP has maintained a disciplined focus on meeting scientific objectives while simultaneously evolving their research methods to incorporate new and relevant exploration technologies and strategies. As such, the PLRP has become a unique analog site that provides significant insights into early Earth history while concurrently informing future human and robotic space exploration.

PLRP research activities demand the seamless integration of science and exploration in an underwater environment. The physical, mental, and operational rigors and challenges associated with PLRP field science and exploration are comparable to extravehicular activity (EVA) scenarios on other planetary bodies where scientific investigation is a key driver of exploration. In order to explore and collect samples underwater at Pavilion Lake, humans must, as they do in space, coordinate with unmanned robotic systems and contend with limitations associated with communications, visualization, and sampling of their environments, and their life support systems (LSS) (Lim et al., 2010). These working constraints are not simulated, but are real and inextricable from the PLRP's activities. As such, Pavilion Lake has become an important analog research environment in which to garner operational information applicable to the design of human planetary exploration strategies.

The goal of this paper is to present a historical synopsis of analog science and exploration activities at Pavilion Lake with the specific aim of highlighting the unique contributions of the PLRP to the development of human planetary exploration strategies. To ensure that the complexity and richness of the project are properly captured in this paper, two appendices are included that document some of the PLRP's additional initiatives and activities (e.g., education and public outreach).

THE SCIENTIFIC DISCOVERY OF PAVILION LAKE

Discovery

Recreational SCUBA divers have long told tales of the dramatic "freshwater coral" in Pavilion Lake, British Columbia, Canada (50°51′N, 121°44′W) (Fig. 1). For years, while many people knew about the unusual structures in Pavilion Lake, no one understood what they were or why they were in that particular location. In 1995, Harry Bohm, project manager of the Underwater Research Laboratory (URL) at Simon Fraser University (SFU), viewed footage shot by a tourist diver of these structures. Bohm's research eventually brought to light that these rocks were similar to ancient stromatolites, or microbialites, which are organosedimentary structures. Microbialites are commonly formed through the trapping and binding of sediment and/or mineralization of microbes (Burne and Moore, 1987).

Bohm's chance viewing of microbialite video from Pavilion Lake eventually led to the involvement of Chris McKay at the National Aeronautics and Space Administration (NASA) Ames Research Center. Consequently, the seed was planted for nearly a decade of research and exploration at Pavilion Lake. McKay joined small expeditions to Pavilion Lake in 1997 and 1998. During these initial investigations, Sherry Cady (formally at SETI Institute/NASA Ames, now Portland State University) first identified the major morphological varieties of "freshwater coral" as being microbialites because their internal structures did not display internal layered fabrics typical of stromatolites.

The findings and descriptions of rare macromorphologies that resulted from these initial expeditions are published in Laval et al. (2000). This research established a scientific framework for the PLRP. A notable feature presented by Laval et al. (2000) was the observation of the systematic distribution of microbialite macromorphologies, which ranged in size and shape and were found to be distributed as a function of increasing depth in the lake. Specifically, the Pavilion Lake microbialites were classified into four facies based on differences in the macromorphology and their distribution with depth: shallow-to-intermediate (~10 m) mounds; intermediate (~20 m) domes; intermediate-to-deep (20–30 m) cone-shaped mounds; and deep (30–40 m) "leaf-like" mounds (Fig. 2).

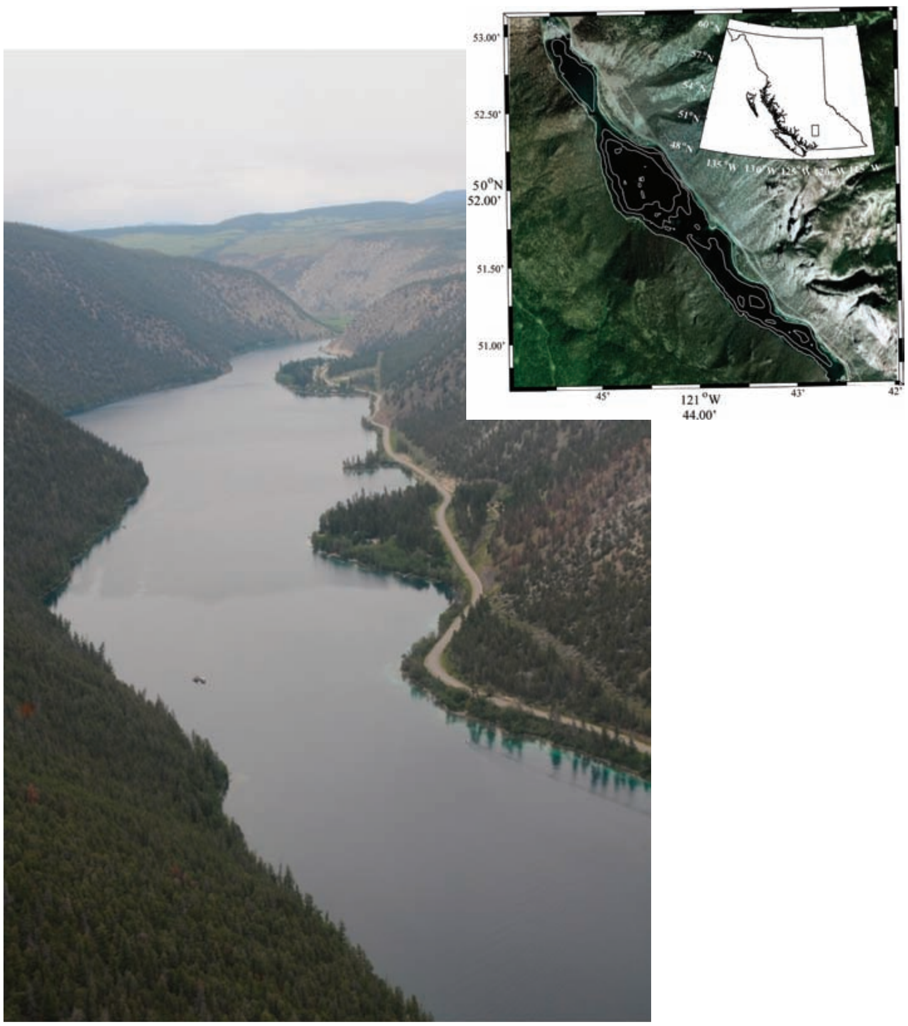


Figure 1. (Left) Aerial photo of Pavilion Lake, British Columbia, Canada (photo by: Donnie Reid). (Right) Google Earth image of Pavilion Lake with 20 m depth contours shown in white. Inset shows location of Pavilion Lake within the province of British Columbia, Canada.

Figure 2. Clockwise from top left: Shallow to intermediate (~10 m); intermediate (~20 m); intermediate to deep (20–30 m); and deep (30–40 m) morphological designations as described in Laval et al. (2000). (Photo by: Donnie Reid.)

The Establishment of the Pavilion Lake Research Project (PLRP)

In 2004, Darlene Lim joined the NASA Ames Research Center (ARC) as a National Research Council (NRC) postdoctoral fellow with Chris McKay. Her task was to revisit the data from Pavilion Lake and begin an in-depth limnological and geobiological investigation into the abiotic and biotic controls on microbialite development. Lim and McKay put together a small team to head back to Pavilion Lake in August 2004. It quickly became evident that the lake was a scientific gold mine, having relevance to the geosciences, astrobiology, and human planetary exploration. It was agreed that the research potential at the lake could be best maximized through a multidisciplinary team effort.

In early 2005, Lim, in partnership with Bernard Laval of the University of British Columbia, founded the PLRP. Its goal was to create a highly collaborative team environment that would be guided by the following four principles:

1. safety,
2. environmental stewardship,
3. advancement of science, and
4. advancement of human exploration.

The disciplined adherence to these principles over the years has helped the project grow, evolve, and add new research directions without losing focus of the most important aspects of the PLRP's activities.

PLRP SCIENCE AND EXPLORATION, 2004–2009

In 2005, Pavilion Lake became one of the inaugural sites of the Canadian Space Agency's (CSA) newly founded Canadian Analogue Research Network (CARN). Infrastructure and research funding associated with the CARN program, along with funding from the National Geographic Society's Research and Exploration program and continued support from NASA, allowed for rapid expansion of PLRP facilities and personnel, as well as the formal establishment of a PLRP research program that would focus on: (1) exploring the physiochemical properties of Pavilion Lake that pertained to microbialite formation, (2) using geochemical and molecular tools to test the hypothesized biological origin of the microbialites, and (3) using geochemical and microscopic tools to characterize potential biosignature preservation in the microbialites.

Exploring the Physiochemical Properties of Pavilion Lake

Water Chemistry

One of the first research thrusts of the PLRP was to understand the limnological characteristics of Pavilion Lake and to compare it to other regional water bodies as a means of providing geochemical context for this unusual lake. Most importantly, there was the need to determine whether unique physiochemical features were responsible for microbialite development in Pavilion Lake.

To begin this phase of the research, a first-order question needed to be answered: Did other lakes in the area (~30 km circumference), particularly those affected by the same groundwater and geological influences as Pavilion Lake, support the growth of similar types of microbialites? To answer this question, a series of lakes was earmarked by the PLRP for exploration, including Crown, Turquoise, Pear, and Kelly Lakes, along with a series of local, shallow evaporite ponds and three saline, alkaline lakes located further north (~80–120 km) on the Cariboo Plateau.

Donnie Reid and Dale Andersen conducted SCUBA exploration of Crown, Turquoise, Pear, and Kelly Lakes and discovered that Crown, Turquoise, and Pear Lakes did not have microbialites, while Kelly Lake did. The latter was a significant discovery: Though Ferris et al. (1997) had previously described small, centimeter-scale microbialite structures, specifically stromatolites (characterized by laminated fabrics) and thrombolites (characterized by mesoscopic clotted fabrics), in the marl (carbonate-rich sediment) benches of Kelly Lake, the larger structures were not discovered prior to the exploration dives by Reid and Andersen. Drop camera work and a series of SCUBA-based photographic excursions subsequently enabled documentation of the meter-scale microbialites in Kelly Lake. Subsequent synoptic exploration of Kelly Lake was conducted by autonomous underwater vehicle (AUV) teams from the University of British Columbia (UBC) and then by the University of Delaware, resulting in the first complete geo-acoustic maps of the bathymetry and distribution of microbialite facies in Kelly Lake (Trembanis et al., 2010).

The nearby salt ponds and the three lakes located further north on the Cariboo Plateau all lacked microbialite growths. However, the Cariboo Plateau lakes were chosen for further study by the PLRP geochemistry research group, led by Greg Slater (McMaster University), due to their unique carbonate-rich geochemistry and extensive microbial mat development (Brady, 2009).

With this team's first question answered, PLRP members began research activities to describe and quantify the seasonal physiochemical properties of Pavilion Lake and to put it in a broader limnological context. Specifically, the key questions now were whether Pavilion Lake was limnologically distinct from the other study sites and whether it shared limnological similarities with Kelly Lake. PLRP team members collected seasonal physiochemical data over 2004–2007 from Pavilion Lake and the other study sites, in addition to local wells and streams. Lim et al. (2009) presented results from these investigations and provided evidence that Pavilion Lake was indeed limnologically differentiated from the surrounding local lakes, including Kelly Lake. These distinct properties were hypothesized to impact the lake's ability to support continued microbialite morphogenesis.

The limnological investigations also highlighted another interesting aspect of Pavilion Lake—it was not an "extreme environment," yet it supported a diverse array of distinctive and rather uncommon microbialites. Extreme geochemical conditions (e.g., hypersalinity, high alkalinity) that preclude the presence or diversification of metazoans have been suggested as factors that allow for the development of modern microbialites. Such extreme environments have been highlighted as indirect support for the association between the decline of stromatolites in the fossil record and the development of metazoan communities. However, modern microbialite-rich environments may, in some cases, present a challenge to this causal association with the co-presence of well-developed microbialites and recognizable metazoan populations. Pavilion Lake is a modern microbialite-rich environment in which microbialites continue to accrete in the presence of populations of metazoan grazers. The ecosystem is complex, and in addition to metazoans, it supports diverse populations of bacteria, viruses, macro-algae, aquatic mosses, and (stocked) fish (Lim et al., 2009). In addition, while the water chemistry of the lake is distinct from other regional water bodies (Lim et al., 2009), the lake geochemistry is not "extreme." As such, Pavilion Lake presents an excellent opportunity to test the impact of small metazoan grazing populations on microbialite development, and also, most importantly, the opportunity to characterize other macro- and microscale influences on microbialite development and morphological variation. Assessment of the interactions and individual effects of these bio- and physiochemical factors on microbialite development would impact our understanding and interpretation of stromatolite and microbialite diversity and abundance declines in the fossil record and help with the development of life-detection strategies for application to other planetary bodies such as Mars.

Field science activities in 2008–2009 continued the work of Lim et al. (2009) by monitoring the temporal variability of Pavilion Lake and the nearby lakes (Kelly, Pear, Crown, Turquoise, and the Cariboo Plateau lakes). Routine sampling of atmospheric conditions and physical water properties (temperature, salinity, clarity) also continued. In 2008, geochemical sampling included a more intensive temporal sampling throughout the year in February, April, June, July, and October. This extended sampling allowed for geochemical and isotopic analysis of the lake water, microbial lipids, and carbonate, as well as an assessment of the seasonal variation in isotopic distributions. In general, negligible seasonal chemical variation has been documented in Pavilion Lake, including no observed evidence of "whiting events" ($CaCO_3$ precipitation within water column) via either sampling or observations made by local residents.

It is important to note that historically, many PLRP discoveries and insights have been garnered as a result of the strong relationship between the PLRP scientists and the Ts'Kw'aylaxw First Nation and the local Pavilion Lake residents. The continuing dialog between Pavilion Lake residents and all, past and present, research and exploration team members has led to new revelations about the structures, access to groundwater sources that would otherwise have been inaccessible to the research team, and a growing database of knowledge about the microbialites and their environment.

Bathymetric Mapping

In parallel with this limnological research, remote-sensing techniques were used by the PLRP to gain a contextual understanding of microbialite distribution and the environmental

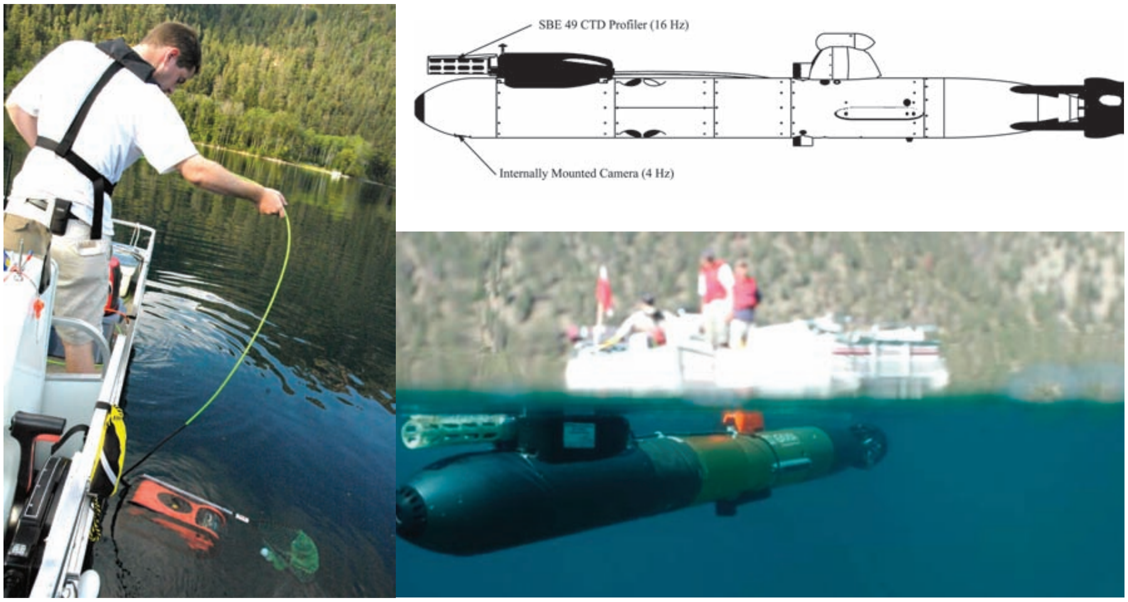


Figure 3. Remotely operated vehicle (ROV) in Pavilion Lake (left) (photo by: Harry Bohm). *UBC-Gavia* (2.5 m total length) with locations of the camera and CTD (conductivity temperature depth) profiler indicated (top right). *UBC-Gavia* standing by for mission commencement in Pavilion Lake (bottom right) (photo by: Donnie Reid). AUV is 20 cm in diameter.

influences affecting their placement throughout Pavilion Lake. The team used drop cameras, a remotely operated vehicle (ROV), three-dimensional (3-D) bottom-imaging surveys using multi-angle swath bathymetry (MASB) sonar, and an autonomous underwater vehicle (AUV) (Fig. 3) to map and image the lake (Fig. 4). The 3-D bottom imaging surveys using MASB sonar were conducted in September 2005 and 2006 by John Bird and his student Geoff Mullins of Simon Fraser University. An

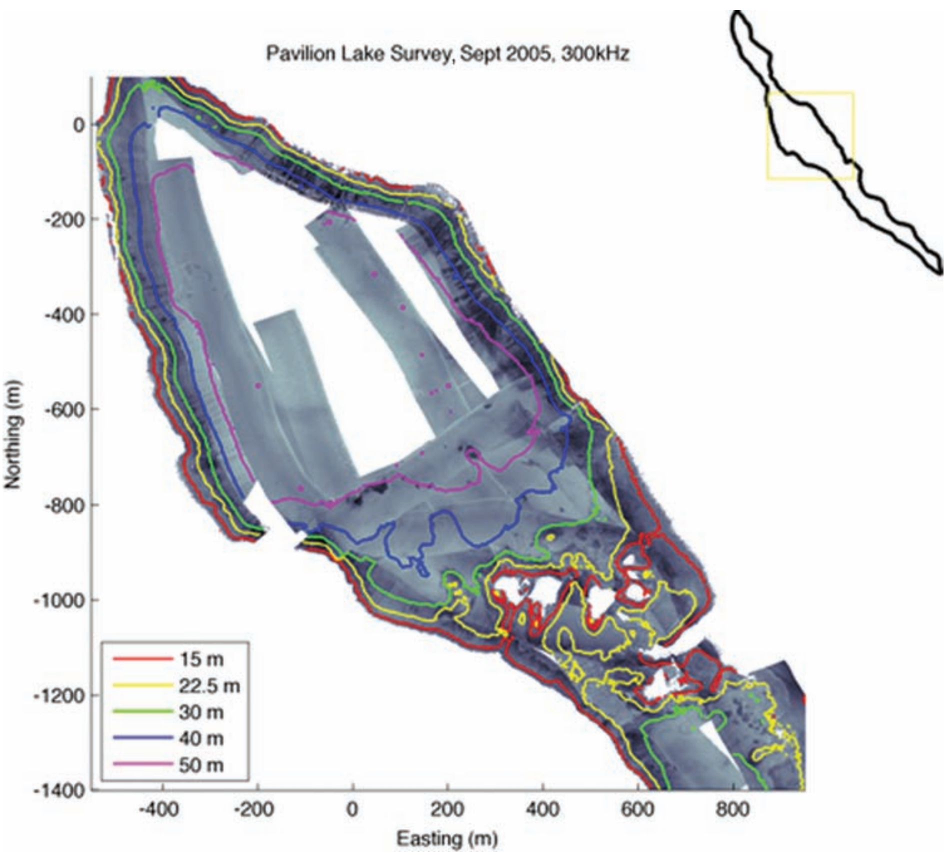


Figure 4. Bathymetric map generated by multi-angle swath bathymetry (MASB) sonar surveys of Pavilion Lake. Depth contours are shown in various colors.

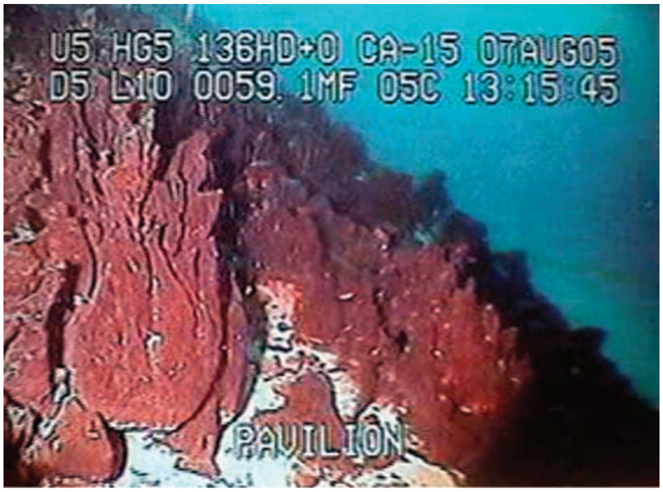


Figure 5. First images of deep (50–60 m) microbialite mounds in Pavilion Lake taken from remotely operated vehicle imaging systems, August 2005.

early discovery based on MASB sonar maps and drop camera activities was that several deeper (40–60 m) microbialite-rich mounds existed in Pavilion Lake in previously unsurveyed areas. The depths of these mounds were well below the 35 m depth limit for microbialites in Pavilion Lake that had been previously established by Laval et al. (2000). ROV imaging in 2005 (Fig. 5) confirmed the presence of microbialites on these deep mounds and gave a tantalizing look at structures that had different macromorphologies and surface colors than those previously documented by Laval et al. (2000). Unfortunately, the depths at which these new structures were found was beyond the SCUBA capabilities of the PLRP diving program, which meant that another means of studying and sampling these structures was needed before further exploration could continue.

In 2006, PLRP Ph.D. student Alexander Forrest began using *UBC-Gavia*, a 2.5 m, 55 kg autonomous underwater vehicle to survey Pavilion Lake. Mission objectives of the early *UBC-Gavia* deployments in the summers of 2006 and 2007 were to collect photographic imagery of the benthic region in order to chart the microbialite distribution in the context of the physical water-column properties that were being concurrently characterized by the conductivity-temperature-depth (CTD) profiler mounted on the AUV. While there were some initial successes, lake terrain (bed slope angles >20°) combined with vehicle performance (i.e., the inability to reliably track bottom terrain >10°) prevented a full lake survey, particularly around the sides of the lake where the microbialites are most widely distributed. However, enough data were returned from the collection of remote-sensing tools to indicate that microbialites were likely distributed throughout the lake, and that they were found at depths not previously characterized by the MASB maps.

In 2009–2010, an AUV team from the University of Delaware lead by Art Trembanis and his students Jonathan Gutsche and Stephanie Nebel set out to conduct a complete 3-D sonar mapping of both Pavilion and Kelly Lakes using an AUV. They utilized both phase measuring bathymetric sonar (PMBS) and side-scan sonar. The resulting high-resolution (<1 m/pixel) maps of bathymetry, slope, rugosity (roughness), and backscatter provided a comprehensive morphologic context for further mission planning and physicochemical analysis of microbialite morphotypes (Gutsche and Trembanis, 2010a, 2010b; Trembanis et al., 2010). Presently, mapping efforts are focusing on automated classification techniques for analyzing sonar return amplitude data with respect to the macromorphologic patterns of distribution of bottom type in both lakes.

Effects of Light on Microbialite Development at Pavilion Lake

Light sets the limit on the energy sources available for photosynthesizing organisms, which can affect carbonate precipitation and macro- and micromorphology of the structures. As such, a characterization of the light regimes in Pavilion Lake was a key to developing a holistic understanding of the factors influencing the development of microbialites in the lake. Light in and around the lake was measured year-round by a weather station located on the northeast shore of the lake and by two moored light sensors situated at 8.2 m depth on the west and east sides of the central basin (at Willow Point and Three Poles, respectively). Light profiles of the water column were obtained using a conductivity-temperature-depth (CTD) probe with an attached light sensor (Fig. 6). The multiyear record from the weather station and the moored

Figure 6. Margarita Marinova and Bernard Laval conducting CTD (conductivity temperature depth) and Licor (light sensor) casts in Pavilion Lake. (Photo by: Donnie Reid.)

underwater sensors, as well as the CTD-light measurements provide the needed data for modeling the light availability in the lake and attempting to disentangle the effects of biology on the microbialite system. Specifically, these measurements suggest that sufficient light is available throughout the lake water column to support photosynthesis.

Paleolimnological Reconstruction of Pavilion Lake

The paleolimnological history of Pavilion Lake was also investigated by Lim and Université Laval researcher Dermot Antoniades. Sediment cores were retrieved from the lake with the intent of reconstructing past lake levels using diatom communities as bioindicators of change. Gravity coring proved difficult in the lake because penetrable sediment was limited to less than 30 cm. Recovered cores were analyzed at the University of Laval, and while some diatoms were catalogued in the upper 1 cm of the sediment, dissolution was apparent thereafter.

Geobiological and Molecular Investigations

During this phase of the PLRP, various geobiological and molecular investigations were conducted to understand the hypothesized biological origin of the Pavilion Lake microbialites and the potential for biosignature preservation within the deposits. This involved extensive field work at Pavilion Lake. The following is a summary of these research efforts, which, in many cases, are still ongoing.

Isotopic Analyses and Microvoltammetry

In-depth work commenced to test the hypothesized biological origins of the microbialites in Pavilion Lake. Photosynthetic microbial communities are thought to play a significant role in the formation of microbialite structures through trapping and binding of carbonate particles and/or influences on carbonate precipitation (Merz, 1992; Riding, 2000; Altermann et al., 2006). However, abiotic processes resulting from changes in geochemical parameters (e.g., mixing of lake and groundwater) and/or sedimentation have also been proposed as mechanisms of microbialite precipitation (Council and Bennett, 1993; Grotzinger and Rothman, 1996).

Isotopic analysis of ^{13}C and ^{14}C distributions was used at Pavilion Lake to determine the carbon source(s) for the microbialites and the associated microbial communities in an effort to identify biological influences on carbonate precipitation. Specifically, samples were collected from 2004 to 2006 in order to trace the inputs of groundwater carbon to the lake and to assess evidence for groundwater dissolved inorganic carbon (DIC) contributing to the microbialite formation (Fig. 7). Atmospheric CO_2 and groundwater DIC flowing through the surrounding limestone geology represented two end members with significantly different ^{14}C contents, thereby providing a means to assess the relative contributions of each carbon source to Pavilion Lake DIC, microbialite carbonate, and the active microbial community living on the surface of the structures. Results of these investigations determined that groundwater DIC contributed a maximum of 9%–13% of total DIC in the lake and minimal inputs of groundwater derived carbon to the microbialite carbonate and associated microbial communities (Brady et al., 2009). A carbonate-encrusted branch also enabled estimation of a microbialite growth rate of 0.05 mm/yr over the last ~1200 yr. This growth rate was faster than the previous growth estimate determined by U-Th dating of between 2.5 and 3.0 cm/k.y. (Laval et al., 2000). This demonstrated that the microbialites are still actively growing in the lake; however, there is significant variation in the size of the microbialites currently found

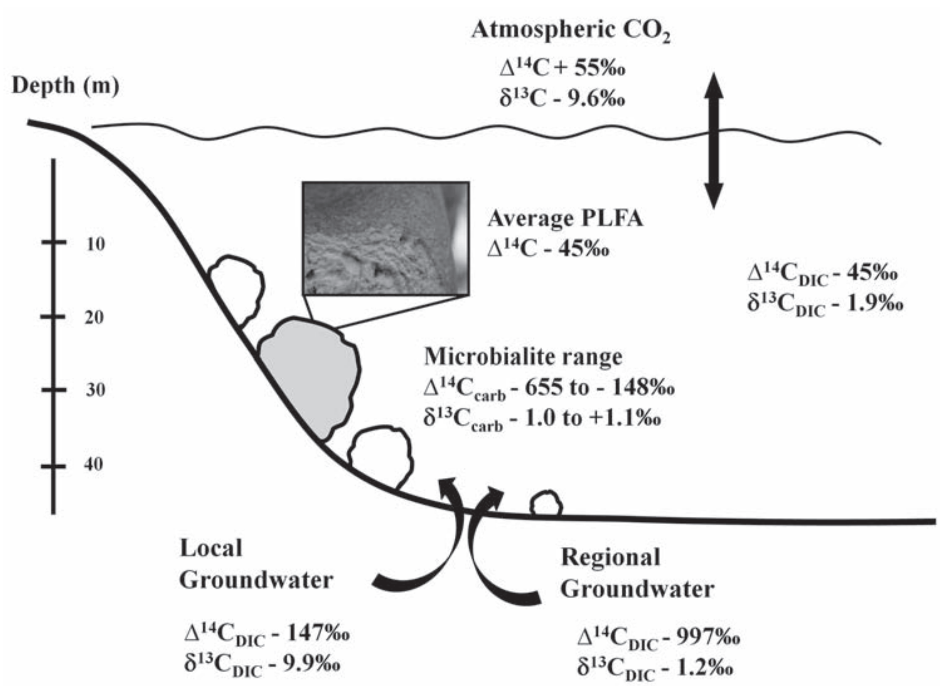


Figure 7. Summary carbon isotope analyses showing values of various carbon sources into Pavilion Lake. DIC—dissolved inorganic carbon; PLFA—phospholipid fatty acids.

within Pavilion Lake, and efforts are currently under way to further investigate growth rates of these microbialites.

In addition to the isotopic sampling and analyses, new research activities initiated in 2008 included microvoltammetry of Pavilion Lake microstromatolitic nodules associated with the microbialites and Cariboo Plateau lake mats to characterize distributions of oxygen concentrations, metal and sulfate reduction, and other redox conditions. The results of this work, combined with further isotopic and scanning electron microscope (SEM) investigations, demonstrated photosynthetic activity in both microbialite surface nodules and microbial mats that could be spatially related to visible features (Brady et al., 2010).

Molecular Analyses

In 2007, molecular techniques were first used to determine the uncultivated microbial diversity in Pavilion Lake microbialites across all three life domains (Archaea, Bacteria, Eukarya). Work was begun to establish the extent of variation in microbialite community structure by location, depth, and morphology over various seasons. These analyses are still ongoing, but preliminary results indicate that ~90%–99% of recoverable phylotypes in microbialites are bacterial. Archaeal and eukaryal phylotypes are present, but at low abundances (Olivia Chan, 2011, personal commun.). In addition, results to date indicate that location and seasonal changes have a significant effect on variation in 16S and 18S Ribosomal ribonucleic acid (rRNA) gene phylotypes (Olivia Chan, 2011, personal commun.).

Curtis Suttle and his team of aquatic microbiologists joined the PLRP in 2008 and continue to work on the project. They initiated a research stream looking at the relationship between the integrated microbial composition of the microbialites and mats of Pavilion Lake and the Cariboo Plateau lakes, respectively, as well as the surrounding water. Their goal is to address questions such as the abundance and distribution of viruses and other microbes and their relationship to environmental variables that are available from concurrent investigations. Preliminary data indicate that bacterial abundances in Pavilion Lake waters range from ~0.7 to 1.1×10^6 mL^{-1}, while viruses are 10- to 20-fold more abundant.

Microbial mat characterization. Understanding the genesis of complex morphology and mineralization by modern microbial mats will help us to interpret the ancient microbialite record, thereby improving our understanding of the early establishment and evolution of the biosphere. Microbial mats found in the upper 5 m of Pavilion Lake exhibit peak and ridge structure and carbonate encasement that, together with the multilayer structure of the mats, are seen as an analog to Archean fenestrate microbialites. This research is still ongoing and is being led by Rebekah Shepard and Dawn Sumner at the University of California–Davis.

Biomineralization Analyses

Interest in the lack of evidence for groundwater seepage through the cone-shaped structures that sit atop many of the intermediate-depth microbialites led to detailed microscopic study of these structures. This research, by Sallstedt and others at Portland State University, began in 2006 and resulted in the observation that the extracellular matrix of the mats in this variety of microbialite affects not only its microstructure, but also its macrostructure. Optical and high-resolution SEM analyses showed that calcite precipitation in the conical-shaped mounds is spatially related to the distribution of the extracellular polymeric substances (EPS) of the mats, although the morphology of the EPS-associated mineral phases reflects the bulk geochemistry of the lake. Separation of the characteristics of the microbialites that are biologically influenced from those created purely by environmental factors is an ongoing goal needed to understand biomineralization and the morphogenesis of the intermediate- to deeper-water microbialites in Pavilion Lake.

Magnetotactic bacteria (MTB) investigations. The presence of magnetotactic bacteria in Pavilion Lake and the surrounding alkaline ponds is relevant to the search for possible life on Mars. These bacteria are able to orient and move themselves along Earth's magnetic field lines, and investigations to date have focused on identifying the environmental factors that affect MTB population dynamics, and the effect of alkalinity and substrates such as microbialites on the bacteria. This research is led by Alfonso Davila at the NASA Ames Research Center.

In situ microelectrode investigations. To address the research team's interest in the biological contribution to microbialite precipitation and accretion, during the 2009 field season, in situ microelectrode probing commenced. These research activities were led by Dale Andersen, Ian Hawes, and Dawn Sumner. The pH and O2 profiles were generated, as well as Pulse Amplitude Modulation (PAM) fluorometry, to identify the occurrence and extent of photosynthetic activity on the microbialite surfaces and its relationship to structural morphology. Their research provided further in situ data in support of a biological control on microbialite morphogenesis.

In parallel with these investigations using PAM fluorometry and microelectrode probing, Allyson Brady continued her use of isotopic techniques to investigate mechanisms of biological formation of microbialites in Pavilion Lake. The potential for microbial metabolic activity to change local water geochemistry and promote the precipitation of calcium carbonate (Merz, 1992; Sumner, 2001; Shiraishi et al., 2008) represents the greatest potential for generating a biosignature that may be preserved through geological time. In particular, microbial metabolic activity has the potential to influence not only the concentration but also the isotopic composition of the dissolved inorganic carbon (DIC) and the associated precipitated carbonate (Sumner, 2001; Andres et al., 2006). Recent observations in stromatolites in the Bahamas (Visscher et al., 2000; Andres et al., 2006) and microbialites in Cuatro Ciénagas, Mexico (Breitbart et al., 2009), have identified isotopic and geochemical evidence for a primary role of sulfate reduction in carbonate precipitation. In contrast, at Pavilion Lake, Brady et al. (2010) observed ^{13}C-enrichment in nodule carbonate concurrent with phospholipid fatty acid (PLFA) distributions and isotopic compositions within the nodule microbial community consistent with photosynthetic cyanobacteria. These observations correspond to the micromanipulator profiles of Druschel with Andersen and Hawes, which show high levels of oxygen saturation and elevated pH values within the nodules, supporting the observation that a biosignature of photosynthesis is being imparted to the carbonates precipitated in situ within the surface nodules. However, these ^{13}C enrichments do not appear to be preserved throughout the interior of the structures, and future investigations will address the extent of preservation of biosignatures. These observations provide a fundamental basis for understanding the way in which precipitation is currently occurring on the surface of the microbialites and the biosignatures that might be expected to be preserved throughout the structures.

PLRP DEEPWORKER SCIENCE AND EXPLORATION (DSE) PROGRAM—INTO THE DEEP, 2008–2009

While PLRP members were making significant progress on answering many of the research questions and priorities, by late 2007, two areas of research still remained inadequately addressed: (1) a contextual understanding of microbialite distribution and morphological variation, as well as the environmental influences affecting microbialite placement throughout the lake; and (2) a characterization of deep (40–60 m) microbialites within Pavilion Lake. PLRP science diving operations were sufficient for sampling activities and instrument deployments only in localized regions and from 0 to 35 m depth. However, science diving did not prove adequate for mapping and sample recovery throughout the large and deep (0.8 km × 5.7 km; 65 m maximum depth) lake. After reviewing several options from diver tows to further AUV surveys, the ideal tool was determined to be the DeepWorker single-person submersible (Fig. 8) because it met the PLRP's guidelines and in doing so gave the team a safe, environmentally sensitive way to advance their science and exploration goals. Importantly, it also provided an analog for understanding many of the challenges associated with optimizing operations for human exploration.

2008: Establishment of the PLRP DeepWorker Science and Exploration (DSE) Program

Through a partnership with Nuytco Research, Ltd., in Vancouver, Canada, the PLRP established their DeepWorker Science and Exploration (DSE) program in early 2008 (see Appendix 1 for DeepWorker specifications). These submersibles have a 1 atm pressurized cockpit and carry sufficient battery storage to permit scientific operation for up to 8 h. Life-support systems permit 80 h of subsurface idle time in the unlikely case of battery failure. The scientific payload consists of a domed hatch, enabling a 360° pilot view, onboard high-definition video capture, surface-to-underwater communications with voice capture, a manipulator arm, and a sample basket. These tools allowed photographic imaging and microbialite survey and sampling to be accomplished in all areas and depths of the lake, with the advantage of simultaneously having the researchers see, experience, and interact with the entire lake firsthand. The PLRP DSE activities presented a unique opportunity to integrate active science and real exploration field activities in a hostile environment. The challenges associated with the human scientific exploration of underwater environments are analogous to those we will encounter on other planetary and small solar system bodies, such as Mars, the Moon, and near-Earth objects, respectively. 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.

In May 2008, the first team of DeepWorker science pilots met in Vancouver, Canada, for a week of submersible training (Fig. 9). It was decided early on that the trainees would represent a mix of experience (senior scientists to graduate students), gender, research backgrounds, and nationalities. The 2008 team consisted of Allyson Brady, Bernard Laval, Darlene Lim, Greg

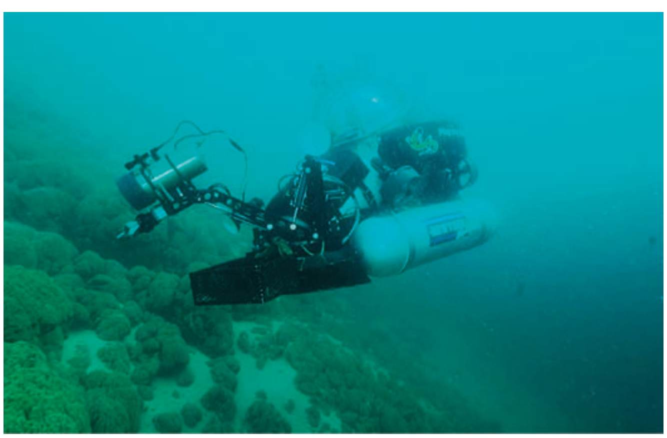


Figure 8. DeepWorker science pilot (SP) surveying microbialite field in Pavilion Lake (photo by: Donnie Reid). Manipulator arm is extended with high-definition video camera mounted on top. DeepWorker submersible is 2.4 m long.

Figure 9. May 2008: First group of Pavilion Lake Research Project DeepWorker Science and Exploration program science pilots during their training session in Vancouver, Canada. Clockwise from top left: Bernard Laval, Michael Gernhardt, Rebekah Shepard, Greg Slater, Darlene Lim, and Allyson Brady.

Slater, Rebekah Shepard, and NASA astronaut Michael Gernhardt. Gernhardt joined the team because of his interest in identifying field analog sites that could help prepare humans for a return to the Moon. While in Vancouver, the team began planning DeepWorker flights ("dive" was used for SCUBA, while "flight" became used for submersible activity). The focus was to accomplish the project's research goals by capitalizing on the technological assets that the DeepWorkers brought to the field work. Specifically, the DeepWorkers would enable researchers to stay underwater for extended periods of time in the safety of a 1 atm environment and thereby provide long-range mapping capabilities, as well as enable surveying and sampling of the deepest microbialites in Pavilion Lake. These capabilities would allow the PLRP team to reach its two stated research goals for the 2008 field season. To maximize the use of DeepWorkers, existing remote-sensing data from the acoustic surveys by Mullins and Bird were used to define contours for the science pilots to follow throughout the lake that would help in understanding the distribution and variation of microbialites. In addition, directed missions for survey and sample activities were planned to the "deep mounds" discovered in 2005.

Through these discussions, it became readily apparent that in addition to meeting these mapping and sampling goals, the DeepWorkers also enhanced the opportunity for discovery. In particular, the team had been searching for groundwater input and microbialites growing on datable structures such that their growth rates could be better constrained. These and other features summarized in Figure 10, and were named "targets of opportunity" (TOPs). However, protocols also had to be developed such that if one of these items was discovered, each science pilot had a set of protocols to follow regarding the allowable time to deviate from the flight plan to investigate their finding. This included protocols for documenting and describing a TOP or other discoveries. These became known as the PLRP DSE flight rules, and, for the 2009 and 2010 field seasons, they were further developed to include required science pilot observations and video protocols (Fig. 10). The decision-making processes involved in forming these flight rules are useful for developing flight rules applicable to scientific exploration activities on other planetary and small solar system bodies where humans are responsible for making similar choices.

2010 PLRP GENERAL FLIGHT RULES

- **Sampling with the DW is highly discouraged due to the likely damage to the sample and surroundings. Common exceptions to this rule are for (1) locations below no-decompression diving limits, (2) when specific science objectives are listed in a Detailed Flight Plan, and (3) if sampling clearance is received from the CC.**
- **The Herm region is now designated a PLRP Research Zone and considered a "Highly Protected Area" (HPA).**
- **All SPs should stay within a safe operating distance from the bottom and minimize sediment disturbance by using minimal thrusters when close to lake bottom.**

VIDEO PROTOCOLS	OBSERVATIONS	TARGETS OF OPPORTUNITY (TOPs)
1. Ensure camera is powered on and Anovia deck is recording 2. Ensure camera is completely zoomed out (first position) and positioned at proper survey angle prior to commencing flight 3. During Life Support Checks and CapCom updates ensure that camera is at proper zoom and angle for current task 4. Return camera to first position after completing close-up shots 5. Stow camera for sub recovery once at surface	• Depth • Substratum • Morphology • % cover • Transitions • Potential TOPs • Slope characteristics • Environmental degradation • Topography • Chimneys • Interesting sediment characteristics & candidate sites for slope sediment collection experiments • Potential sampling location • Clustering characteristics	Groundwater input * video and make audio observations for ~20 min * note extent of flow * note associated flora/fauna or microbialite morphology Datable structure * video and make audio observations * do not collect Microbial mats * video (macro and micro) and audio observations for ~20 min * note thickness, texture, and color Unusual morphology * video (context and zoom) and audio observations ~20 min * note specific differences from other microbialite morphologies Particulate matter * video (context and zoom) and audio observations for ~20 min * stop moving and assess whether particulate is from sub or is actually moving through water column (e.g., copepods)

Figure 10. DeepWorker (DW) flight rules that give each pilot guidelines to promote scientific productivity and efficient usage of the submersible resource. CC—Capsule Communications.

Several other exploration activities aimed at (1) training astronauts in the rigors of scientific exploration, (2) shaping scientific and mission operation protocols for EVAs, and (3) informing tool design were also discussed during that May meeting in Vancouver. The group identified an opportunity to use a real field science expedition conducting work in the hostile environment of an underwater setting as a basis for understanding how to conduct scientific exploration with humans on other planetary and small solar system bodies. As their guide, the DeepWorker science pilots laid out the question, "How could our science and exploration at Pavilion Lake benefit human space exploration?" The group had the opportunity to develop mechanisms to judge the effectiveness of flight plans and flight rules in enabling science while working in a real field science setting. As such, metrics were designed to provide the team with a mechanism to gauge the scientific merit and data quality of each DeepWorker flight by means of five-point two scales, as seen in Figure 11. The scientific merit was assigned both pre- and postflight, and it is currently being reassigned, 2 yr after the 2008 flights, in order to judge whether there has been a change in the science merit as a consequence of further data analysis over these 2 yr. Data quality was assigned postflight by a quorum of pilots as a judgment of the success of video, sampling, and voice data return. By looking at these metrics in combination with the percent completion of the flight and any deviations from the flight plans as a consequence of TOPs and/or other discoveries, the group could begin an assessment of the level of science success enabled by the flight plans and flight rules. The first group of science pilots was trained, and a new research direction was set for the PLRP team.

2008 DSE Program and Scientific Field Work

The PLRP DSE program prioritized the human observer/science pilot to be the primary data recording system on board the submersible, while the high-definition video and voice capture systems provided a means to archive their thoughts and discoveries. In addition to these observations, each science pilot was required to safely operate a submersible, monitor their life-support systems, collect representative samples in a safe and environmentally sensitive manner, produce clear and useful video data, and carry out communications procedures. This level of multitasking and identified correlations between workload and the quality of data collected offer insight into the ability of astronauts to collect valuable scientific data while performing complex operational activities.

The first field deployment of the PLRP DSE program was from 21 June to 4 July 2008, during which the DeepWorker operations ran for 10 d, and boat, AUV, and SCUBA-based operations comprised the remaining period of field time. The 2008 DeepWorker operations were busier than anticipated, and all crew and science pilots worked from early morning to long past midnight each day. Two submersibles were deployed four times daily (two flights per submersible) with crews switching out after the morning flights. High-definition video was brought back to shore on digital tape, and students Margarita Marinova and Zena Cardman were tasked with the job of uploading and duplicating tapes through the night. As a consequence of this technical setup, science pilots were only able to discuss their flights through verbal recollections. They were unable to view video from their flights due to the lengthy video-processing period. Detailed postflight discussions were limited by this lack of corroborating video; however, these postflight

PLRP Science Merit Scale

METRIC	DESCRIPTOR	DEFINITION
1	Limited	Data provide limited scientific value
2	Adequate	Data reaffirm existing hypotheses and facts
3	Significant	Data elucidate existing hypotheses in new areas or detail
4	Exceptional	Data resolve a major scientific question or highly significant hypothesis
5	Discovery	Data introduce a novel idea or hypothesis

PLRP Data Quality Scale

METRIC	DESCRIPTOR	DEFINITION
0	No data	No data collected.
1	Limited	Video and navigation did not support scientific observations and other relevant data were of limited use. Dive must be reflown.
2	Adequate	Quantitative data adequate for general documentation of findings. Provide useful context and enable efficient return. Data are marginally publishable.
3	Significant	Quantitative data adequate to support specific documentation of scientific findings and yield publishable results.
4	Exceptional	High-quality video, navigation, and other quantitative data that support and enhance scientific merit.

Figure 11. 2008 Pavilion Lake Research Project (PLRP) metrics: science merit and data quality scale.

discussions were of scientific and operational worth to all of the DeepWorker science pilots and support crew. At the behest of Chris McKay, the PLRP also ensured that each evening two discussion sessions took place: one that included all members of the PLRP from the cook to the field assistants to the DeepWorker techs to the science pilots, and a second that included the science pilots and relevant research assistants (Fig. 12). While the latter was ideal for detailed planning and data review, the former ensured that the adventure and the science were not just those of the science pilots, and that all thoughts and input from the diverse and talented team could be solicited in a free and open manner. As a lesson learnt, this was a positive and valuable one in building a cohesive and supportive team. This venture has had a lasting impact well beyond the field season on the group's collaborative productivity.

While the field season was demanding, the first PLRP DSE program successfully met the two stated goals for the 2008 season: (1) to map Pavilion Lake along predetermined depth contours, and (2) to collect representative microbialite samples below no-decompression diving depths. Important insights into the relationship between microbialite distribution and the physical aspects of the lake such as depth, bathymetry, slope angles, and available substrates (e.g., rocks) were garnered during the 2008 season. New deep microbialite mounds and large (13 m circumference) microbialite structures were discovered, and surveys of large herms (mounds) in the central region of the lake revealed a section of the lake with a high concentration of microbialites and a shallower distribution of chimney structures than had been previously documented (Fig. 13). Also, microbialite growth substrates such as logs and rocks (Fig. 13) were identified throughout the lake. Furthermore, for the first time, scientists had the ability to stop, take in, and think about their underwater environment in much the same way that one can do while conducting terrestrial field work. The DeepWorkers allowed science pilots to gain a new, broader perspective on the lake, and to put their SCUBA dives, which were essentially spot views of the lake, into context. The 2008 season both met and exceeded scientific and exploration expectations and teased the team with a firsthand glimpse at the extent and diversity of microbialites, and the complexity of the whole lake ecosystem.

In parallel with the 2008 DSE program, AUV research continued at Pavilion Lake. By focusing on the deep, flat bottom region of the central basin of Pavilion Lake (the "Central Plain"), Weston Pike and Forrest had their most successful AUV-based photo-imaging deployments. This Central Plain region of Pavilion Lake is the deepest and therefore the highest-risk environment in Pavilion Lake for direct human exploration, and from the acoustic surveys, it was also expected to have the least scientific interest. Therefore, this region was

Figure 12. Daily science meeting in 2008 (top) and 2009 (bottom). In 2009, the mobile mission command center (MMCC) was added to the Pavilion Lake Research Project field infrastructure, thus allowing for a centralized area to process data, produce flight plans, conduct science discussions, and engage in dry laboratory activities.

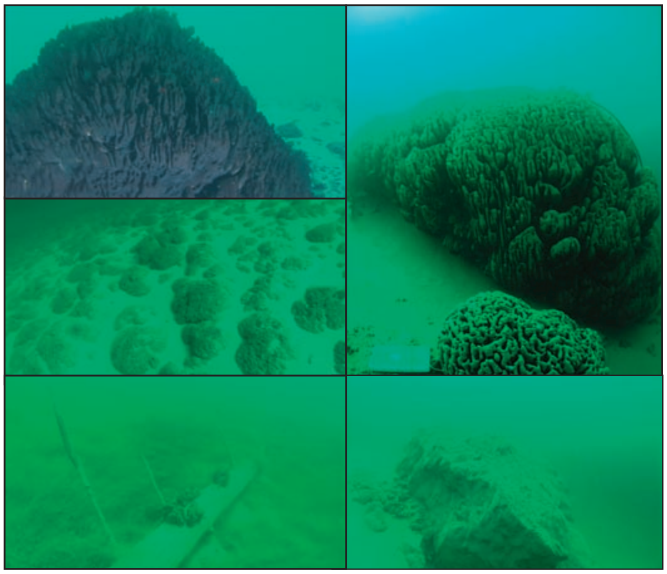


Figure 13. From top left (clockwise): DeepWorker image of deep (50–60 m) microbialite (photo by: M. Gernhardt); large microbialite (background) development (MOUSE 1) in Pavilion Lake, where microbialite structure is 13 m in circumference (photo by: Donnie Reid); microbialites on top of large rock (photo by: A. Brady); microbialites on logs (photo by: A. Brady); section of shallow herms showing concentration of microbialites in this region of Pavilion Lake (photo by: D. Lim).

excluded from DeepWorker surveys in 2008. The survey of the Central Plain by *UBC-Gavia* provided an excellent complement to the DeepWorker surveys of the steep, contoured lake sides where *UBC-Gavia*, as previously discussed, was unable to maintain constant altitude above the lake bed within tolerances suitable for bottom imaging. The AUV remote surveying missions collected extensive imagery of the deepest area of the Central Plain, which had not previously been explored or photographed (see MASB survey Fig. 4). From this imagery, benthic characteristics throughout the Central Plain were identified at a photographic resolution of ~1.2 cm and mapped by benthic type. Bathymetric data were also compiled from these missions to expand upon the bathymetry collected by Bird and Mullins. The benthic survey of this area effectively filled in the largest remaining unmapped area of the lake, where the Mullins and Bird MASB survey left off. Results from *UBC-Gavia*'s imaging surveys of the Central Plain led to and helped plan DeepWorker-based exploration of this region in 2009. This experience provides support for analogous human-robotic exploration scenarios on planetary or small solar system bodies where autonomous or semi-autonomous robots would be sent ahead of human explorers in regions of high risk and/or low expected scientific return.

PLRP Safety Standards for Terrestrial Analog Research

Prevention of incidences and provision of medical services for the specialized, highly trained researchers, who were operating in a remote and hostile environment, were deemed essential by the PLRP. From 2005 through 2007, water and microbialite sampling activities enabled through SCUBA diving (Fig. 14) were the backbone of the team's science and exploration activities. This SCUBA diving added another operational dimension to the research. It necessitated formal dive and safety training for all participating science divers. Underwater, scientists needed to concentrate on their observations while also constantly monitoring their life-support systems (LSS). As such, Donnie Reid developed a formal science diver training program at Pavilion Lake, which continues to run to this day. This training program falls under the governance of both the American Association of Underwater Scientists (AAUS) and the Canadian Association for Underwater Science (CAUS), and it is focused on building relevant underwater experience so that divers will be well equipped to efficiently problem solve and tackle scientific tasks. This training program has important application to the preparation of humans for the scientific exploration of other planetary bodies.

Figure 14. Pavilion Lake Research Project SCUBA diver hovering next to microbialites in Pavilion Lake (photo by: Donnie Reid).

With the commencement of DeepWorker submersible operations, further safety standards were necessitated. Surface-based operations at Pavilion Lake were subject to several different regulatory bodies and organizational guidelines, often bridging both the industrial and scientific sectors. This posed a challenge in creating effective and relevant safety guidelines. A team of PLRP participants led by Damien McCombs and Donnie Reid developed a dynamic, terrestrial-safety plan that offered a framework for a safe research, living, and work environment that facilitated maximum scientific productivity at an analog site. These safety plans were fully integrated into the team's flight plans and DeepWorker logistics.

2009: Evolution and Growth of the PLRP

As a result of the 2008 activities, several research, technical, and operational areas were identified as high priorities for the PLRP to either develop or evolve. Scientifically, this included, but was not limited to, further study of the biological contribution to microbialite development, the influence of lake bathymetry and sedimentation characteristics on microbialite distribution, the effect of substrate on microbialite development, and the variation of microbialite macromorphologies throughout the lake. Exploration science was also deemed a research stream that needed further emphasis. Specifically, the team was interested in evolving their metric measurements to include other relevant components such as the science pilots' observational skills. The team was also interested in understanding the scientific return of joint human-robotic missions, and in further developing the DSE program to include a more formal astronaut training opportunity for the field sciences. Technically, the team identified the need for improvements to the submersible-to-surface communications. The highest priorities were having DeepWorker video captured directly to hard drives, and having improved acoustic positioning of the submersibles for data georeferencing. Although wide-angle video (to provide context) and high-resolution still-image capture systems were also prioritized, due to funding constraints, these could not be addressed in 2009.

The group also saw a safety and scientific benefit in being able to stream audio and visual submersible communications and operations data to shore. Operationally, as a top priority, the team needed a better location to conduct their dry and wet laboratory activities, computing, and meetings. Prior to 2009, these activities occurred in the local accommodations. Given that the team was working nearly around the clock, this arrangement was not ideal for the residents nor the scientists and technicians. The team also identified the need for a coordinated data management plan and a mechanism to organize the DeepWorker tracking, audio, and visual data, ideally in real time to provide immediate feedback to the pilot. Postflight, it was also deemed a priority to be able to rapidly view video, audio, and submersible positioning data to enable richer scientific conversations and to allow all science pilots to share their ideas on ways in which to interact with and capture the lake environment. Also, now that the team had 2008 data in hand, PLRP team members could use those and other data to produce flight plans, analogous to preplanning space missions, well in advance of the field season in order to alleviate planning stress while in the field. Finally, the team's need for a formal project manager to support the exciting growth of the project full time was identified. In early 2009, this need was fulfilled, as Donnie Reid, who had been volunteering with the project for many years, formally joined PLRP as its Logistics and Operations Manager through the support of the Canadian Space Agency.

DSE Research Activities

Mapping Pavilion Lake. From late 2008 to June 2009, PLRP science team members delved into the 2008 DeepWorker video and tracking data. PLRP engineers provided assistance to the science team by integrating tracking, still photos from video data, and sonar data. This work identified the need to further investigate the biological contribution to microbialite development, the influence of lake bathymetry and sedimentation characteristics on microbialite distribution, the effect of substrate on microbialite development, and the variation of microbialite macromorphologies throughout the lake. The video data also revealed richness and diversity of microbialite morphologies in the large herms that were found near the southern end of Pavilion Lake's central basin.

Another interesting find brought to light the need to carefully measure the role of human factors in decision making. During the 2008 field season, although general flight plans had been developed prior to commencing the season, the detailed flight planning occurred while in the field. As a team, it was decided that transects across the deepest portions of Pavilion Lake should be de-prioritized as DeepWorker objectives, and instead assigned to AUV data-collection surveys. The primary reason for this decision was that it was deemed a better use of the human payload to have their sights on the microbialite-rich sections rather than what was thought to be the more sediment-rich regions. However, upon closer inspection of the AUV-based images and video data from DeepWorker flights that covered deeper, sediment-rich areas en route to the deep mounds or while surveying microbialite clusters that extended into deeper sections of the lake, it was found that there were unusual sediment characteristics, potentially small deep mounds and dark carbonate crusts similar to those associated with the deep (50–60 m) microbialites on what looked like rock substrates. In all cases, the available data were limited in providing further details, but it was enough to reverse the team's 2008 decision to avoid those deeper sections with the DeepWorkers. As such, in 2009, DeepWorker flights were planned for those deep, sediment-filled regions of the lake's basins.

Commencing in the spring of 2009, the DSE analytical team began flight-planning activities in advance of the summer field season. Based on identified 2009 science goals, hypotheses were developed and flights were planned to test them. From the examination of the 2008 DeepWorker contour flight data, specific regions of the lake were identified for further detailed exploration. These sites would be surveyed by conducting closely spaced DeepWorker cross-shore transects to track microbialite morphological changes, transitions, and sediment and slope characteristics, among other observable factors. The goal was to refine our understanding of these lake features and to capture macrovideo of the microbialites such that during postflight data analyses, the macro- to micromorphological characteristics of the microbialites could be discerned. The isotopic and geobiological characteristics of the deep (50–60 m) mounds were shown to be distinct from the rest of the lake (Brady et al., 2009; Olivia Chan, 2011, personal commun.), and as such, further sampling and surveying were deemed to be a scientific priority. In response to aforementioned science objectives and the possibility of finding new deep microbialites, 2009 flights were planned for the deep mound region of the central basin, and to other deep, sediment-rich sections of the lake that had not been previously surveyed by DeepWorker.

The 2009 DeepWorker flight plans included flight methods, specific flight rules, planned tracks and associated timing, and prescribed data collection for each of the 40 flights. Figure 15 shows a composite of these flight-planning documents. Hundreds of personnel hours were allocated to these planning activities; although it was well recognized that in the field flexibility and adaptation to unforeseen circumstances would be necessary, the backbone of a successful field deployment would be a high level of in-advance organization. By the commencement of the 2009 field deployment, the planning team had completed each of the flight plans, the science pilot submersible rotation was set, and each science pilot had been extensively briefed on the scientific, technical, and operational factors relevant to each of their flights.

In May 2009, four new DeepWorker science pilots were trained: Margarita Marinova, Alexander Forrest, NASA astronaut Richard Arnold, and Donnie Reid (as backup). A formal roster of nine science pilots from the PLRP DeepWorker classes of 2008 and 2009, plus one visiting science pilot (Dave Williams, McMaster University, former CSA astronaut) rotated through 40 submersible flights over 10 d of field operations. The 2009 flights successfully met all of the team's research goals and emphasized the relationship between lake bathymetry and microbialite development. Topographical highs and steep-sided slopes seemed to support high concentrations of microbialites as well as large (>2 m) microbialites. In 2008, M. Gernhardt discovered large microbialite developments that have since become known as "microbialites of unusual size"

DEEPWORKER FLIGH	20090706A	PILOT:	Mars	DATE:	6.07 Monday					
PLANNING CODE #	CB1	CAPCOM:	Bekah	Launching Location:		Brock Barge		Classification:		
FLIGHT TY	Contour	SCI COM:		Basin and Mooring:		CB, BrockMooring		Pre-Flight Science Merit		
TRAVERSE DATA SHEET				Raw Flight Name:		AB CB1		Post-Flight Science Mer		
			Pre-Flight	Mid-Flight			Post-Flight			
Timeline	**Leg**	**Waypoint**	**Value of Traverse Objective**	**Workload / Operator Compensation**		**Time**	**% Complete**	**Data Quality**	**Planned Duration**	**Estimated Elapsed Time**
Launch	P1								5 min	5 min
Surface Transit	P2	Pre-Flight							10 min	15 min
Descend to Depth	P3	Fatigue:							3 min	18 min
CommCheck/Orientatio	P4								2 min	20 min
	1	CB11							2	0:22
	2	CB10							11	0:33
	3	CB9							15	0:48
	4	CB8							11	0:59
	5	CB7							9	1:08
	6	CB8							8	1:16
	7	CB9							10	1:26
	8	CB10							14	1:40
	9	Barge							10	1:50
	10									
	11									
	12									
	13									
	14									
	15									
Ascend to Surface		Post-Flight								
Surface Transit		Fatigue:								

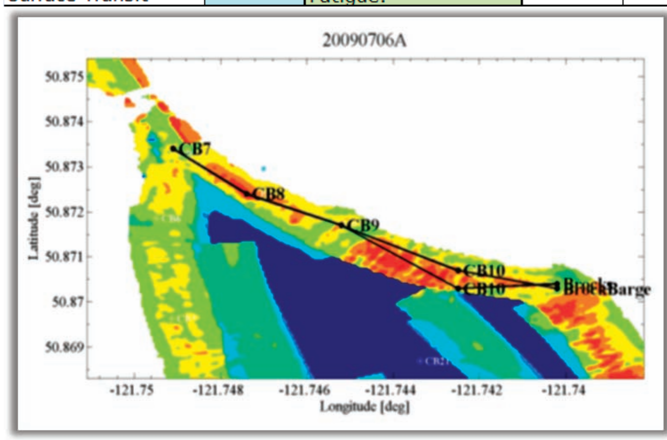


Figure 15. Example of flight plan worksheet (top) and map of planned flight track (bottom).

(MOUSE) to the PLRP team. These MOUSEs were mainly located in the south basin of Pavilion Lake, and they were all greater than 5 m in circumference. Subsequent 2009 DeepWorker surveys revealed that these large structures were most likely concentrated growths of microbialites on boulders and other hard, exposed substrates. Figure 13 shows an example of one of these large developments, MOUSE 1. After the 2009 DeepWorker surveys, D. Lim, M. Delaney, M. Shortridge, D. Reid, and B. Shepard used SCUBA to conduct measurements, set out sediment accumulation experiments, and take a closer look at MOUSE 1. Their investigations revealed that the structure was 13 m in circumference and 4 m in height above sediment. Exposed rock was visible throughout the structure, confirming that the microbialites had accreted on a fallen boulder of considerable size. Furthermore, the maximum height of microbialite growth above the substrate was estimated at ~2 m, indicating that the large structure was actually composed of a concentration of smaller microbialite growths. DeepWorker flights in 2009 also resulted in the discovery of deep (50–60 m) mounds in a new region of the lake and the successful recovery of more samples from these depths. Surveys of the sediment-rich regions also revealed sediment patterns, rock exposures, and different microbialite morphologies that had never before been seen or documented.

One of the primary objectives of the PLRP was to create a map that integrated physical, chemical, and biological features of Pavilion Lake, as well as the microbialite morphological distribution. As such, morphological classification of the DeepWorker data was at the core of reaching this goal. Therefore, in parallel with the flight-planning activities, the core planning team, led by the efforts of B. Shepard, designed a microbialite morphology guide. This was based on the seminal work by Hofmann (1969) on stromatolite morphologies, but it was modified to reflect the morphological variations in Pavilion Lake. The goals of this cue card, as it became known, were twofold: (1) It provided science pilots and all PLRP members with standardized morphological terminology for the description of macro-, meso-, and micro microbialite features, and (2) it became the foundation for all postflight morphological classification activities. The latter was a ground-breaking effort by the PLRP team to morphologically classify all of the video data from the 2008 and 2009 flights. No study of this extent had been previously accomplished. Furthermore, the need to complete the morphological classification of the video data prior to leaving the field was identified, and this would require the effort of the entire team.

Analysis of the 2008 video data had taken the core team hundreds of hours given the sheer amount of data to review (~1 Tb/156 h of high-definition video). Even then, the team had only achieved a first analytical pass and identification of sites of interest for the 2009 field season. No morphological classification had been accomplished. With the assistance of new technological and operational developments that will be discussed in the following sections, nearly all of the 2009 video data were reviewed and classified by all members of the PLRP team, from field assistants, to graduate students, to astronauts, to engineers, prior to even leaving the field site in 2009. This accomplishment has since been enhanced by the completion of a similar classification exercise on all the 2008 data. Morphological trends associated with depth and other physical features were characterized as a consequence of these efforts. The analyses of the 2008 data were accomplished by a group of incredibly motivated and talented high-school student volunteers from the San Francisco Bay area, along with M. Marinova, M. Wilhelm, and Z. Cardman. At time of press, M. Marinova continues to lead the development of a facies map of Pavilion Lake. However, it must be emphasized that this map is truly the end product of a remarkable team effort.

Exploration operations strategies. An inextricable relationship exists—in any environment—between hardware and the associated concept of operations, particularly navigational and communications infrastructure. As such, if we fail to dictate the way in which we want to conduct future space exploration, then our modes of exploration will be largely dictated by the hardware. By conducting rigorous investigations at field sites such as Pavilion Lake, at the intersection of science and operations, functional requirements can be identified to help maximize the exploration and scientific capabilities of future planetary, Moon, or near-Earth object surface systems.

Specifically, the PLRP 2009 Exploration Operations protocol continued a multiyear quantitative investigation of the inter-relationships between operator fatigue levels, workloads, science back-room support roles, crew-member autonomy, navigation, communications, and the productivity and science merit of the work being performed. The effects of changes in these variables within years and from year-to-year continue to be quantitatively evaluated with the objective of identifying the concept of operations and surface system functional requirements that will optimize future planetary, Moon, or near-Earth object exploration in terms of maximizing science and exploration return and minimizing time/cost.

As a mainstay of the exploration operations research at PLRP, data quality and scientific merit assessments were once again planned for 2009, and the "anticipated scientific merit" of each flight plan was scored before the field season began. Traverse science merit scoring was also applied to measure the pre- and postscores for science merit of each traverse section of the planned flights. In 2009, new metrics were also collected both during and after the submersible flights; these included an "observational quality" metric designed by B. Shepard and refined by the team. This metric was designed to score each science pilot's scientific observation capacity, and to monitor improvements through the field season and over the years as a by-product of both constructive feedback and experience. Data on human factors were also collected, ranging from fatigue to operator workload to time-line management. All of the metrics and associated scales are presented in Figure 16. The results of this research are planned for future publication once the data-gathering period is completed in 2013.

Other Exploration Activities

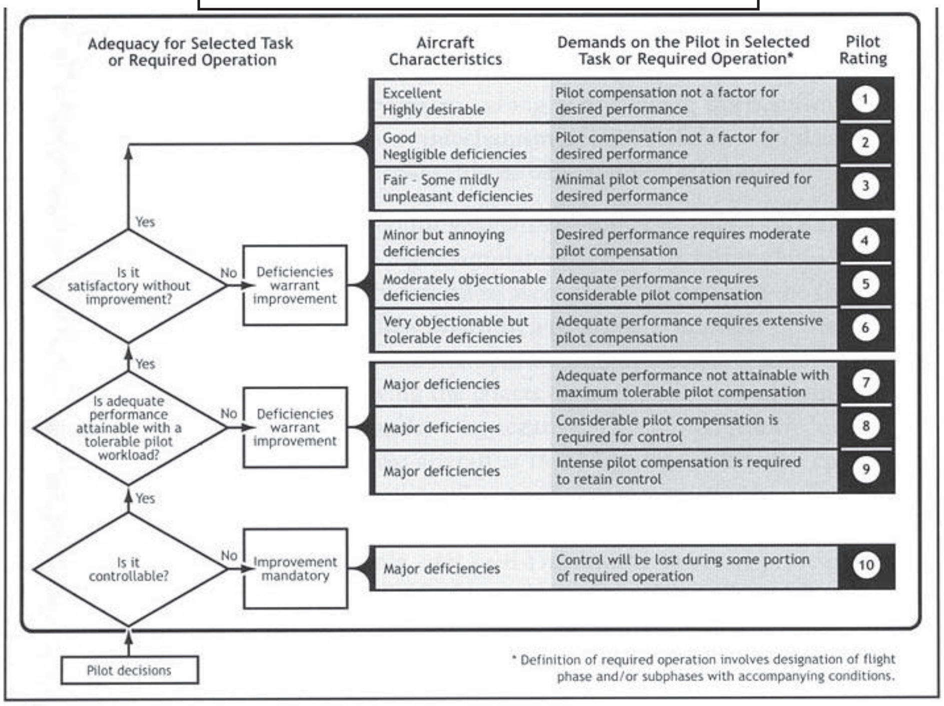
In 2009, further AUV work continued; however, this time, there was a high level of coordination between the AUV and DeepWorker operations to examine and compare scientific efficiencies. Building upon his planetary space science publication (Forrest et al., 2010) that compared human versus robotic platforms, A. Forrest, along with collaborators from the University of British Columbia and the University of Delaware, began examining the optimization of human-robotic survey systems to maximize scientific return. Robotic platforms operate in extreme conditions and environments with greater endurance and less risk than human explorers. Autonomous underwater vehicles (AUVs) are an excellent analog for robotic tasking in extraterrestrial settings in the domains of communication, positioning, and navigation. One of the focuses of the 2009 deployment of *UBC-Gavia* and DeepWorkers was to coordinate manned and unmanned (robotic) underwater platforms, since this is essential to maximize the scientific success of future analog and space missions. In space exploration, robots will be used to identify targets of interest for further manned investigation. Rendering coordinated data sets and common targets into a single georeferenced interface is critical for mission success. This results in significant near-real-time data postprocessing, emphasizing the need for unified, scalable, and exchangeable mission visualization systems for planning, playback, and real-time operational awareness.

Two types of missions were conducted during the field deployments: joint objective (examining a static, nonevolving system) and joint mission (coordinating exploration platforms to explore a system that is evolving temporally). Joint objective mission design was focused on exploring the deep-water microbialite mounds (~55 m) found in the central basin of the lake. DeepWorker missions were designed to visit specific targets to provide close, detailed imagery (0.5–1 m) of each of the sites. *UBC-Gavia* missions were designed to collect overview imagery (closest proximity of 2–3 m) in addition to both side-scan

Operator Workload

Insignificant Workload		Light Workload		Moderate Workload		Significant Workload		Maximum Workload	
Insignificant mental effort - Significant spare capacity remaining		Light mental effort - Desirable spare capacity remaining		Moderate mental effort - Moderate spare capacity remaining		Significant mental effort - Limited spare capacity remaining		Maximum mental effort - No spare capacity remaining	
1	2	3	4	5	6	7	8	9	10

Operator Compensation



Observation Quality Scale

METRIC	DESCRIPTOR	DEFINITION
1	Poor	Observations acquired by observer are poor in quality; limited in scale and context.
2	Fair	Observations acquired by observer are fair in quality; adequate scales and context.
3	Good	Observations acquired by observer are good in quality; sufficient scales and context.
4	Very good	Observations acquired by observer are very good in quality; very good spectrum of relevant scales and context.
5	Excellent	Observations acquired by observer are excellent in quality; maximum of relevant scales and context.

Figure 16. In 2009, workload (top box), operator compensation (central box), and observation quality (bottom box) metrics were added to the data quality and science merit scaling developed in 2008 to rate science pilot science productivity and quality.

and multibeam sonar data (e.g., Fig. 17). Because the targets of interest (i.e., microbialites) in Pavilion Lake are stationary, simultaneous AUV and DeepWorker missions were not necessary to evaluate temporal variability. The selected target for the temporally evolving case was the fate and transport of submerged groundwater sources. Mission design included using the DeepWorker, equipped with an in situ water-temperature and electrical conductance (related to total dissolved solids) (CT) sensor mounted on the front of the vehicle, to explore the near-benthic region (0.5–1.0 m) from the discharge site of the groundwater (the far south end of the south basin) to the deepest part of the basin while *UBC-Gavia* concurrently collected horizontal CT profiles in the epi-, meta-, and hypolimnion. Finally, vertical variation in the water column was explored using a

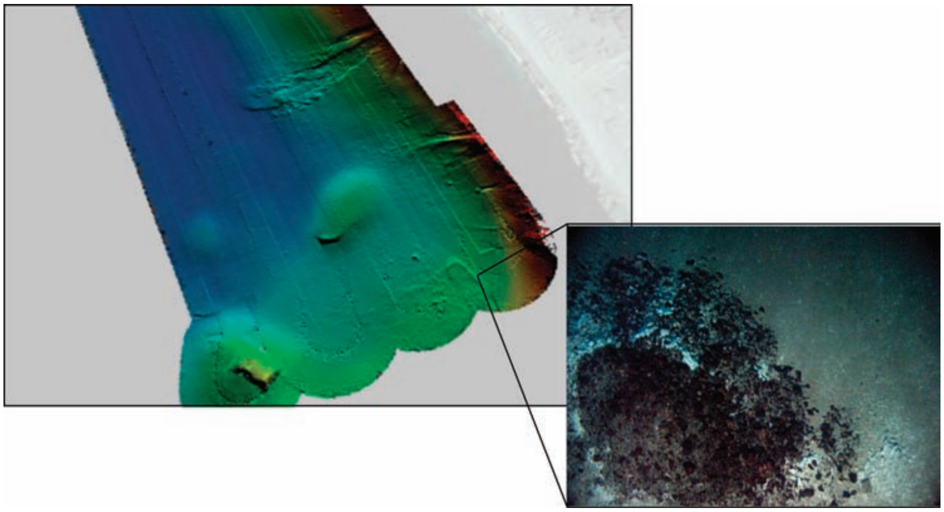


Figure 17. Overview of the bathymetry of the central basin of Pavilion Lake using Geoswath sonar as collected by *UBC-Gavia* with offset image also collected by same platform showing leading edge of mound. Colour swath of data is about 200 m across.

vertical CT profiler that was continuously deployed from the surface vessel during the two, 3 h testing periods. Use of all three platforms (*UBC-Gavia*, DeepWorker, and the surface vessel) allowed the spatiotemporal variability of the groundwater discharge evolution to be examined in unprecedented detail.

One of the goals of the conducted missions was to render the data sets from the two platforms into one common data visualization interface (e.g., Google Earth™, Fledermaus™, etc.). This is essential for a variety of reasons, including: increasing multiplatform mission planning efficiency; rendering the data set in near-real-time to maximize scientific return; and making compiled data more accessible to other scientists and the public. In addition to this ongoing work, further studies are examining the efficiency of each platform in collecting data and looking at various tasks (e.g., collecting images, surveying microbialites, etc.) and identifying the tasks that are necessarily platform-specific. This builds on the work of Forrest et al. (2010), who used three different mission evaluation tools, (1) a task efficiency index (TEI); (2) performance metrics; and (3) exploration metrics, to independently evaluate mission performance of DeepWorker, AUV, and remotely operated vehicle (ROV) missions. Data collected during the 2009 deployment were focused on developing a maintenance performance ratio of maintenance time versus data collection as a potential tool for cross-platform evaluation. The final objective of this work is to develop a unique set of mission evaluation tools that can be used for any platform in unknown exploration environments.

Technology and Operations

The choice of technical and operational developments for the 2009 PLRP program was identified based on the team's scientific needs. In particular, overall improvements to the submersible-to-surface communications, tracking accuracy, data coordination and surface data support systems, and camp infrastructure in support of laboratory- and computer-based activities were needed to facilitate both in-flight, real-time data synthesis, and pre- and postflight in-field data analyses. Accomplishment of these goals would enable the team to process data rapidly, have scientific discussions while viewing data from recent dives, conduct morphological classifications, alter flight plans based on new scientific discoveries, and construct the foundational elements of the facies map even prior to leaving the field.

Communications. In 2008, communications were limited to voice exchanges with the supporting surface vessels and acoustic tracking from the submersibles at Pavilion Lake that could be reviewed at a later date. In 2009, NASA Moon-Mars Analog Mission Activities (MMAMA) program funding enabled the participation of Marc Seibert, Michael Downs, and Bill Dearing from NASA Kennedy Space Center (KSC) in the PLRP field operations. The KSC team provided a mobile mission command center (MMCC) (Fig. 18) on the shore to provide work space for the science and exploration activities. This trailer was linked to the public Internet via a broadband interface

Figure 18. Photo of mobile mission command center along Pavilion Lake shore (photo by: Michael Downs).

on the shore through a local Internet Service Provider. Aside from contributing this important infrastructure component to the team, the task of the KSC team was to work with Nuytco Research, Ltd., to begin the implementation of major communications improvements that would ultimately link a science backroom team to the explorers underwater. Figure 19 presents an overview of the communications data flow that in 2009 allowed for two-way communications between the submersibles to chase boats on the surface, and one-way communications between the submersibles and the shore. By 2011, the PLRP was able to provide a full suite of full-duplex voice and data exchanges between the submersibles and a science back-room team; this setup has high-fidelity relevance to human exploration architectures. Perhaps the most challenging segment of the PLRP network has been the data exchanges between the submersibles and the surface vessel. In terms of science, the human exploration strategies require the exchange of information products such as imagery, video, checklist, tracking, and traverse maps with the explorers in order to grant them the highest level of autonomy possible. Publicly available technology is lagging in the area of broadband underwater communications.

Dedicating one chase boat to each DeepWorker resulted in major improvements in both acoustic communications and submersible positioning accuracy. During the 2008 deployment, a single chase boat tracked both submersibles simultaneously, and acoustic voice communication and submersible positioning system, referred to as an ultrashort base line (USBL), could degrade or be lost altogether when the two submersibles were separated or acoustically shadowed in complex bathymetry. This system used a single topside transceiver with multiple transducer elements located in the same housing. It sent out an interrogation signal, which was then received by the subsea transponder on the submersible. When the transponder replied, multiple elements in the topside transceiver recorded the direction from which the signal came and measured the time delay between the elements to determine a slant range and a horizontal displacement between the submersible and the surface vessel tracking station. The communications system mimics two bidirectional hydrophones in direct communication with one another.

The addition of a second surface submersible-tracking vessel in 2009 allowed for each submersible to operate independently. Each surface tracking vessel was fitted with global positioning system (GPS) beacons, a heading sensor, a serial data hub, a LinkQuest High Accuracy USBL navigation system, WinFrog Integrated Navigation software, and an acoustic underwater telephone. With these systems in place, each surface tracking vessel could hold station over top of their respective submersible with no loss of tracking data or communications.

The USBL system used in the 2009 field season was a high-accuracy model, which had an angular error of only 0.25° (better than 0.5% of slant range) and a slant range error of only 0.20 m. This accuracy far exceeded that of the system used in 2008. This high accuracy coupled with the fact that slant ranges could be minimized by positioning the surface tracking vessel over top of the submersible resulted in extremely accurate position fixes.

During the 2008 field season, flight plans were designed such that each submersible would start and end their activities from a common moored location. However, by 2009, the team's comfort level with the overall submersible systems and operations had increased. As such, the flight-planning team designed the 2009 submersible flights to include "live drops" and "live recoveries." This required the launch and recovery barge to conduct operations from a nonmoored position. This allowed each submersible to have a different start point and a different recovery point with respect to each other. Start points between the launch of each submersible were kept to within 500

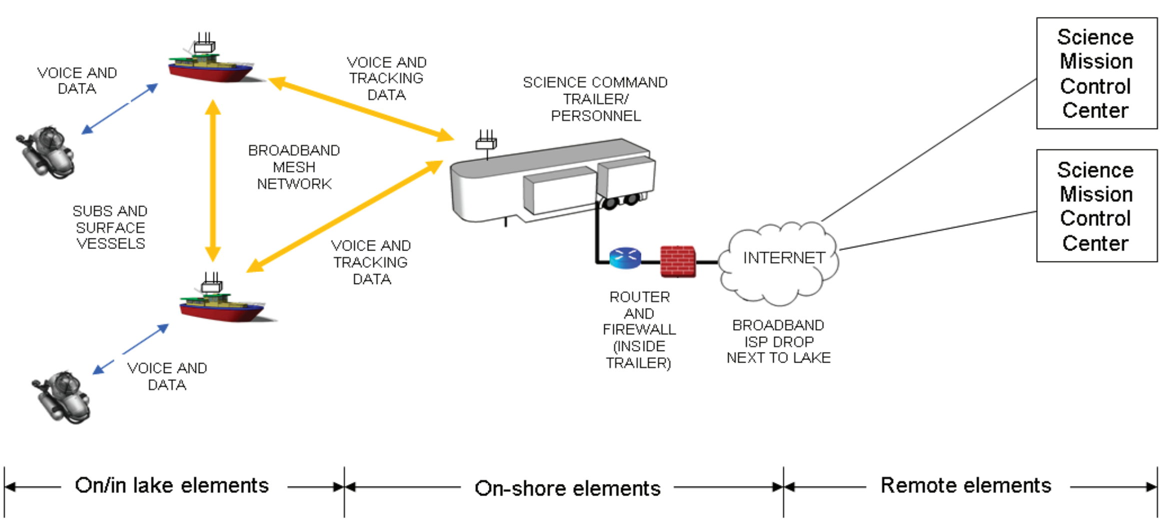


Figure 19. Communication targeting map of Pavilion Lake Research Project DeepWorker Science and Exploration (DSE) operations.

m of each other to minimize the time loss associated with long transits by the launch and recovery barge. The addition of an electric hoist for launch and recovery in 2009, originally added to minimize pilot discomfort due to overheating on launch and recovery, was instrumental in providing the speed necessary to make the live drops and recoveries possible.

A final addition of note about the 2009 PLRP field season was the addition of hard drive video recording devices. In 2008, all submersible video was recorded on tape to permit time stamping. In 2009, addition of hard drive recorders with removable media drives meant that there was no requirement to remove hardware from the submersibles between dives. The addition of an upgraded high-definition video camera allowed the time code to be recorded onto the media drive. The hard drive recorders also incorporated an event "mark" feature, which allowed the submersible pilots to flag events on the video record for rapid access during postflight analyses. The associated audio overlay of the pilot's voice onto the video record allowed for in situ annotation by the pilot. These improvements resulted in the ability to conduct a majority of data analysis on site and improved pilot readiness by means of improved mission debriefs and predive briefings.

Surface data systems—supporting science operations. During the July 2009 Pavilion Lake field test, NASA Ames' Intelligent Robotics Group (IRG) supported submersible "flight" operations using Google Earth as a primary operator interface, supplemented by a custom software tool-set. IRG had previously developed ground data systems for NASA missions, Earth analog field tests, disaster response, and the Gigapan camera system. Leveraging this expertise and an existing software library, a set of tools was assembled to support submersible tracking and mapping, called the "Surface Data System (SDS)." This system was used to support flight planning, real-time flight operations, and postflight analysis.

For planning, overlays were created of the regional bedrock geology, sonar bathymetry, and sonar backscatter maps that show geology, depth, and structure of the bottom. Place markers showed the mooring locations for the start and end points of submersible flights. Flight plans were shown as polylines with icons for waypoints. Flight tracks and imagery from previous field seasons were also embedded in the map for planning follow-on activities. These data provided context for flight planning. Figure 20 shows Pavilion Lake bathymetry overlaid on the Google Earth base map, with a planned flight track shown in orange.

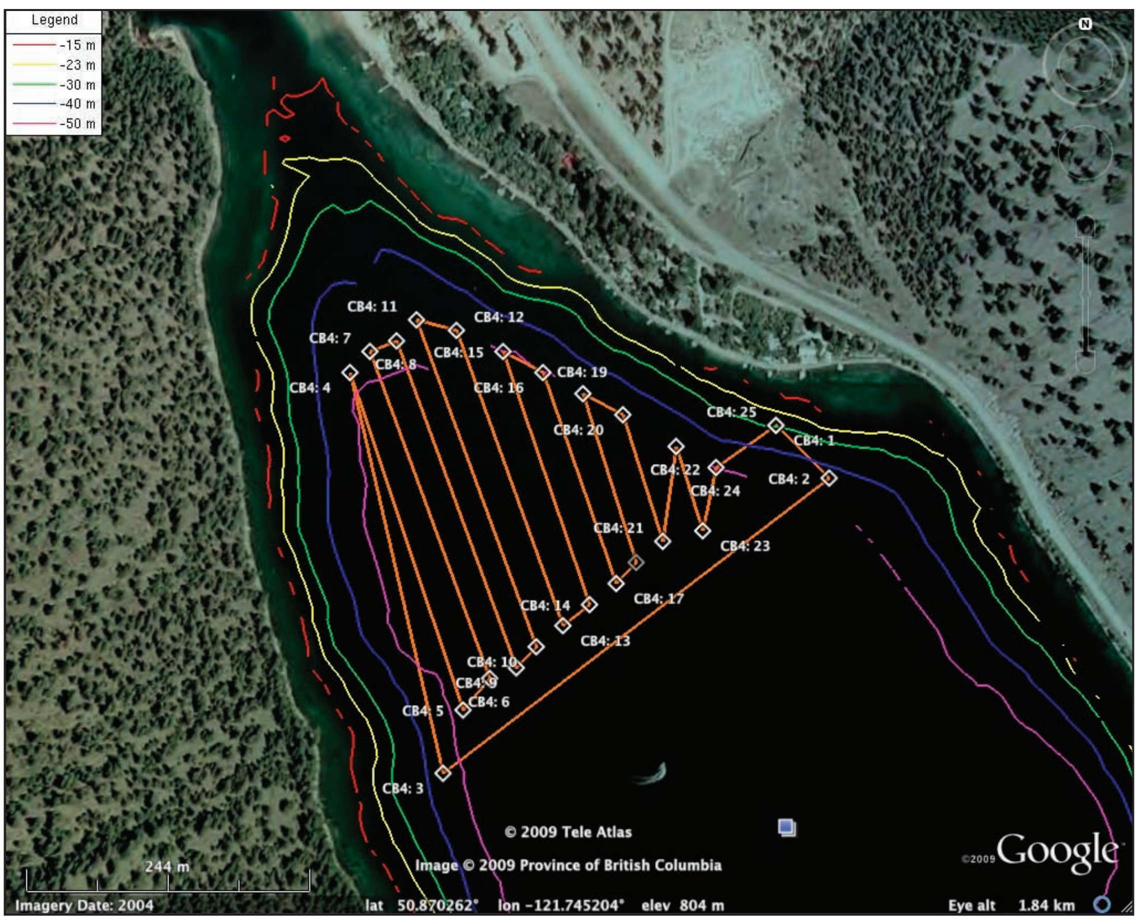


Figure 20. A flight plan for the 2009 field season. The planned path is shown in orange. The other colored lines show the lake depth contours (see legend at upper left).

The planning phase, in particular, demonstrated the advantages of an “end-user” tool, like Google Earth, for planning submersible operations. It provided nearly all of the capabilities needed for conceptual operations planning, without demanding the effort and expense required to write a custom tool or the expense and training required to use a “professional-level” geographic information system (GIS) or navigation tool. The majority of the PLRP team was familiar with Google Earth, and those who were inexperienced with the software were able to download and rapidly familiarize themselves with basic techniques. There were, of course, situations when a dedicated tool was important (e.g., the submersibles were tracked and controlled with a high-end navigation software package, WinFrog). Simple export tools were created to meet this need, and they allowed the transfer of planned flight paths from Google Earth to the submersible’s navigation system or to tools like MATLAB™ for specialized analysis and planning.

Figures 21A and 21B show the operational structure of the team during a submersible flight, and Figure 22 shows the software architecture of the Surface Data System (SDS) used at PLRP. The Science Stenographer (Steno) worked closely with the Capcom (Capsule Communications) and Navigator during a flight to log the submersible pilot’s observations in real time (Fig. 23). A custom software module interfaced with the submersible’s navigation system (WinFrog) and generated a Keyhole Markup Language (KML) file showing the submersible’s track for display in Google Earth in real time (Fig. 24). The submersible’s position and stenographer notes were also logged to a MySQL database to support postflight data analysis and search.

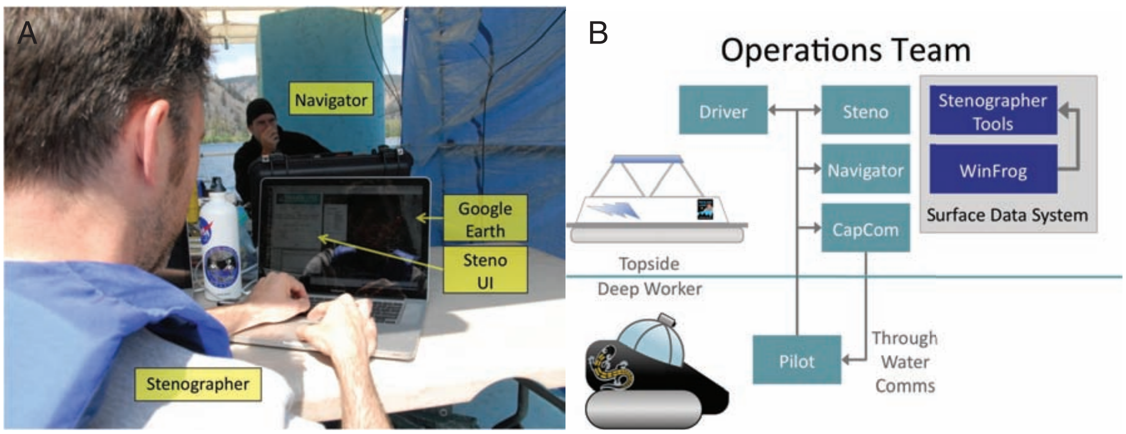


Figure 21. (A) Operations team on navigation boat during a submersible flight. (B) Operations team structure.

UI—User Interface

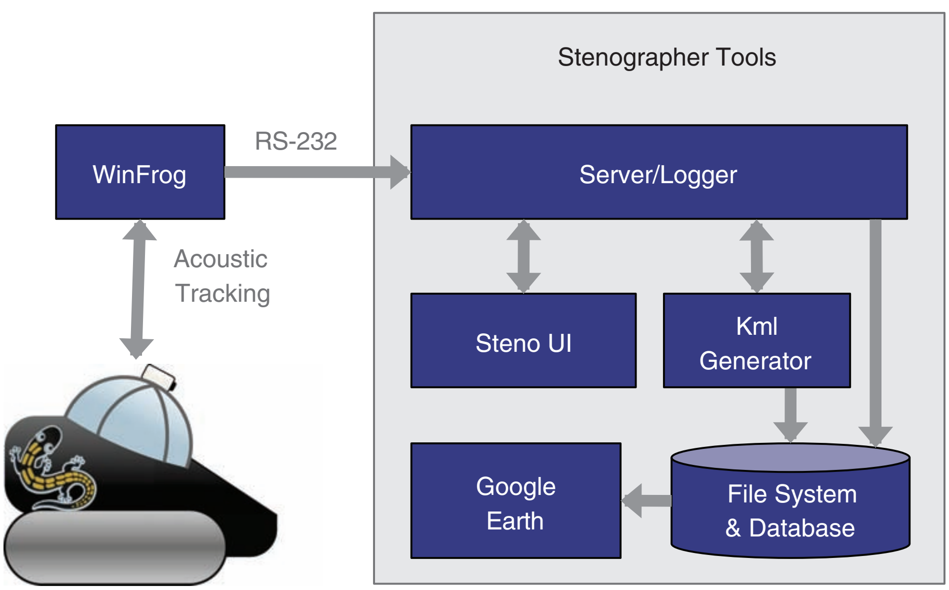


Figure 22. Surface Data System (SDS) data management architecture.

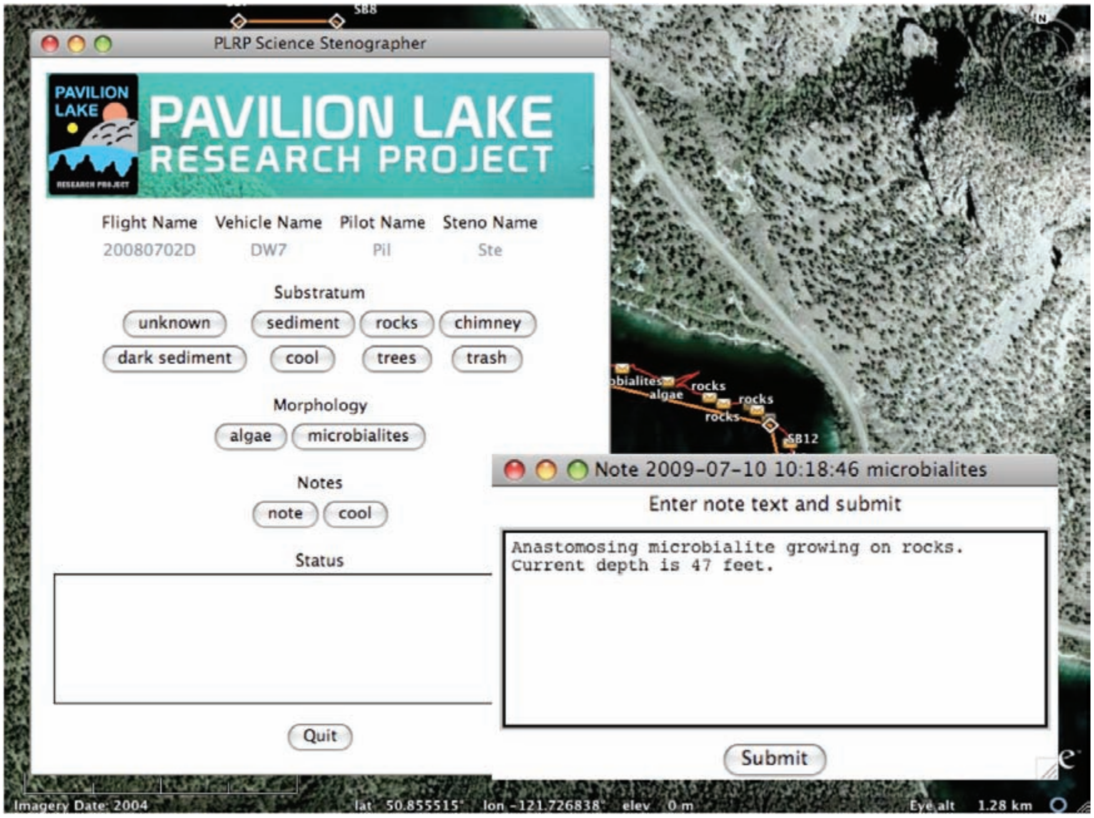


Figure 23. Example of a science stenographer note-taking interface.

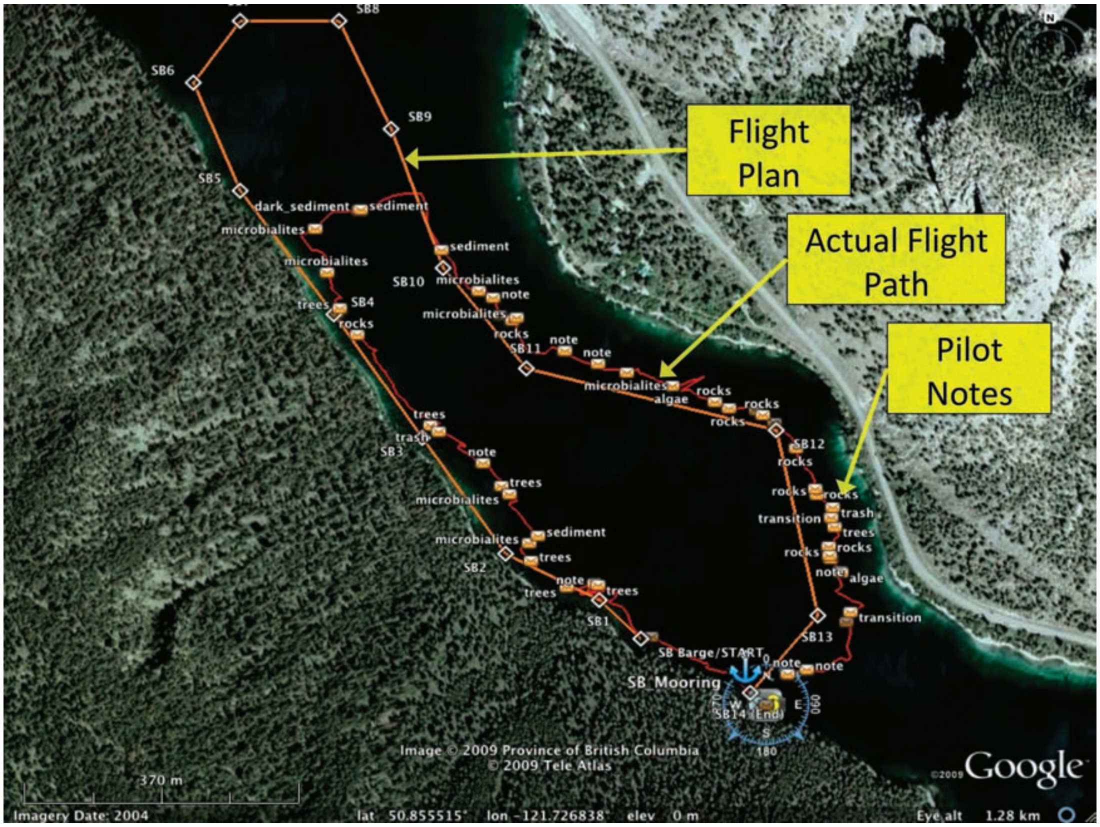


Figure 24. Real-time flight track (in red) collected during a flight. "Envelope" icons show the position of pilot notes recorded by the science Steno. Note that the actual flight was truncated from the planned flight (in orange) because of time and power limitations.

During a flight, submersible position was updated every 5 s from the navigation computer on the chase boat. This position was used to automatically generate submersible-track KML files, which were refreshed via network links to show the submersible's track in Google Earth. A submersible icon showed the current location of the submersible, and a compass rose showed bearings to indicate the heading to the next waypoint. Significant observations were transmitted by the submersible pilot on the voice loop and transcribed by the Science Stenographer in real time. Observations that were called up to the surface by the pilot appeared immediately on the map as icons with date, time, position, and notes about what was said (Figs. 23 and 24).

After each flight, the science backroom team had immediate access to the flight track and georeferenced notes from the pilots. Additional information was added during postprocessing. High-definition video was recorded continuously on the submersibles, with "event" time stamps marked by the pilot. Because of the challenges of transmitting high-definition video through water, all of the video processing was done postflight. Recorded video was transferred from the cameras in the submersibles to a computer at the operations center after each flight, and the event time stamps were cross-correlated with the position logs to geolocate events and allow a preview image and compressed video clip to be properly placed within the map (Fig. 25). Animated flight tracks were also generated, which showed time-stamped submersible position and provided a time-lapse playback of the flight. These same mission playback and animation tools were also adapted to work with AUV mission data, providing a single common visualization environment for evaluating human and robotic operations.

A substantial benefit of the real-time annotation system was that the video clips were indexed and ready to be used for science team debriefs and planning shortly after a flight was completed. It was possible to transfer the video from the submersible's recorder and extract clips at the event markers within ~90 min after the end of a flight. The video could then be viewed by the science team on a central computer in the operations center, and this information was used to fine-tune future flight plans.

As an example, in one case, video from a morning flight was used to identify a sample return location, and another flight was sent in the afternoon to retrieve the sample (Fig. 26). It was often, though not always, possible to compress the video into a more portable format and embed it into the flight map in Google Earth in time for the evening science meeting. By contrast, in the previous field season (2008), where none of these tools were available, video processing was not completed on site, so it could not be used for planning/tuning flights during the field season.

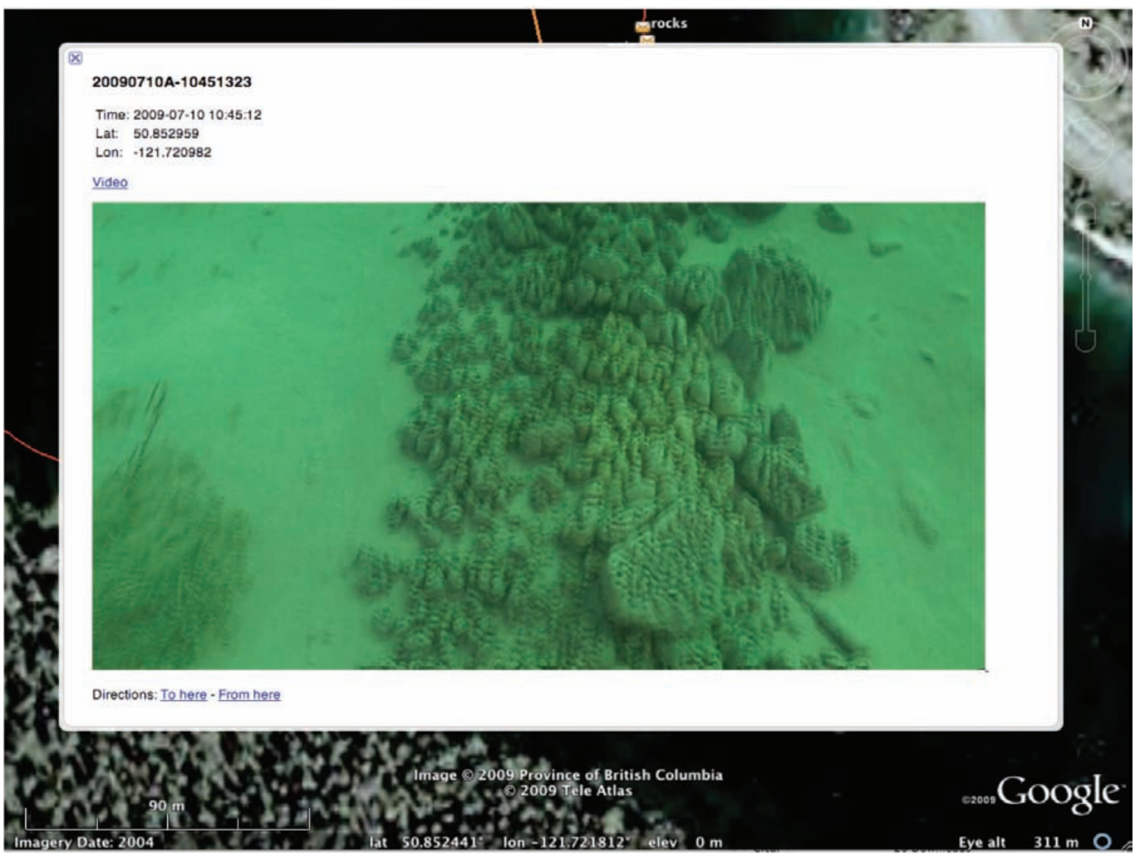


Figure 25. During postflight processing, geolocated place marks for video events integrated into our flight map. A half-size compressed version of the DeepWorker video could be viewed directly in the map.

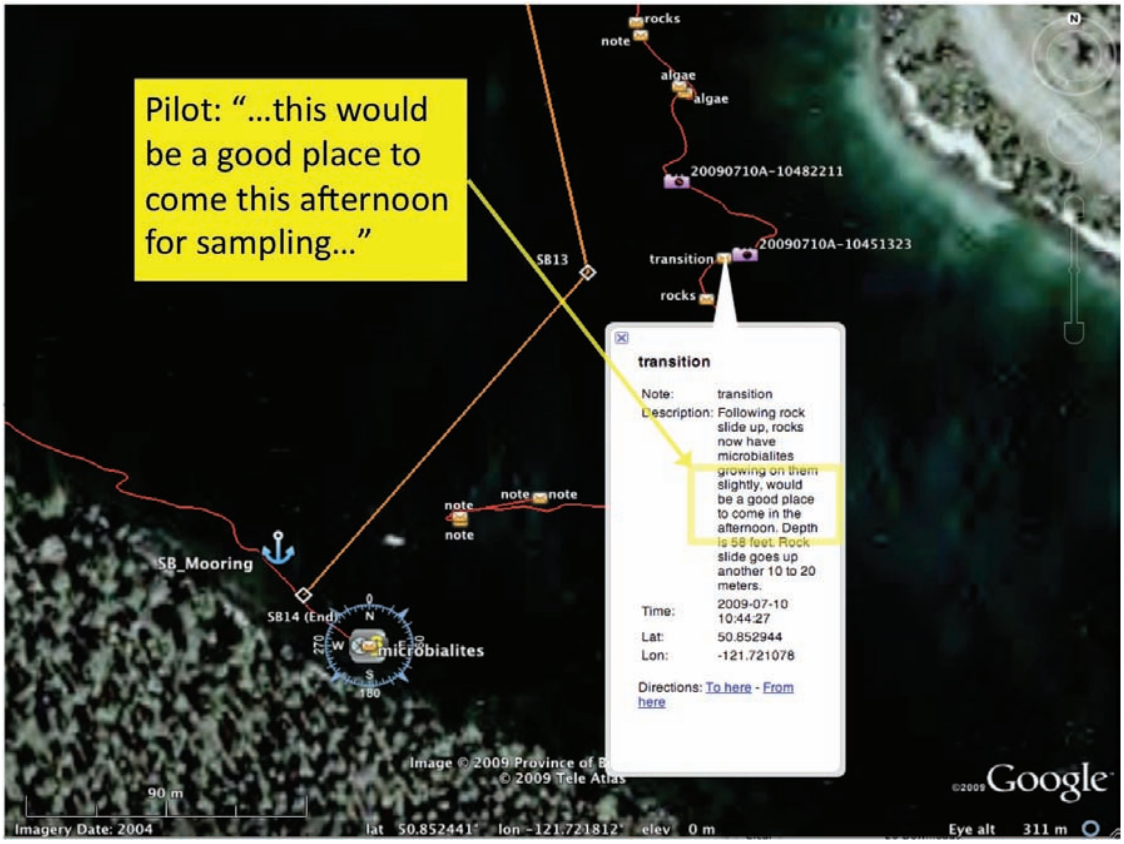


Figure 26. Time and position coded place mark from 10 July 2009 morning flight used to retrieve a sample later in the afternoon.

One lesson learned from our experience in 2009 was that transferring and processing high-definition video are unavoidably time- and space-hungry operations. Even with the "semi-automated" system that was deployed in 2009, constant attention was required to extract and process video quickly enough for it to be useful for scientific analysis and flight planning during the field season. In preparation for future operations, our postflight processing work flow will be reviewed and, ideally, automated and streamlined even further.

Finally, field operations illustrated the primary need of the science and operations teams to review the current day's data (i.e., the most recent maps and video), and the data archive was rarely used. It is anticipated that the opposite pattern will hold during planning for future tests, and there will be a much greater need to search and organize the archived data. A Web interface and the software needed to search for events and video in our archive database are currently in use and continue to undergo development with the goal of producing a fully interactive data review and flight-planning tool. The "Flight Analyzer" tool allows science team members to quickly locate all events of a certain type or from a particular time or location, and subsequently plan flights in relation to these points of interest. For example, a search could be conducted for all events that the Steno marked as "microbialites on a log" during a particular flight or in a certain region.

Neogeography tools are becoming increasingly popular and offer an excellent platform for geoinformatics. The scientists on the PLRP team were already familiar with Google Earth, which eliminated the need for up-front training on new tools. Because the flight maps and archived data were generated in KML for Google Earth display, they were immediately available to all members of the science team in an easily usable and distributable format.

Google Earth provided a wide variety of measurement tools, annotation tools, and other built-in functions that were used to create and analyze flight maps. All of this information was saved to a shared file system so that everyone on the team had access to all of the same map data.

Currently, the mapping data from previous field seasons are being used by PLRP affiliated graduate students to analyze and correlate information from different locations on the lake and across different flights and years to support their research, and to plan future years' activities.

Data management and archiving strategy. The PLRP has maintained a private database for research participants to upload and share their data with the team since 2004. However, with the growth of the project, and such a wide variety of research activities being conducted at the PLRP, implementing a new, but straightforward plan for organizing and distributing project data became a necessity. Each summer, hundreds of gigabytes to several terabytes of data are generated, and a structured approach to coordinating this volume of information is required to prevent data loss and to maximize the return on time spent in the field. As the PLRP has continued to grow in scope and sophistication, a scalable approach to data coordination is being implemented to address current and future needs.

In 2009, a formal "Data Management and Archiving Strategy" was implemented and led by Nicholas Wilkinson from Rask Systems. Working closely with all PLRP team members, he broke down the task of addressing this issue into three general phases: preseason coordination, deployment operations, and postseason dissemination. During the preseason phase, basic information is obtained regarding the types of data sets that will be generated during the deployment, and the storage capacity required for each data type is estimated. This information helps to formulate an initial work flow regarding the specific individuals involved in the collection of field data, the frequency at which this data should be collected (daily, weekly, end of season, etc.), the locations where the data will be stored, and the methods with which it will be accessed by project participants at the lake.

Preseason coordination activities also help to flesh out an appropriate directory structure and file-name conventions for all of the season's project data, which are mapped to a network attached storage (NAS) device deployed during field season operations. Throughout the season, team members are able to upload content to the NAS for immediate dissemination at the lake. At the end of the season, several redundant copies of the NAS are produced and provided to key researchers for safe keeping at their home institutions. Postseason, the data are made available online to ensure that all team members have access to the data that they require to conduct their analyses.

Future improvements include the development of an online interface for the directory structure, which would enable users to search for and aggregate data into a single view, as opposed to being forced to obtain data by navigating between individual folders. Software is also being developed to help automate administration of the NAS during the field season (i.e., enforcing file-name conventions, conducting automatic checks to ensure that data sets are complete, etc.), in addition to providing new ways of accessing and interacting with stored data. In the end, it is hoped that the lessons learned and solutions implemented in support of science operations at the PLRP will contribute to future analog deployments, and in turn, help enable a productive return to human space exploration.

Astronaut Training

Building upon the 2008 season, the PLRP endeavored to develop a formal astronaut training program that would address future expertise requirements for human scientific exploration of planetary bodies such as the Moon and Mars. In particular, given the science focus and operational environment of the PLRP field season, the opportunity was ripe to embed astronauts as science pilots and immerse them in training for the skills necessary to be a productive field scientist. Lim et al. (2010) described a set of learning design principles focused on optimizing astronaut learning in field science settings. It is these principles that were the backbone of the training curriculum that was designed for the 2009 Astronaut Field Science Program (AFSP) at Pavilion Lake. The 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 four learning design principles (LDPs) are as follows:

LDP#1: Provide multiple experiences—Experience in varied field science activities will hone astronauts' abilities to adapt to novel scientific opportunities.

LDP#2: Focus on the learner—Fostering intrinsic motivation will orient astronauts toward continuous informal learning and a quest for mastery.

LDP#3: Provide a relevant experience—Selecting field sites that share features with future missions will increase the likelihood that astronauts will successfully transfer learning.

LDP#4: Provide a social learning experience—Ensuring that 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.

In May 2009, NASA astronaut Richard Arnold joined M. Gernhardt as an astronaut science pilot on the DeepWorker team. Most recently, NASA astronaut Stanley Love and CSA astronaut Chris Hadfield both joined the science pilot team at Pavilion Lake. Prior to the field season, each astronaut received intensive and focused classroom training on geological, biological, and chemical topics relevant to the science and exploration of the PLRP. The AFSP preseason training curriculum was designed to ensure that the astronaut participants were provided with adequate background on the science of the project to allow them to become fully integrated members of the field team. Jeremy Hansen and David Saint-Jacques, newly selected CSA astronauts, also joined the PLRP field seasons in 2009 and 2010, respectively, although they did not participate as science pilots. However, both astronauts were also fully briefed on the science and exploration and took part in many operational aspects of the field science and exploration program.

The astronaut participants found that their experience with the PLRP AFSP provided a significant and helpful shift in astronaut training, particularly as plans are being made for long-term exploration-driven excursions upon lunar and Martian surfaces. Within the AFSP, the astronauts, regardless of their academic background, are immersed in a field science activity that is driven by well-articulated science objectives that are coupled to the inevitably fluid nature of discovery as it occurs in the field. Astronauts received the unique experience of being part of the initial planning team while also serving in an analog to the Mission Control "back room," where current data dictate the next day's excursions. Most importantly, the experience gained by this immersion provided the astronauts with the background and the freedom to make immediate judgments in the field, where current data dictate a real-time reprioritization of the day's excursion and autonomous decision making.

This skill becomes particularly important when communication constraints are considered for lunar exploration, near-Earth objects, and particularly the Martian surface.

Finally, as vested members of the science team, the astronauts were involved in the compilation, analysis, and presentation of the mission findings. Thus, they became members of the group of investigators that will bring postmission findings forward for peer review. The fact that the astronauts take ownership in the scientific returns is a unique characteristic of the training an astronaut receives as part of the PLRP AFSP.

PAVILION LAKE RESEARCH PROJECT—THE FUTURE

At the time of publication, the PLRP team continues to plan for further field science at sites beyond Pavilion and Kelly Lakes, including further DSE activities. In 2010, the project tested an "Artist in Residence" pilot program. The objective of this program was to integrate artists into the field research to catalyze new and innovative problem-solving mechanisms and scientific ideas. Also, multimedia representations of the lake environment are an expected outcome of this program. These will be showcased in public forums to promote the integration of the arts and sciences in exploration activities.

Over the coming years, the PLRP team will be focused on integrating and refining our scientific research to date. Forrest et al. (2008), Lim et al. (2009), Brady et al. (2009, 2010), and other ongoing research outline what is currently known about the interactive role of the physical, chemical, and biological components in the growth and morphological development of Pavilion Lake microbialites. Based on this research, the PLRP team has identified the opportunity to pair molecular, geological, and limnological techniques to refine our understanding of the factors responsible for microbialite morphogenesis and morphological variation in Pavilion Lake. In particular, ongoing studies are planned that will integrate both a "bottom-up" and "top-down" approach to understanding the factors responsible for the morphological development of microbialites in Pavilion Lake, including: (1) physical factors, such as slope, depth, sediment loading, debris flows, and substrate availability; (2) surface microbial and viral communities; (3) small grazer (macro-invertebrate) populations; and (4) diagenetic and biosignature preservation factors.

The opportunity to integrate bio- and physiochemical data with the lake-wide DeepWorker mapping and morphological classification data is unprecedented in the literature and speaks to the scientific opportunities of Pavilion Lake. However, it is the diversity of research applications that the PLRP has developed after nearly a decade of science and exploration that speaks to the strength of Pavilion Lake as an analog both for the earth science and planetary exploration communities.

CONCLUDING STATEMENTS

The historical accomplishments outlined in this paper reflect the PLRP's desire to address important scientific and exploration questions while developing innovative operational designs, field techniques, and management practices. From the early years to present day, the PLRP has endeavored to maintain and preserve the human experience throughout all of its science and exploration activities, and this has contributed to its steady growth as much as the excitement of the science and exploration. The project has grown from 8 to 158 participants from around the world, with the mean participant age being 28—similar to that of NASA's workforce during the *Gemini* and *Apollo* missions. However, no matter the age, every member of the PLRP team possesses a youthful vitality that continues to drive the project. It is this energy, along with the strong sense of camaraderie, integrity, and desire to succeed, that truly characterizes the PLRP family of volunteers, engineers, scientists, students, camp personnel, local residents, and astronauts.

APPENDIX 1. TECHNICAL SPECIFICATIONS FOR DEEPWORKER 2000 SUBMERSIBLES

Nuytco Research's DeepWorker 2000 submersible is a compact, deep-diving submersible that is capable of supporting a variety of auxiliary systems and equipment.

Specifications

- Operating depth: 600 m (2000 ft)
- Air weight: 4000 lb
- Length: 8 ft
- Width: 5 ft
- Height: 5 ft
- Pilot: One
- Passengers: None
- Life support: 80 h
- Dive time: 6 h per charge (charge time ~6 h for full charge)
- Total power capacity: 12 kW; 2 × 120 V battery pods (240 V nominal); 12 VDC @ 500 W, 24 Volts Direct Current (VDC) @ 500 W
- View port: 24-inch-diameter acrylic, serves as entry hatch
- Thrusters: 2 × 1 horsepower (HP) horizontal, 2 × 1 HP Ver-trans
- Thruster control: Foot controllers

Accessories

- Ritchey Fluxgate Compass
- Imagenex 881A Digital Multi-Frequency Imaging Sonar
- Imagenex Heading Sensor
- Five-function manipulator
- Sample collection basket
- Newtcam high-definition video system
- Nnovia 80 GB hard drive high-definition video recording system with event "mark" feature
- Laser scaling device for measuring distance and camera aiming
- 200 Watt Hydrargyrum medium-arc iodide (HMI) Lights × 2, 5600 K
- Underwater telephone: Nuytcom DSP Digital 27 kHz
- Onboard programmable logic controller (PLC) to provide auto depth functions

Optional Equipment

- DVL (Doppler velocity logger), recording depth, altitude, distance over ground, and bearing
- 5.0 megapixel digital camera (external); ~400 frames per dive; synchronized to 250 W-s (watts-seconds) strobe with optional 2 × 80 W-s slaves synched
- Optional tether for real-time video signal to topside
- Quick-change battery trays for rapid turnaround time

DeepWorker Deployment

The infrastructure at Pavilion Lake would not allow for the deployment of a large surface vessel typical for submersible operations at sea. As such, Nuytco Research had to design and build a launch and recovery platform that was small enough to be deployed on Pavilion Lake. The solution was a sectional barge with an A-frame arrangement and a moon pool through which the submersible could be launched (Fig. A1). This barge could be dismantled entirely at the Nuytco facility in North Vancouver, mobilized to Pavilion Lake on a tractor trailer, and reassembled directly on the lake. Each piece of the system was designed to be light enough that it could be handled with a truck-mounted mobile crane. Removable decking panels were used to span the gap between the barge sections. When the submersibles were lifted clear of the deck, the panels could be removed, and the submersibles could be launched between the barge sections.

APPENDIX 2. AN OVERVIEW OF THE PLRP'S COMMITMENT TO EDUCATION, OUTREACH, AND PARTICIPATORY EXPLORATION

An important value held by the PLRP is that knowledge should be shared, not only within the scientific community, but also with society as a whole. Education and public outreach (EPO) is an essential communication channel by which scientists engage the public directly, as opposed to traditional mass media, where a third party is involved. Through these outlets, we seek to gain increased public discourse about science and exploration, and to inspire a new generation of young people to consider careers in the natural sciences, engineering, and technology. To achieve these objectives, the PLRP uses "traditional" outreach activities: Web site, school visits, and public presentations, and beginning in 2008, a combination of modern social networking tools and Internet-based programs to build a modern, accessible EPO program.

Social Networking and Internet

Social networking and interactive online publishing tools (Web 2.0) are ubiquitous in the general public, are frequently used within the scientific community, and are increasingly being employed to communicate science to the public (e.g., http://blogs.nature.com/). Web 2.0 affords an increased level of interactivity between the science team and the interested public, facilitating two-way transfer of questions and information on a global scale. From an EPO perspective, these online tools are invaluable for developing a connection with the Internet generation. The PLRP is at an advantageous position from an Internet-based EPO perspective because a significant portion of our data (maps and video footage from the submersibles) is also an effective EPO resource. With moderate editing, the data (videos and maps) have been posted online in a format that is accessible to the public within a few hours of collection. Thus, we are able to use this advantageously to communicate science with the general public on a real-time basis.

The primary form of communication from the field is a Wordpress-based blog (www.pavilionlake.com/blog) that encourages contributions from the entire PLRP team: scientists, astronauts, students, field assistants, and the camp cook. These communications personalize the science and exploration activities while sharing information about the project in a way that facilitates a broader understanding of analog science activities. Incorporated into every blog entry, multimedia components (e.g., video from a morning submersible flight, a map generated from the season's data collection, or photos of the cook tossing pizza dough) contribute significantly more to the reader's understanding of the project's day-to-day activities than a text-only version might provide. The blog invites comments at the bottom of each post, enabling interactive online conversations between interested readers and the blog author. These blog entries are consistently the highest ranking (most unique visits, as measured by Google Analytics) pages on the project Web site. While the blog currently focuses on the science activities during the field season, it is updated on a monthly basis outside of field season with a summary of accomplishments, announcements, and discoveries made by teams and individuals within the group. This helps to maintain interest in the PLRP, increase understanding of the role of analog sites within the space research community, and helps the local Pavilion Lake community follow our discoveries when the team is not present at the lake.

In addition to blogging, the PLRP employs several social networking tools to deliver its message, including Facebook, Twitter, Social Follow, Picasa, YouTube, and blip.tv. These tools ensure rapid dissemination of outreach material and can be easily integrated into our major field operations in a relatively remote area. To minimize the impact of EPO work on an already time-limited science team, our social media outlets are integrated to work seamlessly with each other, such that content is not duplicated, and time spent on these activities is minimized. For example, to generate a new blog with photo and video content, photo and video footage is first uploaded to Picasa (http://picasaweb.google.com/pavilion.lake) and YouTube (http://www.youtube.com/user/pavilionlakeblog), respectively. These media channels are automatically shared with the NASA Analog Network (http://www.nasa.gov/exploration/analogs/), which broadcasts to a larger general audience than the PLRP would reach on its own. Media from these external sites are linked directly to a blog, avoiding duplication of bandwidth use, time, and effort while simultaneously reducing

Figure A1. DeepWorker launch platform (barge), showing submersible deployment under way (left) (photo by: Jim Thompson); and DeepWorker deploying through barge moon pool (right) (photo by: Matthew Deans).

storage demand on our Web server. When the new blog is published, it is automatically reposted on Facebook, and linked on Twitter, therefore enabling rapid distribution of information to a wide audience with minimal repetition on the part of the author. This enables more EPO time to be focused on generating new content, and less time spent posting and reposting the same information to multiple sources. The PLRP uses the Social Follow button to ensure visitors to our Web site can instantly track the project via their preferred media tool, without searching for these links via external sites.

Engaging Young People: Students and Teachers

Training Highly Qualified Personnel

Engaging young people and inspiring their participation in science, technology, and exploration are essential to continuing the discovery process through future generations. The mentoring of highly qualified personnel throughout each phase of the PLRP has been an important and valued aspect of the program. Several doctorate- and master-level theses have been generated in part or in whole from research involvement with the PLRP, and countless undergraduate students have conducted internships and senior-level theses with the project. Many of these students were placed in leadership positions with the project, and during their tenure with PLRP, they gained valuable media and outreach experience, and interacted with senior NASA and CSA personnel, including astronauts. These students were also involved in DeepWorker and *Gavia* operations, scientific diving, preseason logistics, and postseason data processing. Many of the students who joined the PLRP as field assistants have gone on to graduate studies at the lake with one or more of the PLRP scientists as supervisors. The involvement of high-school students in the program's research and field activities has been particularly gratifying and enriching for all PLRP members. The following was written by Maria Andersen, a student who has been volunteering with the PLRP since 2006. Here she describes her experiences with the project and summarizes the value of student participation in field research projects:

"Merely being a high-school student, stepping foot into the exhilarating atmosphere of Pavilion Lake brought about a change of perspective I had on science. Rather than meeting the stereotypical scientist that the world sees, I met people who were not only passionate about their field of study but also were able to blur the lines between work and their passions. As strenuous as their work may be, their love for it is what motivated them. Seeing everyone wake up early, work to their upmost all day, and then go to bed late prompted me to do as much as possible to help. Whether it was dish duties, classifying structures, or random jobs that people needed to be done, you name it, I did it. While most high-school students worry about their appearances and other trivial matters, I began to seriously think about my future. Where will I be in ten years? Grades became more than numbers to me. They became the key to my future. Being able to work alongside those who placed a value on learning to the best of their abilities helped me come to terms with what I must do if I want to follow in their footsteps." In the coming years, this training of highly qualified personnel is expected to continue, and several of the students who have since completed their doctoral theses have continued with the PLRP as mentors to a new crop of young minds.

Educational Outreach

The PLRP has also used online interfaces such as Skype and other Web-based interfaces to engage students and teachers from the field. As an example, during the 2008 field season, through the support of NASA Spaceward Bound, a group of 15 students from the local British Columbia area, along with accompanying teachers enjoyed a day of lectures, snorkeling, and microbialite experiments led by Chris McKay. In addition, in 2008, one teacher from California was embedded with the team for 10 d. These projects were expanded in 2009 as three pilot projects involving students and teachers were conducted: a Mission Badge design contest at a school in Richmond, British Columbia; a videoconferencing opportunity with the Shad Valley student group in Vancouver, British Columbia; and a teacher integration program in the spirit of NASA's Spaceward Bound.

The PLRP Mission Badge design contest challenged elementary-school students at Alexander Hamilton Elementary School in Richmond, British Columbia, to design a patch for the 2009 field deployment akin to the badges that were designed for *Apollo* or space shuttle missions. It was requested of the students that they illustrate one or more of the PLRP's guiding principles: safety, environmental stewardship, advancement of science, and advancement of human exploration. To participate, the students would research the analog environment at Pavilion Lake and gain a fundamental understanding of the exploration methods used in "extreme environments" that are already part of the British Columbia curriculum. As a reward for piloting this project, the school was visited by several members of the PLRP, including Nuytco Research founder Phil Nuytten of Nuytco, Inc., and, via Skype videoconference, Canadian astronaut Dave Williams. The videoconference was well received by the students, and the use of technology in this instance allowed us to involve a visit from an astronaut as a reward for the students' hard work, without requiring cross-country travel. In the future, we plan to use these online meetings for EPO on a more regular basis to communicate with school groups remotely, since the experts in the field are not always available in the local area, and the students became noticeably more focused and interested during the videoconference with D. Williams.

The remote learning concept was also applied to EPO and Participatory Exploration (PE) activities through a series of videoconferences with Shad Valley, a science and engineering educational enrichment summer school for exceptional high-school students. To take advantage of the remote location while the team was in the field, similar to Moon-based science where the science team would be inaccessible except by telecommunications, the Shad students led several live question-and-answer sessions with small groups of the Pavilion Lake team via Skype's videoconferencing capabilities. The students were first exposed to an introductory lecture about the current science and exploration activity at Pavilion Lake, to spark their interest, and to meet the project leads. They were subsequently split into small groups to develop questions for the videoconferences that stemmed from this initial conversation, using material available online via the PLRP Web site and blog. This online activity was concluded with an in-person session with PLRP scientists G. Slater, A. Brady, and J. Hansen in Vancouver to summarize and conclude the activity. The questions developed by the students were exceptionally in-depth, and the conversations about analog science were worthwhile from both the Shad Valley and Pavilion Lake perspectives. While this EPO program was designed for, and achieved, the goal of enhancing student inquiry skills through the development of insightful questions relating to microbialites, the early Earth, and the relationships between analog sites and space research, a beneficial by-product was the ability for these next-generation scientists to meet graduate students and researchers who could discuss their career path more directly. The discussions about science careers were perhaps as beneficial as the science component to the students, and this should not be overlooked in future iterations of this activity in other settings.

Teacher integration into space analog research has been the goal of NASA's Spaceward Bound program over the past several years, and in 2008, a pilot program for Spaceward Bound was brought to Pavilion Lake. In the spirit of Spaceward Bound, in 2009, three teachers were integrated within the project to bring ideas together for a Pavilion Lake teaching module for elementary- and high-school students. During their visit, the teachers became part of the science team and participated in many aspects of the project, including back-room data processing and real-time science stenography. After observing the project, and participating in several aspects of the science, they produced an excellent document outlining the types of activities their students would complete,

Figure A2. Photo from Pavilion Lake Research Project 2009 Community Day open-house activities (photo by: Ben Cowie).

and the resources that would need to be provided by PLRP to ensure successful implementation. In the future, this work will contribute to the development of educational modules eventually available online for teachers to download and use in their classrooms to teach about analog science and exploration activity. In 2011, teacher integration played a larger part in the project, with a formalized curriculum and objectives for lesson development being completed as a team while on-site. By involving teachers in the operations, they will share their experience at Pavilion Lake with many more students in their classrooms than individual researchers would be able to reach.

Community Participation in PLRP Field Science

Since 2004, the PLRP has hosted a Community Day event during each of its field seasons (Fig. A2). This has consisted of research presentations, meet-and-greet events, public viewing of PLRP science technology (e.g., AUV, DeepWorkers, MMCC), and other interactive activities aimed at promoting a dialog between the visiting scientists and local residents. These events have been well attended by local residents and involve all of the PLRP team. The interactions have been fruitful scientifically, and they have helped to grow and strengthen the important relationship between the local community and the PLRP.

As the PLRP has expanded its science and exploration operations, its contribution to science literacy in the public has grown in step. By developing an effective EPO program, targeted at the next generation of scientists and engineers, the PLRP has provided opportunities to interact with the science team in a meaningful and positive way, built support for planetary analog scientific research, and worked to improve scientific literacy in the local Pavilion Lake community, and the general public.

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