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Diving at Extreme Altitude: Dive Planning and Execution During the 2006 High Lakes Science Expedition

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Abstract

The NASA Ames Diving Safety Office supported the successful diving operations of the 2006 High Lakes Project, HLP, in the 19,400 ft (5,913 m) crater lake of the Licancabur volcano in Bolivia. The HLP explores the limits of life in some of the highest lakes in the world located in the Andes at elevations up to 20,290'. The unique extreme diving environment required the development of new sets of diving standards, techniques, and technical diving protocols, early literature surveys having established the limitation of existing recreational, commercial, and military guidelines. Here we document the process of developing and executing a dive plan that enabled the dive team to achieve its scientific objectives while adhering to a high standard of safety. Key elements of the dive plan included use of closed-circuit oxygen rebreathers to mitigate combined altitude- and decompression-related risks, derivation of new dive tables, a novel diver suspension system, and definition of protocols for a broad spectrum of dive-related activities and contingencies. The elements of the dive plan were tested individually and in combination, to the extent possible. A description of the two successful dives is given along with a summary of lessons learned and recommendations for future expeditions.

Introduction

In November of 2006 the High Lakes Project (HLP) mounted an expedition to the Andes mountains of southern Bolivia that included diving operations in the 19,400 ft (5,913 m) crater lake of the volcano Licancabur. The team's objectives were to retrieve biological and sediment samples and to document the unique underwater habitat. Since the remote location and extreme altitude of the dive site posed unique safety challenges, a highly specialized dive plan was developed in order to meet those challenges and maintain a high standard of safety.

Background

Funded by the NASA Astrobiology Institute (NAI), the HLP has made annual expeditions to the region since 2002. Its purpose is to explore the limits of life in some of the highest lakes in the world located at altitudes up to 20,290'. The project focuses on characterizing lake habitats, the organisms that populate them, and the short and long-term effects on these organisms of the high ultraviolet (UV) radiation found only at these altitudes and latitudes. Understanding how life has adapted to cope with extreme environmental stresses will give scientists insight into both the evolution of life on early Earth and the possibilities for life on other planets. Most specifically, the lakes in this region are of unparalleled interest as Earth-analogs to the ancient lakes thought to have existed on early Mars, c.a. 3.5 billion years ago. The high UV flux (up to 216% that at sea level [Cabrol *et al.*, 2007]), dramatic temperature swings, aridity, low oxygen, low pressure, and volcanic geology combine to give us what is perhaps the closest approximation on Earth to conditions on early Mars. Learning about the limits of life, its survival strategies, and its bio- and geosignatures is a critical step in preparing the next generation of NASA planetary surface missions which will be searching for evidence of past or present life on Mars. Since conditions on Mars are thought to have changed rapidly, the HLP also seeks to understand the effects of rapid climate change on life and habitats and to identify adaptations that have aided survival in the face of such change.

So far, the HLP has investigated a dozen lakes at altitudes above 14,240 ft (4,340 m). The highest of these is located in the crater of the volcano Licancabur at 19,400 ft (5,913 m). Based on a shore sampling from 2005 (the lake was covered by 18 ft [5.5 m] of ice) it was determined that 12% of the microscopic organisms isolated are currently not classified at the phylum level, and 70% are not classified at the level of genus [Cabrol *et al.*, 2007]. Free diving efforts in 2003 and 2004 yielded some samples from the lake bottom, but divers tired quickly and were unable to obtain sufficient samples given the diversity of the ecosystem they discovered there.

The diversity and uniqueness of the ecosystem encountered in the summit lake provided justification for further diving efforts. It was felt that divers in the water could much more effectively identify and sample interesting locations than could be done by remote sampling from the surface.

Diving Objectives

The diving objectives were: 1) to sample the diversity of organisms and sediments in the lake and 2) to obtain high-quality underwater video and image documentation of a) the diversity and extent of the lake's ecosystem (habitat and life), b) the sampling sites in order to provide context, c) the sampling methodology, and d) of the team's underwater activity in general. Required supporting data for each sample consisted of its GPS latitude and longitude, its depth, the time at which it was taken, and a contextual image or video of the sample site prior to collection. The final sample set was to include samples of each visually discernible type of bottom material and samples collected at depth intervals of 50 cm over the full depth range of the lake.

Diving Environment

The physical parameters of the dive site are listed in Table 1. Licancabur's summit crater is a rocky amphitheater roughly a quarter of a mile across with slopes of 25-35 degrees running down to a small (300 ft x 200 ft) lake at its center. Since there is precious little flat area inside the crater, camp was placed on the more spacious North shoulder of the volcano at 19,300 ft (5,883 m). Each of the four work days at the lake required the team to hike up over the 19,620 ft (5,980 m) rim into the crater and then back out and down at the end of the day. Weather inside the crater is usually sunny and calm from morning through midday with winds increasing after about 1400. Although precipitation, already scarce in the region ($\leq 100 \text{ mm} \cdot \text{y}^{-1}$), is rare in November, bad weather can develop rapidly.

The lake itself is exceptionally clear with visibility in excess of 40 ft (12 m) with the bottom undisturbed. The bottom material consists of rocks, sand, and a soupy muck that reduces visibility to near zero once disturbed. Ice cover has varied each year ranging from none in 2003 and 2006 to 18 ft (5.5 m) covering the entire lake in 2005. The dive staging area was situated along the northern shoreline where there was sufficient flat area for a small tent and diving equipment. Figure 1 shows the staging area and lake bottom.

Dive Planning

Dive planning was driven jointly by science objectives and the need to mitigate risk. In accordance with American Academy of Underwater Sciences standards the final plan was required to pass the scrutiny of a Diving Control Board, which included personnel from five NASA offices (medical, safety, diving safety, management, and science). Early consultations with technical diving experts identified closed-circuit oxygen rebreathers as the safest option for shallow diving at extreme altitudes. This was the starting point from which the rest of the plan evolved through an iterative process of testing, revision, and review. This section describes the elements of the final plan along with the rationale for important decisions along the way. In its final form, the plan called for two dives, each to be carried out by three divers. The purpose of the first dive was to perform exploratory sampling of bottom materials and to obtain video- and photo-documentation of the underwater environment. The purpose of the second dive was to obtain bottom samples at 50 cm depth intervals.

Table 1. Summary of the diving environment

altitude	19,400 ft
surface pressure	0.48 atm
air temperature	~5°C at midday
wind speed	<20 mph in crater
water temperature	4 C at surface 2°C at 2 m depth
lake dimensions	300 × 200 ft.
max. depth	16 ft
pressure at max. depth	0.91 atm
visibility	1-40 ft
bottom	rocks, sediments organic; muck
ice cover	none in 2006
shoreline	talus, scree, sand
lake access	easy from North, South, and West shores

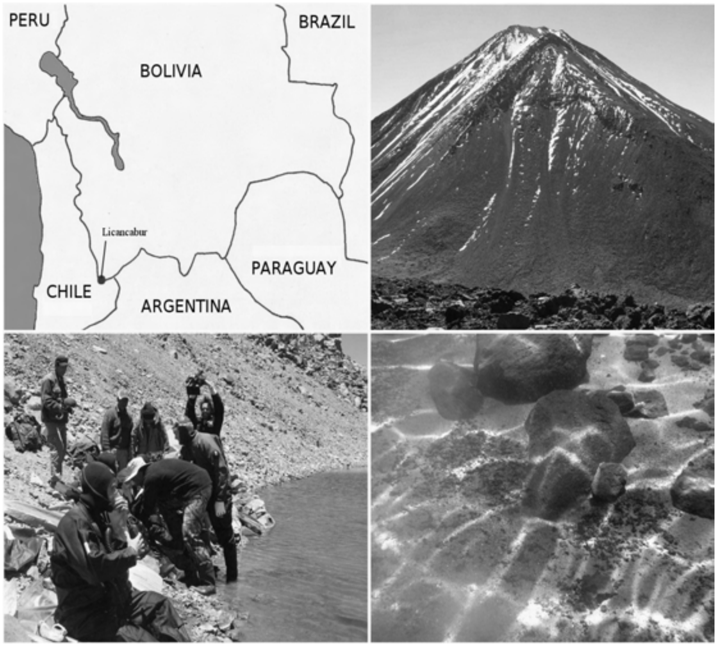

Figure 1. Clockwise from upper left: location of the Licancabur volcano, Licancabur as seen from Juriquès, a neighboring peak, the underwater environment of the summit lake (photo Clayton Woosley), and the dive staging

Special Challenges of Diving at Extreme Altitude

Absence of Safety Guidelines for Extreme Altitudes

Early surveys of the available literature revealed the absence of tested dive tables giving safe decompression and ascent rate limits above 14,000 ft (4,267 m) [Heine *et al.*, 2004]. Although the NASA Diving Safety Office extrapolated its own tables from US Navy tables, these were untested and were therefore treated with caution. Following the standard practice of rounding up to the nearest 1,000 ft (the daily high point of the team was 19,620 ft [5,980 m]) a maximum safe ascent rate of 14 ft·min^{-1} (4.3 m·min^{-1}) was calculated for altitude of 20,000 ft (6,096 m).

Maintaining Safe Ascent Rates

The calculated safe ascent rate of 14 ft/min (4.3 m/min) is extremely slow and it was determined through pool trials that most divers would be unable to reliably maintain it using fins and buoyancy control devices. To address this problem along with others, a novel diver suspension system was developed and tested, enabling divers to precisely control their depth and maintain safe ascent rates.

Combined Risk of Diving- and Altitude-related Illnesses

How does extreme altitude affect the incidence of diving illnesses? How does diving affect the incidence of altitude illnesses? The absence of statistics makes these questions difficult to answer. Because of the uncertainties, steps were taken to eliminate mechanisms of injury and otherwise mitigate risks wherever possible. Perhaps the most significant such step was the decision to dive on closed-circuit oxygen, which prevented the loading of tissues with inert gases while simultaneously mitigating risks stemming from hypoxia at high altitudes.

While supplemental oxygen can prevent and/or relieve the symptoms of acute mountain sickness (AMS), symptoms may then be exacerbated by its removal [Houston, 1980]. Concerns about diving on pure oxygen followed by a period of oxygen starvation upon exiting the water led to the planning of a transition period following each dive, during which divers rested on medical oxygen while being closely monitored for signs and symptoms of illness.

Hypoxia

Almost by definition, people become hypoxic at extreme altitudes. Although they may experience no illness, individuals at high altitudes show diminished physical and mental performance. Since diving can be physically demanding and requires alertness for safety, the effects of hypoxia pose a serious danger that increases with altitude. The HLP dive team addressed this danger both by using 100% oxygen for diving and by carefully scripting and rehearsing all diving-related activities.

Health and Safety: Concerns, Prevention, and Response

Health and safety planning consisted of anticipating potential problems and defining preventative measures, in-the-field responses, and a plan for evacuation to advanced medical facilities. Baseline prevention consisted of rigorous medical screening prior to departure and daily health monitoring in the field for early detection of developing problems before they could become emergencies. Daily medical statistics included blood oxygen saturation, blood pressure, heart and respiratory rates, weight, and responses to subjective questions.

Altitude Illnesses

Altitude illnesses comprising AMS, High Altitude Pulmonary Edema (HAPE), and High Altitude Cerebral Edema (HACE) are caused primarily by hypoxia, though the physiology behind individual susceptibility is not well-understood [Wilkerson, 1992]. HAPE and HACE, both life-threatening conditions, can be thought of as advanced forms of AMS. The best prevention is proper acclimatization and the only effective treatment for advanced illness is immediate descent or equivalent re-pressurization.

Primary preventative measures included a rigorous acclimatization regimen and close monitoring of all team members for signs and symptoms. Secondary measures included avoidance of overexertion by climbing slowly, maintaining a high-carbohydrate diet while on the mountain, and adequate hydration. The team developed an acclimatization program similar to those implemented by other mountaineering expeditions, including a multi-stage ascent over 10 days, modified diet, and medication with acetazolamide.

The previously mentioned concerns regarding re-exposure to the oxygen-depleted atmosphere following a dive on 100% oxygen were addressed by introducing an oxygen transition period into the dive plan. Divers exiting the water would transition from their rebreathers onto medical oxygen, which could then be regulated to slowly reintroduce them to the hypoxic conditions at the summit. During this period divers would also be closely monitored (visual/verbal, blood oxygen saturation, and vitals) for any signs of deteriorating health.

Individuals experiencing mild to moderate symptoms of AMS would make an accompanied descent to base camp, using supplemental oxygen if needed. In the event of advanced altitude illness, the sick individual would either walk assisted or be transported by litter down to the base of the mountain at 14,800 ft (4,511 m) and then evacuated by vehicle from there. In the event of unforeseen delays in transporting a seriously injured party, the team carried a Gamov bag which could be pressurized to roughly the equivalent of a 7,000 ft (2,134 m) descent and then carried down.

Accidents Due to Hypoxia
At altitudes approaching 20,000 ft (6,096 m), some degree of hypoxia is unavoidable. The accompanying decline in physical and mental performance increases the risk of accidents resulting from fatigue, inattention, and poor judgment. Prevention consisted of highly detailed written procedures covering every aspect of diving operations, well-rehearsed and familiar to everyone on the team. In theory, divers breathing pure oxygen could not be hypoxic and were therefore at no risk of its effects for the duration of the dive.

Diving Illnesses and Injuries
When diving on closed-circuit oxygen, nitrogen and other inert gases are purged from the breathing loop save in small amounts. Loading of tissues with inert gases is therefore not possible, eliminating one of the principal mechanisms behind DCS. An ambient absolute pressure of less than 1 atm at the deepest point in the lake (16 ft [4.9 m]) meant that the risk of Central Nervous System (CNS) oxygen toxicity was also small. The risk of pulmonary oxygen toxicity, which occurs with long-term exposure at relatively low pressures, was mitigated by limiting dive duration to 45 min or less.

The main concern among diving illnesses was arterial gas embolism (AGE) due to rapid ascent. As previously mentioned, maintaining the calculated safe ascent rate of 14 $\mathrm{ft \cdot min^{-1}}$ (4.3 $\mathrm{m \cdot min^{-1}}$) was problematic. This and other problems led to the development of a diver suspension system that both enabled precise depth control and enabled the diver to return to depth quickly even in the event of accidental release of a weight belt. Extensive pool practice with these systems habituated divers to ascending at a rate well within the safe limit.

Using rebreathers introduced the risks associated with failure or improper use of equipment, including hypoxia, hypercarbia, hypocarbia, and chemical injury. It was decided that, with sufficient training, careful maintenance, careful testing of oxygen sources, and careful handling and storage of CO_2 absorbent, these risks were small in comparison to the margin of safety gained.

Divers were to work closely together in groups of two or three. The level of coordination their activities required would make it obvious if one of the divers became incapacitated or was experiencing serious symptoms. In such an event, able divers would commence a rehearsed rescue procedure to bring the injured diver to the surface and return to the staging area. Once there, the dive master would begin treatment and would decide whether evacuation was necessary.

In the event of an AGE, the patient would be administered supplemental oxygen and evacuated immediately. Likewise, field treatment for hypoxia and hypercarbia consisted of supplemental oxygen. A diver with hypocarbia would be calmed and encouraged to breathe slowly. Chemical injuries would be treated by having the diver rinse his/her mouth with water and then drink water to dilute stomach contents. Squeezes, including those caused by middle ear oxygen absorption would be treated with a combination of decongestants and valsalva.

Exposure and Hypothermia

Hypothermia was a risk for all personnel on the mountain, but diver's exposure to near-freezing water followed by exposure to freezing air and potentially high winds on the surface made the risk particularly serious for them. Moreover, the tendency for people to become dehydrated and hypoglycemic at high altitude added to the concern since both conditions increase a person's susceptibility. Risk was mitigated by using dry suits and sufficiently warm undergarments, limiting dive times to prevent overexposure, adequate food and water, and post-dive rewarming in a tent with bottles of warm water.

Emergencies Requiring Prompt Advanced Medical Care

The remote location of the dive site limited our access to advanced medical care. It also meant that self-rescue was the only option for the team in the event of an emergency. It was estimated that transporting an injured party down the mountain and then to the nearest hospital and hyperbaric facility would require a minimum of eight hours. Transportation to the hospital was complicated by the need to cross the border from Bolivia into Chile. This minimum time estimate assumed excellent logistical support from below, good communications with base camp, and a litter or backboard on hand at the site of the injury. Had any of these assumptions proved false, the actual evacuation time would likely have been significantly longer.

Equipment

Each diver was equipped with a rebreather unit, dry suit, undergarment, neoprene hood, gloves, mask, fins, and a suspension system comprising a buoy, tether, and weight belt. Additional equipment pertaining to sampling and documentation was distributed to divers according to their roles and included mesh bags containing sample bottles, a digital still camera, a video camera, a GPS unit, and a tape measure. Safety equipment at the staging area included a throw line, medical oxygen, a medical kit, a Gamov bag, and a tent and stove. A complete check list of all diving-related equipment was created and used prior to equipment portage and again upon arrival at the dive site.

Aqualung CODE Rebreather

The CODE (Compact Oxygen Diving Equipment) rebreather is an extremely simple, compact, light, and durable closed-circuit oxygen rebreather unit used mainly for military applications. Oxygen is injected into the counter lung by a demand valve and carbon dioxide is removed from the system by a canister containing a soda lime absorbent. Prior to use, the breathing loop must be purged of gases other than oxygen and carbon dioxide. Closed-circuit oxygen rebreathers have a distinguished history in mountaineering and were used with great success by Hillary's 1953 Everest ascent team (Hunt, 1954).

Accurate knowledge of one's breathing gas is fundamental to safe use of any closed-circuit system. To this end, a small certified bottle of oxygen was obtained in advance from a facility in Santiago, Chile. The certified bottle was used to calibrate a hand-held gas analyzer with which larger volumes of gas obtained near the dive site were tested.

Although the CODE was a major asset to diving safety, there were some disadvantages in using it. Since the system is completely closed there are no bubbles, making divers difficult to locate from the surface or in poor visibility. Also, the oxygen bottles contained only a small volume of gas, 0.6 L/2030 psi, so a separate air cylinder would be required in order to use a buoyancy compensator (BC) for depth control. These issues and others unrelated to the CODE were addressed by the diver suspension systems described below.

Table 2. Summary of rationale for CODE rebreathers

Advantages
- mitigates high-altitude hypoxia
- avoids loading of bodily tissues with inert gases
- oxygen is indicated for any diving or altitude illnesses
- compact and light-weight

Disadvantages
- not conducive to BC usage (insufficient gas for BC inflation)
- no bubbles – lost divers may be difficult to find
- cannot surface and talk without re-purging the rigs
- consequences of failure or improper use of equipment

Diver Suspension System

The difficulty of maintaining safe ascent rates and the need to hover above the soft lake bottom while working motivated the development of a novel Diver Suspension System (DSS), which allowed the diver to hang suspended at any depth (Figure 2). The DSS consisted of a buoy, adjustable tether, and modified weight belt connected together with locking aluminum carabiners. Buoys were constructed using inner tubes and nylon chord, while tethers consisted of 20 ft (6 m) off-the-shelf cam-buckle straps. A taught line running from hip to hip on the weight belt allowed the diver to adjust his roll angle from left to right. Divers were weighted to be about 10 lbs heavy, requiring between 40 and 60 lbs of lead per diver. Having weights evenly distributed around the diver's waist made it easy to maintain the desired roll angle.

In addition to enabling precise depth control, the DSS addressed several other safety concerns and technical challenges. The overhead buoy served as a marker for tracking divers from the shore, a platform for GPS tracking of sampling locations, a reference for depth measurements, an attachment point for equipment, and an emergency float. The configuration of weight belt and tether served to mitigate the risk of rapid ascent and AGE following accidental release of a weight belt. Although releasing the belt would detach the diver from the DSS, the belt and tether would remain connected and would still provide a viable up/down line. In the event of an accidental release, the diver could grab the tether to stop an uncontrolled ascent, or use it to quickly return to depth afterward. These advantages were felt to strongly outweigh the disadvantages listed in Table 3.

Table 3. Summary of rationale for diver suspension systems

Advantages
- precise control of depth and ascent rate
- ability to hover over work site with no up/down drift
- easy tracking of divers from surface
- mitigated danger of losing a weight belt
- enabled GPS tracking of sampling locations
- provided a place to clip and keep equipment
- provided a reference for depth measurements
- buoy could serve as an emergency float
- materials are cheap and easy to obtain almost anywhere

Disadvantages
- some added complexity over a BC and/or fixed ascent line
- risk of tangling
- inability to dive under ice
- transportation of extra weights to dive site

Using the DSS required some training for efficiency, but was otherwise straight forward. Downward depth adjustments could be made by pushing the button on the cam buckle and allowing the tether to extend. This could be done easily with one hand while maintaining a downward-facing orientation and working with the other hand. Upward adjustments were made by pulling on the tail of the tether and were facilitated by the 2:1 mechanical advantage inherent in the configuration (Figure 2). Because of the relative ease of moving downward, dive profiles were planned from shallow to deep water. At the end of a dive, divers would slowly ascend and would release their weight belts when they reached the surface. The entire system, with the belt hanging just underneath the buoy, could then be either towed back to shore or left for retrieval.

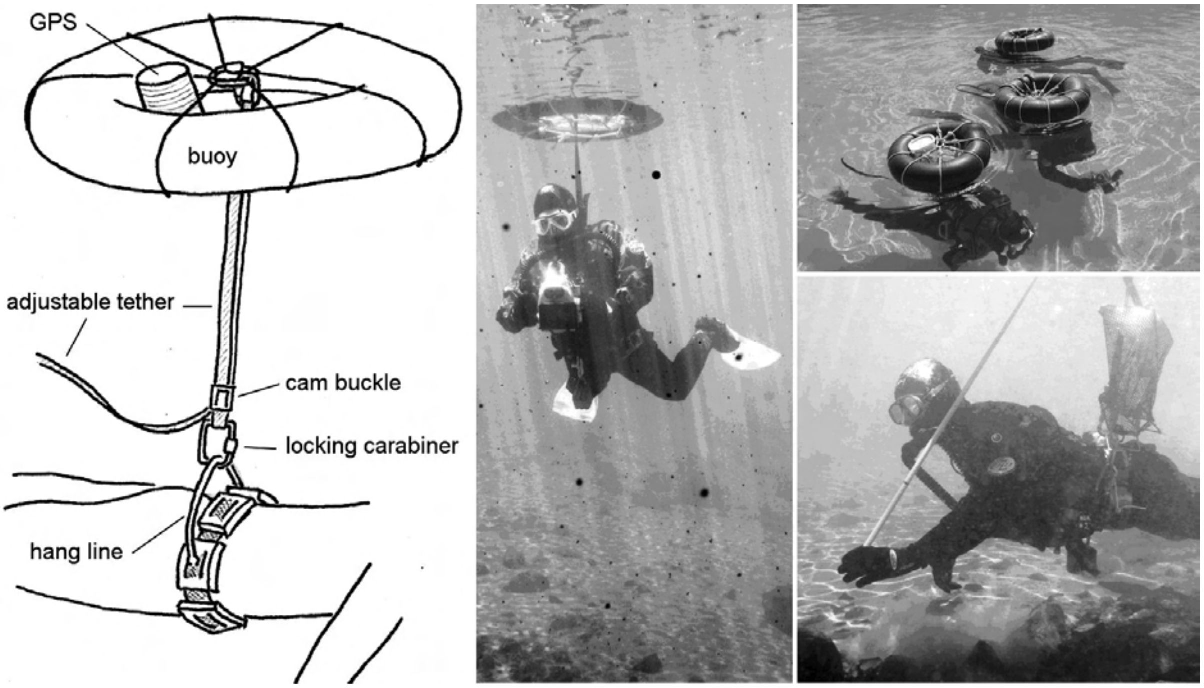

Figure 2. Diver suspension system (photos Clayton Woosley and Christian Tambley). *All photo credits The High-Lakes Project: NAI/SETI CSC/NASA Ames Research Center*

Diving Safety Limits

Quantifiable diving limits for the HLP dive team included ascent rates (Table 4), oxygen diving tables (Table 5), and limits for safe usage of the rebreathers. Ascent rates were extrapolated from existing navy tables using the formula

$$\text{Altitude Rate} = \text{Sea Level Rate} \times \exp(-0.0381 \times \text{altitude}/1000\text{ft}).$$

Table 5 gives oxygen exposure limits for single depth dives. Although these limits prove safe for the vast majority of divers, certain individuals succumb to oxygen toxicity even when maintaining them [U.S. Department of the Navy, 2005]. Because of the remote setting and extreme altitude the HLP planned very conservative dive profiles, limiting dive times to 45 minutes or less.

Safe use of rebreathers required aviation-grade oxygen (99.5% O_2) in order to avoid build up of impurities in the counter lung leading to hypoxia. The brand of CO_2 absorbent used by the HLP was selected mainly for its specified storage temperature range (-30°C to 50°C). Absorbent materials exposed to temperatures outside of the recommended range should not be used. The lifetime of a single canister was estimated to be roughly 60-90 minutes depending on work load and diving environment.

Sampling Technique

The dive team consisted of a lead diver responsible for collecting samples from the lake bottom, a sampling assistant whose job was to photograph both the sample sites and (numbered) sample bottles just prior to collection, and a third diver using a video camera to document the dive and the environment. A GPS unit set in tracking mode was placed in a waterproof container and clipped to the lead diver's buoy prior to diving. By synchronizing the internal clocks of the GPS and the assistant's digital camera, one could later determine where the lead diver was when a particular photo was taken (digital image files contain a time stamp). The latitude and longitude of each sample site was obtained using this technique.

Table 4. Ascent rate limits as a function of altitude.

Altitude (ft)	**Pressure** (atm)	**Ascent Rate** (ffw/min)
0	1.000	30.9
1,000	0.963	29.7
2,000	0.927	28.6
3,000	0.892	27.6
4,000	0.859	26.5
5,000	0.827	25.5
6,000	0.796	24.6
7,000	0.766	23.7
8,000	0.737	22.8
9,000	0.710	21.9
10,000	0.683	21.1
11,000	0.658	20.3
12,000	0.633	19.6
13,000	0.609	18.8
14,000	0.587	18.1
15,000	0.565	17.4
16,000	0.544	16.8
17,000	0.523	16.2
18,000	0.504	15.6
19,000	0.485	15.0
20,000	0.467	14.4

Table 5. Single depth oxygen exposure limits per 24 hour period.

Depth	**Maximum Oxygen Time**
25 fsw	240 min
30 fsw	80 min
35 fsw	25 min
40 fsw	15 min
50 fsw	5 min

Determining the depth at which a given sample was taken was done differently for the first and second dives. The approximate depths of sample sites from the first dive were recovered by correlating the GPS position with a bathymetric map of the lake obtained via sonar prior to diving. On the second dive, a pre-marked tape measure was attached to the overhead buoy and was used to sample at precise depth intervals.

To obtain a sample, the lead diver would indicate the desired location by pointing and removing an empty sample bottle from his/her bag. After the sampling assistant had photographed the number on the top of the bottle and the undisturbed site, the lead diver would turn the bottle upside down and carefully remove the top, preventing the air inside from escaping. The bottle was then scooped down into the bottom material and turned upright, effectively sucking the material into the bottle. The bottle was then recapped and returned to the bag.

Procedures

Highly detailed written procedures and checklists were developed as the dive plan evolved. These documents served as scripts during training and then again as references in the field to prevent errors and oversights in the hypoxic high-altitude environment. Table 6 illustrates the level of detail that was characteristic of procedural planning. Written procedures covered dive preparation, activities in the water, post-dive activities, emergencies and other contingencies, and some aspects of operations management.

Training

All dive team members underwent 32 hours of training on the CODE rebreather under a USIA diving instructor. All team members were certified in medical oxygen administration.

Extensive pool training was an important factor in both dive plan development and diver safety. The pool served as a test bed during development of procedures, techniques and equipment. Integrated tests were done in the form of simulations of both planned dives.

Table 6. An example of the level of procedural detail typical of dive planning

Dive Preparation

1. Prepare tent with bags/blankets, warm clothing, and thermos
2. Prepare diver suspension systems
   (a) assemble buoy (inner tube, cord, and carabiner)
   (b) attach knotted yellow line with a carabiner
   (c) set up cam strap with locking carabiner and attach to buoy
   (d) set up weight belt (marked weights, front carabiner, hip-to-hip hang line)
3. Pre-dive CODE units (refer to CODE pre-dive checklist)
4. Prepare medical O_2 cylinders at entry/exit point
5. Prepare cameras, GPS, sonar, and sample bottles (10 for each dive)
   (a) record times of camera and GPS clocks and/or image the GPS clock with the still camera
   (b) set GPS to tracking mode
   (c) seal GPS unit in a dry bag or dry goods container
6. Attach GPS, sonar, cameras and sampling bottles to buoys and place buoys at entry/exit point
7. Diver's don dry suits, CODEs, weight belts, gloves, hoods, and masks
8. Dive Master dons dry suit
9. Dive Master performs final gear checks:
   (a) layering (vest, CODE, weight belt)
   (b) check for good vacuum and good seal at canister insertion
   (c) straps (have diver rotate)
   (d) mouthpiece (orientation, hose attachment, zip tie, head band)
10. Dive Master turns on O_2, checks, and records pressure
11. Dive Master walks divers through purge protocol, ensuring proper execution
12. Divers breathe O_2 for two minutes before entering water
13. Dive Master checks each diver's alertness and either gives or denies permission to enter water

Dive Execution

The only major setback suffered by the expedition occurred one day before departure for South America when a key member of the team was medically disqualified from both diving and climbing above base camp. The approved dive plan included contingency plans for such an event and called for a redistribution of roles and responsibilities on the mountain. This in turn required additional training and pool simulations to familiarize team members with the changes.

The team was fortunate to find access to pool facilities in Chile where training was completed. Three 20-minute dive simulations were performed using the same equipment and procedures used for the summit dives. Changes to the original dive plan included reassignment of roles and responsibilities and assignment of an assistant to each diver to help him/her get suited up and in the water.

A full evacuation plan was established in the field prior to deployment up the mountain. The plan was based upon experience from previous non-diving expeditions to the area, advice from local points of contact including the Bolivian National Park Service (SERNAP) and the contracted in-country logistics manager. The plan included the identification of local and regional medical services. With the help of the Divers Alert Network (DAN), provisions were made for specialty medical care for divers, including chamber identification and access. General transportation logistics were arranged, including provisions for all-wheel drive vehicles that could accommodate a stretcher. A companion communications plan was framed utilizing anticipated local resources in the region.

The evacuation plan was revised and improved to account for unanticipated complications involving access to vehicles and nonexistent services and capabilities, *e.g.* access to advanced medical care 24/7, and communication equipment. Unanticipated were the problems with crossing international borders by certain types of licensed vehicles. The nearest medical facility was a local clinic that operated on an irregular business hours basis. However, a more substantial hospital 60 miles (100 km) away would have been needed to treat any serious or off-hours medical emergencies. Chamber access turned out to be via a local mining company, which operated on a limited schedule. Contact was never established with the local diving medical officer referenced by DAN. The communications plan integrated the use of identified local radio, which proved to be unreliable. Our satellite phone proved to be the only reliable means of communications.

Equipment was assembled at base camp and prepared for portage to the dive site. The majority of the load was distributed over eight hired porters who made daily trips to the summit, pre-staging much of the equipment before the team's ascent. The remainder, including CO_2 absorbent, cameras, and other sensitive electronic equipment, was carried by expedition team members on their ascent to the summit. Absorbent was carried by diving team members who ensured that it was never exposed to temperatures below the specified threshold of -30°C.

In accordance with the acclimatization plan, the team ascended from base camp at 14,200 ft (4,328 m) to a mid camp at 17,700 ft (5,395 m) on November 16. On November 17 they ascended to the summit camp at 19,300 ft (5,883 m). November 18 was spent setting up equipment and doing science in the crater. The first and second dives were carried out on November 19 and 20, respectively. The team descended to base camp on November 21.

Dive Day I

A morning medical assessment indicated that all divers were fit to dive. The team arrived in the crater at 0900. After staging equipment at the entry point, divers suited up and entered the water at approximately 1030. In the first few minutes of the dive it became obvious that one of the divers was too buoyant. The divers returned to shore, made the necessary adjustment, and re-entered the water. Sampling and documentation proceeded as planned, although the team wasn't able to cover much ground before succumbing to cold. The maximum depth was approximately 2 m and the total bottom time was 31 min. Average oxygen consumption during the dive was 58 bar from a 0.6 L bottle.

Dive Day II

The team arrived in the crater at 0900. Divers entered the water at approximately 1100. At the beginning of the dive the lead diver experienced some vertigo and mild nausea due to unequal vestibular stimulation by frigid water after rolling on his side. Samples were taken at depth intervals of 0.5 m starting at 1.5 m and continuing to the deepest point reached at 4.5 m. Total bottom time was 25 min. Diver's surfaced near the center of the lake, detached from the DSSs and towed them back to shore. All divers were fatigued and cold and two experienced mild headaches during the transition to medical oxygen. Divers recouped in the tent for roughly one hour under the supervision of the Dive Master. Average medical statistics for the oxygen transition and recuperation period are shown in Table 7. Average oxygen consumption per unit of dive time was similar to day one (actual data was not logged due to divemaster tasking overload, a lesson learned) and average post-dive medical oxygen consumption was roughly two D-size cylinders per diver.

Table 7. Average post-dive medical statistics for the three divers in the aftermath of dive II. Time begins when all divers are out of dry suits, in the tent, and on medical O_2. Average blood pressure (BP) is given as average systolic pressure over average diastolic pressure. Respiration rates were determined manually, BP and heart rate with a digital wrist BP cuff, and blood oxygen saturation with a fingertip pulse oximeter. Note the dramatic drop in oxygen saturation following the removal of medical oxygen.

Time (min)	**Blood Oxygen** (%)	**Heart Rate** (bpm)	**Blood Pressure** (mm Hg)	**Resp. Rate** (bpm)
0	96	101	120/89	17
18	*Off Medical O_2*			
20	80	99	137/86	19
33	80	96	124/83	19
53	78	104	127/86	19

Conclusions

The scientific research requirements to manually obtain samples at this unique high-altitude site required the development of unique diving equipment, training and the extrapolation of existing tables. A number of lessons were learned through the experiences of the High Lakes Project, which led to the following recommendations for projects considering similar constraints and environments.

Diving teams which must operate in such extreme environments require specialized training in disciplines outside of normal diver training, *e.g.*, high altitude acclimatization techniques, advanced medical care, general survival techniques for long term field site occupation and the development of an extensive set of plans and procedures.

All the elements of the dive plan (equipment, procedures, and techniques) must be tested in as high a fidelity simulation as possible. Contingency operations must be planned for, options defined, tested and exercised for each element. The plans must consider the remoteness, time to obtain or access advanced medical care and provide for self-sufficiency as much as possible. Assumptions must not be made for local support availability. Communications plans must be exercised in advance. Special consideration must be made to assure that facilities necessary for emergency operations are contacted in advance and all aspects of availability are confirmed: hours of operation, staff availability, limitations of services, transport time, etc.

The success of any expedition in a remote location depends on the team's training and cross training. The expedition must have sufficient depth to absorb the loss of a member and personnel must be ready to perform functions outside of their normal skill set. This is especially important when considering the multiple stresses experienced by team members diving in an extreme environment. Even the most well trained team, armed with adequate planning must consider the variability of individual responses to the environment. Thus far there are no models that can predict how an individual will respond physically or psychologically to extreme environments. This is especially true at 20,000 ft (6,096 m).

Finally, no expedition should rely solely only on its internal knowledge base. A review of all the elements, science requirements as they drive data gathering, training, planning, and logistics, by external experts can provide mission-critical insight.

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