EXPLORATION OF MONO LAKE WITH AN ROV: A PROTOTYPE EXPERIMENT FOR THE MAPS AUV PROGRAM

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ABSTRACT

This paper describes a field experiment to explore Mono Lake using the Telepresence Controlled Remotely Operated Vehicle (TROV). This experiment was a prototype study demonstrating the science capabilities defined for a new AUV planned for development by a consortium project called MAPS.* The goal of the experiment was to study mineralization processes associated with thermal and non-thermal spring inflow into Mono Lake, a hypersaline, alkaline lake in eastern California located in a volcanically active area.

TROV is a tethered ROV, which can be controlled using a virtual reality-based user interface. TROV's video capabilities included a matched pair of stereo video cameras on a rapid pan and tilt platform and a single fixed downward pointing camera. Additional capabilities included high resolution 750 kHz pencil beam SONAR and 1 MHz scanning SONAR for navigating in the murky water, instruments for measuring water column properties (C,T,D, pH), a syringe water sample, and a three function manipulator arm used to collect mineral samples and place them in a sample box mounted on the vehicle. TROV was navigated using a DiveTracker acoustic navigation system. TROV was deployed from the deck of a houseboat anchored above the field sites with control and data recording equipment also onboard. The boat's location was continuously recorded using differential GPS system during 10 days of field operations. TROV had a total of 38 hours of bottom time. We studied 4 sites including (1) a broad, gently sloping, ooze-covered mound SE of Paoha island with copious methane gas seeps, (2) shallow, tufa-coated pinnacles of volcanic origin associated with islets NE of Paoha Island, (3) subaqueous thermal springs located along the SE shore of Paoha Island, and (4) a deep area (~50m) E of Paoha Island.

* MAPS stands for the first initials of the collaborators in the project. MBARI, NASA Ames, Naval Postgraduate School, and Stanford University

1. Introduction

The development of Autonomous Underwater Vehicles will prove enabling the study of a certain class of scientific problems. One such problem is the study of hydrothermal vents in the deep ocean at the time when they are first manifested at the surface. Study of such phenomenon will require a rapid response vehicle, which can be deployed with days of the manifestation of a new vent. MAPS is a program with the goal of developing a light weight, portable AUV which can be used in a rapid response mode. MAPS, which stands for the first initials of the collaborators (Monterey Bay Aquarium Research Institute (MBARI), NASA Ames Research Center, Naval Post Graduate School, and Stanford University), plans to make a major step forward in developing and using an AUV for scientific field work.

In August 1995, the MAPS program performed a field experiment in Mono Lake, a hypersaline lake in eastern California. The purpose of this paper is to describe the Mono Lake field experiment as a prototype for the type of missions envisioned for the MAPS AUV. The experiment was performed with TROV, a tethered ROV, which carried the same type of science payload and performed the same type of mission that is proposed for the MAPS AUV. While Mono Lake has been the focus of considerable scientific study, our experiment was the first deployment of a Remotely Operated Vehicle in the lake. Previous underwater investigations have been performed by diving or by deploying instruments and sampling systems from the surface. The high PH and salinity make diving operations very unpleasant and dangerous. Buoyancy control in the lake water is very difficult due to strong thermal and chemical gradients, which occur in the lake. The high pH is very toxic to a diver's skin, eyes and nose. Thus, using an ROV in Mono Lake has yielded new scientific results while also serving as a prototype experiment for the MAPS program.

Mono Lake is a hypersaline lake situated in a terminal basin on the eastern edge of the Sierra Nevada Mountains, near Yosemite National Park. It covers 160 km2 and has a mean depth of 17 meters at an elevation of 1943 m [1]. Mono Lake is renowned for its unusual biology and geology. The lake is highly alkaline (pH ~10) and highly saline (80-100 ppt dissolved solutes) with large concentrations of carbonate, bicarbonate, chloride, and sulfate. Tufa towers on the shoreline of the lake are a national scenic attraction. These calcium carbonate structures precipitate where subaqueous freshwater springs bring Ca ions into the carbonate supersaturated lake waters. The lake hosts high microbial productivity which supports large populations of the brine shrimp Artemia monica that provide a rich food source for over a million migratory birds [1]. Mono Lake is also in a region where hydrothermal springs have developed in association with volcanic activity. Hydrothermal environments provide nutrient-rich habitats for microbial ecosystems because of the high rates of chemical effluents that remote bacterial growth. Where rates of mineralization are high, hydrothermal deposits can be excellent sites for microbial fossilization because precipitating minerals frequently entrap microorganisms, preserving biological information as characteristic biofabrics and geochemical signatures [2].

The scientific focus of MAPS is to study the chemistry, geology, and biology of hydrothermal environments. Hydrothermal environments are of interest because they are thought to have played a central role in the origin of life on Earth. Also, hydrothermal environments have almost certainly occurred on the planet Mars in the past, and may persist to the present [3,4]. They may also occur elsewhere in the solar system such as on various satellites of the outer planets Jupiter, Saturn and Neptune [5,6]. Thus they could be important sites to search for life elsewhere in the solar system.

Mono Lake was chosen for the first MAPS mission because it is a good analog environment for life on Mars. There is considerable geologic evidence for lakes on ancient Mars, which occupy enclosed basins [7] and therefore are likely to have been hypersaline, especially as they dried up. Enclosed basin lakes concentrate minerals, support rich microbial ecosystems, and typically exhibit high rates of mineral precipitation, which favors fossilization. They are therefore high priority sites for searching for fossilized evidence of ancient life on Mars [8,9]. By studying such environments on Earth, scientists are able to develop better strategies for searching for evidence of ancient life on Mars.

2. Science Objectives

The goal of the experiment was to study the formation of mineral precipitates associated with thermal and non-thermal springs in the lake. Our objective was to visit, sample, and determine the origin of positive relief (mounds or pinnacles) and negative relief (deeps) structures previously mapped by SONAR [10]. Our approach was to obtain video recordings and SONAR profiles of the areas studied along with in situ measurements of water column properties, water samples, samples of any mineralization structures encountered, and samples of sediments. We planned to use SONAR imaging to navigate in the murky waters of the lake, and to create SONAR profiles of underwater structures encountered. We also hoped to use SONAR to detect changes in fluid density as would occur from underwater springs.

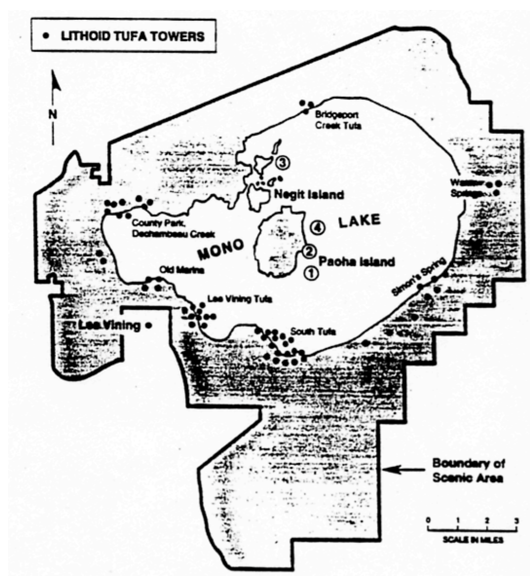

Figure 1. Schematic map of Mono Lake. The numbers show our study sites.

The first target area (Fig. 1, Site 1) of the study was a group of large mounded structures and deeps previously mapped by SONAR [10] in the deeper reaches of the lake, located south and east of Paoha Island along a major volcanic and hydrothermal trend that includes Mono Craters, Paoha and Negit Islands, and Black Point. SONAR maps [10] showed anomalously low densities in the water column above some of the mounds. Such anomalies could arise by differences in temperature, salinity, or from dissolved gases associated with volatile-rich fluids venting from the lake floor. One hypothesis to explain these observations was that the structures are tufa mounds formed by the precipitation of carbonate minerals at sites of sublacustrine springs. The shapes and sizes of the lake floor mounds as mapped were comparable to large, pinnacle-shaped tufa mounds found around the margins of Pyramid Lake. An alternative hypothesis was that the mounds and deeps are formed by volcanic and/or tectonic processes, and the density anomalies in the water column are related to thermal emanations and/or gas venting from upwarps of the lake floor.

Three other sites were visited (Figure 1 sites 2-4). In the second site, tufa coated pinnacles protruded above lake level. The primary objective at this site was to obtain samples of tufa from these structures along a depth gradient to study the mineralization processes and to determine if this tufa formation resulted in microbial fossilization. A secondary objective was to obtain SONAR profiles of the pinnacles. In the third site, we searched for (and found) subaqueous thermal springs. Here, the objective was to determine if mineralization accompanied the intrusion of thermal spring water into the lake. Thermal springs on the South shore of the lake are known to be non-mineralizing, and so are thermal springs along the shoreline of Paoha Island. However, subaqueois thermal springs had never before been investigated. Finally, the fourth site was chosen primarily to obtain measurements of water column properties and collect water samples in the deepest part of the lake.

<u>3. Equipment Description Capabilities</u>

For this study we used a tethered ROV called TROV [11] (Telepresence Controlled Remotely Operated Vehicle_ developed at NASA Ames using a modified Phantom S2 from Deep Ocean Engineering of San Leandro, CA. Figure 2 illustrates the TROV functions. Vehicle motion is controlled by four electrically powered thrusters. A 340 meter umbilical tether provides power to the TROV and a video and data link is provided via a fiber optic cable attached to the umbilical. A pair of high-resolution video cameras is mounted as a stereo pair at a human interocular distance on a rapid pan and tilt platform that can slew +/- 90 degrees at rates approaching that of the human head. The camera vergence angle is set so that stereo convergence is at about 0.75 meters so that stereo vision is focused in the manipulator arm work envelope. The system is designed to simulate human eye positions, head motions, and slew rates, which is important in operating the vehicle in a telepresence mode. The TROV also carries a downward pointing camera, mounted at the vehicle's center that is used to image the area directly below it.

The TROV was outfitted with a suite of instruments from Falmouth Scientific, Inc., that measured temperature, depth, conductivity, and pH in the water column. These were mounted below one of the vertical thruster propellers, to ensure a flow of water past the sensors. Water samples were obtained using an array of 8 syringes mounted on the top surface of the TROV that were pulled open with clastics under switched control from the operator.

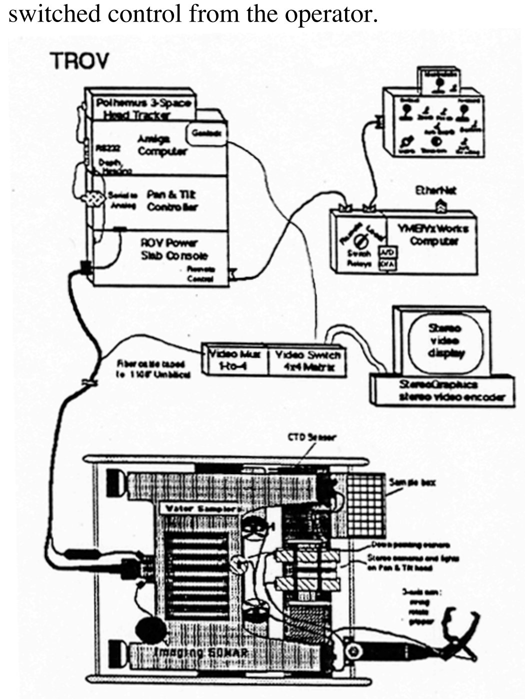

Figure 2: TROV components include: stereo pan and tilt cameras, downward point camera, 2 SONARs, manipulator arm with collection box, water column instruments, water sample collector.

A three function (swing, rotate, and grip) manipulator arm from Benthos, Inc., was mounted on the front of the crash frame that surrounds the TROV hull. Since the manipulator has few degrees of freedom, the operator typically uses the vehicle motion in conjunction with the arm. Indeed, one method used to collect samples of tufa was to get a good grip on a desired sample and drive the thrusters full astern to break it off. A box with a screen mesh bottom was mounted on the crash frame below the arm to hold collected samples. Since this box extended forward beyond the envelope of the crash frame, it was also able to function as a mud and sediment scoop although it was not originally intended for this purpose. The arm was mounted so that it could collect rocks when fully extended and drop them into the collection box when fully stowed. Both the box and the arm were mounted within the viewing envelope of the pan-tilt stereo cameras.

The TROV operator at the surface controls vehicle functions with joysticks while viewing stereo images on a StereoGraphics TM field sequential monitor. Other monitors display video from a camera selected by the operator (one of the stereo pair, or the down camera), the vehicle's track from the DiveTracker navigation system, and the scanning SONAR PC display. An Amiga computer is used to control the position of the pan-tilt camera platform by using the mouse to position a graphic icon, as well as provide a graphics overlay on the video display that includes heading, depth, time camera position, and data from water column instruments. The Amiga also provided local data logging of all the video overlay data items.

An embedded VME chassis in the surface controller contains the 68030 computer running VxWorks, and peripherals to manage the control and data functions over multiple RS232 serial links. All TROV functions can be controlled remotely via Internet through a satellite link to this embedded processor. This mode of operation was demonstrated in the Antarctic in 1993 [12] but was not used during this Mono Lake mission.

3.4 DiveTracker Acoustic Navigation System

A DiveTracker DTX TM acoustic navigation system was used to pilot TROV. DiveTracker was chosen because of its versatility, small size and low cost. The system provides position data not only to the surface team but also to the mobile stations. DiveTracker also incorporates sensor data acquisition and SONAR telemetry capabilities.

The Mono Lake DiveTracker system consisted of a mobile station mounted on TROV, a surface station located aboard the houseboat, and two buoy-mounted baseline stations. A personal computer connected to the surface station served as the data display and entry device. The SONAR transducer (antenna) of the surface station in conjunction with the two baseline stations formed DiveTracker's SONAR baseline. DiveTracker determines the position of the mobile station(s) (in this case TROV) relative to this baseline by means of SONAR triangulation (Fig 3).

The DiveTracker remote stations were mounted on submerged buoys to provide a long baseline in a fixed reference frame. An alternative to mount a short baseline system by suspending the remote stations from the side of the support vessel was rejected because the reference frame moves with the boat, and the position accuracy (1% of baseline nominal) would have been much lower.

The Mono Lake mission presented navigation challenges because of the lake's unusual salinity. It is well established that sea water absorbs energy of passing sound waves due to a variety of chemical and mechanical processes [13]. This absorption becomes increasingly severe at higher frequencies. The TROV DiveTracker system operates at 34-41 kHz. At this frequency, seawater absorbs sound at a rate of about 5 dB per kilometer. 30 dB per km is reached at 100 kHz and absorption zooms to about 100 dB per kilometer at 300 kHz. While no absorption data is available for Mono Lake, we suspected that its hypersaline environment along with strong thermoclines and the mixing of fresh and salt water could make acoustic navigation difficult. SONAR propagation tests conducted prior to TROV deployment confirmed these suspicions. In the open ocean, DiveTracker signals decay to noise level at a range of around 1000 meters. In Mono Lake, the signals would (at times) completely vanish at a distance of as little as 100 meters. Shifting to a different location signals could be detected to a distance of over 300 meters. Strong fading was continuously present, the amplitude of which increased with distance. Based on these results, we estimate the SONAR signal loss rate due to absorption, reflection and refraction to bin the range of 50 to 500 dB per km at 34 kHz. This is at least at order of magnitude greater than in the ocean.

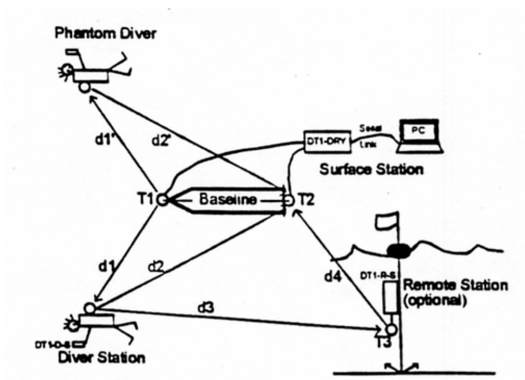

Figure 3. A typical DiveTracker system configuration used in Mono Lake.

Figure 4. shows a typical DiveTracker plot of a TROV dive at Mono Lake. The RADAR style screen represents the dive site. The barge mounted surface station is S0, at the center of the screen. B0 and B1 are the two buoy mounted baseline stations. TROV (DO) spent most of this two hour dive in the vicinity of the houseboat. It then moved to the bottom of the screen, where it is located in this snapshot. Displayed on the right is the mission's (inverted) depth profile. This data is relayed by DiveTracker as acoustic telemetry to the surface station. Clearly visible are the two vertical transects of the water column that were make to obtain profiles of water column properties.

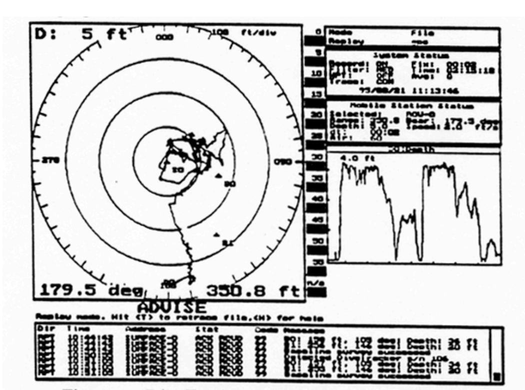

Figure 4: DiveTracker plot of a typical TROV dive. The scale is 100 ft/division.

The adverse SONAR conditions did not prevent DiveTracker from functioning. Indeed, the fine definition of the TROV track indicates good accuracy and the depth plot shows that telemetry was functional. The conditions did however mandate operations in rather tight bounds. While DiveTracker performs well in the ocean to a range of about 500 meters, contract with TROV at Mono Lake was not reliable beyond 150 meters. Even at close range, contact was at times lost and regained when TROV was moved a short distance.

3.5. Surface Control Station Setup

The control center for the TROV equipment was set up on a leased houseboat (dimension 15mx3m) in one day before the start of the experiment. The houseboat had two main compartments, a forward cabin with a kitchen and sitting area and an aft cabin with bunks. The pilot station was in the forward sitting area. The control equipment was set up in this area and consisted of the TROV control console, two video monitors (a StereoGraphics video monitor for viewing stereo video, and a video monitor for viewing a camera chosen by the pilot) and two video recorders. TROV functions are controlled via an Amiga computer and two IBM PC close computers were used for controlling the DiveTracker SONAR-based navigation system, and for controlling imaging SONAR. In the future, it would be preferable to have all the systems controlled by a single multitasking computer but for this experiment we did not have time to accomplish the necessary software development since DiveTracker and SONAR manufacturers provide PC based software for these systems.

The TROV tether was stored in loops on the front deck of the houseboat and was managed by hand. The TROV was stored on the rear deck of the boat where it was launched and retrieved using a boom and a hand-operated winch.

The DiveTracker Navigation system required that the surface control station remain at a fixed point. Thus the houseboat was kept on a 3 pt anchor. However, Mono Lake frequently experiences high winds, which come up quite suddenly. Fixed anchoring meant the houseboat did not swing into the wind, which put tremendous stress on the anchor lines. On two occasions we were forced to suddenly drop anchor and head for a sheltered location.

5. Highlights of Results

In 10 days of field operations we had 38 hours of bottom time with the TROV. During this time, we studied four sites (Figure 1), which are described below, along with the types of data obtained for each site.

5.1 Sites Visited

Site 1: The first field site was chosen to investigate and determine the origin of a large closed contour structure mapped by SONAR [10] and shown with a diameter of 120m and peak height above the lake floor of 18m. Nearby this structure, the map shows a line of smaller closed-contour structures along a N-S trend. Water density anomalies are also noted in this area. We identified several working hypothesis for the origin of these structures including tectonic origin, a cold spring origin, and finally, a possible association with the entry of hydrothermal water into the lake.

With some difficulty, we located the largest closed-contour structure by triangulating from landmarks at the surface using USGS topographic maps and then performing transects with a lead-line until a mounded structure in roughly the right area was found. However, this mound proved to be a broader, ooze-covered feature lacking the relief indicated on the map. Fine grained sediments covered the bottom and the TROV left an imprint several cm deep each time it hit bottom. There was also a flocculent substance on the sediment surface that appeared to be organic-rich detritus. There were cm-scale ripple marks in some areas indicative of periodic bottom currents. We discovered a cluster of small vent holes in the fine sediments, which lacked any evidence of microbial mat development or mineralization. The bottom sediments did not produce a SONAR return and the forward looking SONAR was not used for navigation. The study area had very strong gas venting and bubble trains were observed at the surface. Previous reports suggest this gas is methane [14] but we made no direct determination of composition. Imaging SONAR showed occasional ghosts, which we attributed to gas venting. In situ measurements of water column properties showed strong thermal and chemical gradients with temperature dropping from 20 C at the surface to 5 C at 20 m and below. In the deep water below the thermocline, the visibility was very low (<1/3 m) and there appeared to be suspended dark material.

We interpret this area to be tectonic origin and not related to tufa deposition or spring outflow processes.

Site 2: This site was an outcrop of tufa-coated volcanic rock located within an area of small islets between Paoha Island and the north shore of the lake. These islets consist of small, rubbly intrusions of dacitic volcanics that were intruded through the lake floor sediments. The site is located along the southern margin of a small spine of brecciated dacite about ten meters high that is coated with 2-5 cm of whitish-gray tufa. The houseboat was anchored between two islets formed of the same material. The target area was a small spine of volcanic breccia that forms two small pinnacles protruding about 10 m above the surface of the lake. Below the surface, the southeastern margin of the spine dropped off rapidly as a steep-sided, vertical outcrop that descended to ~15m where the margin was buried in an apron of fine-grained sediment. To the southwest, the subaqueous outcrops formed extensive ridges that dropped off steeply along their margins to depths of 10m or so.

The tufa-coated surfaces were covered by well-developed microbial mats that appeared to change color and texture with depth. There was no evidence for active spring discharge at the site and the tufa deposit coatings are believed to have formed by wave-induced outgassing, a process that accounts for tufa deposition along many of the shallow shoreline areas along the northern shores of Mono lake.

Visibility at Site 2 was several meters and we obtained good video images of surface outcrops and mats all along depth gradients. It was only where the TROV encountered the ooze covered bottom in deep water that visibility became poor. We also obtained SONAR imaging of the outcrops at close range, which were used for navigation, water column properties, and rock samples from depths of 10m, 5m, and 3.5m, in addition to a variety of sediment samples. The useful range of SONAR for imaging the rock outcrops at site 2 was found to be 2m or less. The high absorptivity of Mono lake water to SONAR was an unexpected result of this experiment, and is attributed to the high concentrations of salts in the lake water, but may have also been mitigated by high concentrations of plankton and clines in water density observed in the lake.

Site 3: This site is near the southeast corner of Paoha Island. (Fig. 1) Hot springs flow into the lake for at least 100 m along the shoreline where we found other thermal sources under water. Temperatures of thermal sources at the shoreline of Paoha Island ranged from 35C to 85C. Water samples taken from the onshore springs indicate that the thermal source water has lower salinity than lake water implying a freshwater source for the thermal springs. There are several active fumaroles along the ridge above the on-shore thermal springs. We determined the direction of the fault trend from these fumaroles and the on-shore springs and found offshore thermal sources underwater by driving TROV along that trend starting at the on-shore springs.

Underwater thermal vents were detected by changes in the water temperature and by schlieren patterns visible on the video record of the water column when pockets of warmer water were encountered. On some occasions, a SONAR ghost was observed in association with warm water pockets. Rock outcrops along the shoreline near the spring vents are only sparsely tufa coated, or not coated at all, and the shoreline shows a lower density of wave deposited tufa than can be seen at other locations on Paoha Island. There was no evidence of tufa formation or mineralization associated with the thermal springs where thermal water entered the lake bottom.

Data obtained at site 3 included water samples collected using a syringe sampler, in-situ measurements of water column properties, SONAR profiles of the hot spring area, small pebble samples (not tufa coated) obtained with the manipulator, and sediment samples. Most rocks in the area were volcanic cobbles too large to be grasped by the manipulator, but the dark color of the rocks also suggested they were not tufa coated.

Site 4: This site (Putnam Basin) represents the deepest part of Mono Lake, 50 m vs. 30-35 m maximum depth at the other sites. We obtained in situ measurements of water column properties along a depth gradient and water samples via syringe sampling device described above. As in other sites, a strong thermocline was observed in which water temperature drops from 20C at 10m to 5C at 20m then is isothermal below 20m. The turbidity of the water increases dramatically in the isothermal layer and visibility drops to near zero. We interpret this to be a pycnocline where fine biological ooze has accumulated. The bottom appeared to be soft sediments covered with a thin flocculent material that was easily disturbed when TROV impacted the bottom.

6. Conclusion: Lessons for the MAPS AUV Program

This field experiment represented the first time that the MAPS team worked together to perform a scientific experiment. The rigors of going out into the field with a new suite of equipment brought to light a number of operational issues and provided valuable lessons for the MAPS program. One of the products of the Mono Lake experiment was the development of team training protocols, job assignments, and prelaunch checklists for the TROV and auxiliary equipment. Again, field work provides a very rigorous test of these protocols.

Mono Lake was a surprisingly difficult environment for the use of SONAR, both for imaging and for navigation. Furthermore, we did not foresee the problems with the imaging SONAR and were not well equipped to diagnose them in the field. Effective maximum SONAR range at 750 kHz was approximately 2 m and, initially, we thought the imaging SONAR simply was not working. Further work will be needed to understand why Mono Lake water is so opaque to SONAR. Possible explanations include the strong thermal (and density) gradients and the high salinity and unusual salts composition. However, fur future applications of SONAR imaging in other environments, strong thermal and salinity gradients may also occur, so the use of SONAR-based imaging systems must be carefully evaluated with field testing.

DiveTracker acoustic navigation system operating at 34 kHz worked adequately in a relatively short horizontal range but because of the strong thermocline which produced a strong change in water density with depth, DiveTracker only worked consistently when the remote stations (mounted on buoys) and the TROV were in the same temperature water. This expedition served to emphasize that not all waters are alike when it comes to SONAR. Phenomena ranging from excessive sound absorption rates and multi-path propagation to underwater noise and path distortions have challenged SONAR engineers and operators since the technology's inception. Mono Lake showed that, while acoustic systems such as DiveTracker can be made to operate in difficult waters, they do so with restrictions of data throughput, range, accuracy and other performance parameters. Success is best achieved by carefully considering the SONAR environment when selecting, configuring and operating underwater acoustic systems.

Even with the difficulties encountered with the SONAR in the deeper water environments, we managed to learn a great deal about the structure on the water column and nature of the bottom of the lake at several key locations in the basin. We were able to test each of the hypotheses formulated in the pre-test planning with the following conclusions:

1) The slope and relief of pinnacle-like structures present in the high resolution SONAR maps [10] were not accurately represented, and are broad, ooze-covered features that are not related to spring outflows and tufa deposition processes. They are associated with extensive methane venting which may account for water column anomalies observed in previous SONAR surveys. We interpret them to be tectonic in origin formed by an upwarp of the lake floor sediments. Although the bottom of the basin in this region of the lake is probably ooze-covered, there is also evidence of active bottom currents in some areas, due to the presence of well-developed, cm-scale ripple marks.

2) Water column profiles indicate that both temperature and conductivity decline with depth. The likelihood of extensive freshwater spring inputs to the lake floor east of Paoha island seem unlikely although it is possible that some broad seepage from regional fracture systems contributes to the decline in conductivity with depth. Alternatively, it may reflect a stable density stratification based on temperature. Mono Lake is known to have long periods of meromixis with limited turnover [15]. Under such conditions, stable stratification can result from the downwelling of could, dense surface waters during winter months even though they are of lower salinity.

3) Tufa-coated pinnacle structures north of Paoha Island were found to be cored on volcanic spines that had been intruded through the lake floor sediments. The tufas were not associated in any clear way with springs. The extensive tufa coatings in the shallow shoreline areas north of Paoha Island represented by Site 2 are likely formed by wave-driven outgassing of CO_2, and not discrete spring outflows from vents. The extensive coatings on rock surfaces may also represent several generation so f lake level changes to account for their presence in deeper areas below probably wave base. These tufa-covered surfaces support extensive microbial mat communities that show differences in color and texture with depth that appears to relate to increasing light attenuation with depth.

4) Subaqueous thermal springs occur along the shallow shoreline east of Paoha Island in association with the dacitic plugs that formed the uplift of the island. Analysis of samples collected from the onshore thermal springs indicate that they are less saline than lake water, indicating that they are not fed exclusively by the recirculation of lake water but rather by freshwater input into the mid-lake thermal spring system.

The MAPS program has adopted an iterative process of development where engineering upgrades are followed by field trials and then upgraded further as a result of the learning experience in the field. Most AUV work to date has been done in the lab and tested in a shallow pool without much input from a science team. The rigors of field work will present a much tougher challenge for any AUV. Field environments will uncover unexpected flaws in design assumptions. Realistic system tests can be both difficult and expensive and thus there is a temptation to skip them. However, this is a bad mistake because once the AUV reaches the site of its intended use, problem solving and engineering changes in the field are frequently impossible. Teasing an AUV in the pool or on the lab bench, while important, must be augmented by field work in a field environment as close to the one the AUV is intended for as possible. Without this realistic field testing, an AUV program is unlikely to be anything more than an engineering exercise.

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